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# Fission-track analysis: principles, methodology and implications for tectono-thermal histories of sedimentary basins, orogenic belts, and continental margins *

P.A.M. Andriessen
*Faculteit der Aardwetenschappen, Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, the Netherlands*

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## Abstract

Fission tracks, formed by natural fission of $^{232}$Th, $^{235}$U and $^{238}$U, are damage zones in the crystal lattice. The decay constants of the first two isotopes are so small that, for all practical purposes, all fission tracks are derived from fission of $^{238}$U. The spontaneous fission-track (FT) density is proportial to the elapsed time and the uranium content. The latter parameter is determined by irradiation of the sample with thermal neutrons, causing the $^{235}$U-isotope to fission. A new set of induced fission tracks is made and the induced FT density is proportional to the amount of uranium, because the $^{235}$U/$^{238}$U ratio is constant. FT dating is commonly performed on volcanic glass and accessory minerals such as apatite, zircon and sphene.

Compared to other radiogenic age determinations, FT apparent ages are systematically younger, except for rocks that cooled rapidly such as volcanics and shallow-depth intrusives. Laboratory experiments show that fission tracks are not stable at high temperatures. This provides an explanation for the comparatively young FT ages and at the same time, opens a new important field of application: FT analysis as a geochrono-thermometer. Within a mineral-specific temperature range, fission tracks begin to anneal until they are completely erased at the high temperature boundary. The temperature, at which total annealing occurs, depends on the timescale of the heating event and the chemical composition of the mineral. Data from drill holes confirm the laboratory experiments over geological timescales. For apatite it is possible to establish an annealing zone for spontaneous fission tracks under geological time–temperature (T-t) conditions. Annealing is temperature-dependent and as the process progresses the length of the fission track shortens. This results in a reduction of the spontaneous track density and hence in a decrease of the FT age. The apparent age, single-age grain distribution, FT mean length and length distribution are diagnostic of the temperature histories of rocks. Recent advances in understanding annealing kinetics of fission tracks in apatite permit computer modelling of age and length parameters for given T-t pathways.

FT analysis thus constitutes a powerful and unique tool for the reconstruction of thermal, uplift and subsidence histories, and also for provenance studies of sediments. Particularly in hydrocarbon exploration, the application of fission tracks to the study of thermal and burial histories has proven the unique ability of the method in understanding the formation and evolution of sedimentary basins. FT analyses are also used for studying uplift, exhumation, unroofing, denudation and erosion histories of basement rocks. These parameters are important for our understanding of tectonic processes and for numerical modelling studies, because they constrain temperature histories in diverse geological settings like subduction and collision zones, extensional areas of continental breakup during rifting, and intra-plate settings.

## Introduction

Some 30 years ago a new geochronological method based upon the natural decay of spontaneous fission

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of $^{238}$U was introduced (Price & Walker 1962a, b). Today fission-track (FT) analysis is a well-established technique and the method is widely used in the earth sciences.

In the search for nuclear tracks in solids, tracks were detected in geological materials such as glass and minerals when heavy isotopes like $^{238}$U fissioned, producing fragments capable of penetrating the crystal lattice. It is beyond the scope of this lecture to explain particle track formation and relevant theories: the interested reader is referred to the works of Fleischer et al. (1975), Durrani & Bull (1987) and Wagner & Van den Haute (1992). However, a short introduction of the principles and methodology is essential to understand the application, interpretation and implications of FT analysis.

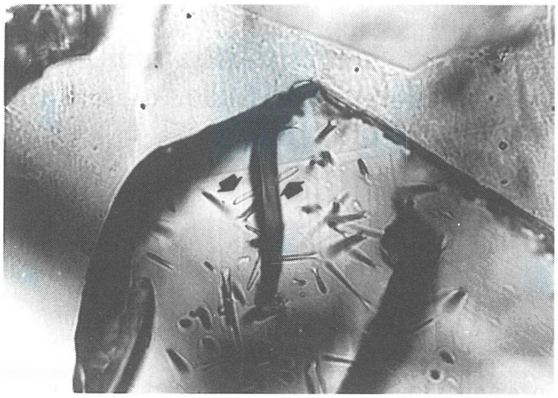

*Fig. 1.* Etched fission tracks in apatite. Also shown is a confined spontaneous fission track (see arrows) revealing its total length of 14 $\mu$m.

## Principles and methodology

The natural isotopes $^{232}$Th, $^{235}$U and $^{238}$U spontaneously fission. Each fission produces two heavy positively charged high-energy fragments that recoil in opposite directions. Along their path they strip electrons from the atoms in the lattice, forming a zone where the positive ions repel each other electrostatically. In this manner a track of lattice damage is formed. Only $^{238}$U produces a significant number of fission events. The other two isotopes have such long half-lives and/or their abundance is so low, that all natural fission tracks can be assumed to have come from $^{238}$U. It should be noted that $^{238}$U also decays by alpha-emission, and that millions of uranium atoms decay by alpha-emission for each atom that decays by spontaneous fission.

Natural fission tracks are only a few angstrom wide and between 10 and 20 $\mu$m long. Each fission track in a certain material has originally the same length. This length depends on the density of the material. In a more dense lattice the fission tracks are shorter than in a less dense one, because the reduction in travel velocity of the FT fragments through the crystal is determined by the probability of collision with atoms along their path.

Fission tracks are visible under an electron microprobe. Counting of fission tracks is done microscopically on internal crystal surfaces, that are set free by grinding and polishing after the material has been embedded in epoxide or teflon. The internal crystal surface represents a two-dimensional plane where fission tracks, derived from fissioned atoms distributed in a three-dimensional volume, are revealed by chemical etching. By choosing proper chemical etchants and using favourable conditions the damage zone is preferentially dissolved, while the bulk etching is kept to a minimum, and fission tracks become visible under an optical microscope with moderate magnifications of 500 to 1000 × (Fig. 1). It is clear that not only fission tracks are etched, but all kinds of crystal lattice damage. These so-called ‘spurious tracks’ should not be confused with true fission tracks. Fortunately, there are simple criteria to identify true fission tracks (Fleischer & Price 1964, Fleischer et al. 1975):

- fission tracks are line defects with a limited length,
- fission tracks are straight, and
- fission tracks do not have a preferential orientation.

### *Material*

The geological materials commonly and most frequently used for FT dating are volcanic glass and the accessory minerals apatite, zircon and sphene. Minerals and glass are concentrated by standard separation techniques, using heavy liquids and a magnet. The concentration must have a purity of about 80% for apatite, zircon and sphene. The quantity of sample needed for FT analysis depends on the rock type and the availability of sample material; 1 to 2 kg of sample is sufficient in most cases. For drill hole studies, core samples are preferred to cuttings, because of the danger of contamination. However, core samples are usually limited in quantity, necessitating good mineral separation facilities. The mineral grain size should be at least 60 $\mu$m.

### *Dating principles and techniques*

The principles of FT dating do not differ from those of other isotopic dating methods. The method is based upon the decay of $^{238}$U by fission and the accumulation of 'daughters', the fission tracks (Wagner 1968, Fleischer et al. 1975, Naeser 1979a). An FT density (tr/cm$^2$) is obtained by counting natural or spontaneous fission tracks per unit area. This density is proportial to the elapsed time and the uranium concentration. An accurate and easy way to determine the uranium concentration is to irradiate the sample with thermal neutrons. The bombardment with thermal neutrons causes the other isotope of uranium, $^{235}$U, to fission, inducing a new set of fission tracks. The induced FT density is proportial to the uranium content, because the natural relative abundance of $^{235}$U/$^{238}$U (= 7.2527 $10^{-3}$) is constant. For the details of the fundamental age equation, neutron fluence determination and standard age calibration approach, the reader is referred to the specific literature (Fleischer et al. 1975, Hurford & Green 1982, 1983).

To obtain an FT age two techniques are most commonly used (Gleadow 1981, Naeser & Naeser 1984). In the population method the concentrate is split into two parts and spontaneous and induced fission tracks are counted separately, and in the same material. This approach gives reliable results when uranium is homogeneously distributed and the material is known to originate from a single source (Fleischer et al. 1975, Naeser & Naeser 1984, Wagner & Van den Haute 1992, Ravenhurst & Donelick 1992). Glass, as well as apatite from most igneous and metamorphic rocks, is commonly dated with the population method. However, the distribution of uranium is not necessarily homogeneous in minerals such as zircon and sphene, nor in detrital minerals in sediments, where apatite, zircon and sphene may be derived from various sources. In these cases, the External Detector Method (EDM) is used whereby spontaneous and induced tracks are not counted in the same material. The spontaneous tracks are counted in the mineral grain itself and the induced tracks in the external detector, a muscovite of low uranium content or plastic. The mount with the mineral grains, where the spontaneous fission tracks already have been etched, is covered with the external detector and this 'sandwich' is sent to the reactor for irradiation with thermal neutrons. After irradiation the induced tracks are made visible in the external detector by the chemical etching technique. The induced tracks form an image of the mineral grain (Fig. 2a, b). The EDM technique permits the induced tracks to be counted from exactly the same area of the mineral grain where the spontaneous tracks are counted. The EDM technique has the great advantage that single grains are dated.

## Annealing and the implication for FT analysis

The damage in the crystal lattice is energetically metastable. This means that with time the disorder in the lattice will be restored. This process is speeded up when energy is supplied to the system. By increasing the temperature of the sample, the fission tracks present become shorter and eventually disappear completely. Because of the reduced spontaneous FT density the apparent age obtained will be younger. From the early days of the method it was noted that annealing of fission tracks in geological material is a common phenomenon. In comparison to other radiogenic age determinations, the FT apparent ages of igneous and metamorphic rocks in almost all cases turned out to be younger (Naeser & Faul 1969, Wagner & Storzer 1970, Calk & Naeser 1973, Wagner et al. 1977). Only rocks that were cooled rapidly after crystallization and that were not reheated significantly, yielded concordant mineral ages by various dating systems. Temperature is the main parameter controlling the annealing process, but chemical composition also influences the thermal retentivity (Green et al. 1989a). The annealing temperature depends on: a) the material involved, every mineral has its own annealing temperature, and b) the duration of heating. So, the amount of annealing achieved during a short period at high temperature is the same as during a long period at low ambient temperature. Annealing is a function of both time and temperature.

### *Annealing temperatures*

Laboratory experiments have established for many different materials the stability of fission tracks for various temperature–time (T-t) relationships. These experiments provided a ranking for the minerals according to the sensitivity of the fission tracks to temperature (Fleischer & Price 1964, Fleischer et al. 1965, 1975, Naeser & Dodge 1969, Wagner 1972a). In apatite, for example, the fission tracks are annealed at lower temperatures than in zircon. In sphene even higher temperatures must prevail. Extrapolation of the data to geological time conditions shows that for the miner-

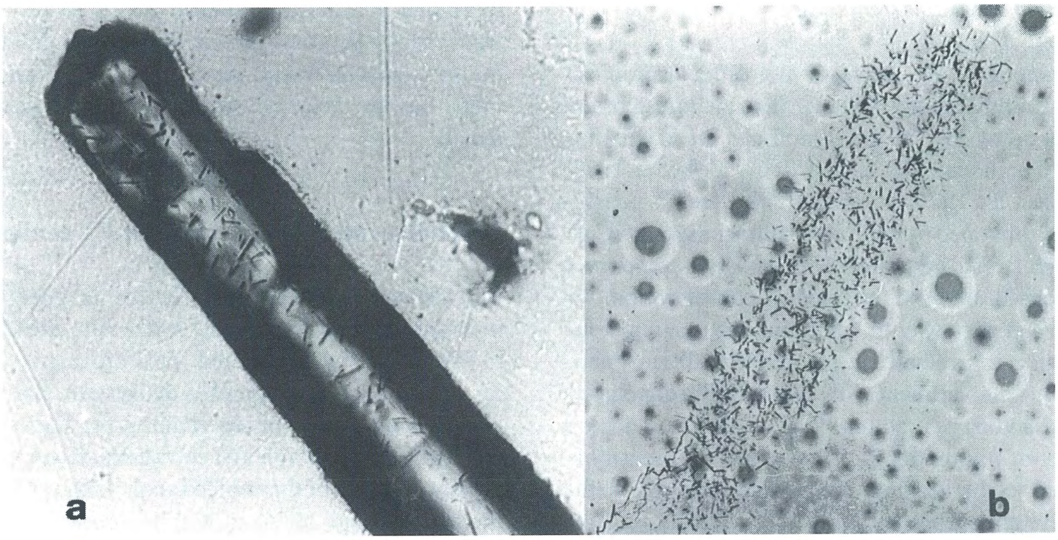

*Fig. 2.* External Detector Method. a: a zircon crystal with spontaneous fission tracks; b: the corresponding image of the external detector with induced fission tracks. The zircon crystal has a length of ca. 100 $\mu$m.

als commonly used for dating, annealing takes place at relatively low temperatures. Recent FT studies in drill holes with approximately known geological temperature histories not only supported, but improved the results of the laboratory experiments (Naeser and Forbes 1976, Naeser 1979b, 1981, Gleadow & Duddy 1981). The drill hole data narrowed the T-t conditions under which fission tracks in apatite are annealed. For instance, in the Otway Basin, Victoria (Australia), the variation of apatite FT apparent ages with depth in several drill holes documents that apatite ages begin to decrease significantly at about 60 °C and are completely reset at 125 °C. The effective duration of maximum heating in this sedimentary basin could be estimated on stratigraphic evidence to be some 30 Ma (Gleadow & Duddy 1981). For cases with a shorter maximum temperature duration, ($\sim$ 1 Ma), complete annealing is only achieved at higher temperatures, up to 140 °C (Naeser et al. 1990), whereas complete resetting is observed at lower temperatures, around 105 °C, when this maximum temperature is maintained for longer periods ($>$ 100 Ma; Naeser 1981). The annealing conditions are well-known only for apatite. Other commonly used minerals like zircon and sphene are less elaborately studied for their annealing characteristics under in-situ geological conditions, because samples covering the total annealing temperature zone require drill holes of more than 10 km depth. Estimates for the effective closure temperatures, i.e. the temperature where more than 50% of the formed fission tracks persist, do exist. For zircon the closure temperature can be taken at around 210±50 °C (Naeser 1979a, Zaun & Wagner 1985, Hurford 1986). For sphene, insufficient data are available, but the closure temperature must be higher than that of the zircon FT system and lower than those of the K-Ar and Rb-Sr biotite systems, because sphene yields intermediate ages in metamorphic and igneous rocks. A closure temperature for sphene is usually taken as 250±50 °C (Gleadow & Brooks 1979, Harrison et al. 1979).

### *Annealing characteristics*

From the foregoing it is clear that understanding the fading or annealing of fission tracks is crucial for the geological interpretation of the FT data. The main track-annealing properties can be summarised as follows (Gleadow et al. 1983):

- temperature is by far the most important parameter,
- annealing is T-t dependent,
- fission tracks do not abruptly disappear; there is a zone where partial annealing takes place before tracks are completely erased at the high temperature side,
- each mineral has its own specific effective closure temperature and partial annealing zone; the order of retentivity is apatite $<$ zircon $<$ sphene, and
- with increasing annealing the fission track length is shortened.

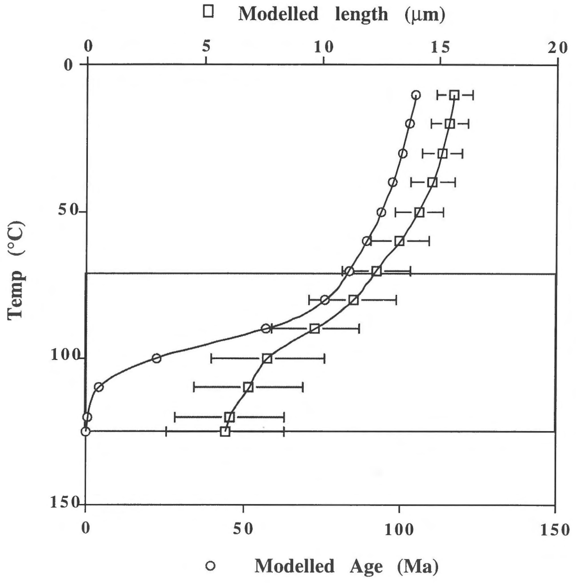

*Fig. 3.* Variation of fission-track age and mean length with temperature (depth) in an area with constant geothermal gradient. The shaded field refers to the Partial Annealing Zone, the zone with fast annealing rates.

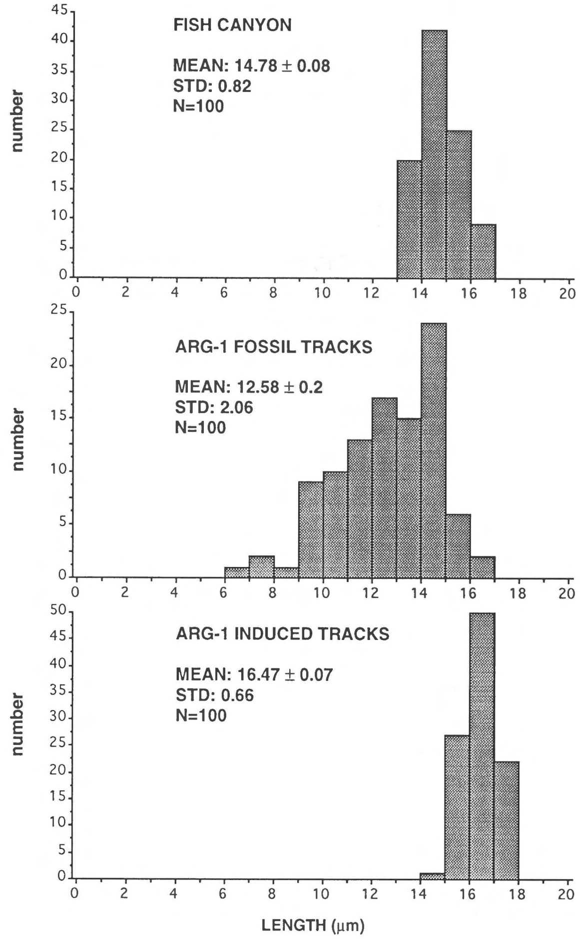

*Fig. 4.* Typical fission-track length distributions of apatite. The upper distribution is measured in Fish Canyon Tuff with a fast cooling history; the middle distribution belongs to a granite in Argentina with a continuous cooling history; the lower distribution is from the same Argentinian granite, but in this case the lengths of the induced fission tracks have been measured (Andriessen & Reutter 1994).

### *(Partial) annealing concept*

A diagram has been developed describing track stability as a function of temperature (Naeser et al. 1971, Wagner 1972b). This diagram is based on the occurrence of a temperature zone in which the annealing rate increases rapidly with temperature and where at the low temperature side annealing is very slow, and at the high temperature side 'instantaneous' annealing occurs (Fig. 3). The zone with increasing annealing rates refers to the Partial Annealing Zone (PAZ) of the older literature. The T-t evolution of the samples determines the annealing characteristics of fission tracks within the PAZ (Naeser et al. 1971, Wagner 1972b, Gleadow et al. 1983, 1986). In the case of fast cooling to (near-) surface temperature, the PAZ will be passed through rapidly and hardly any fission track is affected by the high-temperature annealing. The obtained age closely approaches the age of the cooling event and all the tracks are long, resulting in a narrow distribution. Examples are apatites from volcanic rocks and shallow-level intrusions. In the case of a slow and continuous cooling the sample remains some time (depending on the cooling rate) in the PAZ and gradually reaches the temperatures where annealing becomes very slow. Fission tracks formed in the PAZ have reduced lengths, resulting in a smaller mean length and a negative skewness of the distribution towards the smaller tracks. When the sample stays a long part of the total history at temperatures of fast annealing, a corresponding greater proportion of shorter spontaneous fission tracks is measured. The apparent FT age is younger than the original age and reflects a cooling age.

### *FT length shortening*

Fission tracks initially have a fairly constant length. For example, freshly induced FT mean lengths of about 17 μm have been measured in apatite (Donelick 1988, Donelick et al. 1990). Usually, the induced FT mean lengths range between 15.8 to 16.6 $\mu$m (Gleadow et al. 1986). The largest mean lengths of spontaneous fission tracks, about 14.5–15 $\mu$m , are measured in volcanic apatites (Fig. 4). Only tracks which are fully contained within the body of the mineral, the so-called confined fission tracks (Fig. 1), are used for length measurements. Laboratory experiments and drill hole studies clearly showed that with increasing temperature the average track length becomes progressively shorter (Green 1981, 1988, Gleadow et al. 1983). Thus, annealing of fission tracks is a process where with increasing temperature not only the track density is reduced, but also the tracks become shorter. The FT length distribution is used to estimate (palaeo)temperatures.

Fission tracks are not formed at the same time, but at different times throughout the history of the sample. So different groups of tracks of the total distribution may have experienced a different part of the total thermal history. For instance, tracks produced in the temperature zone with high annealing rates or older fission tracks undergoing these temperatures, will have reduced lengths. Fission tracks in the same sample that formed at a later stage in the history, when the temperature had decreased and annealing became slow, will have greater lengths (Gleadow et al. 1986).

### *Length distribution: a diagnostic tool for thermal histories*

Volcanic apatite that has cooled rapidly after crystallization and is not thermally disturbed, yields a characteristic distribution of FT lengths (Gleadow et al. 1986). The mean value lies between 14 and 15 $\mu$m, with a standard deviation of the distribution range between 0.8 and 1.4 $\mu$m and practically all tracks have lengths between 13 and 16 $\mu$m. Apatites from continuous cooling basement samples yield mean FT lengths that generally lie between 14 and 11.5 $\mu$m, independent of the age of the sample. The standard deviation increases with decreasing mean lengths, indicating a much broader distribution of measured lengths, and tracks smaller than 13 $\mu$m become more pronounced in this kind of distribution (Fig. 4). A distinct feature is the bimodal length distribution representing two components of fission tracks, one short and the other long. Less straight-forward distributions inevitably point to complex thermal histories.

### *Density - length relationship of fission tracks*

Apatites of different depths from deep drill holes experiencing their maximum temperatures, have been studied for their temperature–spontaneous FT length and their temperature–spontaneous FT density relationships (Green 1988). A one-to-one relationship in mean track length shortening and reduction of FT density (age) is predicted from a theoretical point of view. Fission tracks that are shorter are less likely to intersect the internal surface of the crystal, where counting and measuring is performed, than the original long tracks. The experimentally determined relationship between density and length shows a linearity in only a part of the whole annealing trajectory (Green et al. 1986, 1989b, Laslett et al. 1987, Duddy et al. 1988). Nevertheless, the existence of a relationship stresses the need to measure FT lengths before a proper geological interpretation of the ages can be made.

### *Computer modelling*

The relationship between FT length shortening and FT density reduction as a function of T-t conditions has been used to develop computer modelling programs (Laslett et al. 1987). In this way it became possible to simulate the accumulation of fission tracks as a function of time and temperature. Forward modelling generates ages and FT length distributions consistent with particular, well-defined T-t pathways. The generated data can then be compared to the actually measured data and coherent thermal histories may be deduced. In this way computer modelling facilitates prediction of FT age and length distribution in various tectonothermal settings. A different approach is using the measured age and length data to obtain best-fit thermal histories that match the data. When geological constraints obtained from well-established field observations are taken into account, the existing programs are very useful to limit the number of possible solutions. However, both the forward and the inverse modelling depend heavily on our understanding of the kinematics of annealing processes, which still require more fundamental research. Nevertheless, the models show quite clearly that temperature dominates the behaviour of FT annealing and that the geological interpretation of FT data depends essentially on the thermal history of the rock. In geology, cooling is associated with uplift (tectonic and/or isostatic) and exhumation, denudation, unroofing or erosion, and also with a change of a high to a low thermal gradient. Temperature increases in geology often mean subsidence and burial, metamorphism and magmatism, and of course a change of a low to a high thermal gradient. Thus a precise knowledge of the thermal history is essential for our interpretation of geological processes and mechanisms, now and in the past.

## Tectono-thermal implications and vertical movements

Rb-Sr and K-Ar mineral dating systems are used as geochrono-thermometers to establish cooling histories by analysing different coexisting minerals. Each mineral has its own characteristic closure temperature or temperature zone, above which the elements of the decay system can move freely in and out of the lattice structure (Dodson 1973). For fission tracks the same principle holds, because net accumulation of tracks only occurs when the temperature drops below the closure temperature. As pointed out by England & Molnar (1990) such cooling curves are the result of exhumation or denudation of the basement and not of tectonic uplift. Exhumation is defined as the process by which material is removed from the Earth's surface, accompanied by a rise in a deeper part of the crust. This process actually is the isostatic response of the terrain to the removal of material by erosion, keeping the elevation of the mean Earth surface or rocks unchanged relative to a reference frame. Uplift *sensu stricto* is defined as the vertical change in the mean elevation of rocks or the Earth's surface relative to a reference frame. The reference frame can be, for instance, sea level corrected for eustatic changes. The uplift of rocks in mountain belts is therefore the sum of tectonic uplift and the uplift caused by exhumation or denudation. FT analysis can differentiate between the vertical movements of rocks towards the Earth's surface due to denudational processes, and due to tectonic uplift (Brown 1991, Hejl & Wagner 1991). The basic idea is that horizontal or vertical sample profiles contain remnants of the fossil partial annealing zone, because they are 'frozen' when a critical denudation rate is exceeded. The base of this fossil PAZ can be readily identified on apatite FT age and FT length profiles. It corresponds to a distinct break-in-slope, both in age and mean length. The palaeotemperature of this break-in-slope point is 110–125 °C for the apatite FT system and the corresponding FT age approximates the time at which cooling began (Naeser 1979b, Omar et al. 1989, Lewis et al. 1992). The position of the 110–125 °C isotherm is controlled by the average palaeo-landsurface in that region and the prevailing geothermal gradient. The base of the PAZ, the break-in-slope point, therefore provides information on the amount and timing of vertical motions. The actual amount of the vertical change depends of course on the palaeothermal gradient.

Changes in the elevation of the Earth's surface are the product of a dynamical interaction between tectonics, denudation and sedimentation. Several mechanisms related to material fluxes in crust, mantle and asthenosphere, and to elastic effects of crustal loading may cause vertical movement, both upwards and downwards. Determination of the vertical component of movement is often more difficult than that of the horizontal component. Sedimentological and geomorphological studies and direct observation by geodetic measurements provide clues to detect the vertical component. FT analyses of both basement rocks and sediments provide unique information on the timing and rates of vertical movements, i.e. on the quantification of these processes. This analytical method is therefore crucial for our understanding of the dynamical interaction between asthenosphere, mantle and crust. Rocks at or near the surface contain unique information on processes and mechanisms occurring at deeper levels of the lithosphere and even the upper mantle. FT analysis is capable of deciphering this kind of information. Several examples demonstrate that FT analysis is a powerful tool to detect thermal histories related to uplift and subsidence events.

## Applications, examples from South America

### *Sedimentary basins*

The annealing characteristics of fission tracks in apatite are suitable to study thermal histories of sedimentary basins (Naeser 1979b, Naeser et al. 1989, Green et al. 1989a, Naeser & McCulloh 1989). Constraints can be defined for depositional, burial and uplift histories of the sediments, providing insights in the formation and evolution of the basin. The T-t range where annealing of fission tracks in apatite occurs covers the so-called 'window of oil generation'. FT analysis of apatite is therefore frequently used to assess the hydrocarbon potential of sedimentary basins (Gleadow et al. 1983). The locally occurring thermal anomalies and halos can be used to study ore mineralisation related to regional transport of hot fluids and/or to igneous intrusions (Shawe et al., 1986, Arne 1992).

The detrital minerals in the sedimentary rocks can also be used in provenance studies by determining the age(s) of the source(s). Because individual grains are dated, a wide spectrum of ages, reflecting different populations related to various sources, may be obtained. Comparing the age groups to the ages of potential source areas will allow palaeogeographic studies on both local and regional scale (Hurford et al. 1984, Naeser et al. 1987, Hurford & Carter 1991). Very interesting and promising results are obtained from sediments in accretional wedges, where the increase in temperature has not been enough to erase the fission tracks or where uplift of both the accretional wedge and the basement is registered by FT analysis (Brandon & Vance 1992).

In tephro-chronology FT ages of (especially) zircons, but also glass shards from volcanic ashes and their equivalents, are commonly used as time markers (Seward 1979, Hurford et al. 1984, Naeser & Naeser 1984, Westgate 1989). Tephra is rapidly deposited and may extend over wide areas, both in continental and marine environments. Tephra beds are therefore very useful as marker horizons for stratigraphic correlations; when properly dated, they become even more important. Any contamination, which particularly in volcanic ashes may be a problem, can readily be recognized by FT dating because single mineral grains are analysed.

As an example of the application to tephrochronology, the study in the Sabana de Bogota and surrounding area, Colombia, may be cited (Andriessen et al. 1993). The high plain of Bogota is an intramontane basin at a present altitude of 2600 m. The surrounding mountains of >4000 m belong to the Colombian Eastern Cordillera. The Neogene-Quaternary litho- and biostratigraphy and the palaeo- and depositional environments have been studied in detail, resulting in a coherent picture of the evolution of the basin in relation to tectonics, climate and glacial history (Helmens 1990). The biostratigraphy points to a major tectonic uplift of the Eastern Cordillera, because biozones I and II with tropical floras characteristic for altitudes of some 500 and 1000–1500 m, respectively, are now at elevations of about 2500 m. Ash layers exposed within these biozones were used for the FT dating of zircons. They yield ages of 5.3 and 3.7 Ma; evidence that between about 5 and 3 Ma ago, biozones I and II were uplifted by 1 to 2 km to their present altitudes (Andriessen et al. 1993). No FT analyses have been performed for the mountains of the Eastern Cordillera surrounding the Sabana de Bogota basin. However, in the Sierra de Merida area in Venezuela, the northern continuation of the Eastern Cordillera, as well as in the Santander Massif of the Western Cordillera, an uplift of the same order of magnitude as in Colombia has been registered in the Plio-Pleistocene (5–2 Ma ago) by FT analysis of apatite (Kohn et al. 1984, Shagam et al. 1984). The uplift took place along existing graben structures and a certain similarity in the late-stage evolution of both areas seems obvious.

A drill hole in the sediments of the high plain of Bogota (the Funza II drilling) reached the basement after a depth of 586 m (Hooghiemstra 1989). The cores contain several volcanic ash layers and eight were selected for FT dating of zircons (Andriessen et al. 1993). The oldest age of 2.7 ± 0.6 Ma was found at a depth of 506 m and the youngest age of 0.2 ± 0.1 Ma at a depth of 67.7 m. The age determination indicates that the development of the sedimentary basin of Bogota started before 2.7 Ma ago, most probably at around 3.5 Ma. The sedimentary record shows a repeated input of coarse-grained sediments, indicative of an important change in the depositional environment associated with a sudden cooling of the climate. Single-grain zircon FT analyses of an interlayered tuff bed date this climatic change at somewhat younger than 2.7 Ma (Andriessen et al. 1993).

### *Orogenic belt of the Eastern Cordillera*

Although the tectono-thermal history of the Eastern Cordillera of the mid- and northern Andean Mountain Range is very complex and not well understood, it is intriguing that zircons from various localities in the Andes have FT ages around 120–100 Ma; the Venezuelan Eastern Cordillera, the Santander Massif, the Sierra de Perija and Toas island (Kohn et al. 19984). This suggests that the geological history has at least in part been similar. The analysed rocks included Precambrian and Palaeozoic gneisses, Palaeozoic granites and early Mesozoic plutons and extrusive rocks, all older than the zircon FT ages. The interpretation is that the zircons stayed for a long period in the partial annealing zone before being finally cooled. If so, the ages would represent mixed ages, without any geological significance (Kohn et al. 1984, Shagam et al. 1984).

Zircon FT ages of two vertical profiles in the Garzón Massif of the Eastern Cordillera of Colombia range from about 715 to 89 Ma (Van der Wiel & Andriessen 1991). The dated samples come from the Precambrian basement consisting of 1.6 ± 0.3 Ga old augengneisses and 1.2 ± 0.09 Ga old granulites

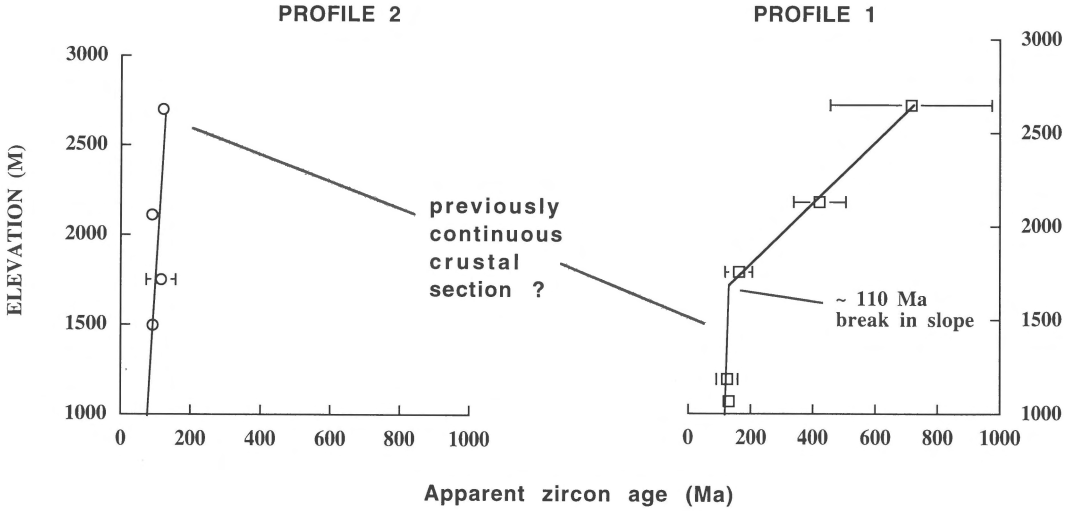

*Fig. 5.* Reconstruction of two vertical zircon age profiles from the Garzón Massif, sampled at a distance of about 50 km from each other in the Eastern Cordillera, Colombia, based on similarities in zircon FT ages. This reconstruction suggests a relative vertical displacement of ca 1.5 km between the two profiles since the Early Cretaceous.

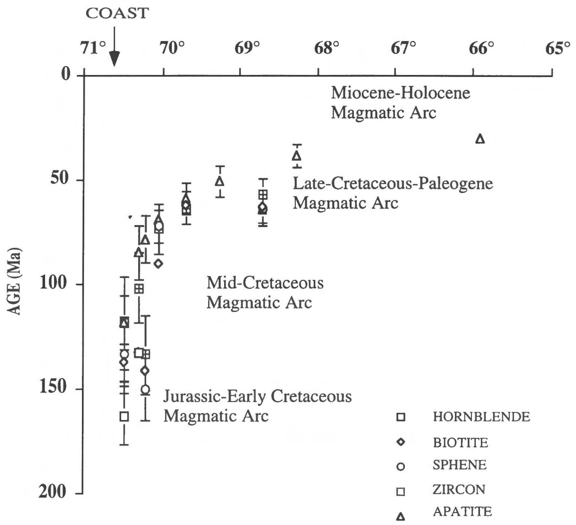

*Fig. 6.* West-East cross section along successive magmatic arcs of the Andean subduction regimes in Chile – NW Argentina (ca 23° S). The K-Ar (biotite, hornblende) and FT (apatite, sphene, zircon) mineral ages of igneous rocks become younger from west to east and this trend corresponds well in time and space with the position of the intra-arc stages related to the eastward propagation of the subduction regime. The concordance in K-Ar and FT mineral ages in various plutons indicates large amounts of tectonic uplift, locally exceeding 10 km (Andriessen & Reutter 1994). Crossed squares indicate zircon.

(Priem et al. 1989), and from Triassic–Jurassic intrusives. The profiles are situated at 50 km from each other, at present-day elevations of 1065 to 2650 m and 1495 to 2700 m, respectively. In the first profile the measured zircon FT ages decrease downwards from about 715 to 161 Ma in the upper 900 m, but in the next 700 m these ages remain constant at 125 ± 20 Ma. The other profile reveals zircon ages of 110 ± 20 Ma for the whole 1200 m. The zircon ages > 125 Ma are interpreted to represent partial annealing before the Early Cretaceous cooling episode. The concordant zircon ages of 110 ± 20 Ma over 1200 m in elevation indicate rapid cooling through the zircon annealing zone during the Early Cretaceous.

The occurrence of similarly old zircons (110 ± 20 Ma) in both profiles indicates that these rocks were situated at about the same crustal level before the Early Cretaceous cooling and uplift event. If this is true, rocks presently exposed in the upper part of the first profile preserve a less deep crustal section than the rocks presently exposed in the second profile. It is concluded that between the two profiles a differential vertical movement of about 1.5 km has taken place since the Early Cretaceous. The zircon FT age versus depth diagram shows the palaeo-PAZ (preserved in the upper part of the first profile) with a break-in-slope point at around 110 Ma (Fig. 5). Analogous to the interpretation of the apatite FT age pattern with temperature, the age of the break-in-slope point should correspond to the initiation of cooling and uplift. The existence of a pre-Tertiary partial annealing zone of zircon is also documented in the Eastern Cordillera of Bolivia (Benjamin et al. 1987).

This Mid-Cretaceous uplift is probably related to geodynamical processes. On a global scale the Mid-Cretaceous was a period of plate reorganization and high spreading rates. In northern South America, the Antilles Arc collided with the north-facing stable continental margin of Venezuela. The Galapagos hotspot, to the west of the South-American continent, burst into activity and erupted voluminous basalts. Spreading on the Farallon-Phoenix ridge ceased and spreading in the Equatorial Atlantic began, separating South America and Africa (Bonini et al. 1984, Burke 1988). Obviously, the zircon FT systems register the subsurface expressions of these processes and mechanisms at much deeper crustal levels or even in the upper mantle.

### *Basement rocks in an active continental margin*

In an elevation versus age plot, zircon FT ages in the Eastern Cordillera of Bolivia (Benjamin et al. 1987) reveal uplift rates of 0.1–0.2 mm/a for the period from 40 Ma to 20 Ma ago. A plot of apatite ages versus elevation shows higher uplift rates of up to 0.7 mm/a for the period from 15 to 5 Ma ago. As pointed out by Benjamin et al. (1987) the change of uplift rates may be related to a plate reorganization at about 25 Ma ago, when the Farallon oceanic plate fragmented into the Nazca plate and the Cocos plate (Pilger 1984). As a consequence, the angle of subduction became less steep and the convergence rate increased. The change in uplift rate may be related to the ensuing change in extensional and compressional regimes at the margin.

Another example is found in Northern Chile and Argentine, where subduction has been active since the Jurassic. The Palaeozoic basement, rocks and structures of the Central Andean Belt in this region along the 23° S latitude were tectonically, thermally and magmatically overprinted by the Meso-Cenozoic Andean Cycle. Figure 6 shows a schematic cross section of the positions of four magmatic arc systems that propagate eastwards through time:

- Jurassic–Early Cretaceous arc in the Coastal Cordillera,
- Mid-Cretaceous arc in the Longitudinal Valley,
- Late Cretaceous–Paleogene arc in the Precordillera, and
- the still active arc in the western Cordillera, which began in the Miocene.

K-Ar and FT mineral ages of the different plutons range from 530 to 30 Ma, the older ages coming from the Palaeozoic basement rocks and the ages younger than 200 Ma from intrusives related to the Andean magmatic arcs (Andriessen & Reutter 1994). The eastward trend of younging ages corresponds well in time and space with the position of the intra-arc stages related to the eastward propagation of the subduction regime during the Meso-Cenozoic Andean Cycle (Fig. 6).

The tectono-thermal histories of the igneous rocks as derived from the geochrono-thermometers indicate T-t pathways with periods of fast cooling corresponding to considerable unroofing. The Early Cretaceous unroofing of the Chilean Coastal Cordillera amounts in most cases to at least 5 km, and sometimes exceeds 10 km. These values are supported by geological field observations. From this study it could be concluded that strong tectonism accompanied the final stage of each magmatic arc system and/or initiated the succeeding magmatic arc system.

## Conclusions

FT analysis is a well-established analytical method with unique possibilities to study thermal histories of sedimentary and crystalline rocks. In sedimentary basins FT age determination on single grains yields valuable information on the provenance of the sediments and basin infill, which are important parameters for reconstructing the palaeogeography. The thermal, uplift and burial history of sedimentary basins can be quantitatively constrained, which is important for our understanding of basin formation and evolution. The method has a strong economic potential in the exploration of hydrocarbons and the recovery of ore deposits.

The method provides crucial information on uplift, subsidence, exhumation, denudation and erosion processes, both on local and regional scales. FT analysis of (sub)surface rocks records vertical movements of parts of the crust, in response to driving mechanisms at deeper levels of the lithosphere or the upper mantle. This information is essential for our understanding of tectonic processes and mechanisms, both current and in the past.

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