Apatite thermochronology in modern geology

F. LISKER[1]*, B. VENTURA[1] & U. A. GLASMACHER[2]

[1]*Fachbereich Geowissenschaften, Universität Bremen, PF 330440, 28334 Bremen, Germany*

[2]*Institut für Geowissenschaften, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 234, 69120 Heidelberg, Germany*

**Corresponding author (e-mail: flisker@uni-bremen.de)*

Abstract: Fission-track and (U–Th–Sm)/He thermochronology on apatites are radiometric dating methods that refer to thermal histories of rocks within the temperature range of 40°–125 °C. Their introduction into geological research contributed to the development of new concepts to interpreting time-temperature constraints and substantially improved the understanding of cooling processes within the uppermost crust. Present geological applications of apatite thermochronological methods include absolute dating of rocks and tectonic processes, investigation of denudation histories and long-term landscape evolution of various geological settings, and basin analysis.

Thermochronology may be described as the quantitative study of the thermal histories of rocks using temperature-sensitive radiometric dating methods such as ^{40}Ar/^{39}Ar and K–Ar, fission track, and (U–Th)/He (Berger & York 1981). Amongst these different methods, apatite fission track (AFT) and apatite (U–Th–Sm)/He (AHe) are now, perhaps, the most widely used thermochronometers as they are the most sensitive to low temperatures (typically between 40 and *c.* 125 °C for durations of heating and cooling in excess of 10^6 years), ideal for investigating the tectonic and climate-driven surficial interactions that take place within the top few (<5 km) kilometres of the Earth's crust. These processes govern landscape evolution, influence climate and generate the natural resources essential to the wellbeing of mankind.

This introductory chapter provides a brief overview of apatite thermochronology and its application to geological studies. We focus on three topics: (1) methodological developments; (2) concepts and strategies for the interpretation of thermochronological data; and (3) applications to various geodynamic settings. For more detailed insights on apatite thermochronology the reader is referred to published reviews by Green *et al.* (1986, 1989*b*), Laslett *et al.* (1987), Duddy *et al.* (1988), Wagner & Van den Haute (1992), R. W. Brown *et al.* (1994), Gallagher *et al.* (1998), Gleadow *et al.* (2002), Ehlers & Farley (2003) and Reiners & Brandon (2006).

Fission-track thermochronology

Basics of the method

Fission-track thermochronology/-chronometry (for differentiation cf. Reiners *et al.* 2005) is based on the analysis of radiation damage trails ('fission tracks') in uranium-bearing, non-conductive minerals and glasses. It is routinely applied on the minerals apatite, zircon and titanite. Fission tracks are produced continuously through geological time as a result of the spontaneous fission of ^{238}U atoms. They are submicroscopic features with an initial width of approximately 10 nm and a length of up to 20 μm (Paul & Fitzgerald 1992) that can be revealed by chemical etching. Crucially, fission tracks are semi-stable features that can self-repair (shorten and eventually disappear) by a process known as annealing at a rate that is a function of both time and temperature. The extent of any track shortening (exposure to elevated temperatures) in a sample can be quantified by examining the distribution of fission-track lengths.

The determination of a fission-track age (a number that relates to the observable track density) depends on the same general equation as any radioactive decay scheme: it requires an estimate of the relative abundance of the parent isotope and of the daughter product. However, unlike most methods of radiometric dating, it measures the effect, rather than the product, of a radioactive decay scheme, that is it refers to the number of ^{238}U atoms and the number of spontaneous fission tracks per unit volume. This fission-track density is obtained by counting the number of spontaneous tracks intersecting a polished internal surface of a mineral grain viewed under high magnification (1000×–1250×) using an optical microscope. Depending on the sample and aims of the study, a typical fission-track sample age consists of a weighted mean of 20–100 single-grain ages. Further details and background information on practical aspects of fission-track age determination are provided by, for example, Fleischer *et al.* (1975), Naeser (1979) and Donelick *et al.* (2005).

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An important dimension to fission-track thermochronology is the semi-stable nature of tracks, whereby annealing can change the significance of a measured age. The observable density of spontaneous tracks in a sample (age) is a function of track length (probability of intersecting the plane of observation). All newly formed tracks in apatite have a length of approximately 16 μm (*c.* 11 μm in zircon). If a sample (e.g. a volcanic apatite) was created at 10 Ma and then resided at low temperatures (<40 °C), the population of tracks reduces in length to a mean value of approximately 15 μm causing an insignificant (not resolvable) reduction in track density and a measured age within an error of 10 Ma. However, if, during its history, the same sample experienced elevated temperatures (but not sufficient to cause total resetting) in its history there will be significant track shortening to a level defined by the maximum heating. This will cause a reduction in observable track density and, therefore, measurable age.

Some milestones in the evolution of the fission-track method

Despite early recognition of fission tracks (Baumhauer 1894; Silk & Barnes 1959), it was not until the early 1960s that their application to geological dating was first proposed (Price & Walker 1963) and subsequently developed (Wagner 1966; Gentner *et al.* 1967; Naeser 1967). Early dating studies were tasked with finding practical ways to etch tracks, measure uranium contents that mirror the dated grain and define the time–temperature stability fields of fission tracks in different uranium-bearing minerals, tektites and glasses. Studies conducted between 1970 and 1983 highlighted the fundamental issues that needed to be resolved in order to enable routine and accurate age determination. Foremost was a lack of consensus on the value of the spontaneous fission decay constant for ^{238}U, to be used in the equation for age calculation. In order to circumvent this and other fundamental problems associated with the measurement of neutron fluence, Hurford & Green (1983) advanced a suggestion made by Fleischer and Hart at a meeting in Austria in 1971 for a comparative approach to AFT dating through the use of a proportionality constant. The resultant ‘Zeta’ calibration method (Hurford & Green 1983) has become the standard approach to fission-track age determination (Hurford 1990).

Until 1980 most fission-track ages were calculated using a pooled age, based on the ratio of total counts of spontaneous and induced tracks. However, Green (1981) highlighted the need for an alternative method for calculating an age when there is significant (or over-) dispersion within the population of single-grain ages. Green pointed out that where there is evidence for heterogeneity (extra Poissonian variation) within a dataset, detected by statistical tests such as χ^2 (Galbraith 1981), the conventional pooled age, based on the ratio of the number of spontaneous and induced tracks (N_s/N_i), with its Poisson standard error, becomes meaningless. An alternative approach based on the mean of ratios of individual track densities (ρ_s/ρ_i) was used to give a larger estimate of the error to allow for an extra-Poisson component in the dispersion of single-grain ages, but this approach implied a sample should have a single age. In reality, there are a number of different causes of heterogeneity within a dataset (beyond a bad experiment), such as variable responses to partial resetting due to variations in apatite grain composition (see later) and/or a range of provenance ages. Thus, it is important to assess to what the over-dispersion is due rather than make to allowance for it with larger errors.

In 1984 Hurford *et al.* proposed the use of probability density diagrams, a type of continuous histogram that plots each grain-age error as a Gaussian density function, as a way of visualizing a mixed age dataset. However, this type of approach can obscure useful information by inappropriately weighting it with poor information (i.e. an overlap effect associated with broad, imprecise, peaks). To overcome this problem Galbraith developed the radial plot (Galbraith 1988, 1990) (Fig. 1), which is now routinely used across the chronological community. Coupled to this development Galbraith & Laslett (1993) also produced the widely adopted random effects model that gives a central age estimate of the population of grains ages with a relative standard deviation of the population of ages known as the age dispersion (normally expressed as a percentage variation).

Having established protocols to measure fission-track ages and assess data quality and structure, the next major developments were related to understanding the significance of the determined ages. Whilst track-length measurement had been used to detect track annealing more or less since the methods inception, it was not until the mid 1980s that studies demonstrated the utility of such data. Advances included moving away from using semi-tracks (projected track) to length measurement based on surface-parallel confined tracks. Although more numerous, semi-tracks contain less information and have significant sources of bias, particularly towards longer lengths (Laslett *et al.* 1994). A key paper by Gleadow *et al.* (1986*b*) demonstrated the utility of confined track measurement and laid the foundation for data interpretation based on thermal history.

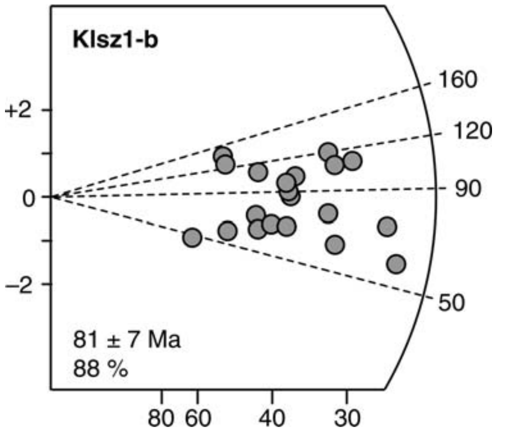

Fig. 1. Radial plots were designed to graphically display single-grain age estimates, taking into account different standard errors (Galbraith 1988, 1990; example from Ventura *et al.* 2009). Single-grain ages (z) with standard error, σ, are plotted (point x, y) according to x (precision) $= 1/\sigma$ and y (standard estimate) $= (z - z_0)/\sigma$, where z_0 is the central age. The error attached to each point is standardized on the y-scale. The value of the age (z) and the 2σ uncertainty can be read off the z-scale by extrapolating lines from point 0, 0 through the plotted age (point x, y) and projecting onto the radial age axis.

Contrary to other radiometric dating methods where the measured age equates to the time a sampled cooled below its closure temperature, the fission-track age records cooling through a temperature interval between total resetting of fission tracks and relative stability, known as the partial annealing zone or PAZ (Wagner 1979). The temperatures relating to the PAZ were defined by systematic investigation of the annealing of fission tracks across laboratory and geological timescales, monitored by changes in confined track-length distribution (Green & Durrani 1977; Gleadow & Duddy 1981; Laslett *et al.* 1982, 1987; Gleadow *et al.* 1986*a*; Green *et al.* 1986, 1989*a*, *b*; Duddy *et al.* 1988; Green 1988; Crowley *et al.* 1991; Carlson *et al.* 1999; Barbarand *et al.* 2003). Quantification of the time–temperature conditions that control the annealing of fission tracks in apatite provide the means to interpret fission track-ages by linking the level of track-length shortening and density (age) reduction to sample thermal history (e.g. Gleadow *et al.* 1986*b*). Typical temperature ranges for the PAZ for heating durations of 10^7 Ma are 60–110 °C for fluorapatite (e.g. Gleadow & Duddy 1981), 170–330 °C for zircon (Zaun & Wagner 1985; Yamada *et al.* 1995) and 265–310 °C for titanite (Coyle & Wagner 1998). Above the upper-temperature values fission tracks undergo total annealing, which removes all traces of fission tracks from the host crystal lattice.

Annealing studies recognized that track fading in apatite is not only governed by temperature, but also by heating duration, chemical composition and crystallographic orientation. Early descriptions of time-dependence on annealing were presented as Arrhenius plots, which generally had a fanning like form. Green *et al.* (1985) noted that fanning plots were probably the result of variable apatite grain composition, such that in effect these fanning plots were no more than a series of overlapping parallel plots. A series of isothermal fission-track annealing studies on apatites (Green *et al.* 1986; Crowley *et al.* 1990; Carlson *et al.* 1999; Barbarand *et al.* 2003) showed that substitution of fluoride and hydroxide ions by chloride ions appears to induce the greatest effects, although other substitutions on the halogen site can also have an influence but have proven much harder to deconvolve from laboratory timescale track-annealing experiments (O'Sullivan & Parrish 1995; Carlson *et al.* 1999). As a consequence of these studies, AFT data interpretation generally takes into account grain composition either by direct measurement of the Cl-content [generally by electron probe micro-analyser (EPMA)] or by assessing grain bulk composition by measuring the solubility of apatite through the c-axis parallel length of track etch pits ($D_{\mathrm{par}}{}^{\circledR}$ of Donelick 1991; Burtner *et al.* 1994; cf. also Murrell *et al.* 2009). Green & Durrani (1977) first described the influence of the crystallographic orientation of spontaneous fission tracks on the annealing of those tracks. Tracks orthogonal to the c-axis anneal more rapidly than tracks parallel to the c-axis (Green 1988). This anisotropy increases with annealing (Green 1981; Laslett *et al.* 1984; Donelick *et al.* 1990; Galbraith *et al.* 1990; Donelick 1991).

The developments outlined above (and many others not cited) have helped establish AFT analysis as a routinely used tool in geological studies, examples of which are published in this Special Publication. Methodological developments continue and it is now possible, following marked improvements in the precision of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) technology, to make direct measurements of uranium content within the counted grains of apatite, providing a fast and precise alternative to neutron irradiation (e.g. Hasebe *et al.* 2004, 2009). A further advance is the arrival of a functioning system for automatically determining the fission-track density and measuring fission-track lengths (Gleadow *et al.* 2009). This will not only increase speed and reliability of data acquisition, but also provides new options, especially with respect to the size (quality) of density and track length datasets.

(U–Th–Sm)/He thermochronology

The last decade has seen the extension of low-temperature studies to include AHe dating. Radioactive decay of the elements uranium and thorium to stable helium represents one of the earliest radiometric schemes available to geologists to investigate the ages of rocks and minerals (Rutherford 1905). Despite initial promise (e.g. Keevil 1943), the (U–Th)/He method was discounted as a dating technique until Lippolt *et al.* (1982) proposed its application as a low-temperature thermochronological tool. Zeitler *et al.* (1987) followed Lippolt *et al.*'s suggestion that, rather than defining a sample's age (implicitly its formation age), (U–Th)/He data provide useful constraints on the sample's thermal history, similar to AFT analysis, and further developed the technique. Fundamental experimental work by Farley and co-workers at Caltech through the 1990s resulted in the development of accurate and precise instrumentation for the extraction and measurement of helium. In practice, an AHe age is obtained by measuring radiogenic ^{4}He trapped in apatite grains by laser or furnace outgassing, and then measuring the relative amounts of uranium and thorium in the sample by solution ICP-MS. A careful selection of inclusion and crack-free idiomorphic apatite crystals with homogeneous U, Th and Sm distribution is essential for this procedure.

AHe thermochronology relies on the accumulation of ^{4}He during the α-disintegration of ^{238}U, ^{235}U, ^{232}Th, their daughter products and ^{147}Sm. The closure temperature (T_C) of mineral grains is dependent on activation energy, a geometry factor for the crystal shape, thermal diffusivity (D_0), the length of the average diffusion pathway from the interior to the surface of the grain and the cooling rate at closure temperature. In addition, ^{4}He diffusion in apatite is impeded by radiation-induced damage to the apatite structure. Therefore, the kinetics is an evolving function of time. The ^{4}He production–diffusion model predicts that the effective ^{4}He closure temperature of apatite will vary with cooling rate and effective U- and Th-concentration, and may differ from the commonly assumed T_C of 75 °C Ma^{-1} by up to ±15 °C (e.g. Farley *et al.* 1996; Wolf *et al.* 1996, 1998; Farley 2000, 2002; Shuster *et al.* 2006; Flowers *et al.* 2009; Shuster & Farley 2009). During radioactive decay alpha (α)-particles are emitted with high kinetic energy and travel significant distances. This poses a complication for the He dating method, as α-particles may be ejected out of the crystal being dated or injected from the surrounding mineral grains.

Farley *et al.* (1996) and Reiners *et al.* (2004) pointed out that implantation or ejection of α-particles may generally obscure (U–Th–Sm)/He dating, whereas He implantation needs to be considered if dealing with low U–Th–Sm phases. Therefore, Farley *et al.* (1996) propose a correction for these effects either numerically by correcting the measured He ages against the specific α retentivity (F_T) or by removal of the outer rim of the crystal (by chemical dissolution or mechanical abrasion) prior to dating. While correcting for α ejection has become a routinely performed practice in recent years, Spiegel *et al.* (2009) demonstrate the potential for possible overcorrection, indicating that abrading the outer rim of a crystal may be favourable. However, mechanical abrasion may lead to erroneous ages when crystals are strongly zoned with respect to uranium and thorium (Farley *et al.* 1996). In this case, a U–Th–Sm zonation-dependent α correction, as proposed by Hourigan *et al.* (2005), needs to be applied.

Usually, an apatite T_C in the range of 70 ± 7 °C (for a monotonic cooling rate of 10 °C Ma^{-1}, a subgrain domain size >60 μm, an activation energy of about 36 kcal mol^{-1} and a log (D_0) of 7.7 ± 0.6 cm^2 s^{-1}), and a He partial retention zone of between 40 and 75 °C, are assumed. The He production–diffusion model relies on homogenous distribution of U, Th and Sm in secular equilibrium, He loss confined to volume diffusion, and spherical diffusion geometry. Meesters & Dunai (2002*a*, *b*) generalized a production–diffusion equation to diffusion domains of various shapes and arbitrary cooling histories. Their set of equations allows α ejection corrected ages to be calculated and accounts for the non-homogeneous distribution of U, Th and Sm.

Preliminary studies on the applicability of (U–Th)/He thermochronology on zircon and titanite suggest closure temperatures about 80 and 130 °C higher than for apatite. These systems have the potential to close the gap between the various mineral diffusion temperatures of the ^{40}Ar/^{39}Ar thermochronological system, and the zircon and titanite fission-track annealing temperatures on one side, and AFT and AHe on the other side (e.g. Farley 2002; Reiners & Brandon 2006; Dobson *et al.* 2009). Moreover, (U–Th)/He analysis of magnetite (T_C: 200 °C/10 Ma) opens new perspectives for dating volcanic rocks (Blackburn *et al.* 2007).

Modelling of low-temperature thermochronological data

Recovery of thermal history information from AFT and AHe datasets is contingent upon a quantitative understanding of how the combination of time and temperature controls fission-track annealing and helium diffusion. Early attempts to use AFT data to track cooling were based on qualitative indicators (e.g. Wagner & Reimer 1972; Gleadow *et al.* 1986*a*, *b*): samples with a single population of long track lengths indicate rapid cooling in contrast to slower and/or stepped cooling paths, which result in shorter and/or more complex length distributions. However, this type of approach limits interpretation to relative rates of cooling and provides no constraints on timing or temperatures. With the advent of annealing studies, algorithms were formulated to describe the time–temperature dependencies of track annealing. The models based on laboratory experiments were extrapolated to geological timescales and verified against well-constrained data from the geological record. The first and, previously, most widely used model (Laslett *et al.* 1987) describes the annealing behaviour of a single type of apatite (Durango). With the realization that annealing is also influenced by grain composition, new experiments extended the annealing database. Carlson *et al.* (1999) published the first multi-kinetic annealing model. In 2007 this model was updated to include the dataset of Barbarand *et al.* (2003) and improved data-fitting techniques. The new multi-kinetic model, now in wide use, is based on 579 experiments and 26 compositionally different types of apatite (Ketcham *et al.* 2007).

Equipped with quantitative descriptions of track annealing it is possible to extract sample thermal histories by using forward or data inversion modelling techniques. Early programs focused on forward modelling data to check annealing models against well-constrained geological examples (e.g. Green *et al.* 1989*b*) and as a guide to the interpretation of real samples (e.g. Willett 1992). However, forward modelling is not a very efficient means of finding solutions for unknown or poorly constrained samples and, since there is no unique solution to a given dataset, such an approach is open to user bias. Data-driven inverse modelling helps to reduce this bias. Most commonly adopted and publicly available AFT modelling programs are Monte Trax (Gallagher 1995, designed for Apple Macintosh), AFTINV (Issler 1996; Willet 1997), AFTSolve (Ketcham *et al.* 2000) and HeFTy (Ketcham 2005, all Windows). These programs differ in modelling approach (Monte Carlo and/or genetic algorithm), annealing models, input parameters and statistical tests to evaluate the level of fit between model results and observed data (cf. Ehlers *et al.* 2005; Ketcham 2005). Some of the modelling programs refer only to AFT data, whilst others derive cooling histories from combined AFT, AHe and VR data (e.g. HeFTy). DECOMP (Meesters & Dunai 2002*a*, *b*) is a popular program to model thermal histories from AHe data. Most recent developments in modelling include a strategy for modelling sample thermal histories jointly (Gallagher *et al.* 2005) and the use of Markov Chain Monte Carlo (MCMC) methods to address the problem of characterizing uncertainties in modelled thermal histories in two and three dimensions (2D and 3D) (e.g. Stephenson *et al.* 2006).

Some concepts in apatite thermochronology

Methodological advancements were accompanied by the development of new strategies for the interpretation of thermochronological data, as the derivation of time–temperature constraints and the conversion of temperature information into geological and geomorphological processes.

Fission-track age types

An important part of fission-track thermochronology relates to using the distribution of measured track lengths in a sample to determine whether the measured age directly records an ‘event’ or a more complex thermal history. Early on in the AFT methods developmental history Günther Wagner suggested a classification of AFT ‘ages’ as *event ages*, *cooling ages* and *mixed ages* based on sample thermal history (Wagner 1972).

According to this concept, an *event age* refers to a rock that cools rapidly through the PAZ (e.g. a volcanic rock) and resides at low, near-surface, temperatures thereafter. The AFT age is essentially identical to the age of entrance into the PAZ, and is associated with a narrow distribution of track lengths about a mean value of 15 μm. Slow linear cooling of a sample through the PAZ produces a *cooling age* that is significantly younger than the entrance into the PAZ, with a broader and shorter track-length distribution. Such a pattern is relatively common in old basement terrains that have undergone cooling over very long periods of geological time. *Mixed ages* refer to an at least two-stage cooling history, in which the first generation of tracks resides at relative higher temperatures within the PAZ, prior to final cooling to lower temperatures. The resulting track-length distribution in such cases is typically bimodal with a short peak representing the higher temperature tracks and a second, long peak being added after final cooling. Crucially, both *cooling* and *mixed ages* have no direct significance in terms of the timing of any geological event.

Uplift, exhumation and denudation

With the availability of low-temperature chronological data, the resolution of cooling events improved considerably, and it became possible to analyse increasingly younger and shallower processes. Early AFT studies usually interpreted

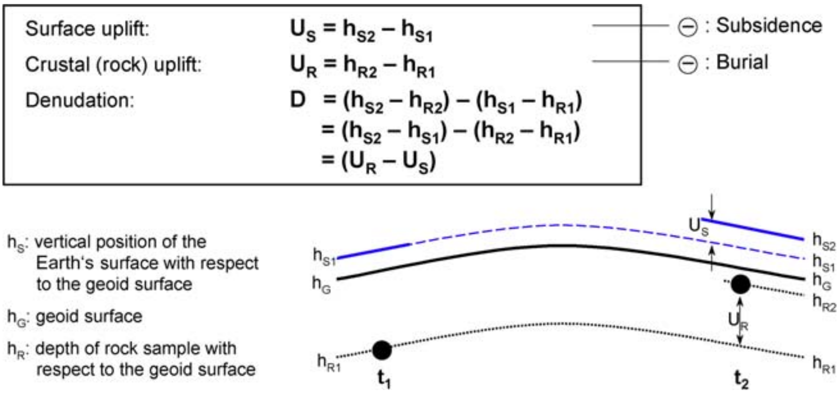

Fig. 2. Sketch illustrating the relationship between surface uplift, crustal (rock) uplift and denudation (see the text for definitions). Abbreviations: h, elevation; R, rock; S, surface; t, time.

cooling patterns in terms of 'uplift and erosion'. However, as this interpretation implicitly assumes that 'uplift' will always be matched by an equivalent amount of 'erosion' (cf. Parrish 1983), a much more precise usage of terminology was required. Terms like denudation, erosion, exhumation and uplift (surface, crustal and rock uplift) were (re-) defined by England & Molnar (1990), and explained further by Summerfield (1991), Summerfield & Brown (1998) and Ring *et al.* (1999) (Fig. 2).

According to these definitions, *surface uplift* refers to changes in the elevation of a surface. It is equal to rock uplift minus exhumation. *Crustal* (rock/bedrock) *uplift* refers to changes in the vertical position of rocks with respect to a fixed reference frame, such as the geoid.

Denudation and *exhumation* both result from the removal of material from a region or point, respectively, on the Earth's surface. Whereas exhumation refers to the unroofing of a point (a single sample or a vertical rock section), denudation applies to an area (cf. Ahnert 2003; see Summerfield & Brown 1998). Reference frame for both is the geometry of the past land surface. Denudation can occur in response to erosion and/or tectonics (e.g. Ring *et al.* 1999). *Erosion* describes the removal of weathered products by geomorphic agents. *Tectonic denudation* typically occurs through processes of extension and normal faulting, and it can result in the rapid removal of large rock volumes. Ductile crustal thinning as a third mode of denudation is not applicable for the uppermost crustal level and related processes.

Thermal histories modelled from thermochronological data, and potentially supplemented by information from vertical profiles, can be converted into an amount of denudation by using a value (measured or inferred) for the local geothermal gradient and taking into account average surface temperature.

Vertical profiles

Much more information than for a single sample alone is available when a suite of samples in a *vertical profile* can be analysed, such as may be obtained by sampling from a deep drill hole or over a significant range of vertical relief. Such vertical arrays are collected across the thermal gradient through which the samples have cooled. A consequence of fission-track annealing/helium diffusion is that AFT and AHe ages gradually decrease from some observed value at the Earth's surface to an apparent value of zero at the depth where no fission tracks/He are retained (Wagner & Reimer 1972).

The decrease in the AFT age with depth, and the associated variation of the length distribution, often deviate from a simple, linear pattern. Gleadow & Fitzgerald (1987) recognized that the exposed base of a fossil (exhumed) PAZ within a vertical sample profile produces a characteristic change in the regression of the age–elevation plot. Both the onset as well as the amount of cooling can be derived from this *break in slope* (Fig. 3). The age of the break in slope approximates the initiation of the last cooling below about 100 °C. Samples from below this break contain only tracks accumulated during and after this cooling stage. In contrast, samples above the break in slope contain two generations of tracks, one from before and one from after the onset of final cooling. The amount of cooling and exhumation can thus be obtained from the elevation of the break in slope within a vertical AFT (or, similarly, an AHe) profile. The actual shape of the age–elevation plot, and the trend of the track-length distributions with elevation, will depend on the geothermal gradient, and on the amount and rate of exhumation (R. W. Brown *et al.* 1994).

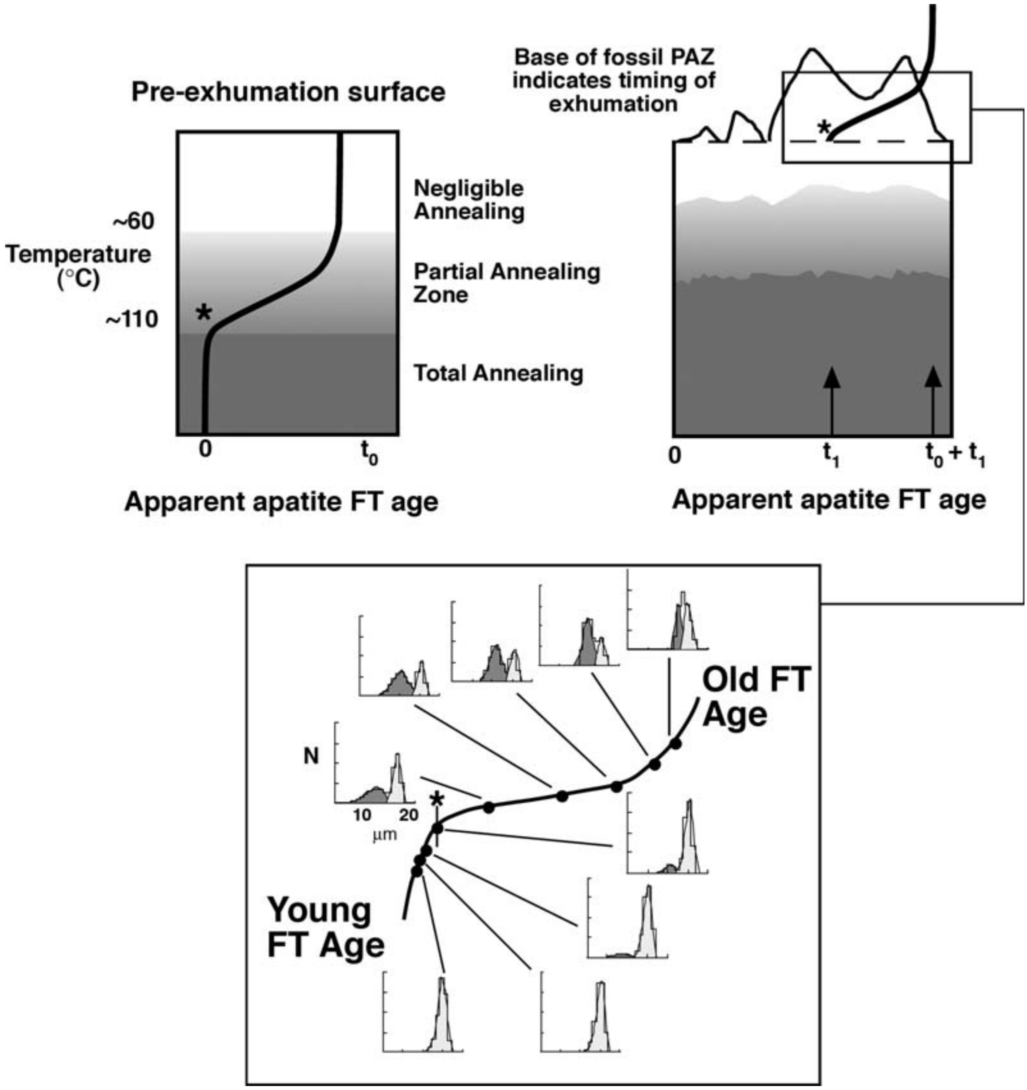

Fig. 3. The concept of an exhumed PAZ (adapted from Fitzgerald *et al.* 1995; Gallagher *et al.* 1998). The left panel illustrates the pre-denudation apatite fission-track age crustal profile, with the initial age as t_0. Denudation at time t_1 exposes different levels of this pre-cooling profile, while the deeper samples begin to retain tracks (central panel). The right panel shows the expected trend in the fission-track data with respect to elevation, that is age increases. The length distribution has two components: tracks formed prior to cooling (dark shading) and those formed after cooling (light shading). The latter are all long, and the composite length distribution depends on the relative proportion of these two components. Only the data below the break in slope (marked by an asterisk) provide the timing for the onset of the cooling/denudation event.

Another advantage of analysing vertical AFT profiles is the possibility of calculating the palaeogeothermal gradient that existed prior to the onset of cooling (Gleadow & Duddy 1981; Bray *et al.* 1992). The palaeogeothermal gradient can be determined by weighted least-squares regression of modelled maximum palaeotemperatures against sample elevation. Palaeogeothermal gradients are not only invaluable for estimating burial depths and amounts of denudation, but also bear important constraints on modes and mechanisms of the related processes (e.g. rifting). A comparison of the palaeogeothermal gradient with a recent one allows the cause of high palaeotemperatures, and the cause of the subsequent cooling to the present temperatures, to be determined.

Thermochronological data patterns

Thermochronological transects (horizontal profiles) across geological units or structures, or regional patterns of the AFT parameters, often allow exhumation trends to be detected or distinct igneous or tectonic events to be verified. Before modelling programs were available, the characteristic relationship between AFT ages, track-length distributions and thermal history was used to qualitatively constrain amount and timing of cooling (denudation) on a regional scale. A plot of AFT age against mean track length of an area that has undergone cooling shows a characteristic 'banana' or 'boomerang' shape that results from the mixing of two cooling components (Green 1986). In such plots, the longest mean track lengths are preserved in samples that experienced rapid cooling without subsequent reheating. Between the two end points of a boomerang there exists a series of transitional bimodal track-length distributions where the abundance of inherited annealed tracks becomes reduced in favour of newly formed tracks while the AFT ages of the samples decrease.

Apatite thermochrononology and topography

Topographic effects and fast rates of cooling. The temptation to collect vertical profiles in active mountain belts where there is considerable relief can introduce a number of interpretative problems for thermochronological data, especially if measured ages are young (<5 Ma). Young AFT (or AHe) ages require rapid rates of cooling and high rates of rock uplift and exhumation, but the calculation of true exhumation rates in such young samples is problematic owing to the combined influences of topographic wavelength and thermal advection. High rates of rock uplift cause perturbation of upper-crust thermal structure as heat is advected at rates that exceed normal heat loss by conduction, driving isotherms closer to the Earth's surface (e.g. modelling studies of Stüwe *et al.* 1994; Mancktelow & Grasemann 1997; cf. also Wang & Zhou 2009). Depending on wavelength and amplitude (height), the underlying thermal structure can undulate with the topography, causing the distance between closure isotherm and surface to vary with sample location. For example, beneath valley floors (lowest elevation samples) the depth to the PAZ will be less than beneath topographic ridges, that is the geothermal gradients will vary with location. Failure to take this effect into account when constructing age–elevation plots to determine exhumation rates can lead to incorrect interpretations. Detailed thermal modelling studies by Braun (2002) show how variable thermal structure can bias the interpretation of low-temperature thermochronological data.

Landscape evolution modelling. Much effort has been devoted recently to understand the coupling between tectonic and surface processes in the formation of recent topography (e.g. Braun 2002; Burbank & Anderson 2001; Burbank 2002; Ehlers & Farley 2003; Braun *et al.* 2006). Quantification of the rate at which landforms adapt to a changing tectonic, heat flow and climate environment (i.e. 'dynamic topography evolution') are performed by combining geomorphological analytical work, low-temperature thermochronological data and 3D thermokinematic modelling. Thermokinematic modelling with the 3D finite-element computer code Pecube (Braun 2003, 2005) predicts time–temperature (t–T) paths for all rock particles that, at the end of the computations, occupy the locations of the nodes at the surface of the finite-element mesh. From the t–T paths, apparent AHe and AFT ages are generated by varying topography, erosion rates, uplift rates and heat flow values. Thus, Pecube allows an overall uplift rate to be created or a block of infinite space, which is bordered by normal faults and/or thrusts, to be defined. When movement is localized at the faults or thrusts, computer-code-generated age data are subsequently compared with the determined real thermochronological age data. As a result, it is now possible to match age data with geomorphological results and cosmogenic nuclide-based age dating in order to test landscape evolution models by processing different timescale resolutions.

Detrital thermochronology

The 'standard' approach to deriving an AFT age is typically based on the measurement of the track density (age) for 20–30 (more if track densities are low) single-grain ages. Detrital thermochronology requires 50–120 grains per sample to enable statistical deconvolution into source-age components. Depending on the objectives of the study, up to 117 grains should be dated if the analyst wants to ensure that no fraction of the dated population comprising more than 0.05 of the total is missed at the 95% confidence level (Vermeesch 2004). Once the desired numbers of grains have been counted, the dataset can be divided into principal age components. Binomfit is a freeware program written by Mark Brandon that calculates ages and uncertainties for mixed distributions of fission-track grain ages. It uses an algorithm based on the decomposition method of Galbraith & Green (1990). Age components are compared with the age patterns of the hinterland and correlated with specific source areas (e.g. Brandon 1996; Bernet & Spiegel 2004; Bernet & Garver 2005).

Detrital thermochronology is routinely used in *provenance analysis*, and for denudation and landscape evolution studies (e.g. Hurford & Carter 1991; Garver *et al.* 1999; Bernet *et al.* 2006). Specific tectonic and geomorphological applications include dating of hinterland uplift to reconstruct early exhumation rates in active orogenic belts, determining sediment-source regions, and reconstructing (palaeo-) drainage systems. A particularly useful interpretative method is to plot the *lag time* (or erosion–transport interval) between sediment deposition age and youngest detrital exhumation age. This provides key information on exhumation history, and conceptually it is possible to use the lag time to monitor the evolution of a mountain belt as it passes from growth stages (decreasing lag times) into topographic and exhumation steady state (constant lag time) into orogenic decay (increasing lag time). Other provenance applications include constraining minimum depositional ages of sediments and the correlation of stratigraphic horizons.

Most sediment is derived from the erosion of pre-existing rocks, and therefore detrital apatite and zircon grains may contain tracks that accumulated in the original source rock. Weathering and physical erosion do not affect the retention and stability of fission tracks (Gleadow & Lovering 1974), but the preservation of provenance-related tracks does depend on the temperature history experienced by eroding source regions and subsequently by the sediment as the basin evolves (Fig. 4). Whereas zircons provide excellent provenance indicators (e.g. Hurford & Carter 1991; Garver & Brandon 1994; Garver *et al.* 1999), the use of apatite for source-rock information is restricted to shallow basins (typically less than *c.* 2 km of burial) and drainage systems (e.g. Corrigan & Crowley 1992; Lonergan & Johnson 1998; Malusà *et al.* 2009). Detrital analyses often combine thermochronological and geochronological data (U–Pb dating of zircon, ^{40}Ar/^{39}Ar dating of white mica), heavy mineral assemblages, grain size/shapes (zircon typology), and isotope signatures of detrital minerals (e.g. Dunkl *et al.* 2001; Carter & Foster 2009). The amount of provenance information can be increased by using double or triple dating techniques that involve more than one dating method on the same mineral grain, for example combined U–Pb or ^{40}Ar/^{39}Ar and AFT dating (Carter & Moss 1999; Carrapa *et al.* 2009) and/or AHe dating (Rahl *et al.* 2003). A detrital dating technique that utilizes petrographic information is fission-track analysis of single pebbles or pebble populations using conglomerates from foreland basin deposits (Spiegel *et al.* 2001; Dunkl *et al.* 2009).

Applications

Application of low-temperature thermochronology is not confined to the obvious, immediate purpose of dating rock formations, as this is rarely possible due to thermal resetting. Much more powerful

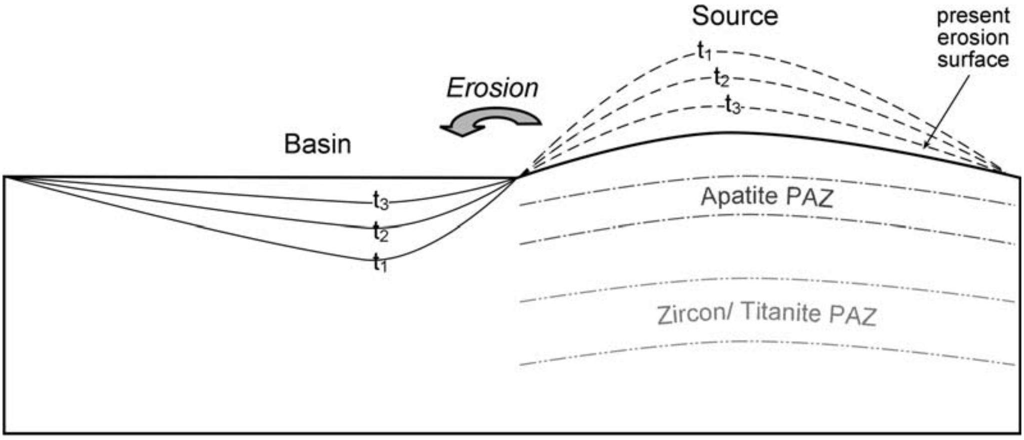

Fig. 4. Cartoon to show the relationship between the progressive exhumation of a source region and deposition of the eroded exhumation record in an adjacent sedimentary basin (modified after Garver *et al.* 1999). The time slices (t_1–t_3) correspond to three progressive and continuous intervals of erosion and deposition. Subsequently, a 'stratigraphy' of apatite fission-track ages develops within the basin, which is the inverse of the source-region exhumation age trend. It should be noted that with progressive burial, sediments may be heated sufficiently to cause annealing of the inherited AFT provenance records. Rarely is such burial-related heating sufficient to reset fission tracks in detrital zircons and titanites. Also, note how topography may cause the upwarping of the lower temperature isotherms.

(and more widely used) are the applications that exploit thermal resetting to reconstruct rock exhumation histories. The main fields of application of AFT and AHe thermochronology include provenance studies, thermal history analysis of sedimentary basins, the evolution of orogenic mountain belts and applications in non-orogenic settings. Recent work in these areas has focused on the coupling between climate and tectonics (e.g. Koons 1989; Willet 1999; Beaumont *et al.* 2000), and thermochronlogical datasets have been used to evaluate the role of climatically driven erosion as a component of exhumation (Blythe & Kleinspehn 1998; Reiners & Brandon 2006).

Fission-track and (U–Th–Sm)/He data are often combined with other sources of data such as thermochronology and geochronological dating to constrain higher temperature histories and/or rock formation age (e.g. ^{40}Ar/^{39}Ar and K–Ar: Daszinnies *et al.* 2009; De Grave *et al.* 2009), and terrestrial cosmogenic nuclide dating to compare with more recent erosion rates (e.g. Cockburn *et al.* 2000; Kuhlemann *et al.* 2009). In addition, interpretations increasingly integrate data from stratigraphic archives, geomorphology, structural geology, remote sensing, petrology, fluid inclusion analysis, vitrinite reflectance, clay mineralogy, conodont colour alteration, zircon typology and seismic data. These multi-method approaches strengthen the interpretation of AFT and AHe data, and help to extend geological histories through time.

Absolute dating

Owing to fission-track annealing and He diffusion at relatively low temperatures, geological events can be dated in well-defined settings, when rocks very rapidly passed the PAZ and/or partial retention zone and resided at the surface or at a very shallow-crustal level thereafter. Rapid cooling to low temperatures mainly occurs subsequent to volcanic or hydrothermal activity (Duddy *et al.* 1998), dyke emplacement, faulting and friction or meteorite impacts (e.g. Miller & Wagner 1979). For these cases, thermochronological ages are more or less identical to those obtained by conventional radiometric techniques, and can be used directly as discrete time constraints. Fission-track analysis is also used as a conventional method for dating glasses (e.g. Fleischer & Price 1964; Bigazzi & De Michele 1996), and has been applied to date stone tools and fossils (e.g. Morwood *et al.* 1998). Moreover, both fission-track and (U–Th)/He techniques have been used successfully to date the formation of supergene minerals such as some phosphates or vanadates, hematite, goethite, limonite, manganese oxides and carbonate minerals (e.g. Bender 1973; Lippolt *et al.* 1995; Shuster *et al.* 2005; Boni *et al.* 2007; Copeland *et al.* 2007).

Denudation and long-term landscape evolution studies

Denudation and long-term landscape evolution studies represent the most common and broadest field of applied low-temperature thermochronology. Studies range from compressional to extensional settings and 'stable' cratonic interiors.

Orogenic belts. Orogenic mountain ranges are characterized by substantial relief and immense uplift/denudation rates, resulting in large-scale advective transfer of heat and increased thermal gradient. The obvious correlation between exhumation and cooling predetermined this setting for an early application of thermochronological research, and expanded the scope of the method(s) from a purely 'age determination' approach to a unique thermo-tectonic tool. Wagner (1968) and Wagner & Reimer (1972) first used AFT data to provide estimates of the time and rates at which rocks approach the surface and cool as a result of 'uplift and erosion'. At present, low-temperature thermochronology is the most efficient method to quantify denudation rates on geological timescales. Changes in erosion rates with time can be constrained using multiple chronometers with different closure temperatures on the same rock sample, or from the distribution of cooling ages from a single system along a vertical transect. Spatial–temporal patterns of thermochronometrically determined erosion rates help to constrain the flow of material through orogenic wedges, orogenic growth and decay cycles, palaeo-relief, and relationships with structural, geomorphological or climatic features (cf. Reiners & Brandon 2006). Subsequent to the first apatite thermochronological works in the Alps (e.g. Schaer *et al.* 1975; Wagner *et al.* 1979; Grundmann & Morteani 1985; Hurford 1986; Hurford *et al.* 1991), most of the world's young orogenic belts were studied (e.g. Parrish 1983; Seward & Tulloch 1991; Corrigan & Crowley 1992; Hendrix *et al.* 1994; Blythe *et al.* 1996; O'Sullivan & Currie 1996; Sorkhabi *et al.* 1996; Dunkl & Demény 1997; Kamp 1997; Sanders *et al.* 1999; Fayon *et al.* 2001; Spiegel *et al.* 2001; Glasmacher *et al.* 2002*b*; Reiners *et al.* 2002; Thomson 2002; Willet *et al.* 2003; Van der Beek *et al.* 2006; Gibson *et al.* 2007; Vincent *et al.* 2007; Glotzbach *et al.* 2008, 2009; del Río *et al.* 2009; Ruiz *et al.* 2009).

Continental rifts and passive continental margins. Continental rifts are elongated tectonic depressions that result from extension and crustal thinning caused either by a regional extensional stress field or in response to asthenospheric upwelling (cf. Olsen 1995; Ziegler & Cloething 2004). Continental separation and the onset of sea-floor spreading mark the transition from a continental rift into a passive margin. Consequently, the general morphotectonic evolution and appearance of rifts and passive margins is similar. In detail, the style of lithospheric extension, geometry of rifting, rate and amount of extension are influenced by local crust rheology coupled to erosion, which in turn is influenced by pre-existing morphology, rift-related magmatism, local drainage and climate (e.g. Gilchrist & Summerfield 1990; Kooi & Beaumont 1994; Olsen 1995; O'Sullivan & Brown 1998; Ziegler & Cloething 2004). Deconvolving these different controls has been the focus of AFT and AHe studies. Apatite thermochronological studies have been reported from most of the world's continental-size rift structures and highly extended terranes (for an overview cf. Stockli 2005) including the West Antarctic Rift System (e.g. Gleadow *et al.* 1984; Fitzgerald & Gleadow 1988; Fitzgerald 1992, 1994; Foster & Gleadow 1992*a*; Balestrieri *et al.* 1994; Fitzgerald & Stump 1997; Lisker 2002; Fitzgerald *et al.* 2006), the East African Rift System (e.g. Kohn & Eyal 1981; Omar *et al.* 1989; Foster & Gleadow 1993, 1996; Van Der Beek *et al.* 1998; Feinstein *et al.* 1996; Kohn *et al.* 1997; Balestrieri *et al.* 2005; Spiegel *et al.* 2007), and the Basin and Range Province (e.g. Armstrong *et al.* 2003; House *et al.* 2003; Colgan *et al.* 2006), as well as many other continental extension zones (e.g. Rohrmann *et al.* 1994; Van der Beek *et al.* 1996; Lisker & Fachmann 2001; Emmel *et al.* 2009). Two studies on the influence of heat-flow variation across major rifts were published by Gallagher *et al.* (1994) and Lisker *et al.* (2003).

Gallagher & Brown (1997) demonstrated how AFT data are used to study the evolution of rift-margin topography (linked to isostatic-flexural responses to erosional unloading) and to test the different geomorphic models of passive margin evolution. Most passive rift margins of the major continents have been extensively studied by apatite thermochronology, with a wealth of papers detailing different aspects of their evolution. These studies include Moore *et al.* (1986), Brown *et al.* (1990, 2002), Dumitru (1991), Kalaswad *et al.* (1993), Gallagher *et al.* (1994), Gallagher & Brown (1999), Carter *et al.* (2000), Johnson & Gallagher (2000), O'Sullivan *et al.* (2000), Persano *et al.* (2002), Gunnell *et al.* (2003), Seward *et al.* (2004), Japsen *et al.* (2006), Raab *et al.* (2005), Emmel *et al.* (2006, 2007) and Kounov *et al.* 2009). Transform margins have seen comparatively little study, with published work confined to the Ghana margin (Clift *et al.* 1997; Bouillin *et al.* 1997; Bigot-Cormier *et al.* 2005).

Cratons. Cratonic interiors were traditionally considered as tectonically and thermally stable features. They are characterized by extensive surfaces of minimal relief that infer low rates of erosion. However, thermochronological studies conducted during the last two decades on different cratons revealed that throughout the Phanerozoic many of these ancient terrains have experienced discrete episodes of kilometre-scale crustal erosion (e.g. Crowley *et al.* 1986; Wagner 1990; Noble *et al.* 1997; Harman *et al.* 1998; Cederbom *et al.* 2000; Bojar *et al.* 2002; Glasmacher *et al.* 2002*a*; Kohn *et al.* 2002; Belton *et al.* 2004; Lorencak *et al.* 2004; Soderlund *et al.* 2005; Flowers *et al.* 2006). On the other hand, cratonic areas often show apparent inconsistencies between AFT and AHe ages. These *crossover ages* are discussed controversially as either resulting from non-thermal radiation-enhanced annealing of fission tracks (e.g. Hendriks & Redfield 2005) or reflecting the dependency of He retention properties from the chemical composition of apatites (e.g. Green *et al.* 2006; Kohn *et al.* 2009).

Basin analysis

Sedimentary basins are major archives of geological history related either directly to the evolution of the basin itself (e.g. subsidence history, tectonics, climate, sea-level change) and/ or indirectly to the geological history of the sediment-source regions (e.g. provenance information, palaeo-basement, geomorphology, tectonics). Traditionally, the burial and deposition history of basin sediments is determined by investigation of the sedimentology and deposition ages derived from biostratigraphy, combined with structural and geophysical datasets. However, establishing the timing of maximum depths of burial, and the timing and extent of uplifts, is often hard to recover owing to stratigraphic gaps, poor biostratigraphic control and sediment types. In this regard, AFT chronology has proven a valuable tool.

Thermochronology becomes most useful when a basin has undergone a period of uplift or inversion, during which a section of strata has been removed by erosion (e.g. Kamp & Green 1990; Bray *et al.* 1992; Green *et al.* 1995). Specific information gained from thermochronological data include estimates of maximum palaeotemperatures, calculations of palaeogeothermal gradients and palaeoheat flow, style (fast/slow) and time of cooling from maximum palaeotemperatures, characterization of mechanisms of heating and cooling, quantification of missing sections, stratigraphic dating, sediment provenance, and evaluation of hydrocarbon maturation (Gleadow *et al.* 1983; Green *et al.* 1989*a*; Kamp & Green 1990; Duane & Brown 1991; Mitchell 1997; Logan & Duddy 1998).

Particularly useful in basin analysis is the integration of thermochronological data with maximum palaeotemperature indicators (Fig. 5), like vitrinite reflectance (VR) and illite crystallinity

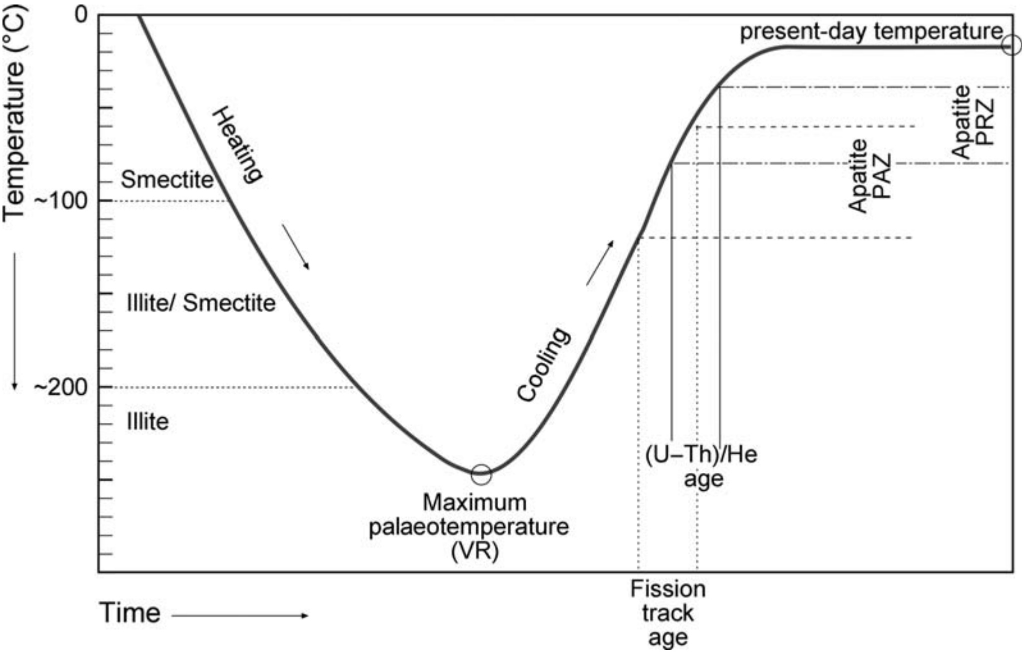

Fig. 5. Schematic to show how the thermal history of a sedimentary basin can be recovered by integration of data from multiple palaeothermometers and chronometers. Illite data constrain the burial or heating phase of a basin's thermal history, VR records maximum temperature, and combined apatite thermochronology constrains the timing of cooling and subsequent denudation (modified after Pevear 1999).

(e.g. Bray *et al.* 1992; Pagel *et al.* 1997; Duddy *et al.* 1998; Mathiesen *et al.* 2000; Ventura *et al.* 2001; Arne *et al.* 2002; Osadetz *et al.* 2002; Tingate & Duddy 2002). VR is the measure of the coalification rank of organic matter, and it is mainly dependent on temperature and time (Burnham & Sweeney 1989). VR data provide a direct estimation of maximum palaeotemperatures across the same temperature range as annealing in fission tracks in apatite, which enables the thermal history modelling of joint VR and AFT datasets to provide a more robust constraint on temperature–time histories. Basin modelling using combined thermochronological and VR constraints has become a routine, and is a valuable tool in the hydrocarbon exploration industry (Gleadow *et al.* 1983; Green *et al.* 2002; Emmerich *et al.* 2005; Underdown *et al.* 2007). Also of economic relevance is the application of apatite thermochronology to the exploration of hydrothermal ore deposits (cf. McInnes *et al.* 2005).

Tectonic processes

Thermochronological methods can be used to detect tectonic activities in two ways. In areas of substantial block uplift, thermochronological ages may be disrupted across tectonic structures. Such offsets in the palaeo-isotherm/-depth stratigraphy can be used to determine relative uplift between different blocks and the amount of throw on bounding faults (Fitzgerald & Gleadow 1988, 1990; Dumitru 1991; Foster & Gleadow 1992*a*, *b*, 1996; Fitzgerald *et al.* 1993; O'Sullivan *et al.* 1995, 2000; Johnson 1997; Rahn *et al.* 1997; Wagner *et al.* 1997; Thomson 1998; Kohn *et al.* 1999; Redfield *et al.* 2007; Ventura *et al.* 2009; Xu *et al.* 2009). Moreover, the timing of tectonic activity may be determined by the direct dating of faults, lineaments or pseudotachylites (Harman *et al.* 1998; O'Sullivan *et al.* 1998; Raab *et al.* 2002, 2009; Zwingmann & Mancktelow 2004; Tagami 2005; Timar-Geng *et al.* 2009; Yamada *et al.* 2009).

Summary

As can be seen from the papers contained in this Special Publication, apatite thermochronology has grown to become a reliable and routinely used method to helping in solving a diverse range of geological problems. Although mature, the method continues to undergo developments. Over the last decade there have been considerable improvements in AFT methodology and data interpretation, but there is still scope for further advances. Future studies to refine models of track annealing in apatite may shift away from laboratory-based experimentation to well-constrained geological experiments (e.g. Spiegel *et al.* 2007) and molecular dynamic simulations (Rabone *et al.* 2008). Further work will also need to be carried out on understanding the controls on annealing in zircons and titanites, as well as the establishment of new fission-track mineral dating systems (e.g. monazite, merrillite: cf. Wagner & Van den Haute 1992; Gleadow *et al.* 2002).

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