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Interpretation of apatite (U–Th)/He ages and fission track ages from cratons

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Abstract

Apatite (U–Th)/He ages from southeast Sweden have been interpreted as proving that the region has remained stable through Mesozoic and Cenozoic times, with no more than 100 metres of sedimentary cover throughout this time. However, we suggest this interpretation cannot be sustained, and present an alternative interpretation involving deposition of 1 km of Mesozoic cover, which explains the observed ages at least as well as the original models. Inconsistencies between apatite fission track (AFT) data and apatite (U–Th)/He ages from this and other regions of Fennoscandia have been explained in terms of fission track ages in these apatites being reset by a non–thermal "radiation–enhanced" annealing process, on the basis that fission track ages are younger than expected on the basis of the "known geological evolution" of the area. We dispute this line of reasoning, and suggest that AFT ages from the region can be readily understood in terms of normal thermal annealing processes. Other evidence put forward to support the concept of "radiation–enhanced" annealing can be explained more simply in other ways. We suggest the discrepancy between AFT and (U–Th)/He ages arises because the He retention properties of apatite change as the amount of He retained within the apatite increases, and further suggest that greater attention should be paid to diffusion of helium in different apatite species.

Keywords: apatite; AFTA; (U–Th)/He dating; thermochronology; fennoscandia; annealing

1. Introduction

Soderlund et al. [1] present apatite (U–Th)/He ages in three suites of sub–surface samples from southeast Sweden, and based on comparison of their measured ages with modelled age vs. depth trends for various scenarios, they claim that their results "demonstrate that the area has not been reheated since the mid–Permian", and that any Mesozoic cover cannot have exceeded 100 metres. They go on to point out that their results are incompatible with previously published apatite fission track (AFT) ages from the same boreholes, and suggest that this discrepancy supports suggestions that "AFT in slowly cooled terrains might be slightly too young due to radiation–enhanced annealing".

Contrary to these conclusions, here we provide an alternative interpretation of the data in [1] which includes burial of the sampled section by 1 km of Mesozoic sediments. The modelled age vs. depth trend for this scenario provides at least as good a match to the measured data as any of the trends proposed by Soderlund et al. [1]. We also propose that the common discrepancy between AFT and apatite (U–Th)/He data arises not from

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an alternative non–thermal annealing mechanism for fission tracks but from an as yet unexplained increase in helium retentivity as the amount of He retained within an apatite grain increases.

2. He ages vs. depth and "open system" behaviour in the (U–Th)/He system

Soderlund et al. [1] begin from the basic premise that "At shallow levels, rock samples yield older ages simply because they crossed the HePRZ (helium partial retention zone) during an earlier stage than their lower counterparts. The rate at which He ages increase with decreasing depth yields the rate of cooling" (p267). By fitting a linear profile to their (U–Th)/He ages as a function of depth, they derive an exhumation rate of 17 m/Myr (equivalent to a cooling rate of 0.26 °C/Myr for a geothermal gradient of 15 °C/km), and this rate becomes the centrepiece of their modelling.

This approach fails to take into account the open–system behaviour of the apatite (U–Th)/He system – i.e. the fact that even at low temperatures the system is never really "closed" (100% retention). For this reason, the change of age with depth does not necessarily portray the rate of cooling. This is illustrated in Fig. 1, which shows modelled age vs. depth/temperature trends resulting from a scenario involving initially rapid cooling followed by long–term isothermal residence. The upper portions of the trends shown in Fig. 1 show a very similar style of variation to the (U–Th)/He ages measured in the KLX02 borehole [1], including the inflection which appears in the measured ages at depths of ~1400 metres. But fitting a slope to the predicted ages as a function of depth over the shallowest 1500 m provides an exhumation rate of 0.1 km/Myr (cooling rate 1.75 °C/Myr) in contrast to the exhumation rate of ~0.5 km/Myr (cooling rate of 8 °C/Myr) used in construction of these trends. In this situation, the slope of the age vs. depth trend contains little or no information on the exhumation rate, being dominated by the open system behaviour of the system, and simply representing the decreasing retention of He with increasing down–hole temperature.

Fig. 1, as well as similar conceptual Figures presented by Wolf et al. [2], emphasises that the HePRZ is in fact a purely notional concept. He is never 100% retained and even at temperatures around 10 °C or less, some small amount of He loss is expected. This is responsible for the gentle initial decrease of He age with depth at shallow depths in Fig. 1, and the results presented by Soderlund et al. [1] can be interpreted in similar fashion. Thus, there is no basis for simply assuming that "The rate at which He ages increase with decreasing depth yields

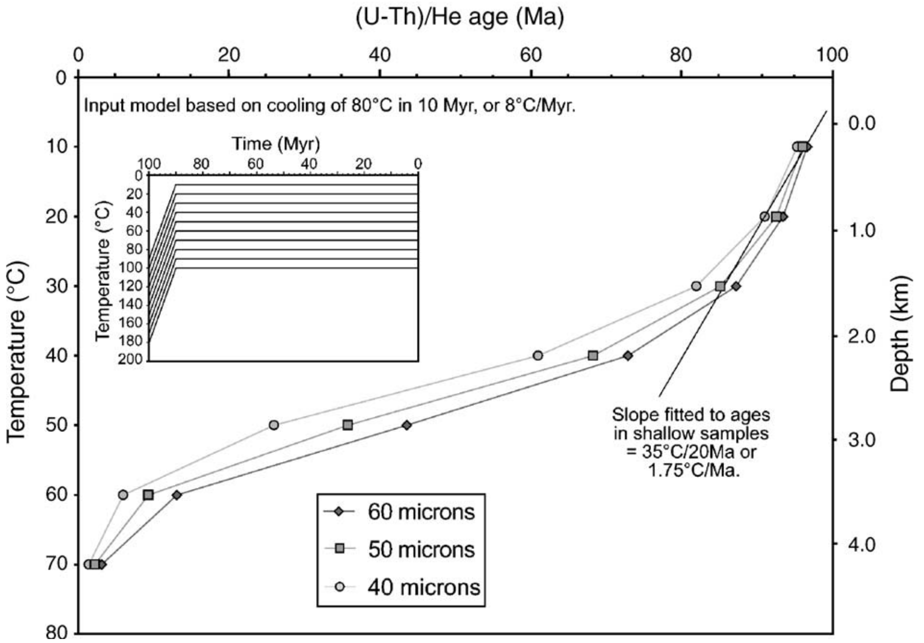

Fig. 1. Modelled apatite (U–Th)/He ages for various grain radii resulting from the thermal histories shown in the inset (based on He diffusion systematics in [12]: for details of modelling procedures, see [17,18]. A depth scale is shown on the right hand side corresponding to the conditions adopted by Soderlund et al. [1], viz: surface temperature 7 °C, thermal gradient 15 °C/km. Ages at shallow depths are considered to be analogous to the ages within the upper 1400 metres reported by Soderlund et al. [1]. But interpreting the ages shown here in terms of progressive cooling through a closure temperature leads to a false value for the cooling rate, as shown.

the rate of cooling" [1], and the exhumation rate of 17 m/Myr estimated by Soderlund et al. [1] is therefore meaningless.

Similar misconceptions have bedevilled apatite fission track studies for many years, with changes in fission track age with depth interpreted in terms of slow cooling and used to estimate exhumation rates. However, the advent of confined track length data [3] revealed that such trends often (invariably?) represent exhumed partial annealing zones [4], with the decrease of age with increasing depth representing progressively deeper levels within "fossil annealing zones" and controlled by the paleogeothermal gradient, having nothing at all to do with exhumation rates. Unfortunately, the He system does not have the advantage of track length data to help interpret the measured age in terms of the degree of partial retention (although changes in age with grain size have the potential to provide similar insight, as pointed out by Reiners and Farley [5]).

3. An alternative thermal history model

Soderlund et al. [1] claim that their results show that any Mesozoic cover "cannot have exceeded 100 metres in thickness", despite convincing geological evidence for an extensive former sedimentary cover in southern Sweden (e.g. [6,7]). In Fig. 2, we present an alternative thermal history model, based on a generalisation of evidence presented by Lidmar–Bergström and Näslund [6] and Japsen et al. [7], incorporating Late Paleozoic cooling (~2 °C/Myr) followed by deposition of a kilometre of Mesozoic cover, subsequently removed during two phases of Cenozoic exhumation. Also shown in Fig. 2 are the He age vs. depth trends for different grain radii predicted from this model. The predicted trends show a good match to the measured (corrected) He ages from the KLX02 borehole [1], suggesting that this history provides a viable explanation of these data.

According to Soderlund et al. [1], there is no geological evidence for rapid late Paleozoic exhumation, despite the fact that their other sub–surface datasets provide strong indications of just such a history (no alternative explanation being offered for these additional datasets). But it is reasonable to ask – what form would such geologic evidence take, given the lack of sedimentary cover? We see no reason to discard histories involving late Paleozoic exhumation, particularly as exactly this style of history has been suggested from a number of previous studies in this region (e.g. [8,9]) without attracting significant comment.

The thermal history model in Fig. 2 provides at least as good a match to the observed ages as any of the

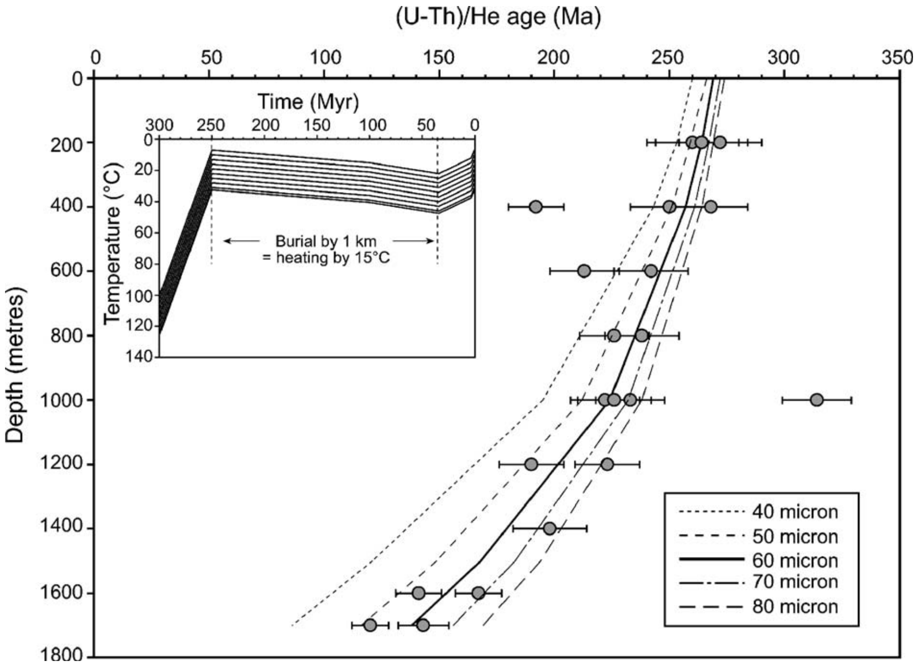

Fig. 2. Measured apatite (U–Th)/He ages in the KLX02 borehole from [1], together with age vs. depth trends predicted for different grain radii from the thermal history model shown in the inset (details of age modelling as in [17,18]). This history is based on Late Paleozoic cooling followed by re–burial under 1 km of Mesozoic cover, followed by Cenozoic cooling in two stages, based loosely on [6,7]. The fit to the data is as convincing as for any of the models proposed in [1], and we see no reason to suggest that such a history is unreasonable, contrary to the suggestions of [1].

models presented by Soderlund et al. [1] – note in particular the lack of agreement in their Fig. 4 between predicted trends and the measured ages in the deepest samples, to which such significance was drawn at the outset by Soderlund et al. [1]. The measured ages thus cannot be used to prove the lack of significant Mesozoic cover in the region.

4. Comparison of (U–Th)/He and apatite fission track ages

Soderlund et al. [1] point out that previously published AFT ages from the KLX02 borehole are not consistent with their measured He ages. Unfortunately the AFT data are not reported in sufficient detail to allow a detailed comparison of the two techniques. Integration of confined track length data is essential in assessing AFT ages in terms of partial annealing (i.e. open–system behaviour) and such data would be required for any meaningful comparison of the AFT and (U–Th)/He datasets. Extensive AFT studies across southern Sweden ([8–11]) have been published in recent years which do incorporate track length data, and these studies indicate a series of major late Paleozoic, Mesozoic and Cenozoic cooling episodes, in contrast to the scenario of post–Permian stability presented by Soderlund et al. [1]. Inclusion of the paleo–thermal events suggested by the AFT data would predict much younger He ages than those reported by Soderlund et al. [1], so there is clearly a major discrepancy between the He and FT ages from the region.

Indeed, there is a growing body of evidence suggesting that in samples with apatite (U–Th)/He ages older than ~50 Ma, the relative responses of the two systems are often not as expected from the accepted systematics of each, as defined by Farley [12] for (U–Th)/He and Laslett et al. [13] and variations thereon for AFT. For example, Spotilla et al. [14] and Persano et al. [15] report He ages around 100 to 200 Ma from the eastern USA and SE Australia, respectively, that are older than expected on the basis of our AFTA data from these regions. Belton et al. [16] reported He ages in apatites from the Davenport Ranges of Central Australia that were older than AFT ages from the same samples, and attributed this to the presence of inclusions in their apatites. But their data fall into the same general pattern as seen in these other studies, and we suggest that the presence of inclusions is not the only factor affecting these samples. These studies contrast starkly with situations involving younger He ages [17–19], in which data from the two systems appear to give highly consistent results.

Soderlund et al. [1] point out that Hendriks and Redfield [20] recently suggested that “AFT ages of slowly cooled terranes might be slightly too young due to radiation–enhanced annealing”, a process by which FT ages could be reset at low temperature by radiation. (They also state that Lorencak et al. [21] made similar claims, but we can find no such suggestion by those authors.) On this basis, Soderlund et al. [1] attribute the mismatch between the two datasets to problems with the systematics of the FT method, and regard their preferred thermal history model as providing a reliable assessment of the evolution of the region.

But as reported by Crowhurst et al. [22] there is considerable evidence to suggest that the problem lies with the He system, rather than FT annealing. The key question therefore becomes – how reliable is the concept of radiation enhanced fission track annealing?

5. Fission track annealing due to radiation?

Hendriks and Redfield [20] suggested that AFT ages across Scandinavia were younger than expected given the stability of the Scandinavian Shield because the ages were reduced by the effects of long term radiation dose due to alpha decay over millions of years. Their main reason for invoking this mechanism was to avoid the need for km–scale exhumation during Phanerozoic times, which is required in order to explain the ages purely in terms of thermal annealing, but which they consider to be geologically unrealistic.

Overturning “accepted wisdom” concerning the geological evolution of a region has been a common outcome in application of AFTA in many parts of the world. One noteable example is the East Midlands Shelf of the UK, where elevated vitrinite reflectance data in hydrocarbon exploration wells which clearly indicate exhumation of around 1 km in magnitude were regarded as anomalous because such an interpretation did not fit with the “known geological evolution of the area” [23]. However, application of AFTA [24,25] confirmed the evidence for km–scale exhumation, and also showed that exhumation began in the Early Cenozoic. Despite continuing attempts at denial based on geological evidence [26,27], recent reassessment of the AFTA and VR data [28] has confirmed these conclusions, and it is clear that “accepted geological wisdom” in this area was not accurate.

AFT ages from cratonic regions are commonly much younger than expected on the basis of the supposed stability of such regions. However, in many of these regions, independent evidence exists to support the concept of considerable exhumation and removal of several kilometres of former sedimentary cover (e.g. Patchett et al. [29] in Canada; Cawood and Nemchin [30] in

Western Australia). In these regions, relatively young AFT ages [21,31] can therefore readily be understood in terms of km–scale exhumation and erosion which has provided detritus to adjacent basins. No extraneous mechanisms are necessary to explain the FT ages in these regions, and there seems no reason why Fennoscandia should be the only place on Earth where radiation–enhanced annealing occurs. This somewhat flippant comment belies the importance of taking into account data from a wide variety of settings rather than seeking a unique explanation of data from one particular region.

In support of their concept of radiation–enhanced fission track annealing, Hendriks and Redfield [20] present trends showing fission track ages inversely correlated with uranium content, such that younger ages are measured in samples characterised by higher uranium content. They also show a plot of decreasing fission track ages vs. depth (their Fig. 3) from boreholes in Finland, previously interpreted in terms of thermal annealing. On the basis of a very similar decrease of age with increasing uranium content in these samples, they suggest that the decrease must alternatively be explained in terms of the effects of radiation–enhanced annealing, and comment that "the data should not be interpreted in terms of geological cooling histories, and cannot be used to quantify burial and denudation".

But the data in this Figure show very clearly that uranium content increases systematically with depth in the sampled rock sequence (deeper samples are higher in U, and shallower samples have lower uranium contents). We therefore see no reason why the decrease in fission track ages with increasing depth cannot be simply interpreted in conventional terms as a result of thermal annealing. Rocks that have been exhumed from greater depth within this sequence will have higher uranium contents, and this will introduce an apparent correlation between decreasing age and increasing uranium content, without any need to invoke non–thermal annealing, and without any causal relationship between age reduction and uranium content.

Hendriks and Redfield [20] draw further support for their concept from " large variations in AFT age for apatite samples with very similar major element composition … observed over short horizontal distances". In principle, such changes could be explained by variations in apatite chlorine content between samples, which could be investigated through measurements of wt% Cl in the apatite grains analysed from these samples, but such information is not available. Hendriks and Redfield [20] report some measurements of etch pit size, which has been suggested to correlate with annealing sensitivity (e.g. [32]). However, we have disputed the evidence in [32] and have shown [33] that etch pit diameters provide only a very poor measure of differential annealing properties. Therefore we consider the local variation in fission track age reported by Hendriks and Redfield (2005) to be most likely due to differences in wt% Cl (cf the major changes in age related to differences in wt% Cl within a single borehole reported by Lorencak et al. [21]).

In summary, we see no reason to question the basis of the AFT technique simply to explain apparently aberrant results from one region because of a perceived conflict with the "known geological evolution of the region". This problem is particularly acute when this is based purely on the absence of any Phanerozoic sedimentary cover on the Fennoscandinavian Shield, which provides no real constraint either way. While it can be argued that any model should be carefully considered and subject to detailed evaluation, we consider that there is no convincing evidence in support of the concept of radiation-enhanced annealing of fission tracks in apatite, and suggest that the concept should be disregarded.

6. Validation of approaches

Soderlund et al. [1] suggest that their construction of a thermal history that reproduces their measured ages validates the general applicability of the diffusion systematics in old (slowly cooled) terrains (p274). However this is not the case. In order to validate their approach, it would be necessary to produce independent evidence from one or more different techniques that provide similar indications, to confirm the conclusions drawn from the He ages. Examples from our own work include Crowhurst et al. [17] who linked AFTA, apatite (U–Th)/He and vitrinite reflectance into a coherent thermal history framework in the Taranaki Basin of New Zealand which also matched independent stratigraphic and seismic constraints, and Holford et al. [34] who linked AFTA, VR and sonic velocity data to produce a consistent exhumation history for the Mochras Borehole, North Wales. When multiple techniques using independent calibrations produce consistent indications of the magnitude of paleo–thermal effects, the approach can be regarded as validated. But presenting a history which reproduces a single dataset proves nothing except that such a history can be identified.

7. Anomalous He retention in apatite?

In contrast to the interpretation of results from the Fennoscandinavian Shield reported by Hendriks and Redfield [20], Lorencak et al. [21] reported that AFT and apatite (U–Th)/He ages in downhole samples from a borehole in the Canadian Shield can both be explained purely in terms of depth of burial and subsequent exhumation. Fission track ages decrease from ~350 Ma near the surface to ~150 Ma at a depth of 3.5 km, while He ages decrease from ~200 Ma to ~50 Ma over the same depth range. Lorencak et al. [21] report that "Generally, we find that AHe results from the basic rock types… with relatively low U and Th content in apatites and the host environment tend to be more consistent and reproducible compared to AHe analyses from the more silicic lithologies found in the Canadian Shield" (which tend to have higher U and Th contents).

This observation is highly consistent with our own experience that (U–Th)/He ages become increasingly difficult to reconcile with AFTA data in the same sample as (U–Th)/He ages increase beyond ~50 Ma unless uranium contents are unusually low [22]. Significantly, this experience is not restricted to cratons, coming from a variety of different settings. Together with the studies discussed earlier [14–16] (also not related to cratonic settings), these observations point to a modification of He retention properties in apatites which have retained He for a considerable time, such that they become more retentive, resulting in older He ages than expected on the basis of accepted He diffusion systematics [12].

In the absence of any convincing evidence to suggest that fission tracks can be annealed by non–thermal processes, combined with increasing evidence He systematics can change with increasing He retention (above), we conclude that the apatite (U–Th)/He ages reported by Soderlund et al. [1], as well as those discussed by Hendriks and Redfield [20] are anomalously old as a result of an as yet unexplained increase in the He retentivity of these "older" apatites, and not because of non-thermal annealing of fission tracks.

Because of this, our alternative thermal history solution presented in Fig. 2 is almost certainly incorrect, because the He systematics employed are inappropriate to these samples. This history is presented merely to illustrate that a history capable of predicting the observed ages can be found (without too much trouble) which includes considerable Mesozoic burial, using the same systematics as those employed by Soderlund et al. [1]. But to obtain an accurate description of the thermal history of the analysed rock sequence, revised diffusion systematics are required which reflect the behaviour of apatites in which helium has been retained for more than 50 Myr.

Extraction of thermal history information from apatite (U–Th)/He ages routinely employs the Durango apatite systematics established by Farley [12], based on the assumption that all apatites behave in similar fashion. But earlier results on He diffusion in apatite [35] showed a much wider scatter in diffusion behaviour. We suggest that a reassessment of He diffusion systematics in a range of different apatite species is urgently required, in order to shed further light on the general applicability of the Durango systematics.

Until this is achieved, we recommend great caution in interpreting apatite (U–Th)/He ages, particularly in terranes where ages are likely to exceed 50 Ma, and especially where such ages are not accompanied by independent evidence (e.g. AFT data, vitrinite reflectance etc) to support the conclusions derived from the (U–Th)/He data.

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