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Discussion

Reply to 'Comment by Guedes et al. on: "Low temperature Phanerozoic history of the Northern Yilgarn Craton, Western Australia" by Weber et al. [Tectonophysics 400 (2005), 127–151]'

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1. Introduction

We welcome the opportunity to reply to the Comment by Guedes et al. (2006-this issue) who have questioned our approach to the thermal modelling history of apatite fission track data in our paper on the low temperature Phanerozoic history of the northern Yilgarn Craton, Western Australia (Weber et al., 2005). Due to the antiquity of the rocks (Archaean and Proterozoic) and the markedly subdued topography it has been proposed that the Western Australian Shield is characterised by a mean denudation rate of 0.1–0.2 m/Ma over ~1500 Ma (e.g. Finkl and Fairbridge, 1979; Fairbridge and Finkl, 1980). The key purpose of our study was to test this long-held paradigm of cratonic stability by applying apatite fission track thermochronology to a suite of surface samples from the shield.

The main point raised by Guedes et al. refers to the use of a mean initial track length value of 14.5 μm in our models instead of the 'default' value of 16.3 μm. It is surprising that Guedes et al. should raise such a concern at this time since the background, assumptions and reasoning of this approach have been treated in some detail in previous works (e.g. Kohn et al., 2002; Gunnell et al., 2003; Kohn et al., 2005). Clearly, further clarification is required to address these concerns and place them in the appropriate context.

2. Initial mean track length value and thermal history models

Guedes et al. argue that the modelling procedure used in our study was inconsistent with the laboratory annealing data upon which it is based. We believe the apparent inconsistency arises in large part from the different ways that fission track ages and track length data are currently handled. By international convention, fission track ages are almost universally calibrated against independent ages for a set of age standard materials (the zeta calibration approach; Hurford and Green, 1982, 1983), in spite of the fact that the standard apatites have mean track lengths of only about 14.5 μm. Thermal history modelling is based on laboratory annealing studies carried out on freshly induced ^{235}U tracks (e.g. Green et al., 1986; Laslett et al., 1987)

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having an initial mean length of approximately 16.3 μm. It is widely acknowledged that age and length parameters, both of which are required in thermal history modelling, are not completely compatible in the way they are treated. No fully satisfactory solution is yet available to this dilemma.

We would argue therefore that, at the current state of knowledge, it is actually more consistent to use a reduced track length of 14.5 μm as the starting point for modelling studies because this most closely resembles the mean length in the age standards used to calibrate ages. Also, the 'equivalent time' principle, which underpins all existing fission track annealing models (Duddy et al., 1988), makes it clear that the further annealing of a fission track at any length is independent of the previous conditions it has been exposed to and can be described by the same annealing model.

The apatite annealing model of Laslett et al. (1987) is formulated in terms of the current measured track length normalised to an initial track length. This is referred to as the reduced track length and is defined as $r=l/l_0$, where l and l_0 are the annealed and 'unannealed' track lengths, respectively. In applications of the original model formulation, using an initial track length of 16.3 μm, the lack of low temperature annealing typically leads to the inference of a marked cooling event in the geologically recent past (e.g. de Buijne and Andriessen, 2002; Kohn et al., 2002; Gunnell et al., 2003). In many cases such a late cooling event is difficult or even impossible to reconcile with the known geological history of the studied area and has therefore been referred to as a 'modelling artefact'. One approach to partly alleviate this question is to consider what the initial track length parameter represents in these annealing models. Mean *spontaneous* track lengths from rapidly cooled geological samples assumed to have undergone little post-formation thermal disturbance rarely exceed ~14.5 to 15 μm while the mean lengths from 'unannealed', artificially *induced* tracks are typically 16.3±0.9 μm (Gleadow et al., 1986; Green et al., 1986).

Donelick et al. (1990) showed that the initial length of induced tracks in apatite is not constant over very short times and that some form of annealing occurs even at room temperature over a matter of hours to days. Guedes et al. point out that Donelick et al. reported that after about 1 month the lengths did not vary over a period of months, but this has little relevance to the behaviour of such tracks on time scales of 10^6 years or more. The important point of the observation of Donelick et al. is that the length of induced fission tracks can no longer be taken as a constant, as was once assumed. The significance of this is currently unclear in terms of the overall long-term physical nature of the annealing process and the generally assumed initial track length may in itself be a variable, implying that 16.3 μm may not be the relevant unannealed track length in apatite over geological time scales. This is acknowledged in the reformulation of the Laslett et al. (1987) model by Laslett and Galbraith (1996), where the initial length is treated as a variable. Hence, for geological time scales, *spontaneous* tracks may effectively be ~10% shorter than those observed on laboratory time scales for *induced* tracks (Gleadow et al., 1986; Laslett and Galbraith, 1996; Ketcham et al., 1999). As a consequence, the Laslett et al. (1987) model, based on the laboratory determined initial length tends to underestimate annealing at temperatures lower than ~50–60 °C and therefore to overestimate total cooling rates in the more recent geological past.

As a model calibrated for reduced track lengths depends strongly on the assumed initial track length, the effect of two values for the initial track length, i.e. 16.3 μm and 14.5 μm for different terranes has been explored (e.g. Kohn et al., 2002; Gunnell et al., 2003). In considering regional denudation in these studies and also in the work of Weber et al. (2005), it has been found that the latter value provides good agreement with one or a combination of independent geomorphic, stratigraphic and tectono-magmatic data. In these works, it has been acknowledged clearly that this is a *departure* from an initial length of 16.3 μm upon which the Laslett et al. (1987) model is based, that this is *not* a definitive solution and that this *does not* provide new insights into the physical mechanisms of annealing. Strategic approaches to tackle the refinement and treatment of initial length estimates to account for the observed amount of annealing have been outlined by Gunnell et al. (2003, p. 192–193) and these need to be further addressed. Our use of the 14.5 μm initial track length is one such approach exploring new parameterisations of existing apatite fission track annealing algorithms.

3. Denudation history of the northern Western Australian Shield

Elaborating further on our approach in Weber et al. (2005). Using the default parameterisation (i.e. an initial mean track length value of 16.3 μm) with identical constraints to the thermal history models used in Fig. 4b of Weber et al. (2005) shows a pronounced Tertiary cooling phase in the 16.3 μm models and a slightly younger age for the onset of cooling below ~110 °C (but still within estimated uncertainty limits) of ~300–

320 Ma±20 Ma compared to 280–300 Ma±20 Ma in the 14.5 μm thermal history models. The 14.5 μm value adopted for the thermal history models in Fig. 4b of Weber et al. (2005) accords with the fact that the major Phanerozoic basins adjacent to the northern Western Australia shield show no evidence for any appreciable section of Late Cretaceous to Recent clastic strata which would reflect a detrital signature associated with a discrete Tertiary cooling phase. As the basins are obvious depocentres for denudation products from the craton and because they host the major hydrocarbon reserves of the North West Shelf of Australia their stratigraphy, sedimentology and structure is well documented. Furthermore, the 14.5 μm thermal history models are consistent with evidence for a prolonged period of regolith formation since at least early Miocene time from a $^{4}He/^{3}He$ thermochronometry study of authigenic goethite adjacent to the study area (Heim et al., 2006).

4. Concluding remarks

The use of a value lower than 16.3 μm with the Laslett et al. (1987) modelling algorithm is a means of exploring new parameterisations of existing apatite fission track annealing algorithms and comparing denudation histories with independent geological data to assess the viability of the model results.

In the northern Western Australian Shield it is not possible to reconcile previously proposed long-term denudation rates with the observed apatite fission track data, no matter which initial mean track length value (16.3 or 14.5 μm) for thermal history modelling is applied. The main conclusions on the thermal history as derived by Weber et al. (2005) are consistent with independent geologic and isotopic evidence, and we consider remain valid on current understanding of apatite fission track annealing behaviour.

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