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Thermal and tectonic history of the Barrandian Lower Paleozoic, Czech Republic: Is there a fission-track evidence for Carboniferous-Permian overburden and pre-Westphalian alpinotype thrusting?

(Critical comments on the paper by Ulrich A. Glasmacher, Ulrich Mann and Günther A. Wagner)

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Abstract. Close scrutiny of apatite fission-track data from Barrandian Lower Paleozoic rocks shows that previous interpretations involving a late Carboniferous to Permian heating stage and the extensive development of pre-Westphalian thrust tectonics are largely speculative. An alternative time-temperature path for the Barrandian sequence based on firmly established geological constraints and an improved version of the AFTSolve annealing kinetic model by Ketcham et al. (2000) is presented as evidence of a simple late Devonian to early Carboniferous Variscan peak heating, followed by a gradual Mesozoic to Tertiary cooling.

Key words: apatite fission-track analysis, Barrandian, Variscan Orogeny, Lower Paleozoic

Introduction

Glasmacher et al. (2002) have recently published an important study in which they applied the technique of apatite fission-track analysis (AFTA) toward revealing the thermal and tectonic evolution of the Barrandian area. They analyzed fission-track distributions in apatite in a set of 39 sedimentary and volcanic rock samples ranging in age from late Proterozoic to Carboniferous. Their interpretation provides an alternative view of the geological history of the Barrandian that, in some aspects, challenges existing opinions shared by many Czech regional geologists. In the present critical review we wish to comment on the main conclusions of that paper that seem to be weakly supported by and/or even contradictory to well-established regional geological observations. We also briefly compare the interpretations of Glasmacher et al. (2002) with those we have recently achieved using an identical set of rock samples with an improved version of the AFTA software and different geological constraint.

During the early stages of our AFTA studies in the Barrandian area (1998–1999) an extensive field sampling and sample processing campaign was carried out in collaboration with the group of German fission-track specialists from the Max Planck Institute (Heidelberg, Germany) led by Dr. Ulrich Glasmacher (Filip and Suchý 1999). After obtaining fission track-length distribution measurements of individual apatite grains, largely accomplished by the first author of this note, a number of serious methodological and geological disagreements divided our team into two groups, resulting in two separate publications presenting different time-temperature interpretations of the data (Suchý et al. 2001, Suchý, Dobeš et al. 2002, Glasmacher et al. 2002). This unfortunate, though not uncommon, situation has created a unique opportunity for critically comparing two different annealing models now widely used for interpreting fission-track length distribution data (Laslett et al. 1987, Ketcham et al. 1999), as well as the differing interpretations applied by Glasmacher et al. (2002) and Suchý, Dobeš et al. (2002).

Geological considerations

There are two principal conclusions presented in the paper by Glasmacher et al. (2002) on which we want to comment:

1. The authors argue that the rocks of the Barrandian area experienced complex thermal evolution characterized by several distinct stages of heating and cooling (Fig. 1a). They assert that an early stage of Variscan heating occurred during the late Devonian–early Carboniferous (~ 360–350 Ma), followed by distinct cooling associated with the erosion and exhumation of a part of lower Paleozoic sequence during the Carboniferous. A subsequent heating stage affected the rocks during the late Carboniferous to Permian periods (~ 300–250 Ma), which the authors ascribe to burial heating beneath the Carboniferous-Permian overburden. The final stage of Cretaceous cooling was interpreted in terms of the long-term, slow to medium exhumation process that occurred in the Central Variscan belt.

2. The authors also claim that the lower Paleozoic sequence of the Barrandian area was disturbed by extensive Variscan (pre-Westphalian) thrusting that influenced the thermal evolution of the rocks. Thrusting divided the sedimentary fill of the Barrandian into several tectonic segments that experienced contrasting thermal development.

Our comments on these fundamental conclusions will begin with the maximum heating of the Barrandian

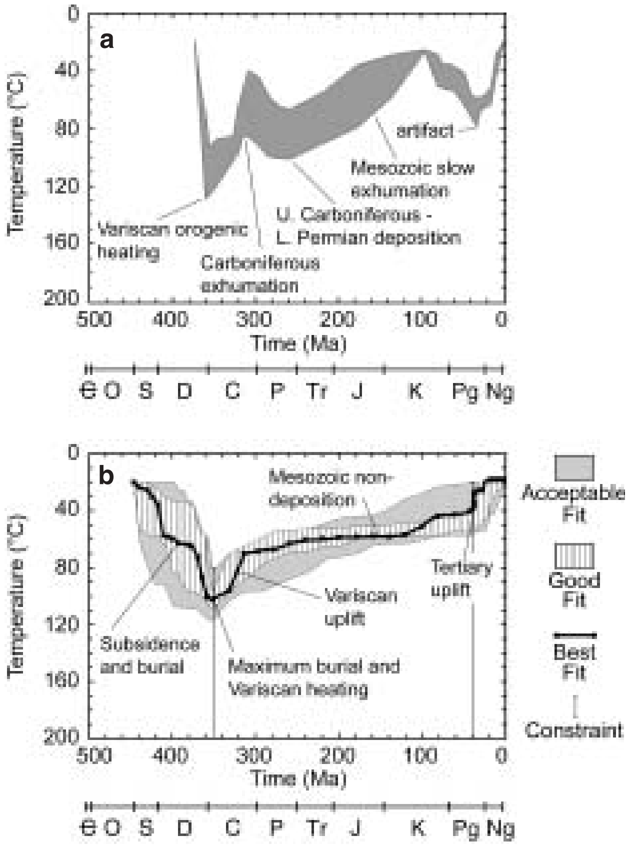

Figure 1. a – Summary of time-temperature paths from various parts of the Barrandian, and interpretation of the respective tectono-thermal events according to Glasmacher et al. (2002; modified after their Fig. 10).
b – An alternative time-temperature path for the Barrandian lower Paleozoic rocks, resulting from the application of the Ketcham et al. (1999, 2000) annealing model and adherence to the Occam's Razor principle of utilizing a minimum of reasonable assumptions. Note that the absence of a late Paleozoic heating event, and the assumption of a slow Mesozoic cooling rate are consistent with current geological knowledge of the region. Though this particular curve relates to an individual rock sample (H7 Ordovician basaltic tuff, from Chlustina near Beroun; adopted from Filip 2001), similar T-t paths are characteristic for most of the Barrandian lower Paleozoic samples processed through that technique.

sequence during the late Devonian-early Carboniferous time. Glasmacher et al. (2002) consider this as one of their most important findings, though it has been clearly known to earlier authors who recognized this thermal event using a number of analytical techniques, including AFTA (Filip and Suchý 1999, Filip 2001, Suchý et al. 2001, Suchý, Dobeš et al. 2002, and many others). A late Devonian age for the regional diagenesis of the Barrandian sediments has also been proposed by Suchý et al. (1996) and Chlupáč et al. (2002), based on wider sedimentological and field observations. It is surprising that Glasmacher et al. (2002) have neglected these earlier publications.

Glasmacher et al. (2002) further advocate an additional late Carboniferous to Permian heating stage (~ 300–250 Ma) as being due to a Carboniferous-Permian stratigraphic and/or tectonic load, which has since been completely eroded. The present authors believe that this interpretation is hypothetical and may contradict well-established geological observations. Although there have been some recent studies suggesting substantial late Carboniferous to early Permian deposition in central-western Bohemia (Zajíc 2000, 2002), the fact is that no remnants of any strata younger than Stephanian C have yet been found in the central or south-eastern part of the Barrandian area. It is questionable whether such deposits ever existed in that area (see also Pešek 1996 and the references therein). Moreover, the rigorous modeling of Barrandian AFTA data that we discuss below does not require any substantial Carboniferous/Permian heating episode.

Glasmacher et al. (2002) also introduce a tectono-thermal concept of the Barrandian lower Paleozoic, according to which various parts of the basin experienced contrasting thermal evolution due to displacement by pre-Westphalian thrust tectonics. However, their Fig. 10, which provides a summary of the best-fit time-temperature paths of samples from various basinal segments, shows a set of apparently similar curves instead of different paths. This clearly suggests uniform rather than contrasting thermal evolution on a basinal scale. It should be also mentioned that the idea of extensive Barrandian thrust displacements remains hypothetical and would require further geological evidence. The same is true with respect to the earlier conceptual work by Havlíček (1998) and Melichar and Hladil (1999a, b), to which Glasmacher et al. (2002) refer as those originally proposing alpinotype tectonics for the area (see also Chlupáč 1999 and the critical discussion therein). In fact, the ages of the major Barrandian thrusts (Očkov Fault, Tachlovice Fault) are at present unknown, as are the subsurface geometry and kinematics of the faults (see also Havlíček 1992 and his discussion of complex fault tectonics in the Barrandian area). The displacements along those faults, if any, also remain hypothetical.

More importantly, many (if not all) of the apatite fission-track data presented by Glasmacher et al. (2002) as evidence for active thrust tectonics can be simply explained in other ways. For instance, the difference in Paleozoic thermal exposure between the two samples of mid-Devonian sandstone (#H20 vs. #H21) can be explained, perhaps more logically, in terms of a selective hydrothermal overprint (Fig. 2). The sample H20 (Zlatý kůň Hill, Koněprusy) that reveals the complete thermal annealing of fission-tracks, was interpreted by Glasmacher et al. (2002) in terms of heating beneath the thrust piles. However, it should be noted that the sample location at Zlatý kůň Hill was affected by repeated episodes of hydrothermal activity, some of which occurred during the Devonian (Zeman et al. 1997, Franců et al. 2001, Melka et al. 2002). Temperatures in the range of 90–120 °C, which are sufficient for annealing fission-tracks in apatite, have been documented immediately below the H20 sampling point based on the organic matter reflectance method (Franců et al. 2001).

The remaining two samples showing contrasting time-temperature paths described by Glasmacher et al. (2002) as another strong case for thrust tectonics (#H7 vs. #H18) can also be interpreted differently. Both samples come from localities near the long axis of the basin, though a horizontal distance of about 19 km separates them from

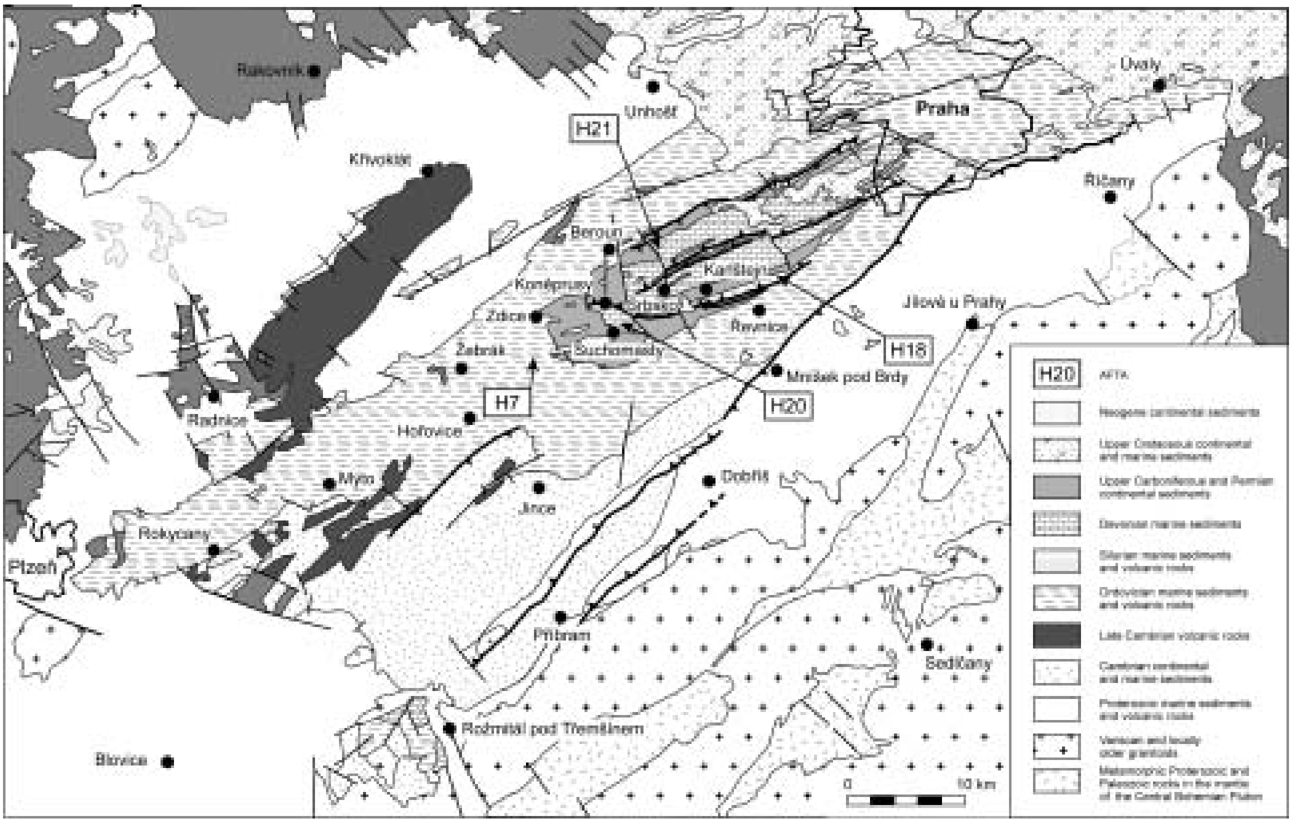

Figure 2. Schematic geological map of the Barrandian area, showing the collection localities of the samples discussed in the text.

each other. A distinct paleothermal gradient that increases to the NE has been recognized for that part of the Barrandian based on a range of independent analytical indices (Šafanda et al. 1990, 2003, Cháb et al. 1995, Suchý and Rozkošný 1996, Suchý et al. 2002, Volk et al. 2002). The recorded paleothermal variations between these two samples can therefore be more logically ascribed to lateral variations in the paleothermal diagenetic field rather than to hypothetical thrust tectonics. Glasmacher et al. (2002), however, apparently ignore the regional knowledge that does not fit to their concept of thrust tectonics.

In summarizing our discussion about a possible role for extensive thrusting, we wish to state that *the above arguments do not imply that the concept of alpinotype tectonics for the Barrandian area is necessarily incorrect.* In the absence of modern structural data and high-quality seismic data, the question remains open and requires further investigation. The concise message from our analysis is, however, that *the AFTA data alone, as interpreted by Glasmacher et al. (2002), do not provide any conclusive evidence in favour of or against the thrust tectonic concept*.

Another problematic point of their paper concerns the time-temperature scenarios for the Barrandian lower Paleozoic sequence. The authors refer to two contrasting T-t models involving late Devonian and Autunian maximum heating, respectively, as proposed by Franců et al. (1998). They state that they "hope to constrain the described alternative burial models and decide which one is more likely" (Glasmacher et al. 2002; p. 385). However, instead of critically reviewing these scenarios, the authors surprisingly integrate both versions into a single model (their Fig. 10; see also Fig. 1a of the present paper), thereby ignoring the fact that they are *mutually exclusive* time-temperature paths (see Franců et al. 1998 and the discussion of the original time-temperature models therein). By doing so, they inevitably leave the readers truly perplexed.

Methodological considerations: aspects of the annealing models and geological constraints

Kinetic annealing models

Kinetic annealing models are used to interpret apatite fission-track length distribution data in terms of the time-temperature evolution of apatite grains in apatite-containing rocks. The annealing models generally ascribe the shortening of fission-track lengths to the combined influence of time and temperature, in a way similar to the time-temperature modeling of organic matter maturation (e.g., Waples 1984, Sweeney and Burnham 1990). Some recent models also consider the chemical composition of apatite and other complex parameters. Of these, the kinetic annealing models proposed by Laslett et al. (1987) and Ketcham et al. (1999, 2000) appear to be the most widely used.

The older annealing model of Laslett et al. (1987) was applied by Glasmacher et al. (2002) toward interpreting their Barrandian AFTA data. However, this model has a significant disadvantage in that it is based on a single type of apatite (Durango apatite). This simplification alone may contribute to considerable error in the resulting T-t paths, since natural apatites, particularly those of sedimentary rocks, actually exhibit variable closure temperatures and annealing kinetics. Moreover, the Laslett Durango apatite-based model predicts insufficient annealing at low temperatures that must be corrected by introducing an artificial late-stage heating episode. This specific feature, in turn, results in "artifacts" which can mask significant thermal events that may have affected the samples during earlier geological times.

The more recent kinetic annealing AFTSolve model of Ketcham et al. (1999, 2000), which we applied in our studies (Filip and Suchý 1999, Filip 2001, Suchý, Dobeš et al. 2002), largely reduces the above mentioned shortcomings by accounting for the complex chemistry of natural apatite and the phenomena of low-temperature annealing that occur in nature. This model is based on data from more than 400 annealing experiments conducted on 15 different apatite types. It corrects fission-track length anisotropy with respect to the crystallographic axes of the apatite. The Ketcham model also utilizes information from "natural labs", such as the down-well measurements made in the Otway Basin (SE Australia), for the annealing of end-member fluorapatite at high temperatures. The influence of low-temperature annealing was eventually implemented in this model using empirical data from deep-sea sediments that have experienced temperatures below 21 °C for over 100 Ma (Ketcham et al. 2000).

Geological constraints

The principal reason for introducing geological constraints into the process of apatite fission-track time-temperature modeling is to reduce the number of possible T-t paths through which a given sample may have theoretically evolved in the geological past. The choice of scientifically justified constraints is not a straightforward process, but requires sound regional geological knowledge combined with clear and logical rules. Among the latter, the principle of Occam's Razor, named after the medieval scientific philosopher William of Occam, is the most prominent. Many versions of this philosophical principle exist in the literature, but in its simplest form it advises *not to introduce more assumptions than the minimum required*. In applying Occam's Razor to AFTA time-temperature modeling, it follows that one should use a minimum of firmly established geological constraints, to the exclusion of those that are vague, hypothetical, biased, or otherwise doubtful.

Glasmacher et al. (2002) generally applied five geological constraints, at least two of which were based on unsure and/or highly speculative grounds (Table 1). The first temperature constraint near the Devonian-Carboniferous transition (~ 360 Ma, T = 60–160 °C) is supported by independent paleothermal data. This is followed by a second one at 310 Ma (Permian), for which the actual evidence for Permian paleotemperatures (T = 35–110 °C) is not given. Similarly, the third thermal constraint situated about 100 Ma (Cretaceous; T = 25 °C) is unsupported by any geological evidence. The next heating event, in the range of 0–50 °C, supposedly occurred about 40 Ma ago (Paleogene); this, however, is an "artifact" resulting from the annealing model used (see above) that, regrettably, masks a substantial part of the younger thermal history of the samples. The final thermal constraint concerns the recent erosional level and the present-day surface temperature (20 °C at 0 Ma). It should be noted that the T-t paths proposed by Glasmacher et al. (2002) have literally been pre-determined by the questionable thermal constraints described above. These, in turn, strongly influenced the characteristic "up-and-down" pattern of the resulting time-temperature curves. These paths represent only one of the *theoretically possible* T-t solutions for the Barrandian lower Paleozoic rocks. We do not claim that this particular solution is completely impossible. We merely claim that the given solution is *unlikely* because it is based on geological constraints that are largely hypothetical and/or doubtful, at least at the present stage of regional research.

An alternative time-temperature path for the Barrandian lower Paleozoic

As an alternative to the largely speculative "up-and-down" thermal evolution of the Barrandian presented by Glasmacher et al. (2002), we propose a simple and geologically elegant T-t path, recently obtained from ten representative Barrandian rock samples by use of the AFTSolve annealing kinetic model of Ketcham et al. (Filip 2001, Suchý, Dobeš et al. 2002). Prior to the modeling we carefully evaluated all existing evidence on the thermal history of each individual sample, and introduced a minimum of necessary geological constraints in keeping with the principle of Occam's Razor.

In general, we applied just two principal geological constraints, both of which are logical and firmly established (Table 1). First, the maximum heating of the samples in the range of 80–200 °C is justified by a large number of available, independent paleothermal data (Suchý and Rozkošný 1996, Suchý et al. 2002, Ša-

Table 1. Geological constraints (ages and respective temperatures) used as defaults in the time-temperature models for the Barrandian lower Paleozoic rocks after Glasmacher et al. (2002), and Filip (2001). See text for details

Glasmacher et al. (2002)		Filip (2001)	
Geological age (Ma)	Temperature (°C)	Geological age (Ma)	Temperature (°C)
360	60–160	350	80–200
310	35–110	–	–
260	60–140	–	–
100	25	–	–
40	0–50	–	–
0	20	0	20

fanda et al. 2003 among many others). We further postulated that the maximum heating occurred around the Devonian-Carboniferous boundary (~350 Ma). Though that timing was indirectly indicated by independent geological data (see below), the key evidence came from the modeling itself. *We simulated a range of heating events that may have occurred during both Variscan and post-Variscan geological history, but the only one of these that allowed the highest degree of data fit was that of the Devonian-Carboniferous heating event.* This empirical conclusion is a simple one, but fundamental with respect to the core of the problem. Anyone having access to the AFTSolve kinetic annealing model and the apatite fission-track length distribution data (given in Filip 2001 and Suchý, Dobeš et al. 2002) can easily reproduce our results.

Our second time-temperature constraint, that of 20 °C at 0 Ma, is self-evident as it corresponds to the present-day position of the samples collected mostly from surface outcrops. Similarly self-evident temperature defaults were also applied to samples of volcanic rocks containing first-cycle authigenic apatite, in order to define the early stages of thermal evolution immediately following the crystallization of the apatite (e.g., our sample H7 of Ordovician basaltic tuff, shown in Fig. 1b).

By applying this logical approach with a minimum of geological constraints, we have obtained a series of Barrandian time-temperature paths that are relatively uniform, simple, and generally different from those proposed by Glasmacher et al. (2002), see Fig. 1b. In fact, our modeling indicates that *the only substantial heating occurred during the late Devonian–early Carboniferous*. This proposed thermal history of lower Paleozoic rocks is consistent with the present stage of knowledge. This heating roughly coincided with the deepest burial of the strata, the intrusion of the nearby Central Bohemian Pluton, and the occurrence of the Variscan folding deformations (Suchý, Dobeš et al. 2002). Elevated burial temperatures in the range of 80–200 °C, characteristic of oil and dry gas window, around the Devonian/Carboniferous transition can be largely explained in terms of heating beneath a thick load (either stratigraphic or tectonic) of post-middle Devonian (Givetian) sediments, which were subsequently completely eroded. Such a hypothetical overburden is quite compatible with the extensive stratigraphic gap that divides the Givetian deposits from the overlying Westphalian B/C coal-bearing molasse sediments. The latter accumulated in a series of small taphrogenic basins along the northern and north-western erosional margin of the Barrandian lower Paleozoic (Holub et al. 1991). It seems reasonable that during this interval, spanning approximately 65–70 Ma, several kilometers of post-Givetian sediments may have been deposited in the area, thus burying the lower Paleozoic sequence to the depth of the oil-gas window. Post-orogenic uplift may have quickly exposed the upper portion of the Barrandian stratigraphic column to intense erosion that may have erased a considerable thickness prior to the Westphalian. In fact, geologically fast and deep pre-Westphalian erosion has been inferred for the Variscan orogenic granites of the nearby Central Bohemian Pluton, which also supports our interpretation (e.g., Kukal 1984, Dudek et al. 1991).

Our alternative model further implies that *no additional Carboniferous-Permian heating is necessary* to explain the recorded fission-track distributions. This, in turn, speaks in favor of the "Devonian scenario" of thermal history as described by Franců et al. (1998). This may imply that Carboniferous and/or Permian strata have never been deposited over the Barrandian lower Paleozoic, at least to a thickness sufficient for substantial heating. We ascribe the long-lasting period of relatively stable temperature that persisted in the lower Paleozoic sequence during the Mesozoic to non-deposition and/or moderate erosional conditions that are well documented from the central part of the Bohemian Massif (Malkovský 1979). Finally, the period of accelerated cooling that prevailed from 40 to 20 Ma ago we attribute to a major uplift that is known to have affected the Bohemian Massif from about 40 Ma ago, and which lasted throughout the Neogene period (Malkovský 1979, 1987). This uplift was probably due to major orogenic deformations propagating northward from the Alpine foreland (Cloetingh 1988, see also Suchý, Dobeš et al. 2002 for further details).

Our critical analysis also shows that regardless of the annealing model used, *the AFTA data alone do not give conclusive evidence for alpinotype thrust tectonics in the Barrandian.* However, we acknowledge that more structural research is required for providing a definitive answer to this challenging problem (see also Filip 2001, Suchý, Dobeš et al. 2002 and Stejskal et al. 2003 for the various aspects of the current Barrandian thrust tectonic debate).

Conclusions

Our critical analysis shows that much of the apatite fission-track data that were previously interpreted in terms of a late Carboniferous to early Permian stage of heating and Variscan alpinotype thrust tectonics for the Barrandian lower Paleozoic are, at best, equivocal. We show that this interpretation is largely the product of 1) pre-selective modeling parameters (time-temperature constraints) that are not adequately supported by independent geological data, and 2) the application of a monokinetic Durango apatite-based annealing kinetic model that does not sufficiently account for annealing at low temperatures. We further demonstrate that another time-temperature path would be more justified using the same input of fission-track length distribution data, but with the application of an improved annealing kinetic model and a careful selection of rigorous geological constraints. According to our alternative scenario, the lower Paleozoic rocks underwent a single but major thermal event during the late Devonian to early Carboniferous period, which was driven by burial or a tectonic load that has since been completely removed by erosion. Following the maximum heating stage in the range of 80–200 °C, the Barrandian sequence gradually cooled down throughout much of the Mesozoic era, with an appreciable acceleration of the uplift-associated cooling during the Tertiary.

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