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Thermal evolution of the Malá Fatra Mountains (Central Western Carpathians): insights from zircon and apatite fission track thermochronology

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Abstract: We apply zircon and apatite fission track thermochronology (ZFT and AFT, respectively) to the Variscan crystalline basement of the Malá Fatra Mts (Central Western Carpathians) in order to constrain the thermal history. The samples yielded three Early Cretaceous ZFT ages (143.7±9.6, 143.7±8.3, 135.3±6.9 Ma) and one Eocene age (45.2±2.1 Ma), proving that the basement was affected by a very low-grade Alpine metamorphic overprint. Although the precise timing and mechanisms of the overprint cannot be unequivocally resolved, we propose and discuss three alternative explanations: (i) a Jurassic/Cretaceous thermal event related to elevated heat flow associated with extensional tectonics, (ii) early Late Cretaceous thrusting and/or (iii) an Eocene orogeny. Thermal modelling of the AFT cooling ages (13.8±1.4 to 9.6±0.6 Ma) revealed fast cooling through the apatite partial annealing zone. The cooling is interpreted in terms of exhumation of the basement and creation of topographic relief, as corroborated by the sedimentary record in the surrounding Neogene depressions. Our AFT results significantly refine a general exhumation pattern of basement complexes in the Central Western Carpathians. A younging of AFT ages towards the orogenic front is evident, where all the external massifs located closest to the orogenic front (including Malá Fatra Mts) were exhumed after ~13 Ma from temperatures above ~120 °C.

Key words: Cretaceous, Tertiary, Western Carpathians, Malá Fatra Mts, thermal overprint and exhumation, thermochronology, thermal modelling, zircon and apatite fission track dating.

Introduction

The Central Western Carpathians (CWC) is an interesting and challenging area in which to study processes of exhumation. Occurrences of the Variscan crystalline basement are common but, exposure can be poor and large portions of the geological record are often missing. Crystalline complex outcrops as isolated crustal blocks, lined-up in several orogen-parallel belts (from the North to the South: the external Tatric, the internal Tatric, the Veporic and the Gemeric belt; Fig. 1A; modified after Andrusov 1968; Plašienka et al. 1997). This spatial arrangement resulted from forces induced during the coupled tectonic processes of lateral extrusion from the Eastern Alps toward the Carpathian region and subduction roll-back beneath the Carpathian arc in the Miocene (Royden et al. 1982; Ratschbacher et al. 1991a,b; Tari et al. 1992; Csontos 1995; Wortel & Spakman 2000; Frisch et al. 2000; Sperner et al. 2002).

Although the exhumation mechanisms are well described (e.g. Ratschbacher et al. 1991a,b; Sperner et al. 2002), the timing of exhumation of individual crystalline complexes in the CWC is still controversial due to a lack of reliable thermochronological data (Kováč et al. 1994; Danišík et al. 2004, 2008a,b). This is somewhat surprising considering that crystalline complexes in the CWC were one of the first sites targeted more than 30 years ago by (at that time) the newly developed fission track dating method (Burchart 1972; Kráľ 1977). After a promising start, the interest of geologists in the low temperature thermochronology and rock exhumation in this region declined. It was a study of Kováč et al. (1994), which proposed a general exhumation model based on fission track data collected over the years by J. Kráľ, combined with geochronological, stratigraphic, and paleomagnetic data. According to this model, crystalline bodies were exhumed over an ~80 Myr period, starting in the internal zones (Gemeric and Veporic Units, respectively) during the Late Cretaceous–Paleocene (90–55 Ma), and terminating in the external zones (external Tatric belt) in the Miocene (20–10 Ma). Despite being favoured by a major fraction of the Slovak geological community, this exhumation model does not seem to be in agreement with tectonic models proposed for the CWC (Ratschbacher et al. 1991a,b; Sperner et al. 2002; Kázmér et al. 2003).

In this study, we apply apatite and zircon fission track (AFT and ZFT, respectively) thermochronology in an attempt to better constrain the low-temperature thermal evolution of the Malá Fatra Mts (MF). We targeted this area because its spatial position and assumed exhumation history does not fit into the general pattern of the exhumation model proposed by Kováč et al. (1994), namely that this mountain range belongs to the external Tatric belt and was exhumed in the Oligocene–Mi-

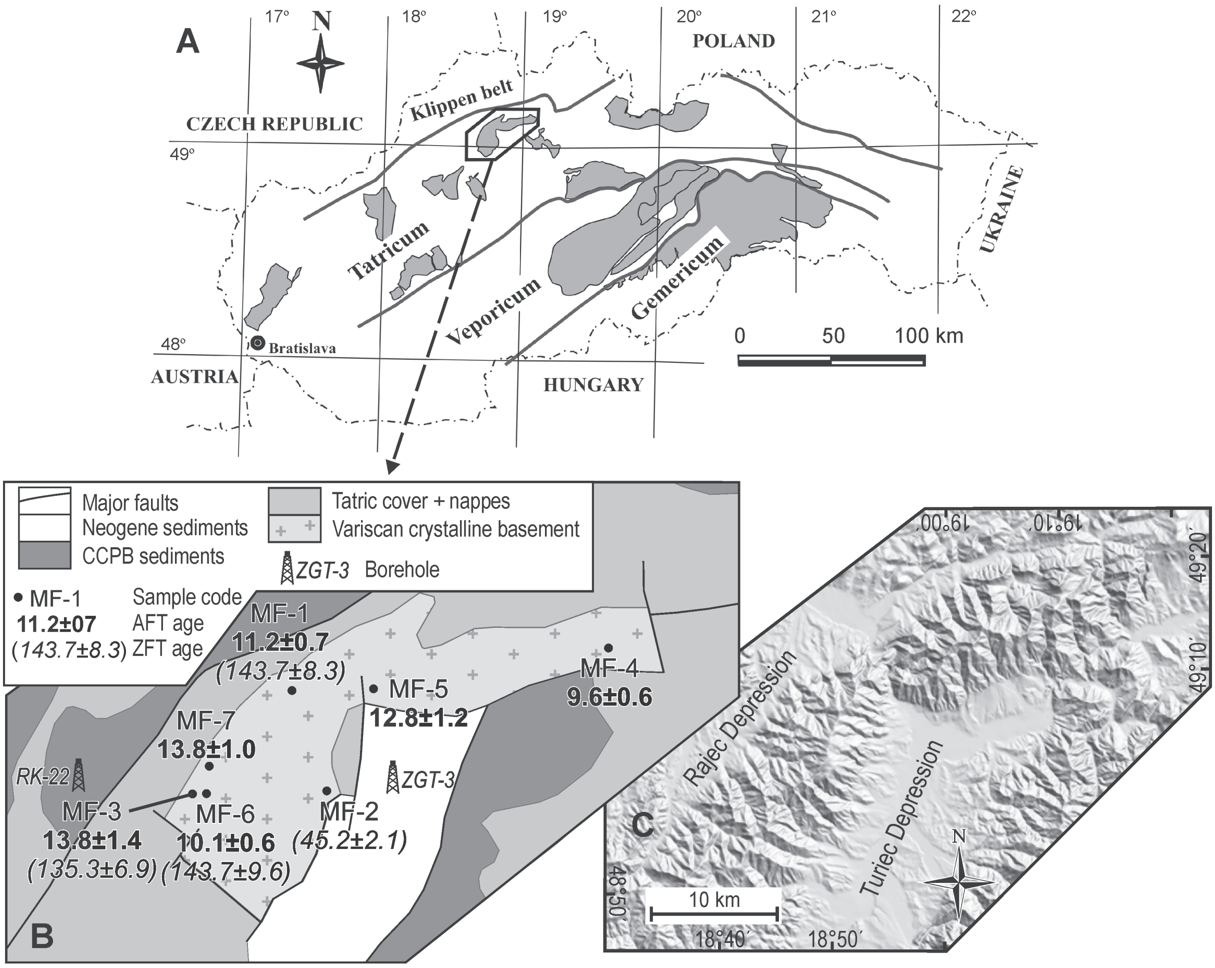

Fig. 1. **A** — Distribution of the pre-Alpine crystalline complexes in Slovakia. **B** — Geological sketch map of the MF (modified after Lexa et al. 2000) with location of the samples (black dots) and fission track ages in Ma. **C** — Shaded digital elevation model of the MF with local names.

ocene (Kováč et al. 1994). This is earlier than another crystalline complex — the High Tatra Mts, which belongs to the same belt and was exhumed between 20 and 10 Ma (Kráľ 1977; Kováč et al. 1994).

Our AFT data allows us to present a new thermal evolution model for the MF and refine the low-temperature cooling history. Moreover, we speculate that our ZFT data revealed a metamorphic event of Eocene age in the MF, which is so far the youngest record of metamorphism ever reported from Variscan crystalline basement in the Western Carpathians.

Geological setting and available thermochronological data

The MF are typical core mountains composed of Variscan crystalline basement covered by Mesozoic units and two superficial nappes, emplaced during Late Cretaceous (Cenomanian–Turonian) nappe-stacking (Fig. 1B; Andrusov 1968; Plašienka et al. 1997). This pre-Tertiary basement forms a horst surrounded by Cenozoic depressions — Turiec Depression in the SE and Rajec Depression in the NW (Fig. 1C).

The MF crystalline basement consists mostly of Variscan granitoids (zircon U-Pb and WR Rb/Sr ages: 353+11/–5 Ma, 360±10 Ma; Shcherbak et al. 1990; Bagdasaryan et al. 1992) with minor Variscan metamorphics (amphibolite-facies paragneisses, orthogneisses and amphibolites, and migmatites). The crystalline basement was affected by an Alpine, very low-grade metamorphic overprint (P-T conditions: ~0.3 GPa at ~300 °C), which resulted in deformation and formation of very low-grade mineral assemblages such as pumpellyite, epidote, chlorite, muscovite, albite and microcline (Faryad & Dianiška 2003). Inferring from analogy with other CWC units, these authors attribute the Alpine overprint to Cretaceous nappe tectonics and collisional processes.

The oldest post-intrusive cooling of the MF granitic pluton is documented by muscovite Ar-Ar dating with a plateau age of 344.8 ± 2.2 Ma (Hók et al. 2000). In the Late Permian, the basement was exposed and the Lower Triassic quartzites were deposited. Sedimentation of the cover unit in epicontinental and marine milieu continued with occasional hiatus until the Early Cretaceous (Albian) when sandstone and carbonate claystone sediments were deposited. During Cenomanian to Turonian times, the crystalline basement with its sedimentary cover was overthrust by two nappes (Krížna Nappe and

Choč Nappe, respectively) consisting mainly of Mesozoic carbonates (Plašienka et al. 1997). The estimated thickness of the overburden after thrusting is up to 3000 m, including internal imbrications within the nappe units (Maheľ 1986; Hók et al. 2000).

There are no post-tectonic sediments preserved on the horst of the MF, but post-tectonic evolution can be traced in the sedimentary record of the surrounding depressions. So-called “Gosau deposits” (Late Cretaceous post-tectonic formations; e.g. Michalík & Činčura 1992) have not been found in the Rajec and Turiec Depressions. The first post-tectonic record is represented by deposits of the Central Carpathian Paleogene Basin (CCPB; Gross et al. 1984). The sedimentation in the Rajec and Turiec Depressions began with basal carbonatic conglomerates derived from the Mesozoic nappes (Borové Formation — Lutetian–Bartonian), reaching an average thickness of ~150–200 m (boreholes RK-22 in Rajec Depression (Šalaga et al. 1976) and NE part of the Turiec Depression (Hók et al. 1998)). It is important to note that there is no evidence of erosion of the MF crystalline basement prior to the CCPB transgression. The Paleogene sedimentary sequence continues with flysch of the Huty and Zuberec Formation (Bartonian–Priabonian), which reaches up to 1400 m in both depressions and indicates rapid subsidence (Gross et al. 1984). There are no Neogene sediments preserved in the Rajec Depression. In contrast, in the Turiec Depression the sequence continues with up to ~1000 m thick column of Neogene (Middle Miocene to Quaternary) sediments (Fendek et al. 1990; Hók et al. 1998).

Exhumation of the MF massif was first investigated by Kráľ (1977) who presented one AFT age (25±18 Ma) measured on granite and argued for Neogene uplift. This interpretation and age was later adopted by Kováč et al. (1994) in a general exhumation model for the CWC. More thermochronological data was presented by Hók et al. (2000), who reported the age of 72 ± 3 Ma (Ar-Ar dating of sericite from an ultramylonite) and argued for Alpine mylonitization of granitoid rocks. The calculated average exhumation rates for mylonites are 500 m/Myr (Hók et al. 2000).

Samples and methods

For this study, seven samples of granite were collected from surface outcrops (see Fig. 1B for sample location). The investigated granites are predominantly hypidiomorphic, medium-grained, without visible metamorphic foliation. They were affected by fluid alteration in the post-magmatic phase and during later low-grade metamorphic overprint. This is shown by the crystallization of secondary mineral association (sericite, saussurite, chlorite), giving the rocks a slightly greenish colour.

Sample preparation and fission track analysis followed the procedure outlined by Danišík et al. (2007a). The external detector method (Gleadow 1981) was applied with the etching protocols of Donelick et al. (1999) for apatite (5.5 M HNO_3 for 20 seconds at 21 °C) and Zaun & Wagner (1985) for zircon (eutectic mixture of KOH and NaOH at 215 °C for 7 hours). The zeta calibration approach (Hurford & Green 1983) was adopted to determine the age. Samples were analysed with a Zeiss Axioskop 2 microscope equipped with a digitizing tablet and drawing tube, and controlled by the computer program FT Stage 3.11 (Dumitru 1993). Tracks in apatites and mica detectors were counted with 1250× magnification using a dry objective while tracks in zircons were counted under the same conditions but using an oil objective (Cargille oil type B, n = 1.515). FT ages were calculated using TrackKey 4.2g (Dunkl 2002). The annealing properties of apatite grains were assessed by measurement of D_{par} values (D_{par} — the mean etch pit diameter of fission tracks on prismatic surfaces of apatite; e.g. Burtner et al. 1994). The low-temperature thermal history based on AFT data (age, track length and D_{par} data) was modelled using the HeFTy modelling program (Ketcham 2005), operated with the multi-kinetic annealing model of Ketcham et al. (1999).

Analytical results

The results of ZFT and AFT analyses are summarized in Table 1 and shown in Figs. 1B and 2A. All samples passed the chi-square test at the 95% confidence interval and thus are considered to form one age population. All ages are reported as central ages with 1 sigma errors.

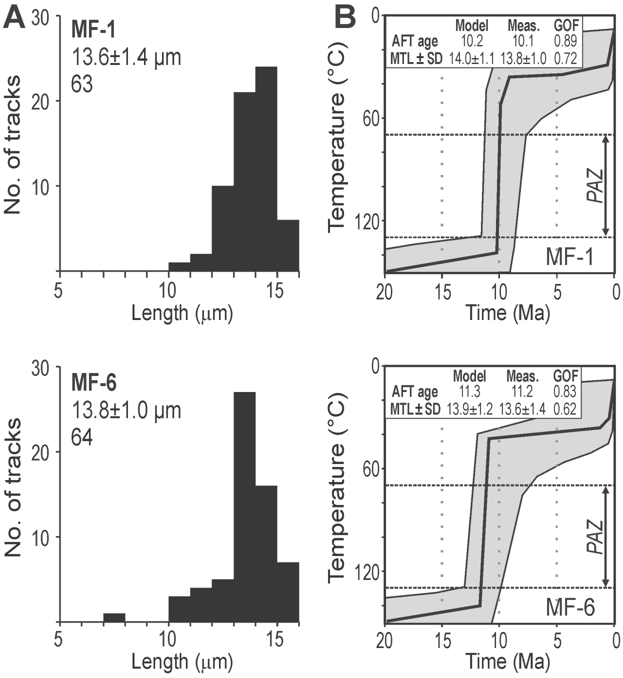

Fig. 2. **A** — Track length distributions; explanation of histograms (from top): sample code; mean track length ± standard deviation in μm; number of measured tracks. **B** — Corresponding thermal modelling results of AFT data displayed in time-temperature diagrams modelled with HeFTy program (Ketcham 2005). Light grey envelopes indicate good fit; solid black lines indicate the best fit. GOF is goodness of fit (statistical comparison of the measured input data and modelled output data, where a “good” result corresponds to value 0.5 or higher). The modelled cooling trajectories are valid only within the partial annealing zone.

Table 1: Fission track data[a].

Sample code	Lat. WGS-84	Lon. WGS-84	Elevation (m a.s.l.)	Lithology	N	ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	$P(\chi 2)$ (%)	Age (Ma)	± 1σ (Ma)	MTL (μm)	SD (μm)	N (L)	Dpar (μm)
ZFT data																		
MF-1	49°08'55"N	18°49'33"E	658	granite	21	167.19	1671	46.926	469	6.6013	3089	>95	143.7	8.3				
MF-2	49°05'19"N	18°51'40"E	802	granite	20	118.70	1289	104.887	1139	6.4896	3089	86	45.2	2.1				
MF-3	49°05'00"N	18°44'15"E	606	granite	20	303.57	2188	89.074	642	6.4896	3089	>95	135.3	6.9				
MF-6	49°05'04"N	18°44'58"E	672	granite	20	202.66	1188	56.976	334	6.6114	3089	>95	143.7	9.6				
AFT data																		
MF-1	49°08'55"N	18°49'33"E	658	granite	25	2.546	319	24.427	3061	6.643	3929	>95	11.2	0.7	13.6	1.4	63	3.0
MF-3	49°05'00"N	18°44'15"E	606	granite	25	4.158	217	31.754	1657	6.713	3929	52	13.8	1.4				2.9
MF-4	49°10'47"N	19°07'31"E	546	granite	25	2.341	319	26.536	3616	6.713	3929	>95	9.6	0.6				2.9
MF-5	49°09'03"N	18°54'25"E	862	granite	25	1.453	128	12.403	1093	6.783	3929	>95	12.8	1.2				3.0
MF-6	49°05'04"N	18°44'58"E	672	granite	25	2.880	382	31.708	4205	6.853	3929	92	10.1	0.6	13.8	1.0	64	3.1
MF-7	49°05'59"N	18°45'09"E	721	granite	25	2.030	280	12.922	1782	5.166	4936	>95	13.8	1.0				2.8

[a] **N** — number of dated apatite crystals; $\boldsymbol{\rho_s (\rho_i)}$ — spontaneous (induced) track densities ($\times 10^5$ tracks/cm^2); $\mathbf{N_s (N_i)}$ — number of counted spontaneous (induced) tracks; $\boldsymbol{\rho_d}$ — dosimeter track density ($\times 10^5$ tracks/cm^2); $\mathbf{N_d}$ — number of tracks counted on dosimeter; $\mathbf{P(\chi^2)}$ — probability obtaining Chi-square value (χ^2) for n degree of freedom (where n = No. of crystals –1); **Age ± 1σ** — central FT age ±1 standard error (Galbraith & Laslett 1993); **MTL** — mean track length; **SD** — standard deviation of track length distribution; **N(L)** — number of horizontal confined tracks measured; **Dpar** — average etch pit diameter of fission tracks. Ages were calculated using zeta calibration method (Hurford & Green 1983), glass dosimeters CN-5 and CN-2 (for apatites and zircons, respectively), and zeta values of 323.2 ± 5.6 (apatites) and 123.6 ± 2.1 year/cm^2 (zircons).

Three samples (MF-1, MF-3, MF-6) yielded Early Cretaceous ZFT ages (143.7 ± 9.6, 143.7 ± 8.3, 135.3 ± 6.9 Ma) while one sample (MF-1) yielded an Eocene age of 45.2 ± 2.1 Ma.

Six samples (MF-1, MF-3, MF-4, MF-5, MF-6, MF-7) yielded a tight cluster of Middle–Late Miocene AFT ages ranging from 13.8±1.4 to 9.6 ± 0.6 Ma. All samples are characterized by D_{par} values of ~3 μm, which indicates chlorine rich composition of apatites that are typically more resistant to annealing than fluorine rich apatites (Green et al. 1989; Carlson et al. 1999; Barbarand et al. 2003). Owing to low uranium content and young AFT age, it was possible to measure track length distributions (TLD) only in two samples (Table 1, Fig. 2A). The TLD's are unimodal, narrow (standard deviations: 1.0 and 1.4 μm), negatively skewed, with mean track lengths of 13.7 and 13.6 μm. Such TLD's are typical of moderate to fast cooling through the partial annealing zone (PAZ) of apatites (Gleadow et al. 1986a,b). This was confirmed by thermal modelling results which revealed fairly similar time-temperature paths for both samples, characterized by two stage cooling history: a period of faster cooling through the PAZ between ~13 and 9 Ma and a slower cooling lasting from ~9 Ma until the present (Fig. 2).

Interpretation and discussion

ZFT data

Since the track lengths in zircons were not measured and thermal history could not be modelled, interpretation of ZFT ages is not straightforward and the meaning of the data is less definitive. Therefore we discuss several scenarios that can explain the observed age pattern (see also Fig. 3).

Three samples from the western part of the range revealed similar ZFT ages in the range of ~135–145 Ma. All three samples passed the chi-square test and thus represent single age populations. At first glance, the ages can be interpreted as cooling ages, recording a cooling of the basement in the Early Cretaceous. However, when plotted together (Fig. 3C), the spectrum of single grain ages is fairly broad and ranges from ~185 to ~100 Ma. Although such a broad spectrum may be representative of a distinct cooling event (see cooling curve '***a***' in Fig. 3B; arguments supporting this interpretation are presented in paragraph 5 of this section), it may also reflect a partial rejuvenation of the ZFT thermochronometer and ZFT ages may thus be apparent.

In the following paragraph we present three arguments supporting this interpretation (i.e. apparent ZFT ages; cooling curves '***b***' and '***c***' in Fig. 3B, and possibly '***d***' discussed further below): (*i*) According to geological record, the area was subjected to normal marine sedimentation during Jurassic to Early Cretaceous times, where the total thickness of sediments hardly exceeded ~2 km and therefore sedimentary burial caus-

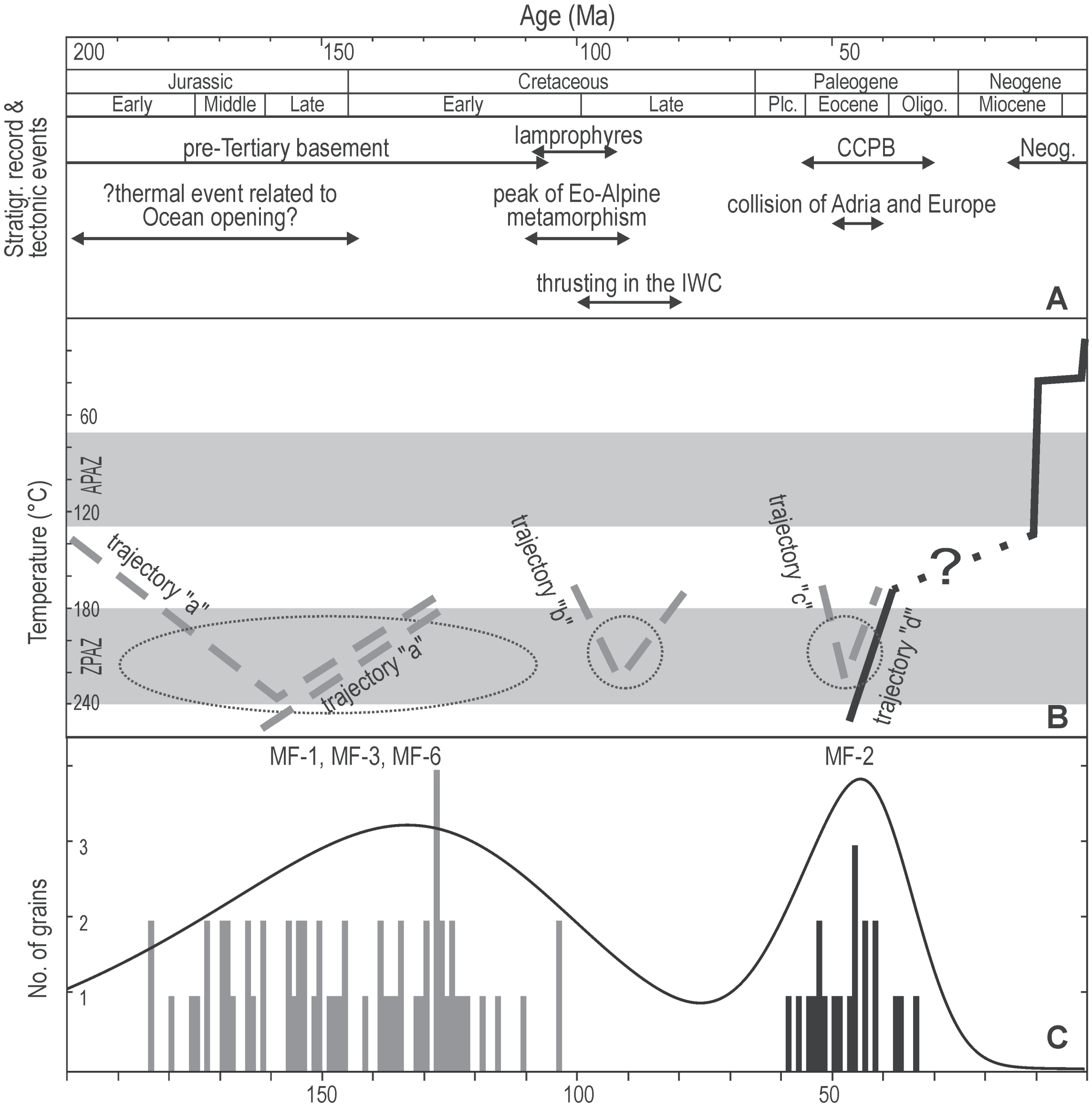

Fig. 3. **A** — Chronostratigraphic chart of the study area and surrounding regions with relevant geodynamic events (Plašienka et al. 1997; Lexa et al. 2000; Frisch & Gawlick 2003). **B** — Schematic thermal trajectories reconciling the data: speculative — dashed lines, convincing — solid lines; APAZ — apatite partial annealing zone; ZPAZ — zircon partial annealing zone (according to Brandon et al. 1998), see text for explanation. **C** — ZFT single grain age distribution showing difference between samples MF-1, 3, 6 and MF-2.

ing resetting of the ZFT thermochronometer in the Early Cretaceous is rather unlikely. (*ii*) To date there has never been a distinct Early Cretaceous tectonic event reported from the Western Carpathians or from the analogous units in the Eastern Alps. (*iii*) The only well known tectonic event in the Western Carpathians during Cretaceous time is thrusting (nappe-stacking) in the Cenomanian–Turonian period, when the Tatric crystalline basement, including the MF, was tectonically buried by Mesozoic nappes (Plašienka et al. 1997). However, the thrusting is of Cenomanian–Turonian age (Plašienka et al. 1997), which is clearly younger than the measured ZFT ages.

Danišík et al. (2008a) argued that Cenomanian-Turonian thrusting is recorded by ZFT ages of ~100 ± 10 Ma in the Žiar Mts, located ~30 km south of the MF (for location see Fig. 4). The authors correlate the event with the Eo-Alpine orogeny in the Eastern Alps (e.g. Frisch & Gawlick 2003), where the Austroalpine basement, which is an analogue of the Tatric basement in the CWC, also experienced peak conditions of metamorphism at ~100±10 Ma (e.g. Thöni & Jagoutz 1992; Thöni & Miller 1996). Therefore, one possible resolution of the ZFT data in the MF is by partial resetting of the ZFT system by Cenomanian-Turonian thrusting (cooling curve ‘***b***’ in Fig. 3B). An additional argument supporting the partial resetting at ~100 Ma is the single grain age spectrum (Fig. 3C), where none of the zircons yielded ZFT age younger than ~100 Ma.

There are also other alternative explanations of the data. It is not clear whether the first suggested interpretation (i.e. a cooling event in the Early Cretaceous; cooling curve ‘***a***’ in

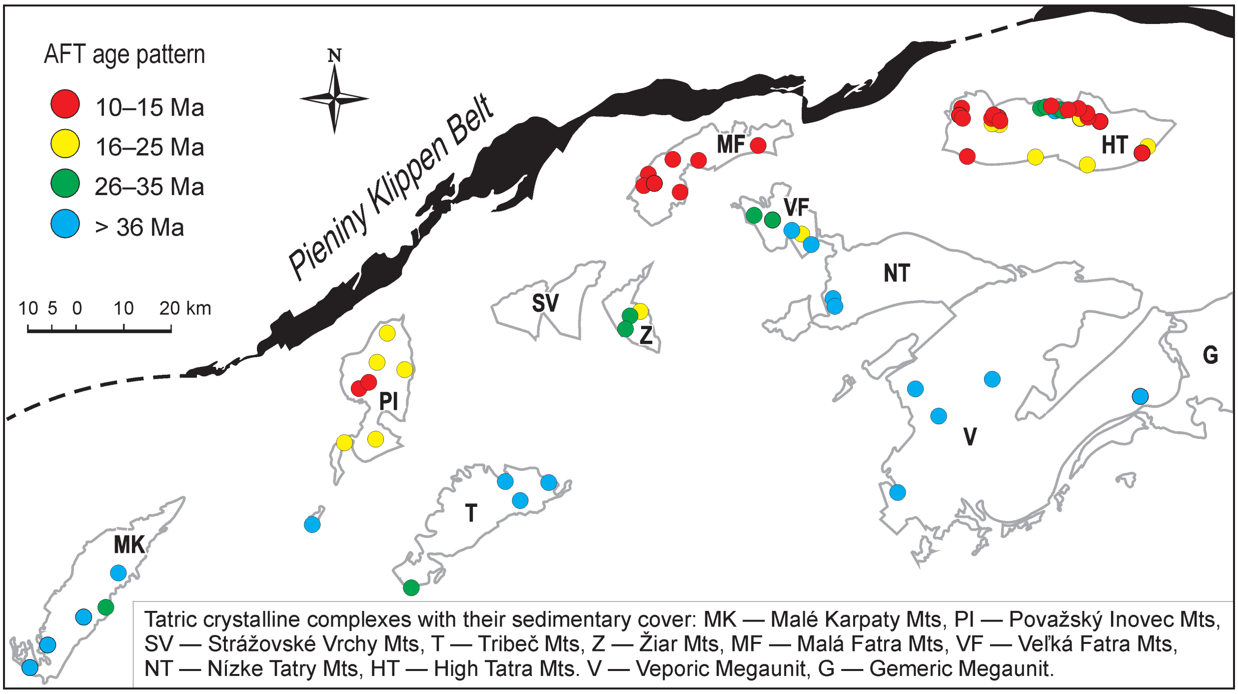

Fig. 4. Spatial distribution of AFT ages reported from crystalline complexes in the CWC, where a clear younging trend towards the former plate boundary (Pieniny Klippen Belt) is visible. Unexposed segments of the Pieniny Klippen Belt are indicated by dashed line. AFT data compiled from the following studies: Burchart (1972), Kráľ (1977), Kováč et al. (1994), Struzik et al. (2002), Baumgart-Kotarba & Kráľ (2002), Danišík et al. (2004, 2007b, 2008a,b, 2009).

Fig. 3B) should be completely dismissed. A growing number of Jurassic to Early Cretaceous ZFT ages found in other crystalline bodies (Kováč et al. 1994; Danišík et al. 2007b; Plašienka et al. 2007; Danišík unpublished data) as well as sparse occurrences of Jurassic/Cretaceous magmatic rocks reported from other parts of the Western Carpathians (Hovorka & Spišiak 1988; Spišiak & Hovorka 1997; Spišiak & Balogh 2002) might indicate that there was indeed a distinct thermal event at that time.

This hypothesis might be supported by an analogous situation in the Western and Central Alps, where numerous ZFT ages in the range 220–100 Ma commonly occur, but their meaning is not entirely clear due to lack of supportive arguments from the geological record. An elegant solution was suggested by Vance (1999), who ascribed these ages to high heat flow related to mantle upwelling associated with rifting and opening of different branches of the Tethys Ocean. Perhaps the CWC were affected by a similar thermal pulse from the mantle, which affected the ZFT thermochronometer but left no other evidence in the geological record. It is worth mentioning that there is some record of Mesozoic magmatic activity in the CWC that might be supportive of this interpretation. For instance, Hovorka & Spišiak (1988) and Spišiak & Hovorka (1997) argued that during late Early Cretaceous times, a climax of the extensional period in the CWC was marked by small extrusions of hyalobasanitic lavas of upper-mantle origin. Further, there are several occurrences of small sill intrusions of alkali lamprophyres reported from several basement granitic rocks, that were dated at 115–93 Ma (Spišiak & Balogh 2002).

The final possible interpretation is based on sample MF-2 (Eocene age), which is so far the youngest ZFT age ever reported from a Tatric crystalline complex in the CWC. While there is inherent danger in drawing broad conclusions from single ages, there are also other examples of Eocene ZFT ages found in other crystalline bodies in the CWC (e.g. in Tribeč Mts, Považský Inovec Mts and Malé Karpaty Mts; Kováč et al. 1994; Danišík et al. 2007b; Danišík unpublished data), and we, therefore, argue that this age cannot be ignored.

Unlike the previous three samples, the single grain age spectrum of the sample MF-2 forms a distinct peak, is narrow, and ranges from 32 to 55 Ma (Fig. 3C). Such a spectrum is typical for relatively quickly cooled samples. Thus we interpret this sample as a record of a distinct thermal event in the Middle Eocene (cooling curve '***d***' in Fig. 3B). There are two possible interpretations: the age may record (*i*) the cooling of the basement following the thermal peak reached during the Cenomanian–Turonian nappe-stacking; or (*ii*) an independent thermal event in the Middle Eocene.

Although we are not sure which option is correct, we tend to prefer the latter as it shows some similarities to data collected in other parts of the CWC. Namely, the ZFT age is almost identical with the age of 46±3 Ma measured by whole-rock K-Ar analysis on a metabasalt from an olistolith in the Belice Unit in the northern part of the Považský Inovec Mts (Putiš et al. 2008) and the ZFT age of 53±12 Ma from the Tribeč Mts granite reported by Kováč et al. (1994). The meaning and robustness of both ages are questionable — whole-rock K-Ar dating on basalts is not a particularly powerful tool, moreover the authors report no analytical results, just refer to 'own unpublished data' (Putiš et al. 2008). The ZFT age of Kováč et al. (1994) does not meet standard international criteria in terms of analytical and statistical requirements. Nevertheless, Putiš et al. (2008) pointed out that this age fits exactly the age of the Early Tertiary orogenic event that was related to collision between the European and the Adriatic plate and was well documented in the Northern Calcareous Alps (Frisch & Gawlick 2003). Putiš et al. (2008) suggest that this part of the Považský Inovec Mts was underthrust and metamorphosed in the Eocene and Early Tertiary orogeny this would also apply to the CWC. We speculate that the Eocene age found in the MF records the same Early Tertiary orogenic event. The same event might also be responsible for partial resetting of the rest of the samples (cooling curve '***c***' in Fig. 3B). This interpretation is, however, not in agreement with the tectonic model proposed for the Eocene. Applying the model of Kázmér et al. (2003), in the Middle Eocene the crystalline basement of the MF should be covered by sediments of the CCPB, whose thickness would have had to be more than ~8 km (assuming a closure temperature of ~240 °C, a cooling rate of 10 °C/Myr, and a paleo-geothermal gradient of 30 °C/km). That is not realistic in our opinion but it is possible that the burial was not solely sedimentary but also had a tectonic component.

In summary, as discussed above, interpretation of ZFT data is extremely difficult. The only conclusion from ZFT that can be made with confidence is that after the exposure in the Late Permian (see section 2), the basement must have been reheated to temperatures sufficient to reset ZFT system. We discussed three scenarios that can explain the observed age pattern and to certain degree incorporate presently accepted tectonic models for the CWC: Jurassic/Cretaceous thermal event related to elevated heat flow (cooling curves '***a***' in Fig. 3B), Cenomanian-Turonian thrusting (cooling curve '***b***' in Fig. 3B) and Eocene orogeny (cooling curve '***c***' in Fig. 3B). It is, however, clear that with more ZFT data, new models will be proposed and ZFT system can reveal many surprising facts about the evolution of the CWC.

Implication for metamorphic evolution

Despite the uncertainty in the interpretation, the ZFT data provide important information on the metamorphic history of the MF: ZFT data clearly show that the basement reached temperature conditions sufficient to fully reset the ZFT system (>210 °C, lower limit of zircon PAZ) during the Mesozoic and/or Cenozoic and would have undergone very low-grade metamorphism. This agrees with conclusions of Faryad & Dianiška (2003) who, citing textural relations and mineral compositions in the MF granitoids, argued for an Alpine very low-grade metamorphic overprint (P-T conditions: ~0.3 GPa at ~300 °C) of the basement. The overprint did not exceed ~350 °C as shown by Variscan mica Ar-Ar ages (Hók et al. 2000) obtained from undeformed granites (assuming ~350 °C closure temperature of Ar-Ar system in muscovite; McDougall & Harrison 1988).

AFT data

Unlike ZFT data, the interpretation of AFT data is straightforward. Our data reproduce within 1 sigma error with AFT data reported by Kráľ (1977) and Kováč et al. (1994), but have much higher precision (1 sigma errors <8 %). The data, combined with thermal modelling, allowed us to constrain the cooling episode to Middle to Late Miocene times between ~13 and 9 Ma, when the basement cooled from temperatures above ~130 °C to ~70 °C, assuming a slightly higher temperature range of PAZ typical for Cl-rich apatites (e.g. Carlson et al. 1999). Our AFT data cannot explain what happened within the basement prior to the cooling onset. We interpret this cooling event in terms of exhumation of the basement because the timing is corroborated by the sedimentary record: the first clastic material derived from the MF are pebbles from Mesozoic nappes deposited during Late Badenian to middle Pannonian times (14.8–9.1 Ma) and the crystalline basement was first exposed to erosion in the Late Pannonian (9.1–8.1 Ma; Hók et al. 1998). The portion of clastic material derived from the basement increased in the Pliocene and totally dominates the Quaternary sediments (Hók et al. 1998, 2000), indicating uplift of the range and creation of the present-day topography.

Modelled cooling trajectories can be translated into exhumation rates, if a reasonable paleo-geothermal gradient is assumed. Adopting a value of 30 °C/km results in average exhumation rates of >1000 m/Myr for a time period of 13–9 Ma, and ~200 m/Myr for time period between ~9 Ma and present. Considering the limited resolution of the modelled cooling path, the maximum and minimum exhumation rates for the fast cooling stage could range from ~4000 to ~400 m/Myr, and for the slow cooling stage, from ~200 to >50 m/Myr. These numbers are likely biased by the chosen paleo-geothermal gradient value, however, there is at least a two-fold difference between pre- and post-9 Ma cooling rates. If the geothermal gradient had not changed in the last 13 Myr, the data imply that since post-mid-Miocene (i.e. since ~13 Ma) about ~3.5 km of overburden has been removed, with the majority (≥2.6 km) being removed between 13 and 9 Ma.

The implication for exhumation of crystalline bodies in the Western Carpathians

Our results significantly refine an exhumation pattern of individual basement complexes in the CWC, which better fits the lateral tectonic extrusion models placing faulting and exhumation of crystalline bodies in the middle and post-Middle Miocene (circa post-13 Ma; Ratschbacher et al. 1991a,b; Sperner et al. 2002). Furthermore, with our data, a much clearer younging trend towards the orogenic front is evident (Fig. 4). The figure shows that internal massifs retain mostly Paleogene or Cretaceous AFT ages, even though some of them experienced a distinct reheating in the Neogene related to mantle upwelling, volcanic activity, and increased heat flow as documented by thermal modelling results based on track length data and also by apatite (U-Th)/He data (Danišík et al. 2004, 2008a,b). The internal massifs were thus in a 'colder' environment (i.e. <~120 °C) during the Tertiary. In contrast, all the external massifs located closest to the orogenic front (i.e. MF and High Tatra Mts) show almost exclusively Middle Miocene or younger AFT ages, which indicates their residence in a relatively 'hotter' environment (i.e. >~120 °C) in the Tertiary. Since there is no evidence of volcanic activity in the external Tatric belt, we interpret the 'hotter' environment in terms of deeper burial of the massifs prior to their final exhumation.

We would like to emphasize that any interpretation of the observed AFT age pattern in terms of surface uplift, rock uplift or uplift without specification of reference point or elevation level (e.g. Kováč et al. 1994; Hók et al. 1998, 2000; Sperner et al. 2002) is incorrect. Instead it should be always kept in mind that the reference frame for the FT system is the thermal structure of the crust and not the Earth's surface. Lastly, tectonic models for the Tertiary evolution of the Western Carpathians incorporating AFT data have to consider the fact that the majority of AFT ages are not cooling ages but apparent ages.

Conclusions

New AFT and ZFT data enabled us to constrain the thermotectonic evolution of the MF Mts. The most important results are summarized as follows:

— The Variscan crystalline basement of the MF Mts was heated to temperatures above ~210 °C and was affected by a very low-grade Alpine overprint as recorded by ZFT data. The time and origin of the heating remains unclear. We propose three explanation that need to be corroborated by future research: Jurassic/Cretaceous thermal event related to increased heat flow associated with mantle upwelling, Cenomanian–Turonian (Eo-Alpine) thrusting and Eocene orogeny related to collision between the European and the Adriatic plate;

— The AFT ages constrain a cooling event between ~13 and 9 Ma, which we interpret in terms of exhumation of the basement in the course of lateral tectonic extrusion;

— The investigated MF together with the High Tatra Mts are the ranges with the youngest exhumation history among all the crystalline complexes of the CWC as they record the youngest cooling AFT ages. This is in good agreement with their position as the external massifs located closest to the orogenic front and fits with the well-known spatial and temporal migration of processes from internal to external portions of the CWC.

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