1661-8726/08/01S225-9
DOI 10.1007/s00015-008-1279-8
Birkhäuser Verlag, Basel, 2008

Swiss J. Geosci. 101 (2008) Supplement 1, S225–S233

Apatite fission track and (U-Th)/He thermochronology of the Rochovce granite (Slovakia) – implications for the thermal evolution of the Western Carpathian-Pannonian region

MARTIN DANIŠÍK[1,*], MILAN KOHÚT[2], ISTVÁN DUNKL[3], ĽUBOMÍR HRAŠKO[2] & WOLFGANG FRISCH[1]

Key words: Western Carpathians, Rochovce granite, fission track analysis, (U-Th)/He dating, thermal modelling, Miocene thermal event

ABSTRACT

The thermal evolution of the only known Alpine (Cretaceous) granite in the Western Carpathians (Rochovce granite) is studied by low-temperature thermochronological methods. Our apatite fission track and apatite (U-Th)/He ages range from 17.5 ± 1.1 to 12.9 ± 0.9 Ma, and 12.9 ± 1.8 to 11.3 ± 0.8 Ma, respectively. The data thus show that the Rochovce granite records a thermal event in the Middle to early Late Miocene, which was likely related to mantle upwelling, volcanic activity, and increased heat flow. During the thermal maximum between ~17 and 8 Ma, the granite was heated to temperatures ≳60 °C. Increase of cooling rates at ~12 Ma recorded by the apatic fission track and (U-Th)/He data is primarily related to the cessation of the heating event and relaxation of the isotherms associated with the termination of the Neogene volcanic activity. This contradicts the accepted concept, which stipulates that the internal parts of the Western Carpathians were not thermally affected during the Cenozoic period. The Miocene thermal event was not restricted to the investigated part of the Western Carpathians, but had regional character and affected several basement areas in the Western Carpathians, the Pannonian basin and the margin of the Eastern Alps.

1. Introduction

The Western Carpathians are bordered to the south by the Neogene Pannonian basin and join the Eastern Alps to the west. They record a complex history related to the Variscan and Alpine orogenies. The internal parts of the Western Carpathians are formed by three orogen-parallel, north-vergent principal structural domains – the Gemeric (south, highest), Veporic (medium) and Tatric (north, lowest) domains (Fig. 1a; Andrusov 1968; Plašienka et al. 1997). These domains comprise Variscan crystalline basement and sedimentary cover, and are defined as thick-skinned crustal sheets, which were tectonically juxtaposed through north-directed thrusting in the early Late Cretaceous (Andrusov 1968; Plašienka et al. 1997).

The Alpine evolution of the Western Carpathians is still a matter of discussion: most published concepts rely on the work of Kováč et al. (1994), who concluded from geochronological, stratigraphic, palaeomagnetic and fission track data that the Gemeric and Veporic domains were exhumed and cooled to near-surface conditions in the course of post-Eoalpine unroofing during Late Cretaceous to Early Palaeogene times (90–55 Ma). Since then, these domains acted as one individual block, which was not thermally affected for the rest of the Cenozoic period (Kováč et al. 1994). This, however, may conflict with the geodynamic context of the post-collisional evolution in the adjacent Eastern Alps and western Pannonian basin, which was dominated by large-scale Miocene extension in the course of lateral tectonic extrusion and subduction roll-back (Royden et al. 1982; Ratschbacher et al. 1991; Csontos 1995; Tari et al. 1992, 1999; Frisch et al. 2000; Wortel and Spakman 2000; Sperner et al. 2002). These processes led to rifting and formation of fault-bounded basins, exhumation and unroofing of basement core complexes, crustal thinning, mantle upwelling and volcanism (e.g. Royden et al. 1983; Horváth et al. 1988; Szabó et al. 1992; Kováč et al. 1993, 1994; Frisch et al. 1998, 2000), and could potentially thermally overprint neighbouring parts of the Western Carpathians.

This paper aims to test the hypothesis of Kováč et al. (1994) with low-temperature thermochronological methods [apatite fission track (AFT) and apatite (U-Th)/He (AHe) analyses]

[1] University of Tübingen, Institute of Geosciences, Sigwartstrasse 10, D-72076 Tübingen, Germany. E-mail: martin.danisik@uni-tuebingen.de; frisch@uni-tuebingen.de
[2] Dionýz Štúr State Institute of Geology, Mlynská dolina 1, 817 04 Bratislava, Slovakia. E-mail: milan.kohut@geology.sk; lubomir.hrasko@geology.sk
[3] Geoscience Center Göttingen, Sedimentology and Environmental Geology, Goldschmidtstrasse 3, D-37077 Göttingen, Germany. E-mail: istvan.dunkl@geo.uni-goettingen.de
*Corresponding author: Martin Danišík. E-mail: martin.danisik@uni-tuebingen.de

applied on the rocks from the boundary zone of the Veporic and Gemeric domains. Our data allow to identify a distinct Miocene thermal event, which was not restricted to the study area but possibly had a regional character and affected large parts of the Eastern Alpine–Western Carpathian–Pannonian area. Consequently, the actual concepts of this region demand careful reconsideration and adjustment, at least with respect to the thermal evolution.

2. Geological setting

The study area is located in the central part of Slovakia and covers the major tectonic contact between the Veporic and Gemeric domains that developed during Eoalpine shortening in the Cretaceous (Fig. 1a; Plašienka et al. 1997 and references therein).

The Veporic unit, occupying the footwall position, consists of Variscan crystalline basement together with an Upper Palaeozoic-Triassic sedimentary cover, overprinted by low- to medium-grade regional metamorphism in Eoalpine time (Vrána 1964; Vozárová 1990; Plašienka et al. 1999; Lupták et al. 2000; Janák et al. 2001). The Gemeric unit, occupying the hanging-wall position, consists of Palaeozoic mostly low-grade metamorphic rocks intruded by Permian granites that underwent an Eoalpine overprint under very low- to low-grade conditions (Hovorka & Méres 1997; Korikovsky et al. 1997 and references therein).

Post-orogenic collapse and exhumation of the Veporic and Gemeric domains started in the Late Cretaceous as indicated by geochronological data (K-Ar amphibole, feldspar, muscovite and biotite; Rb-Sr biotite; Ar-Ar muscovite ages around 90–80 Ma; Bibikova et al. 1988; Cambel et al. 1990; Hurai et al. 1991; Dallmeyer et al. 1996). At the same time, the thrust plane between the Veporic and Gemeric domains was intruded by a small granitic body, the Rochovce granite (e.g. Poller et al. 2001), which is the only known example of granitic magmatism in the Eastern Alps and Carpathians related to the Cretaceous orogenic cycle. This granite is the target of this study and will be described in more detail in the next section.

Kováč et al. (1994) argue that final cooling and exhumation occurred between 90 and 55 Ma, based on AFT ages of Kráľ (1977), which were interpreted as cooling ages, although critically important track length data were not reported. The Veporic and Gemeric domains should thus lack any thermal overprint younger than 55 Ma. However, remnants of Palaeogene flysch of the Central Carpathian Palaeogene Basin (Vass et al. 1979; Marko & Vojtko 2006) and Neogene subduction- and back arc extension-related volcanism (~17–8 Ma; Figs. 1a,d; Repčok 1981; Lexa & Konečný 1998; Pécskay et al. 2006 and references therein) may challenge such an interpretation.

2.1. The Rochovce granite

The Rochovce granite is a subsurface body discovered by the borehole KV-3 (Figs. 1b,c; Klinec et al. 1980) in the centre of a magnetic anomaly (Filo et al. 1974). Subsequent geophysical and drilling exploration revealed that it rests a few hundred meters below surface and has a diameter of ~5×10 km. Petrographical, mineralogical and geochemical characteristics were reported by Klinec et al. (1980), Határ et al. (1989) and Hraško et al. (1998). It is an I(-A)-type granite, which formed in two phases. The first phase comprises two varieties: (i) coarse-grained biotite monzogranites with pink K-feldspar phenocrysts, locally with mafic microgranular enclaves; and (ii) granite porphyries. Medium- to fine-grained biotite leucogranites and leucogranitic porphyries represent the second phase. Locally, narrow leucogranite veins randomly penetrate the coarse-grained granites of the first phase. U-Pb zircon dating yielded a Late Cretaceous crystallization age: conventional method 82 ± 1 Ma (Hraško et al. 1999), and cathodoluminescence controlled single-grain method 75.6 ± 1.1 Ma (Poller et al. 2001). These ages were recently confirmed by Re-Os dating of molybdenite from porphyry mineralization associated with the second intrusive phase, yielding ~80 Ma (Stein et al. in review).

3. Samples and methods

For thermochronological investigations, three samples of the Rochovce granite were collected from two boreholes (RO-6 and KV-3) from depths between ~400 and ~1400 meters (Table 1, Fig. 1c). Apatite grains were separated using conventional magnetic and heavy liquid techniques and dated by fission track and (U-Th)/He methods. Both analyses were carried out in the Thermochronological Laboratory, University of Tübingen. For fission track analyses we used the external detector method (Gleadow 1981) with the etching protocol of Donelick et al. (1999). The zeta calibration approach (Hurford & Green 1983) was adopted to determine the age. For (U-Th)/He analyses apatite grains were degassed under vacuum using laser-heating and analysed for He using a Pfeiffer Prisma QMS-200 mass spectrometer. Following He measurements, the grains were analysed by the isotope dilution ICP-MS method for U and Th at the Scottish Universities Environmental Research Centre (SUERC) in East Kilbride (Scotland) on a VG PlasmaQuad 2 ICP-MS. For more details on analytical procedures, see Danišík (2005).

4. Results

The results of the AFT and (U-Th)/He analyses are summarized in Tables 1 and 2 and shown in Figures 2a,b.

4.1. AFT and AHe data

All samples yielded Miocene AFT ages between 17.5 ± 1.1 and 12.9 ± 0.9 Ma. Due to limited amounts of suitable apatite grains, we could measure a statistically robust number of horizontal confined tracks only in two samples (KVP-3, RO-6; Table 1). Track length distributions (Fig. 2b) are unimodal, negatively skewed, with mean track lengths of 13.6 and 13.9 µm and stan-

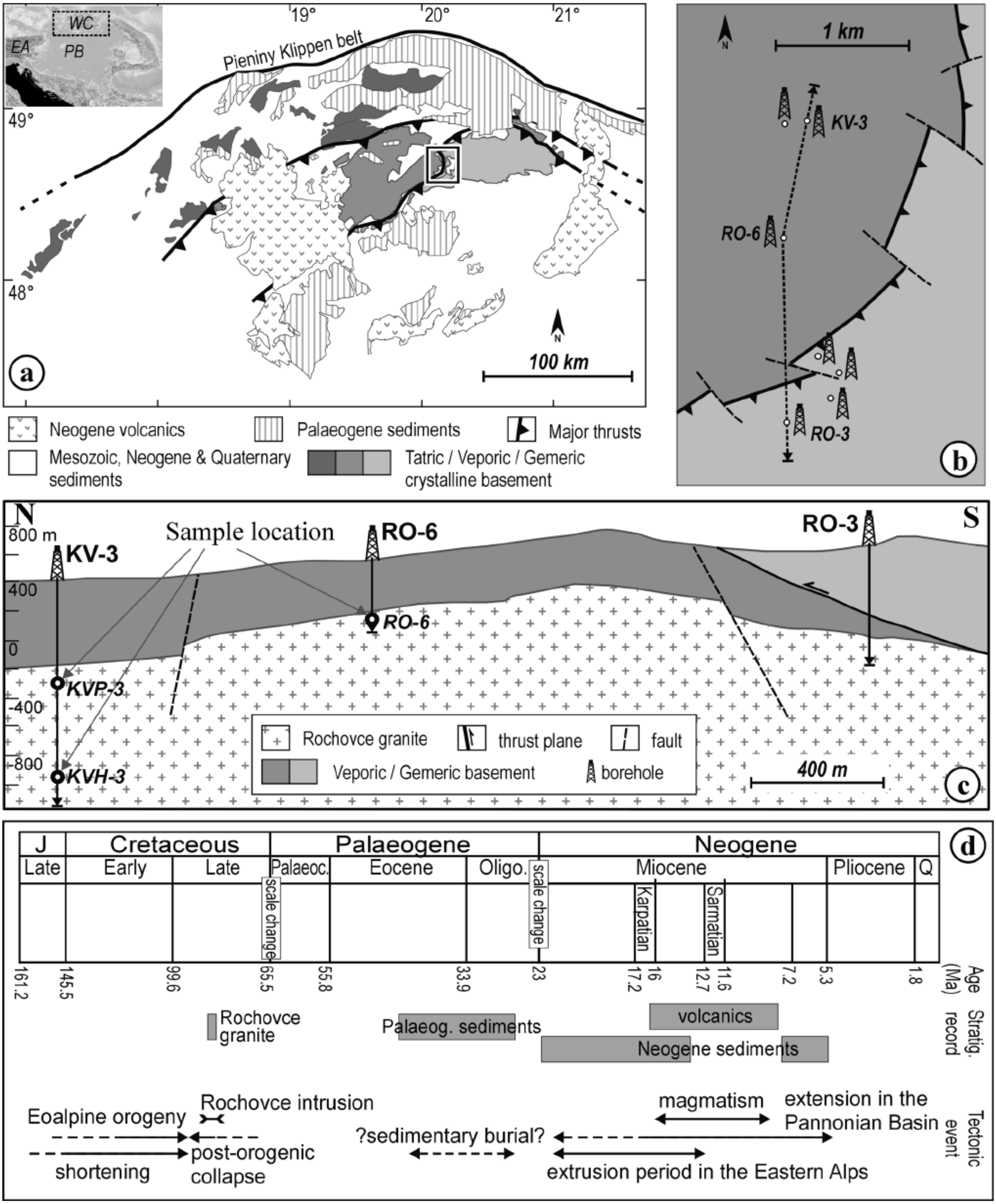

Fig. 1. Inset part of Fig. 1a) Location of the Fig. 1a; WC – Western Carpathians, EA – Eastern Alps, PB – Pannonian Basin. a) Tectonic sketch map of the Western Carpathians with exposures of Variscan crystalline bodies belonging to three principal domains; Tatric, Veporic and Gemeric after Lexa et al. (2000). Location of the study area and map of Fig. 1b are indicated by the rectangle. b) Geological map of the study area with the position of boreholes penetrating the Rochovce granite. c) Schematic profile (for location, see dashed line in Fig. 1b). d) Chronostratigraphic chart of the study area and surrounding regions with relevant geodynamic events (Ratschbacher et al. 1991; Reinecker 2000; Lexa et al. 2000; Poller et al. 2001).

Table 1. AFT data[a].

Sample code	Lat/Lon (WGS84) X	Y	Bore-hole	elevation (m a.s.l.)	Petrography	N	ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	$P(\chi2)$ (%)	Age (Ma)	±1σ (Ma)	MTL (µm)	SD (µm)	N (L)
RO-6	48° 41' 41"	20° 17' 31"	RO-6	167	granite	30	1,863	351	11,765	2216	7,214	4959	>95	17,5	1,1	13,6	1,4	63
KVP-3	48° 42' 03"	20° 17' 34"	KV-3	–324	granite	35	2,159	464	13,947	2997	7,230	4959	>95	17,1	0,9	13,9	1,2	60
KVH-3	48° 42' 03"	20° 17' 34"	KV-3	–975	granite	25	1,646	273	14,120	2342	7,262	4959	>95	12,9	0,9	13,9	1,6	9

[a] N – number of dated apatite crystals; ρ_s (ρ_i) – spontaneous (induced) track densities (×10^5 tracks/cm^2); N_s (N_i) – number of counted spontaneous (induced) tracks; ρ_d – dosimeter track density (×10^5 tracks/cm^2); N_d – number of tracks counted on dosimeter; $P(\chi^2)$ – probability obtaining Chi-square value (χ^2) for n degree of freedom (where n = No. of crystals – 1); Age ± 1σ – central 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. Ages were calculated using zeta calibration method (Hurford & Green 1983), glass dosimeter CN-5, and zeta value of 305 ± 4.3 year/cm^2.

dard deviations of 1.2 and 1.4 µm, respectively, which is typical for rocks with moderate cooling through the partial annealing zone (e.g. Gleadow et al. 1986a,b).

For (U-Th)/He analyses, four to five grains were measured per sample (Table 2), all yielding AHe ages younger than the corresponding AFT ages. Replicates of both samples from the borehole KV-3 reproduce extremely well (all ages are within 1 sigma error). Sample RO-6 revealed a slightly larger spread of single-grain ages. The average AHe ages corrected for alpha ejection range from 12.9 ± 1.8 to 11.3 ± 0.8 Ma.

Both, AFT and AHe ages show positive correlation with elevation that usually allows a direct estimation of long-term exhumation rates, if the closure isotherms of the employed systems remained fairly flat and stationary during cooling (Stüwe et al. 1994). This is, however, not the case with our data, which show decreasing differences between AFT and AHe ages with depth: the AFT ages of the middle and uppermost samples are ~5 Ma older than the AHe ages, whereas the deepest sample (KVH-3) revealed an AHe age overlapping within error with the corresponding AFT age. This pattern shows that the cooling rates changed between ~17 and ~12 Ma (Fig. 2a). The isotherms thus did not remain stationary, and estimation of exhumation rates by the age-elevation relationship is not justified.

4.2. Thermal history

In order to understand the meaning of the data, thermal histories were modelled by the HeFTy modelling program (Ketcham 2005), which allows to compute thermal paths of a sample by combining the fission track annealing and He production-diffusion models. We used an inverse Monte Carlo algorithm (50 000 model searches) with the multikinetic annealing model of Ketcham et al. (1999) and the diffusion parameters of the Durango apatite (Farley 2000).

For modelling, we chose sample KVP-3, whose AHe ages best reproduce (Table 2) and which revealed enough horizontal confined tracks (Table 1). Available information was converted into time-temperature (tT) constraints in the form of

Table 2. (U-Th)/He data[a].

Sample code	Altitude (m a.s.l.)	N_c	Th (ng)	Th error (%)	U (ng)	U error (%)	^{4}He (ncc at STP)	^{4}He error (%)	TAU (%)	Th/U	Unc. age (Ma)	±1σ (Ma)	F_t	Cor. age (Ma)	±1σ (Ma)	AFT age (Ma)	±1σ (Ma)
RO-6#1	167	1	0,111	2,1	0,074	3,1	0,102	0,9	2,7	1,51	8,4	0,2	0,71	11,8	0,7	17,5	1,1
RO-6#2		1	0,393	1,8	0,178	3,3	0,319	0,9	2,5	2,20	9,7	0,2	0,78	12,5	0,7		
RO-6#3		1	0,346	1,9	0,169	2,5	0,221	0,9	2,3	2,04	7,3	0,2	0,68	10,7	0,6		
RO-6#4		1	0,364	2,2	0,198	1,7	0,404	0,9	2,2	1,84	11,7	0,3	0,80	14,7	0,8		
RO-6#5		1	0,298	2,5	0,171	2,6	0,344	0,9	2,7	1,75	11,8	0,3	0,79	14,9	0,8		
Average age ± Std. dev. (both in Ma)														**12,9 ± 1,8**			
KVP-3#1	–324	1	0,130	1,95	0,052	3,30	0,071	1,0	2,6	2,48	7,1	0,2	0,63	11,4	0,6	17,1	0,9
KVP-3#2		1	0,359	2,73	0,145	2,40	0,238	0,9	2,8	2,48	8,6	0,2	0,73	11,8	0,7		
KVP-3#3		1	0,173	2,14	0,065	3,51	0,101	0,9	2,8	2,67	7,9	0,2	0,66	12,1	0,7		
KVP-3#4		1	0,410	2,16	0,145	2,59	0,240	0,9	2,4	2,82	8,2	0,2	0,73	11,2	0,6		
Average age ± Std. dev. (both in Ma)														**11,6 ± 0,4**			
KVH-3#1	–975	1	0,392	2,3	0,185	2,52	0,274	0,9	2,5	2,12	8,1	0,2	0,78	10,4	0,6	12,9	0,9
KVH-3#2		1	0,178	2,3	0,137	3,27	0,220	0,9	2,9	1,30	10,1	0,3	0,82	12,4	0,7		
KVH-3#3		1	0,350	2,6	0,151	2,56	0,245	0,9	2,8	2,32	8,7	0,2	0,76	11,4	0,7		
KVH-3#4		1	0,498	1,8	0,202	2,41	0,332	0,9	2,2	2,46	8,6	0,2	0,77	11,2	0,6		
Average age ± Std. dev. (both in Ma)														**11,3 ± 0,8**			

[a] N_c – number of dated apatite crystals; TAU – total analytical uncertainty; Unc. age – uncorrected AHe age; F_t – alpha recoil correction factor after Farley et al. (1996); Cor. age – corrected AHe age.

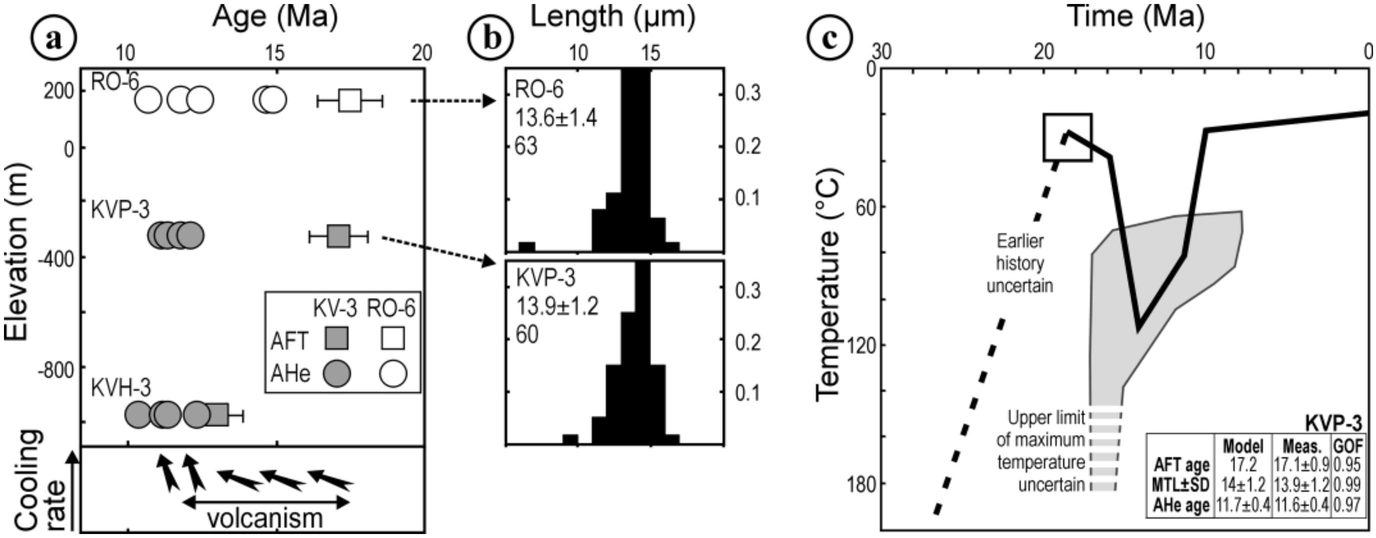

Fig. 2. a) Age-elevation relationship of the Rochovce granite as constrained by AFT (squares) and AHe data (circles; error bars of AHe ages were omitted for readability) and, below, changes of cooling rates with respect to duration of volcanic activity in the study area as estimated from differences of the AFT and AHe thermochronometers. b) Corresponding track length distributions. Explanation in histograms (from top): sample code; mean track length ± standard deviation (both in µm); number of measured tracks. c) Thermal modelling results of AFT and AHe data displayed in a time-temperature diagram modelled with the HeFTy program (Ketcham, 2005). The best fit is shown as a solid black line, shaded polygon shows the values of peak temperature and time at which the cooling began. MTL is mean track length in µm; SD is standard deviation in µm; 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 best” result corresponds to value 1). See text for further explanation.

boxes and the modelled tT path was constrained as follows: the beginning of the tT path was set as T = 800 °C at 80–75 Ma, according to the crystallization age of the Rochovce granite (see Section 2.1.). Geological constraints for the time between Late Cretaceous crystallization and Miocene thermal activity recorded by AFT and AHe data are poor. It was proposed that after post-collisional collapse and exhumation, the Veporic-Gemeric domain was exposed at the surface in the latest Cretaceous-Early Palaeogene (e.g. Kováč et al. 1994). However, this indirect conclusion from radiometric ages is not backed by stratigraphic constraints. The evolution during the Palaeogene is also not clear. Evidently the area was buried by flysch of a forearc basin (Central Carpathian Palaeogene Basin; Vass et al., 1979; Kázmér et al. 2003; Marko & Vojtko 2006), however the thickness of the Palaeogene cover remains unclear. To these issues we cannot draw any conclusion from our data and no constraint was set into the model. An important point for the interpretation of the data is the fact that the Veporic-Gemeric domain was at the surface in the Early Miocene prior to Neogene volcanism, which is well constrained by occurrences of Middle Miocene volcanic rocks that overlie the Veporic basement (Marko & Vojtko 2006). Another important evidence is the occurrence of kaolinitic weathering crusts preserved in situ on top of the crystalline basement, which is overlain by Middle Miocene volcanoclastics along the western margin of the Veporic unit (Kraus 1989). This clearly shows that in the Early Miocene, the Veporic-Gemeric domain was at the surface and the Rochovce granite resided at near-surface temperatures. Thus, another constraint was set as T = 20–40 °C at 20–17 Ma. The end of the tT path was set as T = 20 °C at 0 Ma according to the estimated temperature of the sample in the borehole.

The modelled thermal history (Fig. 2c), which matches both the measured AFT and AHe data, shows that sample KVP-3 experienced reheating between ~17 and 8 Ma, with minimum peak temperatures above 60 °C. Thus, we conclude that the Rochovce granite experienced a thermal event in the Middle to early Late Miocene.

5. Interpretation

The Miocene thermal event can be explained either (i) in terms of changes in the thermal regime, or (ii) in terms of rapid Middle Miocene burial and exhumation of basement units by erosion of a ≳1.5 km thick sediment pile, or (iii) a combination of both.

We favour the first option since the age of the thermal event exactly coincides with that of the Miocene volcanism (Fig. 1d) and mantle upwelling, associated with high, extension-related heat flow in the Carpathian-Pannonian arc and back-arc region (Szabó et al. 1992; Tari et al. 1999; Pécskay et al. 2006). The magmatic activity in the studied part of the Western Carpathians occurred between ~17 and 8 Ma and had its climax at ~16–13 Ma when numerous large stratovolcanoes formed (Fig. 1a; Lexa & Konečný 1998; Pécskay et al. 2006). The time interval of 17 to 8 Ma perfectly fits with the thermal overprint revealed by the modelling results and measured AFT and AHe ages (Fig. 2c, Tables 1, 2). After the climax since ~12 Ma, the volcanic activity started to cease as indicated by the decreasing amount of volcanic products in the region (Pécskay et al. 2006). Concurrently, the elevated heat flow started to decrease as documented by the increase of cooling rates at ~12 Ma as recorded by the deepest sample (Fig. 2a). Cooling recorded by the AFT and AHe ages is thus primarily related to the cessation of the heat source and relaxation of the isotherms.

The second option is less likely since there is no direct evidence for a thick cover on the top of the Gemeric-Veporic domain in the Middle Miocene. Neogene sedimentary formations are not preserved in the study area but only in depressions further south. Secondly, the kaolinitic weathering crusts would not survive deep burial. An at least ~1.5 km thick cover that would potentially induce total reset of the AFT system purely by burial is therefore unlikely. However, the possibility that the region was overlain by thin layers of fine-grained sediments with low thermal conductivity that are typical for Neogene successions of the Pannonian basin (Dövényi & Horváth 1988) and might produce thermal blanketing of underlying rocks (Dunkl & Frisch 2002), cannot be ruled out.

6. Discussion

6.1. Late Early to Middle Miocene thermal event and its implications for the Eastern Alpine–Western Carpathian–Pannonian area

Although this study provides the first evidence of Miocene thermal overprint in the Veporic-Gemeric domain, the idea of the existence of a Miocene thermal event is not new. In the Pannonian basin such an event was recognized more than 20 years ago (Royden et al. 1983; Horváth et al. 1988; Ebner & Sachsenhofer 1991; Lankreijer et al. 1995; Lenkey et al. 2002). Since then, Miocene reheating was reported also from crystalline bodies of the Western Carpathians (Danišík et al. 2004, 2005, 2008) and the eastern margin of the Alps (Dunkl & Frisch 2002), which proves its regional character. For instance, Dunkl & Frisch (2002), based on AFT, structural, sedimentological and vitrinite reflectance data, demonstrated that crystalline basement outcrops along the northwestern margin of

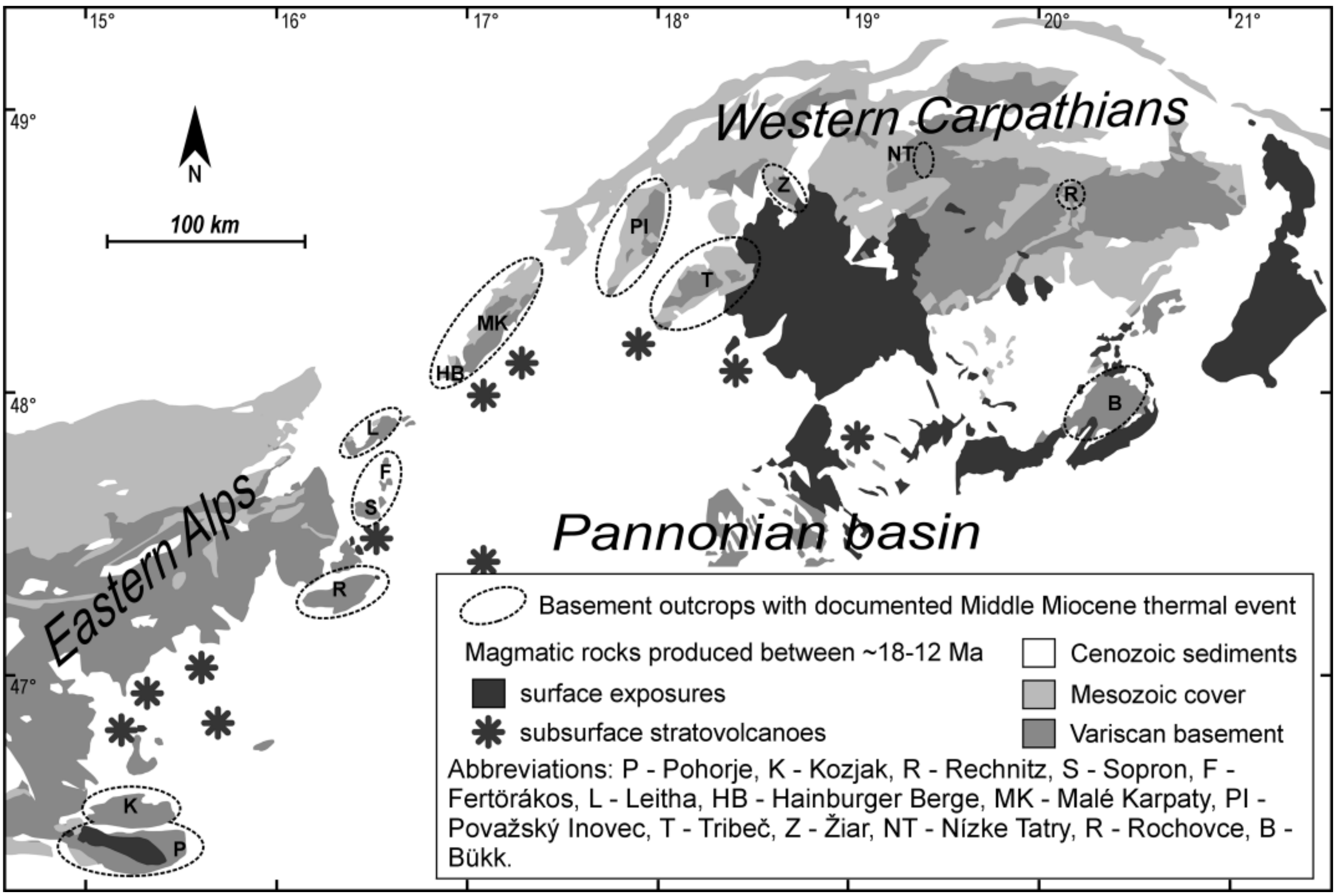

Fig. 3. Spatial relations of Miocene magmatism and crystalline outcrops recording the Miocene thermal event in the Eastern Alpine–Western Carpathian–Pannonian region [distribution of volcanoes modified after Kováč (2000)].

the Pannonian basin, i.e. Kozjak, Pohorje, Rechnitz, Sopron, Fertőrákos and Bükk Mts. (Fig. 3), record a distinct thermal event in the Early/Middle Miocene, when the crystalline bodies were reheated to temperatures >60 °C. The same thermal overprint of several crystalline bodies in the Western Carpathians (i.e., Leitha, Hainburg, Malé Karpaty, Tribeč, Považský Inovec, Žiar and Nízke Tatry Mts., Fig. 3) was reported by Danišík et al. (2004, 2005, 2008) from AFT and thermal modelling data.

Although presence and regional character of the Miocene thermal event are undoubted, opinions regarding its cause are diverse. Dunkl & Frisch (2002) attribute the thermal overprint primarily to burial of the crystalline bodies by Miocene sediments of the Pannonian basin, whereas increased heat flow would play a less important role. Final cooling following the thermal maximum is thus explained by removal of 1–1.5 km of overburden (Dunkl & Frisch 2002).

We favour an alternative explanation and argue that increased heat flow (e.g. Royden et al. 1983; Horváth et al. 1988; Tari et al. 1999) was the main reason for the thermal overprint. Our arguments are the following: The peak of the Miocene thermal event and consequent cooling of the crystalline bodies along the margin of the Pannonian basin occurred at ~18 in the western parts and migrated to the east, where it occurred latest, i.e. at ~8 Ma, as recorded by AFT, vitrinite reflectance and thermal modelling data (this study; Dunkl & Frisch 2002; Danišík et al. 2004, 2008; Fodor et al. 2008). We propose that: (i) this time span conspicuously coincides with late Early to Middle Miocene magmatism of the Carpathian–Pannonian transition area that was constrained to ~20–8 Ma (Lexa & Konečný 1998; Pécskay et al. 2006). (ii) Spatial relation to Miocene magmatism is clear from the distribution of late Early Miocene to Middle Miocene volcanic rocks and basement areas with documented Miocene thermal overprint (Fig. 3). (iii) There are no clear evidences of ~1.5 km deep burial in the Western Carpathians (see Section 4.2.). By contrast, several crystalline bodies were eroded in the Middle Miocene as indicated by stratigraphic record (Kováč et al. 1994; Danišík et al. 2004, 2008). (iv) Heat flow in the Middle Miocene reached extreme values (locally >300 mW/m^2) as demonstrated in the Styrian basin by modelling of vitrinite reflectance data (Fig. 3; Sachsenhofer 1994; Ebner & Sachsenhofer 1995).

These arguments are not meant to disprove the general idea of burial heating in the Middle Miocene (Dunkl & Frisch 2002), but should emphasize the importance of magmatism and elevated heat flow, which relaxes the requirement for deep burial (~1.5 km). One of the implications or our study is that extent and thickness of the Middle Miocene Pannonian basin fill were less than currently believed. Further, there are several examples of extremely high cooling rates in the Miocene reported from crystalline outcrops along the margin of the Pannonian basin, which are readily used as evidence of tectonic denudation (Ratschbacher et al. 1990; Tari et al. 1999). We like to point out that this may merely be an effect of compressed isotherms resulting from elevated heat flow at that time. Thus the observed apparently high cooling rates were in fact moderate and should be interpreted with caution.

7. Conclusion

First AFT and AHe data from the only known Cretaceous Alpine granite in the Western Carpathians are reported. In spite of the fact that our results are based on a limited amount of data, they are of good quality and provide important constraints on the thermal and geodynamic evolution of the entire Eastern Alpine–Western Carpathian–Pannonian region. We conclude:

(i) The Rochovce granite records a distinct thermal event in the Middle to early Late Miocene, likely related to mantle upwelling, magmatic activity, and increased heat flow in the Carpathian-Pannonian region. During the thermal maximum between ~17 and 8 Ma, the granite was heated to temperatures $\lesssim$60 °C. Gradual increase of cooling rates recorded by the AFT and AHe data is primarily related to cessation of the heat source and relaxation of the isotherms associated with the termination of the volcanic activity.

(ii) Our thermochronological data disprove the widely accepted concept of thermal stability of the Veporic-Gemeric domain during the Cenozoic period. Instead, we show that this domain was affected by the Miocene thermal event that was not restricted only to the Veporic-Gemeric domain, but had regional character and affected large parts of the basement outcrops in the Western Carpathians, Pannonian basin and easternmost Eastern Alps. We believe that the Miocene thermal event was primarily related to spatially variable increased heat flow and magmatism, and not to burial.

Acknowledgements

This study was funded by the German Science Foundation. Dorothea Mühlbayer-Renner and Dagmar Kost (Tübingen) are thanked for careful sample preparation. An earlier version of the manuscript benefited from constructive reviews by Christoph Glotzbach (Tübingen), Bernhard Fügenschuh (Innsbruck) and László Fodor (Budapest).

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Manuscript received January 30, 2008
Revision accepted May 7, 2008
Published Online first October 22, 2008
Editorial Handling: Stefan Schmid, Stefan Bucher