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Thermal history of the Podhale Basin in the internal Western Carpathians from the perspective of apatite fission track analyses

ANETA AGNIESZKA ANCZKIEWICZ[1✉], JAN ŚRODOŃ[1] and MASSIMILIANO ZATTIN[2]

[1]Institute of Geological Sciences, Polish Academy of Sciences, Senacka 1, 31-002 Kraków, Poland;
✉ndstruzi@cyf-kr-edu.pl; ndsrodon@cyf-kr.edu.pl
[2]Dipartimento di Geoscienze, Università di Padova, Via Giotto 1, 35137 Padova, Italy

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Abstract: The thermal history of the Paleogene Podhale Basin was studied by the apatite fission track (AFT) method. Twenty four Eocene-Oligocene sandstone samples yielded apparent ages from 13.8 ± 1.6 to 6.1 ± 1.4 Ma that are significantly younger than their stratigraphic age and thus point to a post-depositional resetting. The thermal event responsible for the age resetting is interpreted as a combination of heating associated with mid-Miocene volcanism and variable thickness of Oligocene and potentially also Miocene sediments. Extending the mid-Miocene thermal event found in the Inner Carpathians into the Podhale Basin as a likely heat source suggests that the amount of denudation in the Podhale Basin determined only on the basis of heat related to the thickness of sedimentary sequence might have be significantly overestimated. Two samples from the western part of the basin that yielded 31.0 ± 4.3 and 26.9 ± 4.7 Ma are interpreted as having mixed ages resulting from partial resetting in temperature conditions within the AFT partial annealing zone. This observation agrees very well with reported vitrinite reflectance and illite-smectite thermometry, which indicate a systematic drop of the maximum paleotemperatures towards the western side of the basin.

Key words: Miocene, Western Carpathians, Central Carpathian Paleogene Basin, Podhale Basin, thermal history, thermochronology, apatite fission track dating.

Introduction

The Eocene closure of the Tethys Ocean during the Alpine orogenesis was not uniform. After the closure in the west, a remnant oceanic basin remained in the Carpathian-Pannonian region to the east, separating the Pannonian block from the European platform. In the Western Carpathians, southward oceanic subduction persisted until the Middle Miocene when a collision took place (Nemčok et al. 1989; Rögl 1996; Sperner et al. 2002). The collisional process in the Western Carpathians is often termed "soft collision" (e.g. Sperner et al. 2002), as it did not lead to a large amount of continental subduction, significant crustal thickening or widespread metamorphism, as was the case for the Alps to the west.

In the Western Carpathians, the Podhale-Spišská Magura Paleogene basin forms the northernmost edge of the North Pannonian block, which overrides the European plate (Fig. 1). Although the basin has been subjected to inversion, the sedimentary rocks show little evidence for compressive deformation. Pre-inversion burial history is reasonably well defined mainly by illite-smectite (I-S) data (Kotarba 2003; Środoń et al. 2006), and to lesser extent by vitrinite reflectance data (Marynowski & Gawęda 2005; Poprawa & Marynowski 2005; Wagner 2011). However, these techniques record maximum paleotemperatures and do not provide information on subsequent cooling and inversion history. The goal of this study is to refine the thermal history of the Podhale Basin through the use of apatite fission track analysis.

Geological setting

The Western Carpathians form the northernmost part of the Carpathian belt, which belongs to the Alpine-Carpathian orogenic system (Fig. 1). They are subdivided into two main tectonic units: the Outer and the Inner Carpathians (Birkenmajer 2001). The Outer Carpathians (OC) are composed of Lower Cretaceous to Lower Miocene flysch sequences, which developed in several basins on the northern margin of Tethys (e.g. Csontos et al. 1992). Subsequent northward thrusting juxtaposed the basin sediments forming a large scale nappe stack. The southern boundary of the OC is defined by the E-W trending Pieniny Klippen Belt (PKB) that separates the nappe stack from the Inner Carpathians (IC) Paleogene flysch. This narrow zone predominantly comprises strongly deformed carbonates of Jurassic to Cretaceous age (Birkenmajer 1986; Ratschbacher et al. 1993; Nemčok & Nemčok 1994) and is interpreted as a plate boundary between the European plate to the north and the North Pannonian block to the south. The two blocks collided at the Early Miocene/Middle Miocene boundary (Nemčok et al. 1989; Rögl 1996; Sperner et al. 2002). The IC comprise Variscan crystalline basement, covered mainly by Mesozoic carbonate rocks and by Tertiary sedimentary and volcanic rocks. This sequence is interpreted as the southern (Apulian) margin of the Tethyan Ocean. The Tatra Mountains and the Podhale Basin are part of the IC (Fig. 1).

The Podhale Basin constitutes part of the Central Carpathian Paleogene Basin (CCPB), and comprises marine sed-

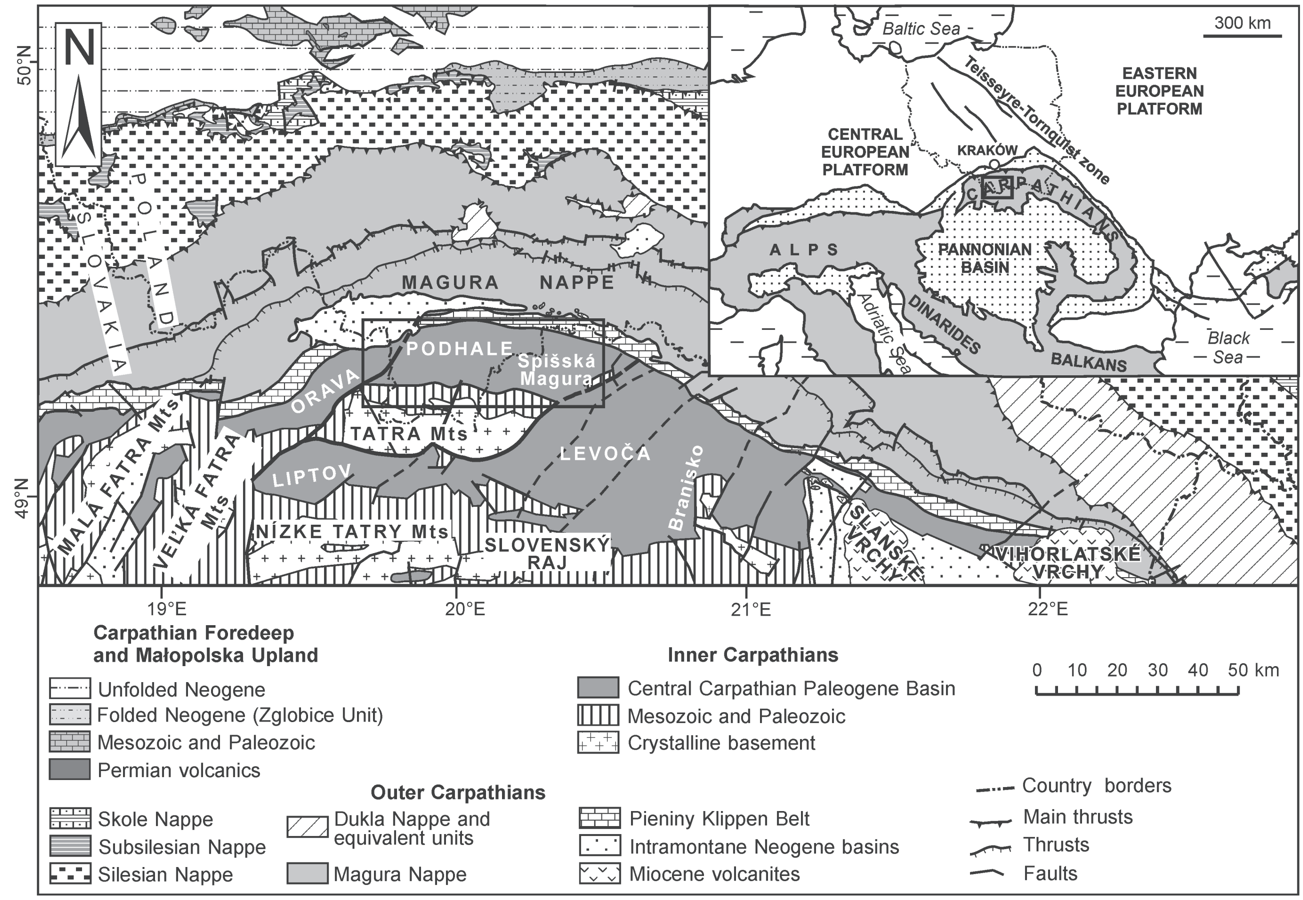

Fig. 1. Tectonic sketch of the Western Carpathians, after Żytko et al. (1989). Black rectangle marks study area. Sketch of the Alpine-Carpathian system in the upper left corner after Roca et al. (1995).

imentary rocks that were deposited on an erosional surface comprising Lower Triassic–Lower Turonian dolomites and limestones that cover the crystalline units of the Tatra Mountains (Bac-Moszaszwili et al. 1990). The basin sedimentary fill consists of up to 100 m thick Eocene carbonates, above which several kilometers of flysch were deposited (Radomski 1958; Andrusov & Köhler 1963; Westwalewicz-Mogilska 1986; Soták et al. 1996, 2001). In Poland, the flysch sequence has been divided into four informal lithostratigraphic units: the Szaflary, Zakopane, Chochołów and Ostrysz beds. In the Spišská Magura region of Slovakia, the eastern continuation of the basin, equivalent units are: the Šambron Beds, Huty, Zuberec and Biely Potok Formations, respectively (Gross et al. 1984). The youngest Ostrysz beds are preserved only in the western part of the basin and were dated as Late Oligocene on the basis of dinocysts (Gedl 2000). Garecka (2005) determined the age of the youngest deposits in the basin as Aquitanian (the earliest Miocene), using calcareous nannoplankton.

The Podhale Basin sequence is considered to represent one of the erosional remnants of the continuous Paleogene forearc basin, which once covered the entire Eastern Alps and the Western Carpathians (Kázmer et al. 2003) and developed on the Mesozoic cover of the Variscan basement probably as a result of extensional faulting (Olszewska & Wieczorek 1989). In its present position, the Podhale Basin forms a gentle, approximately E-W trending depression, bounded to the north by the PKB and to the south by the Tatra Mountains (Fig. 2b). Sedimentary rocks in the Podhale Basin show little evidence of deformation and shortening associated with plate convergence, and the most significant structural discontinuities in the study area are the Krowiarki and Ružbachy faults (Fig. 2a). Our study was conducted in the Podhale Basin, in the area between the Krowiarki and Ružbachy faults, as shown in Fig. 2a.

Sampling and methods

The main goal of this study was to complement previous studies of the thermal history of this part of CCPB conducted by means of illite-smectite (I-S) and vitrinite reflectance thermometry, as well as provide time constraints on the youngest thermal evolution of the basin. To achieve this aim, twenty four sandstone and two bentonite samples were collected from surface outcrops distributed across the Podhale-Spišská Magura basin. The majority of samples come from the Polish part of the basin, while six samples were collected from the Spišská Magura region in Slovakia. Additionally, four samples were collected from the Bukowina Tatrzańska

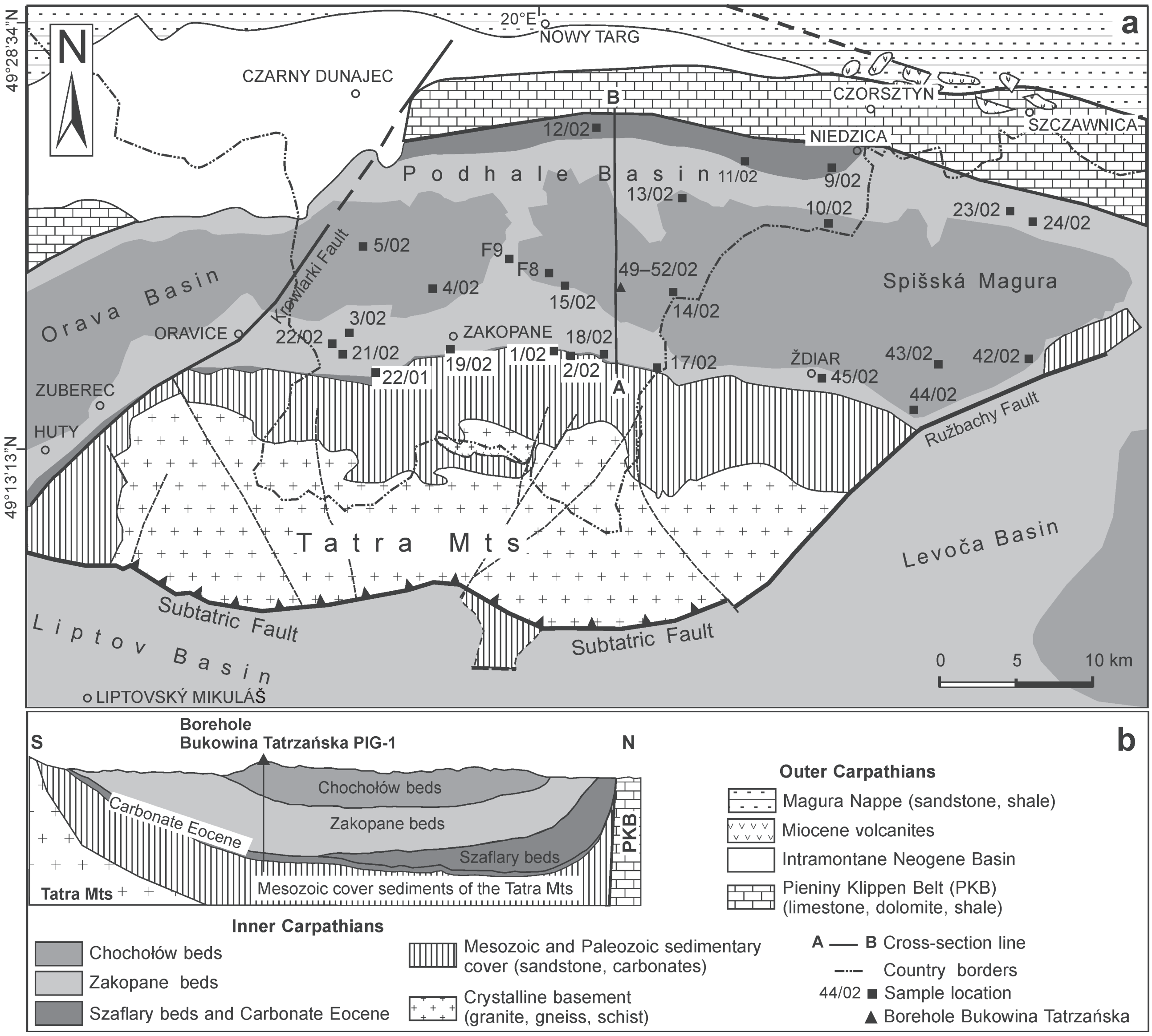

Fig. 2. Sample locations (**a**) on a simplified geological map (compiled by A. Łaptaś) after Żytko et al. (1989) and Janočko et al. 2000. Line A–B marks cross-section shown in (**b**), simplified after Gedl (2000).

PIG-1 borehole. The GPS locations of all samples are given in Table 1 and are shown in Fig. 2a. Where possible, the Podhale samples were collected from the same (or nearby) outcrops to those used in the illite-smectite paleotemperature studies of Kotarba (2003) and Środoń et al. (2006).

The apatite fission track (AFT) dating method is a well established technique used to unravel the thermal history experienced by rocks both during burial and their motion towards the surface (Wagner & Van den Haute 1992; Donelick et al. 2005). Fission tracks are totally annealed at temperatures higher than about 120 °C, but partial resetting occurs down to 60 °C. Some variations in annealing kinetics occur due to differences in the chemical composition of apatites (e.g. Barbarand et al. 2003).

Flysch deposits in the internal and the external Carpathians are usually cut by numerous joints, which served as migration paths for hot fluids. Temperature of the migrating fluids often significantly exceeded regional temperatures (Hurai et al. 2000). Thus, we were collecting samples free of such veins. Where this was not possible, parts of the samples containing mineralized veins were cut out with large margins using a saw. Apatites from sandstones were separated using standard crushing, sieving, magnetic and heavy liquids separation techniques. We used the external detector method and the ζ age calibration approach to determine the fission tracks age (Gleadow 1981; Hurford & Green 1983).

Polished grain mounts were etched for 20 seconds in 5 N HNO_3 at 20 °C. The standard glass CN5 was used as a dosimeter to monitor the neutron flux. Thin flakes of low-U muscovite were used as external detectors. Samples together with age standards (Fish Canyon, Durango, and Mount Dromedary apatite) and CN5 standard glass dosimeters were irradiated

Table 1: Apatite Fission Track results for the Podhale-Spišská Magura basin.

Sample No.	Depositional age	Rocks	Location GPS	Elevation (m a.s.l.)	No. crystals	U [ppm]	Dosimeter ρd	Dosimeter Nd	Spontaneous ρs	Spontaneous Ns	Induced ρi	Induced Ni	P (χ^2) [%]	Mean confined track length (µm±SE)	No. Track measured	Dpar µm	Age (Ma) ±1σ
1/02	Eocene	Bentonite	N 49°17′ 00″ E 20°02′ 14″	1040	25	21.68	1.044	5137	0.1393	84	1.8039	1088	99.69	12.01±0.08	2	1.3	13.8±1.6
2/02	Eocene	Bentonite	N 49°17′ 00″ E 20°03′ 16″	1020	10	17.68	1.136	5492	0.1127	25	1.6497	366	100	n.d.	n.d.	1.3	13.3±2.8
3/02	Oligocene	Sandstone	N 49°17′ 45″ E 19°51′ 12″	760	30	14.16	1.06	5137	0.0876	63	1.2609	907	100	11.35±0.45	2		12.7±1.7
4/02	Oligocene	Sandstone	N 49°19′ 10″ E 19°54′ 11″	970	29	13.24	0.992	4816	0.0801	50	1.1181	698	75.99	11.16±1.53	4	1.5	12.2±1.8
5/02	Oligocene	Sandstone	N 49°21′ 55″ E 19°51′ 03″	760	30	25.9	1.142	5492	0.3092	223	2.5081	1809	0.01	13.07±0.86	8		31.0±4.3
9/02	Eocene–Oligocene	Sandstone	N 49°23′ 56″ E 20°17′ 21″	520	30	14.46	1.028	5137	0.0547	39	1.0959	782	100	n.d.	n.d.	1.4	8.8±1.5
10/02	Oligocene	Sandstone	N 49°22′ 02″ E 20°17′ 30″	580	30	23.36	1.034	5137	0.0894	60	1.9141	1285	100	12.82±0.958	5	1.5	8.3±1.1
11/02	Eocene–Oligocene	Sandstone	N 49°23′ 50″ E 20°12′ 51″	630	28	22.61	0.9865	4816	0.0875	40	1.8353	839	99.95	10.38±0.11	2	1.5	8.1±1.3
12/02	Eocene–Oligocene	Sandstone	N 49°25′ 25″ E 20°04′ 30″	620	18	18.82	1.138	5492	0.1005	52	1.6304	844	100	13.24±0.45	9	1.5	12.0±1.7
13/02	Oligocene	Sandstone	N 49°23′ 14″ E 20°08′ 09″	740	29	18.36	0.9976	4816	0.1088	42	1.5075	582	100	n.d.	n.d.		12.4±2.0
14/02	Oligocene	Sandstone	N 49°19′ 10″ E 20°09′ 06″	850	30	13.50	0.9948	4816	0.0602	35	1.0516	611	100	13.03±1.99	2	1.5	9.8±1.7
15/02	Oligocene	Sandstone	N 49°19′ 43″ E 20°02′ 57″	840	22	24.94	0.9795	4816	0.089	44	1.9672	973	99.82	11.27±0.49	6	1.4	7.6±1.2
17/02	Oligocene	Sandstone	N 49°16′ 32″ E 20°07′ 35″	960	30	21.23	1.106	5137	0.08	58	1.7653	1280	100	n.d.	n.d.	1.2	8.6±1.2
18/02	Oligocene	Sandstone	N 49°17′ 19″ E 20°04′ 20″	920	26	21.18	1.07	5137	0.1105	52	2.0166	949	99.55	11.88±0.63	7		10.1±1.5
19/02	Oligocene	Sandstone	N 49°16′ 55″ E 19°57′ 20″	900	30	18.75	1.139	5492	0.0751	61	1.6923	1375	100	11.28±1.76	3	1.6	8.7±1.1
21/02	Oligocene	Sandstone	N 49°16′ 54″ E 19°51′ 05″	930	20	43.38	1.003	4816	0.1582	67	2.6963	1142	24.8	12.42±0.24	5	1.6	10.1±1.3
22/02	Oligocene	Sandstone	N 49°17′ 06″ E 19°50′ 20″	910	30	49.85	1.136	5492	0.2999	125	4.4264	1845	0	11.28±0.52	10		26.9±4.7
22/01	Oligocene	Sandstone	N 49°16′ 58″ E 19°52′ 57″	950	20	19.14	1.088	3232	0.0674	44	1.6813	1098	100	12.32±1.55	4	1.4	7.5±1.2
23/02	M Eocene–Oligocene	Sandstone	N 49°21′ 33″ E 20°26′ 45″	650	19	19.45	0.9823	4816	0.0578	83	1.5186	2179	99.99	11.07±0.61	10	1.5	6.4±0.7
24/02	M Eocene–Oligocene	Sandstone	N 49°21′ 15″ E 20°29′ 10″	840	19	20.94	0.9934	4816	0.0855	57	1.5709	1047	99.96	n.d.	n.d.	1.5	9.3±1.3
42/02	L Eocene-Oligocene	Sandstone	N 49°16′ 13″ E 20°29′ 10″	620	20	23.74	1.002	4816	0.1025	84	1.9323	1583	99.99	12.48±0.58	7	1.5	9.1±1.0
43/02	L Eocene-Oligocene	Sandstone	N 49°17′ 30″ E 20°24′ 38″	800	23	10.59	1.135	5492	0.0556	28	0.9717	489	99.56	n.d.	n.d.	1.5	11.2±2.2

Continued on the next page.

Table 1: *Continued.*

Sample No.	Depositional age	Rocks	Location GPS	Elevation (m a.s.l.)	No. crystals	U [ppm]	Dosimeter ρd	Dosimeter Nd	Spontaneous ρs	Spontaneous Ns	Induced ρi	Induced Ni	P (χ^2) [%]	Mean confined track length (µm±SE)	No. Track measured	Dpar µm	Age (Ma) ±1σ
44/02	L Eocene-Oligocene	Sandstone	N 49°14′ 36″ E 20°21′ 05″	940	20	17.49	1.101	5137	0.0635	36	1.4807	839	100	12.13±0.55	5	1.5	8.1±1.4
45/02	L Eocene–Oligocene	Sandstone	N 49°15′ 47″ E 20°18′ 06″	860	18	14.06	1.141	5492	0.0715	23	1.265	407	98.52	n.d.	n.d.	1.2	11.1±2.4
49/02	Oligocene	Sandstone	N 49°20′ 32″ E 20°06′ 27″	504*	30	13.55	1.08	5137	0.0604	47	1.1312	880	100	12.86±0.63	8	1.6	9.9±1.5
50/02	Oligocene	Sandstone	N 49°20′ 32″ E 20°06′ 27″	1005*	30	14.34	0.9879	4816	0.0539	52	1.0858	1048	100	11.86±0.21	5	1.7	8.4±1.2
51/02	L Eocene-E Oligocene	Sandstone	N 49°20′ 32″ E 20°06′ 27″	1540*	30	16.17	1.143	5492	0.0561	45	1.4951	1199	100	11.37±0.98	3		7.4±1.1
52/02	L Eocene-E Oligocene	Sandstone	N 49°20′ 32″ E 20°06′ 27″	2044*	24	10.04	0.9907	4816	0.0283	21	0.7856	584	99.99	n.d.	n.d.		6.1 ± 1.4
F 9	Paleogene	Sandstone	N 49°20′ 31″ E 19°59′ 56″	825	27	19.7	1.027	3010	0.0747	44	1.6018	943	99.96	12.16±0.80	8		8.2 ± 1.3
F 8	Oligocene	Sandstone	N 49°19′ 59″ E 20°02′ 40″	875	30	17.99	1.212	5912	0.0675	40	1.7949	1063	100	11.33±0.60	8	1.7	7.6 ± 1.2

Apatite Fission Track results for Podhale-Spišská Magura basin. Footnote to Table 1: * — Sample from borehole, depth below surface. ***ρs*** — density of spontaneous tracks ($\times10^6$ tracks for cm^{-2}); ***Ns*** — number of counted spontaneous tracks; ***ρi*** — density of induced tracks in external detector ($\times10^6$ tracks for cm^{-2}); ***Ni*** — number of counted induced tracks; ***ρd*** — density of induced tracks in external mica detector covering dosimeter CN5 glass ($\times10^6$ tracks for cm^{-2}); ***Nd*** — number of counted tracks in external mica detector. P (χ^2) % — the result of χ^2 test (Galbraith 1981; Green 1981). **Age** — is a central age of a sample (Galbraith & Laslett 1993). Calculations by Trackkey 4.2 (Dunkl 2002). See text for details. **Dpar** — average etch pit diameter of fission tracks.

with thermal neutron nominal flux of 9×10^{15}n/cm^2 at the Oregon State University TRIGA reactor in the USA. After their irradiation muscovite external detectors were etched for about 45 minutes in 40% HF in order to reveal the induced tracks. Spontaneous and induced tracks were counted by optical microscopy at 1250× magnification using a NIKON Eclipse E-600, equipped with motorized stage, digitizing tablet and drawing tube controlled by program FTStage 3.12 and FTStage 4.04 (Dumitru 1993). Data analyses and age calculations based on a Zeta value for CN5 ζ_{CN5} of 344±5 were calculated using program Trackkey 4.2 (Dunkl 2002).

All quoted AFT ages are "central ages" (weighted mean ages) of Gailbraith & Laslett (1993) ±1 σ, and the variation of single grain ages assessed using the % age dispersion of the central age and chi-square test (Galbraith 1981; Green 1981). In nearly all analysed samples about 20 or more apatite grains were selected for analyses. Only clean grains free of defects and inclusions were selected for track counting. Apatites with no tracks were included in age calculations.

Chlorine content in apatites was determined by electron microprobe CAMECA SX-100 applying 20 nA beam current and 15 kV accelerating voltage. The analyses were carried out at the Institute of Mineralogy and Geochemistry, University of Warsaw, Poland.

Results

The results of the AFT analyses are presented in Table 1 and Fig. 3. The regional distribution of ages is shown on the geological map (Fig. 4a). Nearly all analysed samples yielded ages significantly younger than the estimated Eocene-Oligocene stratigraphic age of the layers that they were collected from (Table 1), thus indicating post-depositional temperatures in excess of 100 °C for durations of heating $>10^{6-7}$ yrs, which lead to resetting of the AFT system. They are also younger than the 18–17 Ma K-Ar illite ages from the Podhale Basin, which are interpreted as recording maximum paleotemperatures (Środoń et al. 2006) and as such place the maximum limit on resetting AFT dates. Most samples yield a single population of grain ages as shown by the high P(χ^2) values (Table 1). Central ages range from 13.8±1.7 to 6.4±0.7 Ma with the vast majority grouping between 13 and 8 Ma. Only two samples showed significant dispersion with P(χ^2) <5 % and gave much older ages of 31.0±4.3 and 26.9±4.7 Ma (Table 1). They are interpreted as mixed population ages that reflect temperatures too low to cause full resetting.

Four samples from the borehole Bukowina Tatrzańska PIG-1 were collected at regular intervals of 500 m. The deepest sample comes from the depth of 2044 m (depths given relatively to the surface level), which is ca. 100 m above the Mesozoic cover of the Tatra crystalline units, on which the Tertiary basin was formed. These samples have central ages that range from 6.1±1.4 Ma at 2044 m depth to 9.9±1.5 Ma at 504 m depth. All the ages are younger than the depositional Eocene-Oligocene ages hence indi-

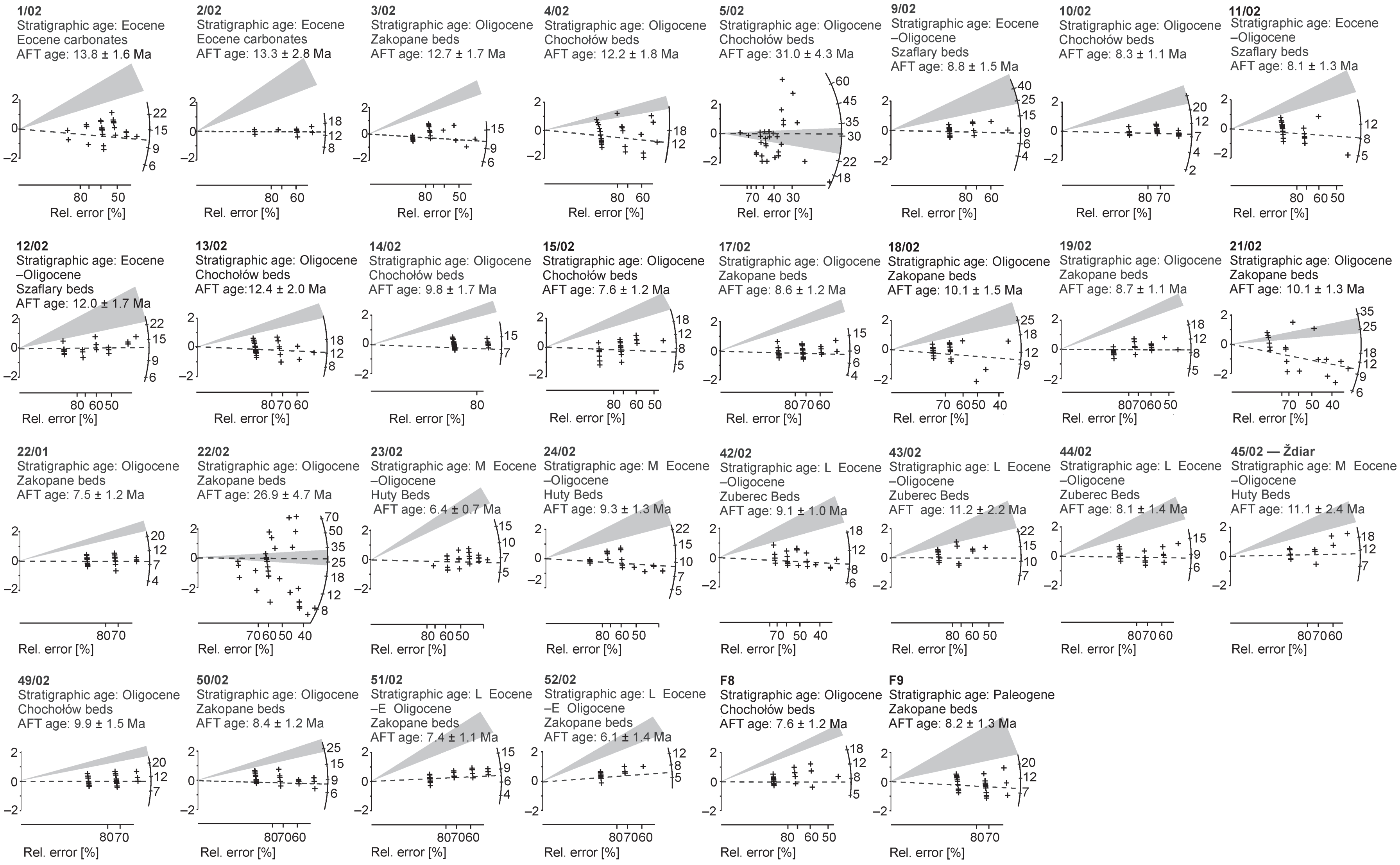

Fig. 3. Radial plots of fission track ages estimated from the analysed samples. Central ages of samples are defined by dashed lines, stratigraphic age is represented by shaded area. The position of the x-scale records the uncertainty of individual age estimates, whilst each point has the same standard error on the y-scale (illustrated as $\pm 2\ \sigma$). The age of each crystal may be determined by extrapolating a line from the origin on the left through the crystal's x; y co-ordinates to intercept the radial age scale (Galbraith 1990).

cating total resetting. The ages show a linear trend with depth (Fig. 4b). The deepest sample (2044 m), from the present-day temperatures of ~40 °C (adopting 20 °C present day geothermal gradient from Kępińska (1995 and 1997)) is well below the >100 °C required to reset the samples, and thus the reported ages are entirely related to the paleogeothermal gradient.

Unfortunately, very few confined tracks could be measured, which did not permit meaningful numerical modelling of thermal history to be carried out. Nevertheless, measured track lengths are significantly reduced and vary from 10.4 to 13.2 μm, with the vast majority oscillating around 12 μm (Table 1).

The observed variations in ages cannot be ascribed either to variations in elevation, which is very similar for all samples (Table 1) or to apatite chemistry. The chlorine content of individual grains in eight samples (3/02, 5/02, 13/02, 18/02, 22/02, 51/02, 52/02, F9) was found to be below 0.1 wt. % and did not contribute significantly to the age dispersion. The etch pit diameter (Dpar) was used to check annealing kinetics (Burtner et al. 1994). Measured Dpars are in the range of standard Durango apatite (Ketcham et al. 2007), indicating that for all samples similar annealing kinetics can be applied. The average Dpar value of 1.5 μm, points to fluorine apatite, which agrees with the composition of apatites determined by electron microprobe (Table 1).

Gently downhole decreasing ages along with reduced track length (ca. 11–12 μm, see Table 1) suggest complex thermal

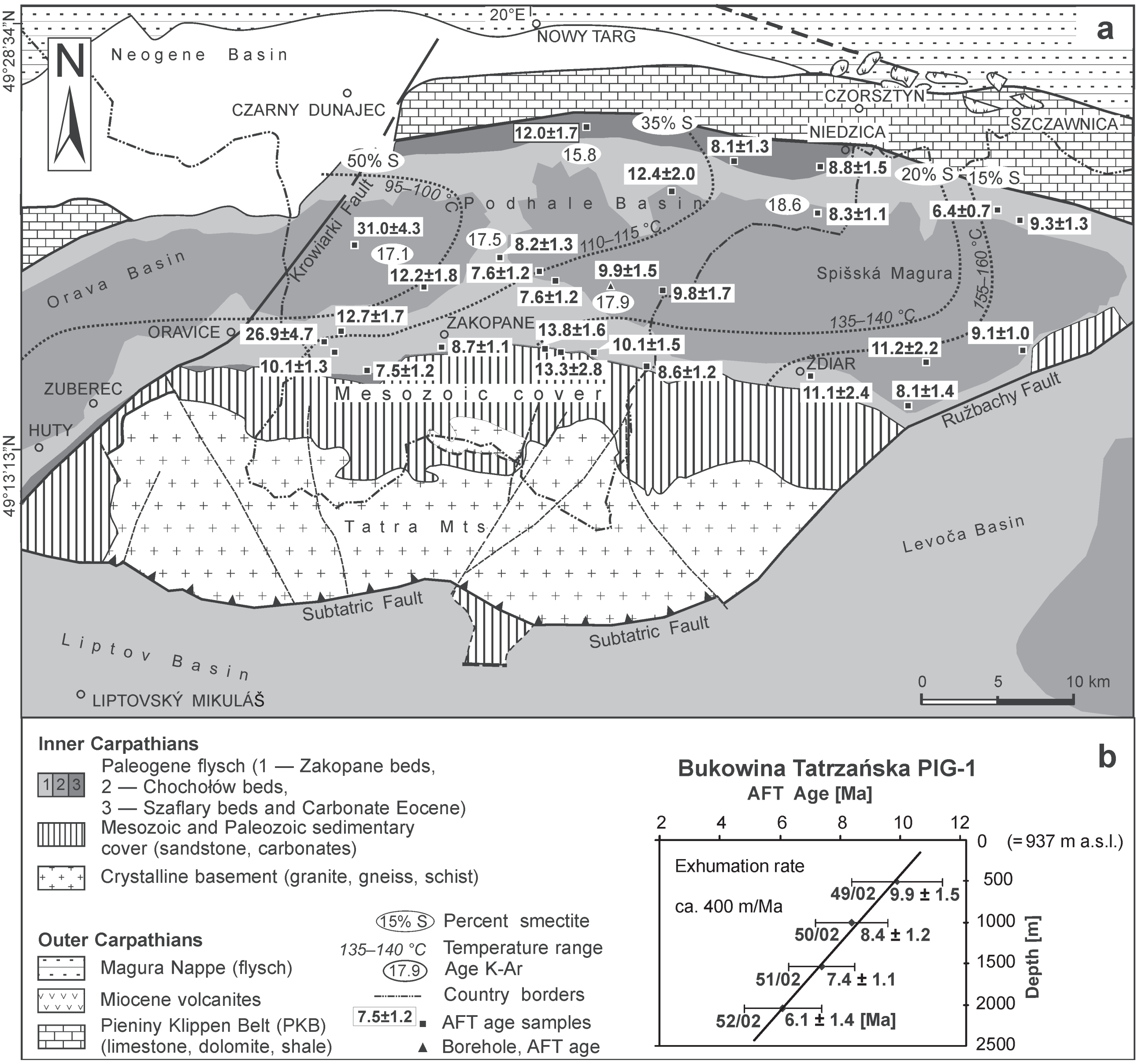

Fig. 4. a — Summary of AFT data for the Podhale-Spišská Magura basin (this study). Isotherms (dotted lines) correspond to paleotemperatures established by the illite-smectite method (Środoń et al. 2006). K-Ar dates of illite (Środoń et al. 2006) are given in white ellipses. **b** — AFT age-depth diagram for samples from the borehole Bukowina Tatrzańska PIG-1 indicates average uplift and exhumation rate of ca. 400 m/Ma.

evolution and may be interpreted either in terms of slow cooling related to exhumation or as a reheating episode (e.g. Hammerschmidt et al. 1984). Naturally, more complex scenarios cannot be excluded. Thus, below we discuss the meaning of our AFT results in more detail, in the context of all previous Podhale-Spišská Magura basin thermal history studies, which include vitrinite reflectance and illite-smectite thermometry.

Discussion

The thermal structure of the Podhale-Spišská Magura basin has received relatively a lot of attention in recent years. The studies focused primarily on applying vitrinite reflectance and illite-smectite thermometry to determine basin evolution (Kotarba 2003; Marynowski & Gawęda 2005; Środoń et al. 2006; Wagner 2011). On the basis of illite-smectite thermometry Środoń et al. (2006) documented a general westward decrease of the maximum paleotemperature on the present day erosional surface from more than 160 °C to less than 100 °C (Fig. 4a). Changes in the temperature were interpreted as resulting strictly from variable thickness of Oligocene flysch deposits, which was increasing in the eastern part of the basin, towards the Ružbachy fault (Fig. 4a). A similar picture was obtained on the basis of vitrinite reflectance study by Wagner (2011), who reports paleotemperatures at the surface ranging from 90 °C to 160 °C. The latter study is based on a dense sampling network and indicates SE-NW rather than E-W trend in temperature change. Somewhat lower temperatures were estimated by Marynowski & Gawęda (2005) who applied the same method and determined maximum paleotemperatures at the surface in the western part of the basin (Chochołów area) as low as 50–70 °C and in the SE part (Poronin and Zakopane area) between 100 and 130 °C. Despite some variations in absolute values of the estimated paleotemperatures, all three studies display the same general trend, showing higher temperatures in the eastern or southeastern part of the basin decreasing towards the northwest.

Lower temperatures in the western part are also manifested in AFT analyses. Botor et al. (2006, 2011) performed AFT dating of apatites from volcanic ash horizons in the NW Podhale Basin obtaining apparent ages between 30 and 20 Ma. This is in agreement with 31.0 ± 4.3 and 26.9 ± 4.7 Ma apparent ages reported in this study, that are also only partially reset, as expected under low temperature conditions determined for the western side of the basin by vitrinite reflectance and I-S techniques (Fig. 4a).

Since our samples were collected from the same or nearby outcrops as the samples of Środoń et al. (2006) and Kotarba (2003), we can make direct comparison of temperature estimates based on clay minerals with the AFT record. Sample 5/02 can be correlated with sample Ost-1 of Kotarba (2003), who determined paleotemperature below 70 °C. Another sample with mixed age (22/02) shows 35% smectite, which corresponds to 95–110 °C temperature (Kotarba 2003). Such low temperature record in sample 5/02 explains the incomplete resetting of fission tracks for all apatite grain types giving the mixed age population. However, in the case of the sample 22/02, the temperature postulated by Kotarba (2003) was sufficiently high to completely reset the earlier thermal record in apatite. This contradicts the above presented AFT result, which points to much lower paleotemperature (ca. 60–90 °C) for this outcrop. We cannot explain this difference but this is a rather small "incompatibility" on the regional scale, and our AFT results support the general picture recorded by clay minerals and vitrinite reflectance data that show higher temperatures in the eastern part of the basin at the present erosion surface (Marynowski & Gawęda 2005; Środoń et al. 2006; Wagner 2011).

The variations in paleotemperature on the present day surface of the Podhale flysch were ascribed to variable thickness of the eroded overlying sediments (Środoń et al. 2006), based on differences in depth-sensitive parameters, such as porosity, grain density, and degree of clay mineral orientation. These authors postulated about 2 km difference in eroded overburden between the Chochołów and Bukowina regions. This interpretation finds qualitative support in the study of Nemčok et al. (1996) who documented westward thinning of the sediments. Adopting burial as the only heat source, the amount of removed sediments solely depends on the adopted geothermal gradient. Low paleogradient of 21 ± 2 °C/km inferred by Środoń et al. (2006) requires from 4 (W) to 7 km (E) of sediment removal. However, such low paleogradient determined by interpretation of I-S and vitrinite reflectance data is incompatible with the results of Kępińska (2006) who estimated the maximum paleogradient as 30–40 °C using the same methods. The latter estimate is in an agreement with the conclusions of Marynowski & Gawęda (2005) who observed a significant rise of vitrinite reflectance with depth. In the Chochołów borehole in the western part of the basin, the near surface paleotemperature was estimated by these authors as 50–70 °C, while at 2000 m depth it was 100–130 °C. This points to an average gradient of >25 °C/km. To the southeast, in the Zakopane and Poronin area, the evaluated paleotemperature increases from 100–130 °C at the surface to 160–200 °C at 2000 m depth, which points to a gradient of about 35 °C/km. These estimates suggest that the gradient not only could have been significantly above the 20–25 °C/km estimated by Środoń et al. (2006) but may have also strongly varied. A significantly lower gradient is obtained for the western part of the basin, where the AFT recorded mixed ages. Accepting such higher geothermal gradients has two important consequences: 1) It reduces the 4–7 km estimate of eroded overburden by at least 2 km, and 2) it seems unlikely that low thermal conductivity sediments could have developed such high geothermal gradient by themselves, which makes more feasible the hypothesis of an additional heat source in the area during the Miocene.

A potential source of higher heat flow during the Miocene in the Inner Western Carpathians is reported by Danišík et al. (2008, 2010, 2012), who named it the "mid-Miocene thermal event". The authors postulated the regional significance of this event by documenting it by means of AFT and apatite (U-Th)/He thermochronology in numerous locations in the Variscan crystalline basement rocks of the Western Carpathians, Pannonian Basin and the margin of the Eastern Alps. They linked the increased heat flux primarily to mantle upwelling and volcanic activity (Král et al. 1987; Szabó et al. 1992; Tari et al. 1992; Danišík et al. 2012). AFT data from the CCPB in the direct vicinity of the Branisko Mts, some 50–60 km to the ESE of the studied area, also show clear indication of thermal resetting (Danišík et al. 2012). Although their data point to the presence of at least two age populations, the Miocene component (16–11 Ma) is very clearly distinguished. The influence of heating associated with Miocene volcanism seems justified on the basis of coincidence of volcanic and AFT ages. Miocene volcanics are common in Slovakia both to the SW and SE of the study area. In the Slanské vrchy Mts they were dated to 17–11 Ma (Pécskay et al. 2006), and were interpreted as being related to subduction and mantle upwelling (Král et al. 1987; Szabó et al. 1992; Tari et al. 1992). The final stage of this episode found its expression in andesite intrusions in the direct vicinity of the studied area, in the PKB and Magura Nappe in Poland. K-Ar andesite dating resulted in wide range of ages reflecting variable degrees of problems related to K and Ar mobility, but the ages group around 11 Ma, which was interpreted as the time of emplacement (Birkenmajer & Pécskay 1999; Birkenmajer et al. 2000).

Although we consider Miocene volcanism as a likely cause of thermal changes recorded by AFT analyses, the contribution of sedimentary cover must not be neglected. In addition to the Paleogene sequence, Środoń et al. (2006) and Danišík et al. (2012) considered a deep burial by Neogene sediments as one of the likely heat sources. Although such possibility cannot immediately be rejected, this hypothesis does not find strong support. Firstly, so far there has been no evidence found for the thick pile of Neogene sediments. Secondly, as discussed above, a thick pile of sediments alone cannot develop a geothermal gradient as high as observed in some studies in the Podhale area (Marynowski & Gawęda 2005; Kępińska 2006) and in other regions of the internal Carpathians and Pannonian Basin (Danišík et al. 2012 and references therein). Thus, the accurate value of paleogeothermal gradient could enable us to decide between the significance of the two major heat sources, and as such is of key significance for interpreting the geological evolution of the Podhale-Spišská Magura basin.

The key question concerning the origin of our young group of AFT ages (13–6 Ma) is whether they: 1) reflect slow cooling caused by uplift and erosion, which followed the mid-Miocene heating or 2) they are apparent ages reflecting thermal relaxation after the heating ceased. Both scenarios could lead to similar age-depth distribution as presented above and to the observed track lengths reduction. Preservation of only partially reset tracks from the western side of the basin, the fairly large 13–6 Ma age span of "single population" ages along with short track lengths seem to favour the latter option. However, a more complex scenario, where thermal relaxation is accompanied by slow uplift and erosion cannot be excluded. Change in thermal regime was certainly accompanied by change in tectonic configuration. The apparent ages recorded by AFT coincide with the collisional period, which likely led to some degree of thickening and uplift and erosion of the overriding block. Most likely, this is the time, when basin inversion happened. The age-depth profile recorded in the Bukowina Tatrzańska borehole allows us to determine an approximate exhumation rate as ca. 0.4 mm/yr, which seems very realistic (Fig. 4b). However, as mentioned above, similar profile could have resulted from the thermal relaxation after Miocene volcanism ceased. Pure thermal relaxation does not seem very likely, especially, when taking into account that both in the Tatra Mts, immediately to the south, as well as in the OC immediately to the north of the Podhale Basin, at the same time exhumation took place (Burchart 1972; Kráľ 1977; Kováč et al. 1994; Struzik et al. 2002; Anczkiewicz et al. 2005; Mazzoli et al. 2010; Śmigielski et al. 2010, 2011, 2012; Botor et al. 2011; Zattin et al. 2011). Hence, we favour a more complex scenario, in which thermal relaxation is accompanied by slow uplift and erosion during the collisional period.

Conclusions

AFT analyses of the Podhale-Spišská Magura basin presented in this study complement previous thermal evolution studies conducted by illite-smectite and vitrinite reflectance. Nearly all analysed samples yielded apparent ages between 14 and 6 Ma, among which vast majority groups between 11–8 Ma. These ages are much younger than the deposition ages of the studied sediments spanning from Eocene to Oligocene. The AFT ages are interpreted as reflecting resetting related to the mid-Miocene thermal event associated with mantle upwelling and volcanism (Danišík et al. 2012) and to variable thickness of the sediments. Such interpretation further shifts the extent of the mid-Miocene thermal episode to the northern edge of the Pannonian block and provides an extra heat source, which additionally helps to explain the elevated paleogeothermal gradient postulated in some studies on the basis of vitrinite reflectance and illite-smectite thermometry (Marynowski & Gawęda 2005; Kępińska 2006). This, however, contradicts the conclusions of Środoń et al. (2006) who on the basis of I-S data postulated a paleogeothermal gradient of 20–25 °C/km. Accepting more elevated paleogeothermal gradients suggests that the erosion of 4–7 km of sediments proposed by Środoń et al. (2006) may be overestimated by at least 2 km.

Two samples from the western part of the basin that yielded 31.0 ± 4.3 and 26.9 ± 4.7 Ma are interpreted as mixed ages resulting from partial resetting under temperature conditions significantly lower than in the remaining part of the basin. This observation is in a very good agreement with reported vitrinite reflectance and I-S thermometry, which indicate systematic drop of paleotemperature towards the western-northwestern side of the basin.

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