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Tertiary burial and exhumation history of basement highs along the NW margin of the Pannonian Basin – an apatite fission track study

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Tertiary exhumation

Abstract

Apatite fission track (FT) thermochronology is applied to constrain the Tertiary burial and exhumation history of the NW margin of the Pannonian Basin. The exhumed structural highs of the rugged pre-Tertiary basement reveal Eocene apparent apatite FT ages in the south and Miocene apatite FT ages in the north. Based on the thermal modelling of the FT data from the basement and by the consideration of the Tertiary sedimentary successions from the surrounding basins, we conclude that Palaeogene sedimentation significantly affected the thermal history of the basement highs and that the entire study area formed a part of the Central Carpathian Palaeogene Basin. During the Eocene, faster subsidence in the north led to a northward tilt. In the Late Oligocene, the entire area experienced exhumation. In the Miocene, collision in the north, together with rifting in the hinterland, reversed the direction of the Palaeogene tilting, resulting in fast exhumation in the north and slow exhumation or even local subsidence in the south.

1. Introduction

The study area is situated in the transitional zone between the compressional belt of the Western Carpathians and the rift-dominated Pannonian Basin. Three basement highs of the Western Carpathians were investigated: the Malé Karpaty Mts., Považský Inovec Mts., and Tribeč Mts. (Fig. 1). The mountains composed of Variscan crystalline basement, autochthonous Permian-Mesozoic sedimentary cover, and overlying Fatric and Hronic Mesozoic cover nappes (Maheľ, 1986), form SW-NE trending horsts with peaks, which rarely exceed 900 m in elevation. The horsts are separated by embayments of the Danube Basin (from west to east: Blatné, Rišňovce, and Komjatice Depressions), filled with approximately 1.5 km of Neogene sediments. The present horst and graben structural pattern was created in a transpressional regime induced by oblique collision of the North Pannonian Microplate with the North European Platform during the Early Miocene (Ratschbacher et al., 1991a, b; Kováč et al., 1994; Fodor, 1995). In Late Cretaceous and Palaeogene times, sediments of two different sedimentary successions were deposited in the study area. In Neogene time, this sediment pile was nearly completely eroded, and only small isolated remnants of pre-Neogene sediments remained preserved. Therefore, the extent and nature of the pre-Miocene sedimentary basins is still poorly understood. The unknown extent and thickness of the sedimentary cover raises the question: how significant was the thermal effect of overprint of the Cretaceous-Palaeogene sediments on the basement?

FT thermochronology is a powerful technique, which can be successfully used for constraining the amount of overburden (e.g. Naeser et al., 1989; Dunkl and Frisch, 2002). The sedimentary columns preserved in neighbouring areas (e.g. in the Eastern Alps and Transdanubian Central Range) imply that possible sedimentary burial could have induced reheating of the basement up to ~ 100 °C, i.e. the temperature of partial or complete reset of apatite FT system. There are few published FT data from the Western Carpathians and the exact location of the samples is not reported (Burchart, 1972; Kráľ, 1977; Kováč et al., 1994). The data are only apparent FT ages and no track lengths were measured. We present new FT ages, track length distributions and thermal modelling results of samples from the pre-Tertiary basement in the western Central Western Carpathians. By combining these data with evidence from stratigraphy, sedimentology and tectonic evolution of the structural highs and the adjacent basins, we try to attain insight into the Tertiary thermotectonic development of the basement, in the transition zone between Pannonian Basin and Western Carpathian orogen.

2. Geology of the study area

The Malé Karpaty Mts., Považský Inovec Mts., and Tribeč Mts. are composed of four pre-Tertiary tectonic units, from bottom to top: Infratatric, Tatric, Fatric and Hronic units (Fig. 1b,c; Maheľ, 1986; Putiš, 1992). The present arrangement of the units was created during the Cretaceous collision. Cooling during this event is registered by some K-Ar isotope ages in the Malé Karpaty Mts. (76 - 74 Ma, on anchimetamorphic white mica; Putiš, 1991). The main phase of the Fatric and Hronic nappes stacking over the Tatric unit took place during the Turonian (Plašienka, 1997).

The Infratatric unit, exposed only in the northern part of the Považský Inovec Mts. (Fig. 1b,c), is a basement-cover unit with strong Alpine overprint (e.g. Korikovsky and Putiš, 1999), submerging below the Tatric unit with negligible Alpine overprint. The Tatric unit comprises Variscan basement (mainly medium- to high-grade metamorphosed volcano-sedimentary complexes and granitoids manifesting very low-temperature Alpine overprint) and Upper Palaeozoic to Lower Cretaceous sedimentary cover. The Fatric unit is a thin-skinned, unmetamorphosed sedimentary nappe system overthrusting the Tatric unit, consisting mainly of Mesozoic carbonates. The Hronic unit represents the uppermost pre-Tertiary unmetamorphosed nappes in the study area.

After nappe stacking, a peneplain formed in the Late Cretaceous (Činčura and Köhler, 1995). However, in the northernmost part of the Malé Karpaty Mts., Triassic rocks are unconformably overlain by Upper Cretaceous Palaeocene successions of alluvial/shallow marine, deep-water hemipelagic, and turbiditic sediments (Myjava and Brezová Groups; e.g. Andrusov, 1965; Samuel et al., 1980; Michalík and Činčura, 1992), correlated with the Gosau Group in the Northern Calcareous Alps (Faupl et al., 1987; Wagreich, 1991; Wagreich and Marschalko, 1995).

During the Palaeogene, the Central Carpathian Palaeogene Basin (CCPB) developed (Fig. 1a; e.g. Gross et al., 1984). It was filled by a flysch sequence with a thickness exceeding 5 km. The subsidence of the basin reached its maximum during the Late Eocene - Early Oligocene. Late Oligocene regression, transition from a transtensional to a transpressional regime, as well as Neogene exhumation and erosion, led to disintegration of the CCPB in the westernmost part of the Western Carpathians. Therefore, only scarce relics of Palaeogene sediments are preserved in the study area.

Structural evolution of the three mountain ranges is assumed to be identical from post nappe stacking until the Late Oligocene to Early Miocene (~ 22 Ma). Since then, each of the mountain ranges, separated by Neogene basins, has undergone its individual evolution. During the Early Miocene, the North Pannonian Microplate was rotated counter-clockwise (up to 90° according to palaeomagnetic data; Márton, 1993; Kováč and Márton, 1998). This process induced the formation of a NE-SW trending fault system defining the present-day borders of the basement highs (Kováč et al., 1994). A compressional tectonic regime governed uplift of the orogen in frontal parts of the plate. In the Eggenburgian (22-19 Ma), the first sediments were deposited in the Vienna and Danube Basins (Royden, 1988; Fodor, 1995; Lankreijer et al., 1995). During Karpatian - Early Badenian time (17.5 - 15.5 Ma), subsidence of high rates occurred in the basins (Fig. 2). Crustal extension in the basins, controlled by listric normal faulting, led to the development of horst and graben structures (Horváth, 1993). In the Middle Miocene (~ 15 Ma), the crystalline basement of the Malé Karpaty and Tribeč Mts. became exposed to erosion, as documented by the occurrence of granitic material in conglomerates and breccias in the Vienna and Danube Basins (Vass et al., 1988; Kováč et al., 1991).

In Late Miocene and Pliocene times, thermal subsidence induced post-rift extension and deepening of the basins (Horváth, 1984; Horváth and Rumpler, 1984). Exhumation of the horsts triggered erosion of the Miocene deposits in marginal parts of the basins, while subsidence in the central regions led to further accumulation of river and lake deposits in the Vienna Basin, where Pliocene deposits reach a thickness of up to 1200 m. The crystalline basement of the Považský Inovec Mts. remained buried until Pliocene times when it was finally exposed to the erosional level (Brestenská, 1980; Kováč et al., 1993).

During the Quaternary, a positive tectonic inversion has been observed in the Western Carpathians, and only a few depocentres in the Vienna and Danube Basins were still subsiding (Plašienka et al., 1997).

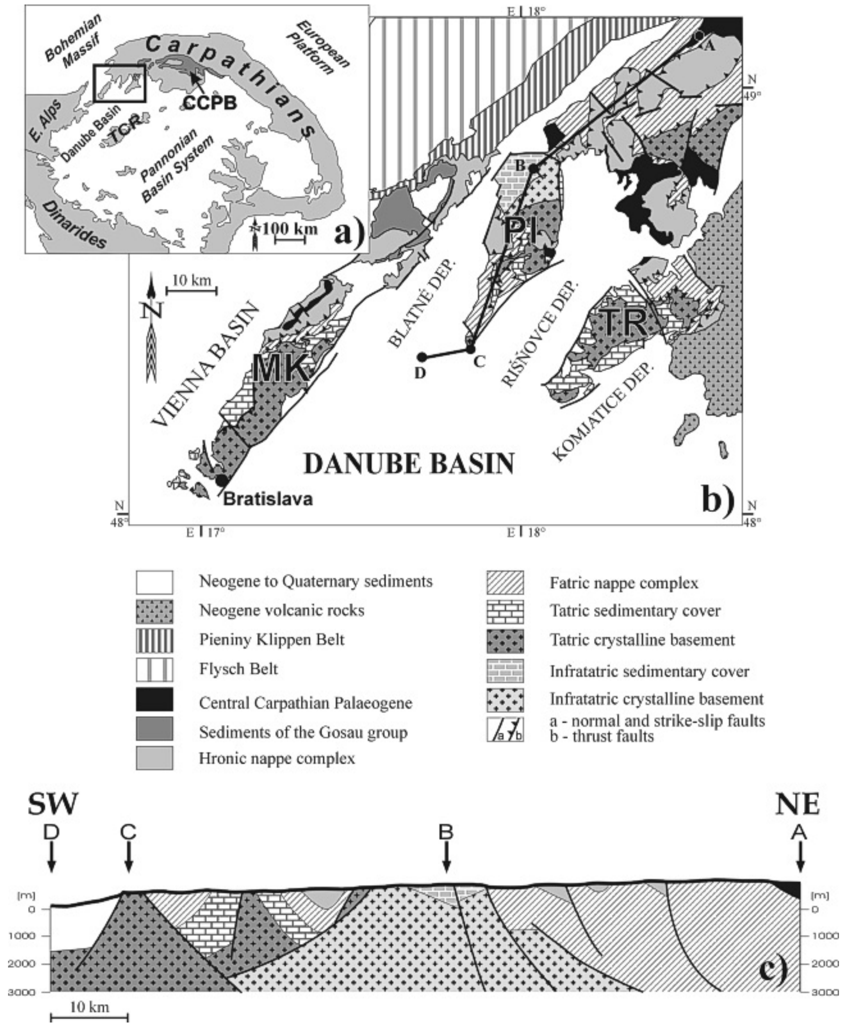

Figure 1: (a) Location map of the study area within the Alpine-Carpathian-Pannonian realm: position of pre-Neogene rocks (light grey); Central Carpathian Palaeogene Basin (CCPB; dark grey); Neogene sediments, volcanic rocks and sea (white); TCR: Transdanubian Central Range. (b) Geological map of the study area (modified after Lexa et al., 2000); profile A-B-C-D is discussed in chapter 6.2; MK: Malé Karpaty Mts.; PI: Považský Inovec Mts.; TR: Tribeč Mts. (c) Schematic structural cross section of the profile A-B-C-D.

3. Post-Eoalpine burial scenarios in the study area

The pre-Neogene sedimentary cover of the study area is only scarcely preserved (see Fig. 1b). In order to evaluate any of the sedimentary cycles, which could potentially influence the thermal history of the studied crystalline highs, we shortly review the sedimentary evolution from surrounding regions, where sedimentary sequences are better preserved. Available data of Tertiary sequences from the Eastern Alps, the Central Western Carpathians, and the Transdanubian Central Range (Figs. 1a and 3) enable us to present the following post-Eoalpine burial scenarios (Tab. 1).

Sedimentation scenario	Trend [Ma] 80 40 0	Description	Thermal modelling
G P M		rapid cooling before Gosau sedimentation	no proper fitting
G P -			
G - M			
G - -			
- P M		works only with Eocene burial	fitting possible
- P -		burial or stagnation in Eocene	fitting possible
- - M		only Early Miocene burial	fitting possible
- - -		continuous (monotonous) cooling	no fitting

Table 1: All possible sedimentation scenarios of the northern margin of the Danube Basin and the summary of the thermal modelling results made on the exhumed crystalline basement highs. G: Gosau scenario, P: Palaeogene scenario, M: Miocene scenario. In the "trend" plots the downward-trending line represents increase of temperature (= burial), upward trending line represents decrease of temperature (= exhumation, cooling).

3.1. Gosau burial scenarios ("G")

Following the Late Cretaceous (up to Turonian) nappe stacking, we consider two possible scenarios for the evolution of the crystalline basement: either (i) with a post-orogenic exhumation and cooling phase, or (ii) with burial immediately after the Eoalpine exhumation and cooling. The first scenario is supported by the widespread development of karstic relief and bauxite deposits, thus we suppose that from the Late Turonian to Thanetian (88 - 60 Ma), a large part of the study area (excluding the northern part of the Malé Karpaty Mts.) was exposed to slow erosion (Činčura and Köhler, 1995). The second scenario is supported by the geology of the northern part of the Malé Karpaty Mts., where post-tectonic sediments of the Gosau Group were deposited between Coniacian and Priabonian times (86 - 38 Ma; Fig. 3; e.g. Lexa et al., 2000). The Gosau sequence reaches up to 2500 m in thickness in the study area, however its extent is not known. In the study area, the Gosau sequence is present only in the northern part of the Malé Karpaty Mts., but there are abundant but structurally limited occurrences of Upper Cretaceous sediments in the Eastern Alps and the Transdanubian Central Range. Thus, it is uncertain whether the study area was completely covered by Gosau sediments.

3.2. Palaeogene burial scenarios ("P")

During the Late Palaeocene (~ 57 Ma), a new sedimentary cycle commenced in the Central Carpathian Palaeogene Basin (CCPB, Figs. 1 and 3). There is an obvious west to east shift in the age of sedimentation (Gross et al., 1984). The sedimentary column of the CCPB is truncated; the youngest preserved member is lowermost Miocene (stage NN 1/2). The thickness of the shallow marine formations reaches 150 m, whereas the bathyal flysch is more than 5 km thick (Soták, 1998a, b). As for the Gosau sediments, the extent of the CCPB is disputable. There are significant accumulations of the Palaeogene sediments in the eastern part of the Central Western Carpathians (reaching 6 km in thickness), while only rare exposures of Palaeogene formations are preserved in the study area. As it is not realistic that the deep marine flysch sedimentation occurred only in patches, it is likely that a general sedimentary cover existed over the entire area (Kázmér et al., 2003).

3.3. Miocene burial scenarios ("M")

During the Early Miocene, another sedimentary cycle commenced in the area of the Danube and Vienna Basins (Figs. 2 and 3). In the Badenian (~ 15 Ma), the crystalline basements of the Malé Karpaty and Tribeč Mts. were already exposed and eroded (Vass et al., 1988; Kováč et al., 1991; Hók, pers. commun.). Therefore, Miocene sedimentary cover did not significantly affect the thermal evolution of these basement highs. In contrast, the northernmost part of the Považský Inovec Mts. was exposed to erosion as late as the Pliocene (Brestenská, 1980; Kováč et al., 1994). Unfortunately, incomplete sedimentary records do not provide reliable constraints on the time of exposure in other parts (especially southern termination) of the Považský Inovec Mts.

4. Methods and analytical procedure

4.1. The dating method

Fission tracks are damages in the crystal lattice produced by the spontaneous fission of ^{238}U and are formed continuously through time (Wagner, 1968). At temperatures above ~ 120°C, in the so-called total annealing zone, the fission tracks in apatite are immediately annealed. When a rock cools into a certain temperature range, retention of the fission tracks starts. The track density is proportional to the time elapsed since the rock has cooled into this temperature range, which depends on the chemical composition of the mineral and the cooling rate and is called the partial annealing zone (PAZ). For apatite the PAZ is generally defined as a temperature range between 60 and 120°C (e.g. Wagner and Van den haute, 1992). Within the PAZ, the fission tracks are progressively shortened, depending on the time spent in the PAZ. By using fission track length distributions in combination with FT ages it is therefore possible to investigate the thermal history of the rocks (Gleadow et al., 1986a,b).

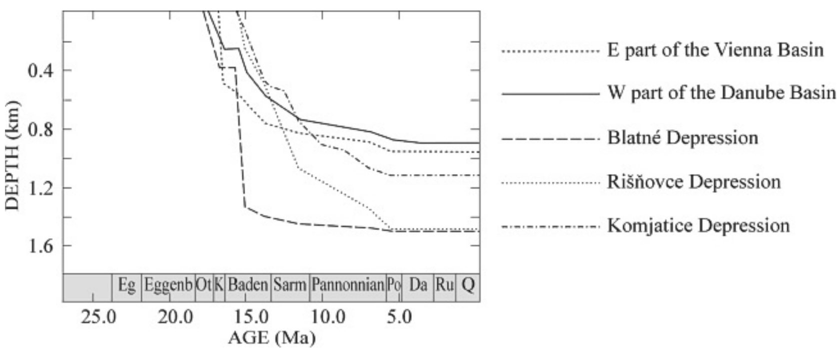

Figure 2: Neogene subsidence curves of the sub-basins in the study area (modified after Lankreijer et al., 1995). Abbreviations: Eg: Eggerian; Eggenb: Eggenburgian; Ot: Ottnangian; K: Karpatian; Baden: Badenian; Sarm: Sarmatian; Po: Pontian; Da: Dacian; Ru: Rumanian; Q: Quaternary.

4.2. Sampling and analytical procedure

Rock samples were collected from the basement (see Appendix). Apatite separates were obtained utilising standard heavy mineral separation techniques, embedded in epoxy resin on glass slides,

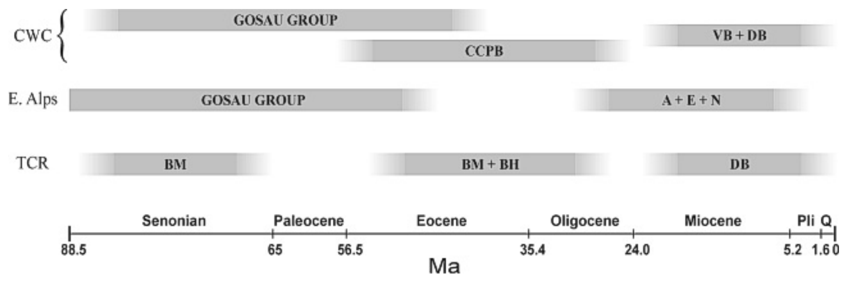

Figure 3: Post-Eoalpine sedimentary phases in the Central Western Carpathians, Eastern Alps, and Transdanubian Central Range; CWC: Central Western Carpathians; TCR: Transdanubian Central Range; CCPB: Central Carpathian Palaeogene Basin; VB + DB: Vienna Basin and Danube Basin; A + E + N: Augenstein Formation, Enns Valley, and Noric Depression; BM: Bakony Mountains; BH: Buda Hills (compiled from: Weber and Weiss, 1983; Császár, 1997; Lexa et al., 2000; Frisch et al., 2001).

ground and polished. Spontaneous fission tracks in apatites were revealed by etching with 5.5 M HNO_3 for 20 seconds at 21°C. The external detector method (EDM; Gleadow, 1981), with low uranium muscovite sheets as detectors, was used to monitor induced fission tracks. The samples were irradiated at the HIFAR nuclear reactor facility (Lucas Heights, Australia). Dosimeter glasses CN-5, containing 12 ppm of natural uranium (Hurford and Green, 1983), were used to determine the neutron fluence. After irradiation the induced fission tracks in the mica detectors were etched by 40 % HF for 30 minutes at 21°C. FT counting, length measurements of horizontal confined tracks and D_{par} values were determined with a Zeiss Axioskop 2, equipped with a digitising tablet and computer-driven stage with 1250x magnification using a dry objective (Dumitru, 1993). The FT ages were calculated using the ζ age calibration method (Hurford and Green, 1983) with a ζ value of 345.95 ± 10.78, utilizing apatites from Durango (Mexico), reference age of 31.4 ± 0.5 Ma (McDowell and Keizer, 1977), and from Fish Canyon Tuff (Colorado, USA), reference age of 27.8 ± 0.2 Ma (Steven et al., 1967; Hurford and Hammerschmidt, 1985), as age standards. Apparent age determination of the samples was performed with the program TRACKKEY, version 4.1 (Dunkl, 2002).

Modelling of the low-temperature thermal history, based on the apparent FT ages and the confined track lengths data, was carried out using the AFTSolve 1.1.3 modelling program (Ketcham et al., 2000). The program defines time-temperature (tT) envelopes that contain all paths, passing statistical criteria and conforming to user-entered constraints, that best reproduce the measured data. It has to be kept in mind, that a perfectly fitting and statistically proven model of a thermal history does not necessarily correspond to the real history of a sample. To avoid such misinterpretation, it is necessary to include all known geological data into the model before the meaning of the measured ages and tT paths are evaluated.

5. Results

5.1. Fission track ages

FT ages were determined for 17 samples (Tab. 2). All samples passed the χ^2-test at a 95% confidence interval. The apatite FT central age pattern forms two well-separated age clusters on the map of the study area (Fig. 4). The first cluster displays the Miocene ages (13.3 ± 0.9 - 21.1± 1.2 Ma) and covers the area of central and northern part of the Považský Inovec Mts. Central FT ages of the second cluster are in the range of 34.8 ± 1.9 to 43.7 ± 1.9 Ma. All of the samples express Eocene ages except the sample T-24 (34.8 ± 1.9 Ma), which falls in the Oligocene. Regardless of such exception, it is considered that this age group forms an Eocene age cluster, covering the Malé Karpaty Mts., Tribeč Mts., and southernmost part of the Považský Inovec Mts.

5.2. Track length distribution

The apatites of 6 samples (PI-8, PI-9, MK-16, MK-17, T-21, T-22) were suitable for track length measurements (Fig. 5). At least 60 horizontal confined tracks were measured in these samples to obtain a representative distribution. In addition, the D_{par} value (the diameter of track etch pits parallel to the crystallographic c-axis; Burtner et al., 1994) was determined in these samples in order to evaluate the track annealing parameters for the modelling procedure (Tab. 2).

Track length distributions of the samples from the Malé Karpaty Mts. (MK-16, MK-17) are broad and bimodal (mean track length of 12.8 ± 1.6 and 12.8 ± 1.7 µm, respectively). Such distributions are typical for rocks having a complex thermal history (Gleadow et al., 1986a,b). The samples from the Tribeč Mts. (T-21, T-22) exhibit broad, unimodal track length distributions, with almost the same mean track length values (13.2 ± 1.7 and 13.4 ± 1.2 µm, respectively). Such distributions may attest to slow cooling as well as a complex thermal history. The samples from the Považský Inovec Mts. are different. Sample PI-8 shows narrow (mean track length of 13.8 ± 1.0 µm), unimodal, characteristic for slowly cooling rocks, whereas the distribution in sample PI-9 is very broad and bimodal, representative of a complex thermal history with a longer stay in the partial annealing zone.

5.3. Modelling the thermal history

The FT age data together with track length distributions were used to model individual thermal histories of the samples. The annealing model of Ketcham et al. (1999) with D_{par} values as kinetic parameter has been used for the modelling. The initial track length was set at 16.0 µm. Considering independent geological information from the Western Carpathian realm and plausible post-Eoalpine sedimentation scenarios (discussed above), a set of time sections was selected for thermal modelling (Tab. 3). The beginning of the tT path was set at 80 Ma and 200 ± 50 °C, according to the characteristic low-grade metamorphic overprint of the basement (e.g. Putiš, 1991; Krist et al., 1992; Kováč et al., 1994), denoting a time of very low-grade metamorphic overprint of the Tatric crystalline basement in the Late Cretaceous (Korikovsky and Putiš, 1999). The end of the tT path was defined by present-day temperatures (10 °C) at 0 Ma.

Modelling was performed in an "unsupervised search" style, i.e. the time values of tT bars were defined following the above listed constraints (see Tab. 3). For temperature values, wide-range limitations (10 to 200 °C) were prescribed. In this setting, up to 50,000 iterations of Monte Carlo search were used. After that, the temperature bars were stepwise shrunk while not limiting the accepted tT envelope. Then in such a new setting, the searching algorithm was repeated again (50,000 iterations), etc. In this way, the minimum bars for temperature were acquired. The results are presented in Figure 6.

The "unsupervised search" resulted in similar trends for all three crystalline regions. Sample PI-9 reveals a Miocene apparent age. This sample represents a crystalline block, which cooled from the hot part of the apatite PAZ during the Miocene. The fission tracks carry only very limited information for the period prior to the apparent age (Fig. 6). Samples from Malé Karpaty Mts. (MK-16, MK-17), Tribeč Mts. (T-21, T-22), and the sample PI-8 from Považský Inovec Mts. show very similar time-temperature patterns, thus they are evaluated together:

- The 55 Ma time boundary (Tab. 3) showed no detectable impact on the modelled cooling paths.
- Modelled tT paths indicate accelerated cooling between 50 and 40 Ma.
- The modelling results suggest that around 40 Ma, the samples were already in a cool position near the surface.
- Between 40 and 20 Ma, the temperature pattern shows stagnation. The exact temperature cannot be determined, but the sampled crystalline levels were at temperatures below 90 °C, possibly even below the apatite PAZ (< 60 °C).
- Modelling results clearly indicate an increase and subsequent decrease in temperature between 22 Ma and 13 Ma. This process occurred rapidly and is evident in all modelling batches.
- Final cooling started around 17 Ma and shows high cooling rates in the Middle Miocene and slower cooling later on.
- At the 5 Ma time boundary, there is no major change in the cooling trend - the minor deflections are below the sensitivity of the apatite thermochronometer, they probably have no meaning.

6. Interpretation and discussion

6.1. Discussion of the modelling results

Due to deep regional erosion, there is little evidence that helps to determine the thickness of the former sedimentary cover of Gosau, Palaeogene, or Neogene age on top of the dated crystalline highs.

Code	Locality	Cryst.	Spontaneous		Induced		Dosimeter		$P(\chi^2)$	FT age			Mean track length	SE MTL	SD MTL	Number of lengths	D_{par}
			ρ_s	N_s	ρ_i	N_i	ρ_d	N_d	(%)	(Ma ± 1σ)			(μm)	(μm)	(μm)		(μm)
PI-3	PI	25	2.6	334	15.0	1935	4.5	6357	100	**13.3**	**±**	**0.9**					
PI-4B	PI	25	2.6	313	14.3	1753	4.5	6357	99.92	**14.0**	**±**	**1.0**					
PI-8	PI	25	3.6	394	6.6	720	4.3	3845	99.99	**41.0**	**±**	**2.9**	13.8	0.1	1	72	1.75
PI-9	PI	25	7.5	744	28.3	2815	4.6	6357	98.54	**21.1**	**±**	**1.2**	13.4	0.2	2	105	1.69
PI-12	PI	25	2.7	269	12.8	1290	4.7	6357	99.71	**16.9**	**±**	**1.3**					
PI-13	PI	25	1.6	167	8.3	863	4.8	6357	99.98	**15.9**	**±**	**1.5**					
PI-14B	PI	25	1.9	218	10.3	1134	4.9	6357	100	**16.1**	**±**	**1.3**					
PI-15	PI	25	2.6	498	11.5	2239	4.9	6357	99.97	**18.9**	**±**	**1.2**					
MK-16	MK	25	10.7	1422	21.7	2877	4.7	3845	99.93	**39.9**	**±**	**1.9**	12.8	0.2	1.6	61	1.63
MK-17	MK	25	13.5	2059	28.2	4310	4.8	3845	99.26	**39.5**	**±**	**1.7**	12.8	0.2	1.7	61	1.67
MK-18	MK	26	6.5	961	14.0	2076	4.6	3845	99.99	**36.9**	**±**	**1.9**					
MK-19	MK	31	2.6	404	8.4	1300	5.4	3845	99.94	**29.2**	**±**	**2.0**					
MK-20	MK	25	2.8	465	5.8	956	4.6	3845	100	**38.3**	**±**	**2.5**					
T-21	TR	25	8.7	1858	15.5	3317	4.5	3845	99.71	**43.0**	**±**	**2.0**	13.2	0.2	1.7	61	1.53
T-22	TR	25	9.9	2128	17.7	3787	4.5	3845	100	**43.7**	**±**	**1.9**	13.4	0.2	1.7	64	1.77
T-23	TR	25	2.8	639	5.8	1325	4.9	3845	100	**40.7**	**±**	**2.4**					
T-24	TR	25	3.2	765	7.8	1838	4.8	3845	100	**34.8**	**±**	**1.9**					

Abbreviations in the "Locality" column: PI : Považský Inovec Mts.; MK: Malé Karpaty Mts.; TR: Tribeč Mts.

Cryst: number of dated apatite crystals.

Track densities (ρ) are as measured ($\times 10^5$ tr/cm^2); N: number of tracks counted.

Apatite ages were calculated using dosimeter glass: CN 5 with $\zeta = 345.95 \pm 10.78$

$P(\chi^2)$: probability obtaining Chi-square value (χ^2) for n degree of freedom (where n = no. of crystals - 1).

FT age: central age ± 1 standard error

MTL: mean track length

D_{par}: arithmetic mean maximum diameter of FT etch pit parallel to the crystallographic c-axis

Table 2: Summary of FT data.

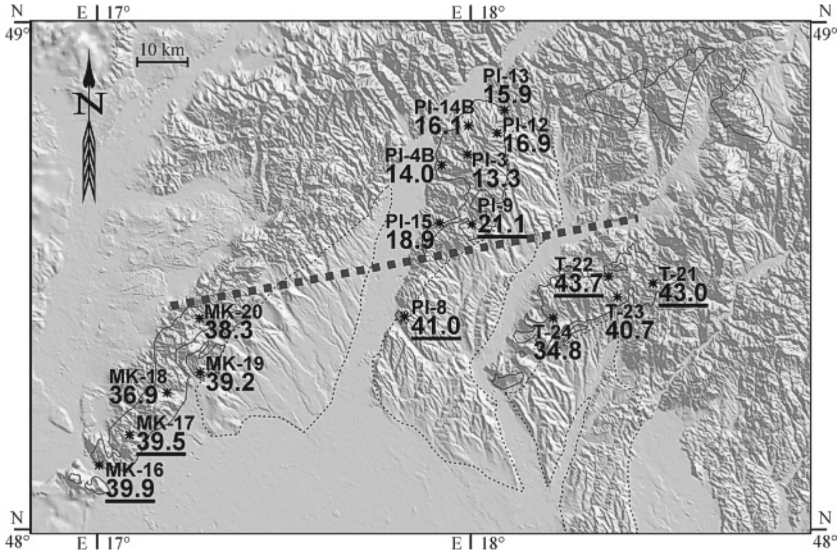

FIGURE 4: Apatite FT ages (in Ma) plotted on the digital elevation model of the northern margin of the Danube Basin. Continuous lines depict outcrops of the crystalline basement; thin dashed lines indicate exposed Neogene sediments; underlined numbers indicate samples with track length measurements. The thick dashed line marks roughly a separation of the areas with Eocene and Miocene FT ages in north and south, respectively. This line is only informal and has no geological meaning.

Considering the sedimentation histories of the adjacent areas, we set up eight possible burial scenarios for the investigated crystalline areas and compared them with the thermal modelling results (see detailed discussion in Chapter 3).

Concerning Gosau sedimentation (from ~ 90 until 45 Ma), it would be necessary to cool down the crystalline rocks to near-surface temperature immediately after the metamorphic peak and nappe stacking at ~ 80 Ma (Tab. 1). This possibility can be supported by widespread tectonic denudation and thus very rapid cooling of many tectonic blocks after Cretaceous metamorphism in the Eastern Alps (Neubauer et al., 1995; Balogh and Dunkl, 1994). However, thermal modelling of the basement highs of the study area does not allow cooling to near-surface temperature at ~ 80 Ma: During Gosau sedimentation in neighbouring areas, the blocks of the Malé Karpaty and Tribeč Mts. were slowly cooling within the apatite partial annealing zone. According to our modelling results, major exhumation to the surface did not occur before the Early Eocene. The modelled thermal/exhumation histories exclude sedimentation on top of the crystalline blocks prior to the Eocene.

The sedimentation in the Central Carpathian Palaeogene Basin started during Late Palaeocene Early Eocene times (~ 55 Ma; Fig. 3). According to the evident cooling trends of the thermal modelling results, the studied structural highs could not be buried under CCPB sediments between 55 Ma and 40 Ma, because they were just cooling in this time period. However, a sedimentary burial starting in the Middle Eocene cannot be excluded. The Eocene transgression was slowly migrating, which is also known from the Transdanubian Central Range (Dudich and Kopek, 1980). The broad acceptable temperature range in the tT plot between 40 and 20 Ma refers to a stagnation period, but may also hide a period of increased temperature due to sedimentary burial. To test this hypothesis, thermal modelling with fixed near-surface tT bars was performed for all the samples with exception of PI-9 (Fig. 7). The modelling resulted in acceptable paths yielding even better statistical indicators than the results of the unsupervised search (compare Kolmogorov-Smirnov test values in Figs. 6 and 7). These results allow the deposition of the Palaeogene sediments above the crystalline rocks in the southern parts of study area, but the sedimentation had to start later than in the Early Eocene.

Unsupervised modelling of the apatite FT data identified a known and significant thermal event of the region in the Miocene. The distinct thermal peak around 17 Ma (Fig. 6) fits to the age of Miocene rifting in the western Pannonian Basin (Fig. 2; Tari et al., 1992; Kováč et al., 1993, 1997). The increase in temperature can be the result of two factors: burial and/or enhanced heat flow due to Neogene rifting. We interpret the high cooling rate between 17 Ma and 13 Ma as cessation of the high heat flow, reported also from other marginal sub-basins of the Pannonian Basin (Sachsenhofer et al., 1998; Dunkl et al., 1998). To reach the predicted temperature of 80 ± 20 °C at 17 Ma, it is required to consider some type of cover above the present crystalline

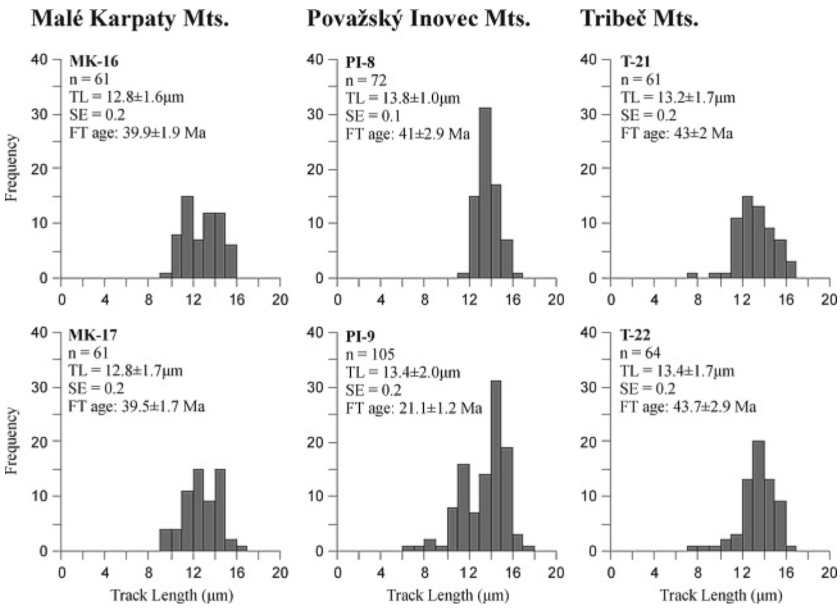

FIGURE 5: Length distributions of horizontal confined tracks. For data see Table 2.

surface. Such a lid could be created either by the basement itself or by burial under Early Miocene sediments. Loose sedimentary rocks have lower thermal conductivity than basement rocks (Dövényi and Horváth, 1988). This means that the required thermal blanketing can be achieved by a thinner Miocene psammitic-pelitic cover as well as by a thicker hard rock cover. If the scenario with Miocene cover is reliable, it means that the exhumed crystalline horsts and the basin embayments along the northern margin of Danube Basin had similar burial history up to the Middle Miocene and that their divergent evolution started after the Badenian.

6.2. Geodynamic interpretation of data and basin evolution in the western part of the Central Western Carpathians

The evaluation of the geodynamic and thermal history of the crystalline highs is based on the following constraints:

- Apparent FT ages form two clusters (Eocene and Miocene) and indicate that the southern and northern belts had different thermal histories.
- Thermal modelling results suggest a complex thermal evolution with two major cooling periods in the Tertiary.
- Basin evolution scenarios, as discussed above.

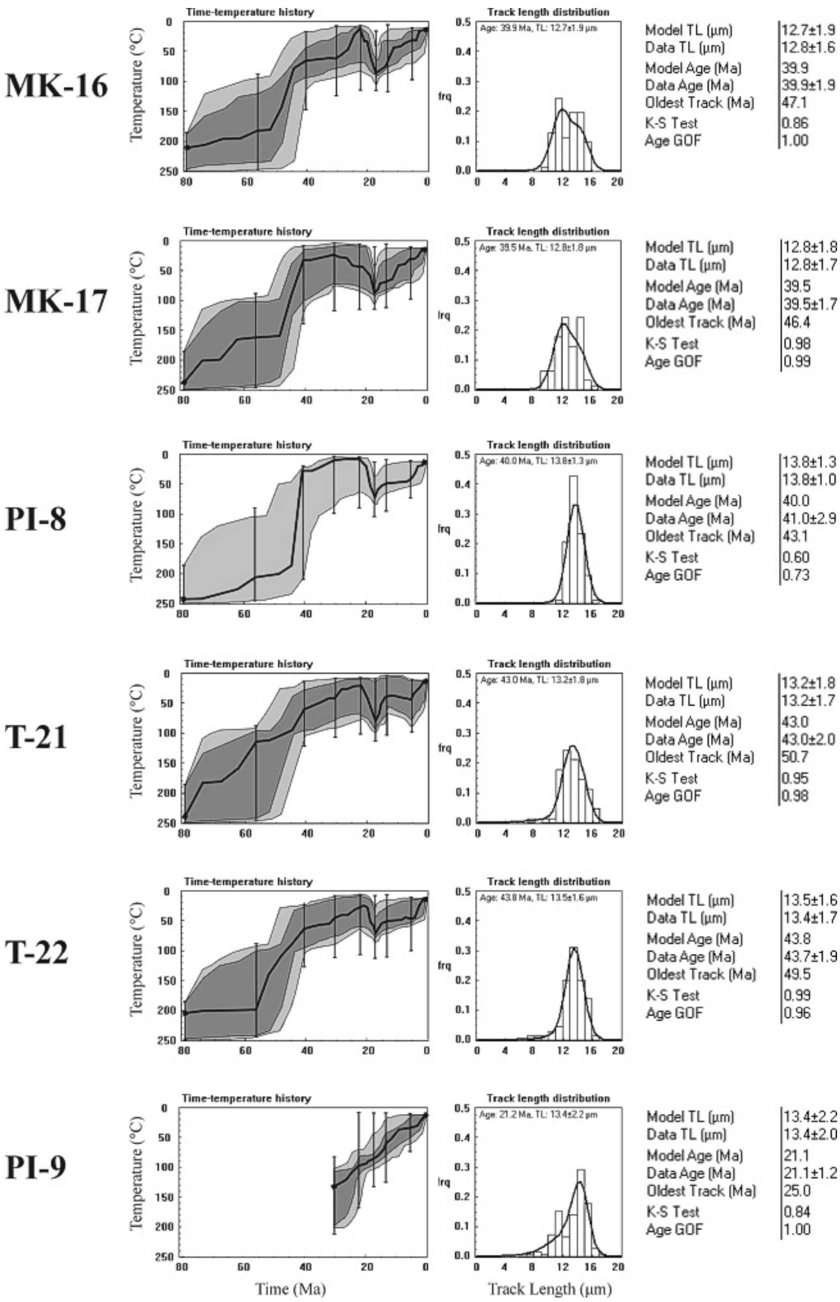

Figure 6: Thermal modelling results of FT data performed by the "unsupervised search" style with AFTSolve®, displayed in a tT diagram and frequency distribution of measured confined track length data overlain by a calculated probability density function (best fit) of a sample. Vertical lines indicate the time sections predefined for the modelling according to the evolution of the region (see Tab. 3). For these sections, no initial temperature limitation was applied. Light grey envelope: acceptable thermal paths, dark grey envelope: paths providing good fit, thick black line: best fit (Ketcham et al., 2000). In case of sample PI-9 from the Považský Inovec Mts., the apparent age falls into the Miocene, thus the modelling gave results only for the last 25 Ma. Model TL: modelled track length data; Data TL: measured track length data; K-S Test: Kolmogorov-Smirnov statistical test; GOF: goodness of fit between modelled and calculated age.

Since the FT ages are considerably younger in the northern part than in the south, the exhumation history is plotted along a roughly N-S trending profile across the Považský Inovec Mts., because this crystalline high has both Eocene and Miocene FT ages (Fig. 1b,c). Both terminations of the profile contain more or less orogen-parallel sections (A-B and C-D), which cross major normal faults and represent the segmentation in the north and the south. With this arrangement, we try to visualize the change in the exhumation/burial trends. The suggested evolution is summarised in six steps (Fig. 8); the time points are identical with the section boundaries used for thermal modelling (Fig. 6, Tab. 3). The lines of argumentation are briefly summarised in square brackets [*italics*]:

For the Palaeocene (55 Ma), the geodynamic event of a northward tilt is characteristic: subsidence and sedimentation began along the northern margin [*conglomeratic sediments in the north at point A* (Gross et al., 1984)], in the south exhumation and erosion commenced, so eroded clasts were transported into the basin in the north [*cooling indicated by thermal modelling (Fig. 7)*].

In the Eocene (40 Ma), transgression towards the south started and the entire area was subsiding [*north: marine flysch sedimentation; south: burial indicated by thermal modelling (Fig. 7)*].

During the Oligocene (30 Ma), the entire study area was buried under CCPB sediments [*deep marine, fine grained sediment remnants preserved in all three structural basement highs (Fig. 1b), e.g., Kiscell clay* (Marko and Kováč, 1997)].

In the Miocene (22 Ma), overall exhumation of the whole region started [*Early Miocene denudation of the whole region is well known* (Kováč et al., 1994)], segmentation along faults between A and B is likely [*supposed fault activity related to the beginning of Neogene basin formation*].

From the Early Miocene onward, two alternative scenarios are presented, as the Neogene sedimentary cover is rather questionable:

If Miocene burial is supposed (scenario with Miocene burial "-PM"), in the late Early Miocene (17 Ma), the northern part of the region was fast-exhuming [*deeply eroded Cretaceous nappes* (Činčura and Köhler, 1995)*, exhumation of Infratatric unit, truncated Palaeogene sequences, and young apatite FT ages ~ 16 Ma*]. In the south, there was no difference of the thermal evolution between C and D. At point D, there was sedimentary burial, as well as at point C, which is presently an exhumed structural crystalline high [*concordant to thermal modelling; pebbles derived from the crystalline highs appear in the basin sediments only in the Middle Badenian ~ 15 Ma* (*Vass et al., 1988; Kováč* et al., 1991)]. In contrast, if no Miocene burial is supposed (scenario without Miocene burial "-P-"), in the late Early Miocene (17 Ma), northern part of the region was fast-exhuming as in the previous case [*deeply eroded Creta-ceous nappes* (Činčura and Köhler, 1995)*, exhumation of Infratatric unit, truncated Palaeogene sequences and young apatite FT ages ~ 16 Ma*]. However, points C and D were separated by a fault, which is the major fault between the Považský Inovec Mts. and the Blatné Depression, and there was no sedimentation at point C. This scenario suggests no Neogene sedimentary cover on top of the present crystalline highs [*in agreement with thermal modelling; faulting is related to extension in the major subsidence period of the Danube Basin*].

During the Middle Miocene (13 Ma), in case of Miocene burial scenario ("-PM"), in the north fast exhumation of the basement still continued [*young apatite FT ages ~ 13 Ma*]. In the south, points C and D were separated by a fault [*post-17 Ma faulting is well known in the region* (Kováč et al., 1994)]. In case of the latter scenario (without Miocene burial "-P-"), in the north exhumation continued as in the previous case [*young apatite FT ages ~ 13 Ma*], whereas in the south the separation of basins and structural basement highs continued [*cooling in the basement due to exhumation and relief building, see thermal modelling; subsidence in the basins, see Fig. 2*].

The digital elevation model of the area shows exhumed and eroding Miocene sediments in the neighbourhood of the crystalline highs (areas surrounded by dashed line in Fig. 4 are mainly eroding Neogene sediments). Thus, we conclude that uplift of the basement highs and the marginal parts of the Neogene basin occurred 'en bloc' since mid-Pliocene.

Age	Characteristic Event
80 Ma	major cooling period after Eoalpine metamorphism and nappe stacking
55 Ma	beginning of the sedimentation in the CCPB
40 Ma	deepest burial in CCPB
30 Ma	termination of CCPB sedimentation in the Western Carpathians, onset of the sedimentation in the Alpine foreland and on the top of the Northern Calcareous Alps
22 Ma	onset of sedimentation in the Vienna and Danube Basins
17 Ma	major rifting period
13 Ma	change in compressional field
5 Ma	beginning of the inversion in the entire Pannonian Basin System

Table 3: Considered possible turning points for the thermal histories of the Malé Karpaty, Považský Inovec, and Tribeč Mts., as deduced from the metamorphic and sedimentation events in contiguous areas.

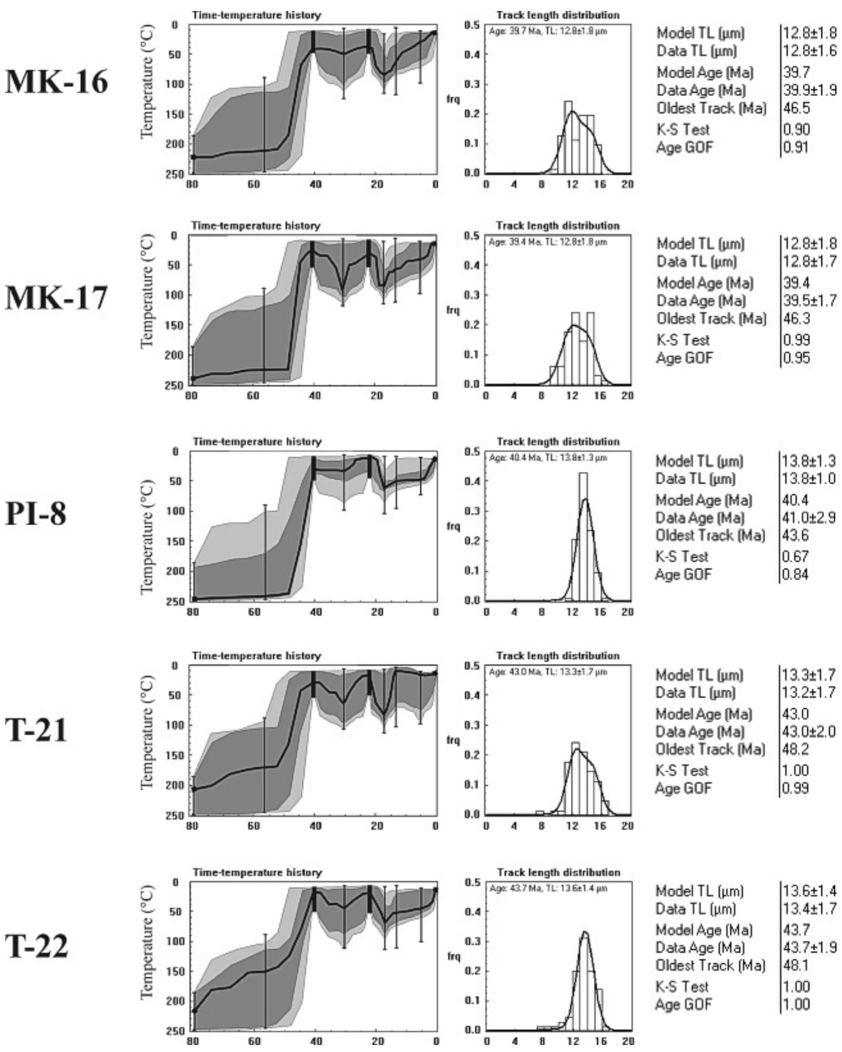

Figure 7: Thermal modelling of apatite data with forced near-surface residence between 40 and 22 Ma (thick black bars). A possible increase in temperature between fixed constraints may account for Palaeogene burial. For explanation and legend, see Figure 6.

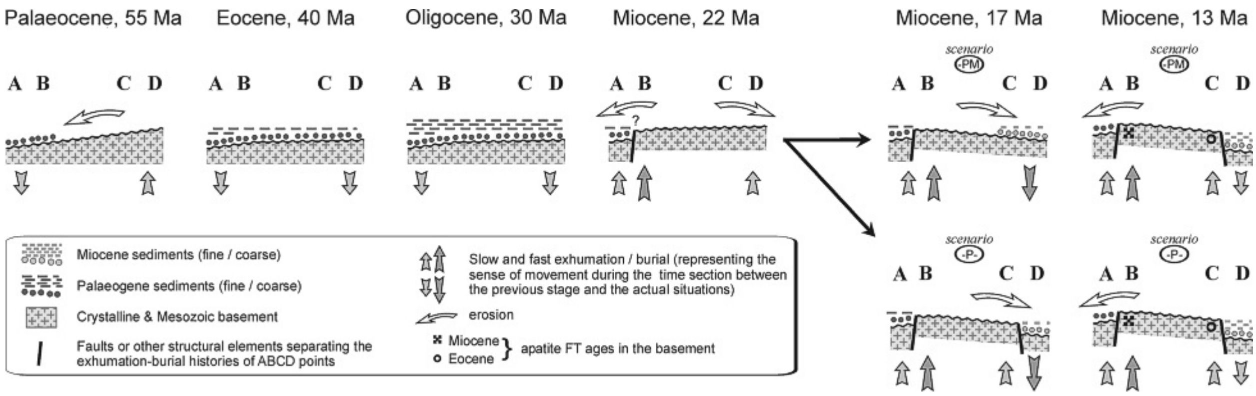

Figure 8: Exhumation and burial evolution of the western Western Carpathians. Trace of the profile see in Figure 1b,c, discussion in the text (Chapter 6.2).

7. Conclusions

On the basis of FT thermochronology, thermal modelling and sedimentation analogies from contiguous areas we conclude the following:

1) The apparent FT ages form two clusters; Miocene ages are characteristic for the northern part and Eocene ages for the southern part of the study area.

2) Cooling below 150 °C was fast during Early Eocene times; the data indicate a significant and widespread Eocene exhumation event.

3) The study area was part of the Central Carpathian Palaeogene Basin. Northern zones of the study area were covered by Palaeocene-Eocene sediments, and the transgression reached its southern zones probably in the Eocene (when the Eocene exhumation event terminated). This shift in burial matches with the overall trend in migration of subsidence of the Palaeogene Basin (Wagreich, 1991; Kázmér et al., 2003).

4) During the Miocene, the northern frontal belt underwent much more exhumation than the southern part. The former Palaeogene sedimentary cover was nearly completely eroded. Segmentation of the northern zone also probably started in the Early Miocene; there are tectonic blocks with contrasting exhumation histories close to each other, separated by faults (Lexa et al., 2000). Some of the blocks were able to preserve the Palaeogene sedimentary cover, others underwent more significant exhumation and show Miocene apatite FT cooling ages.

5) Unsupervised thermal modelling identified an increase in temperature of the crystalline basement during the Middle Miocene. We relate this thermal event mainly to the effect of increased heat flow due to widespread rifting in the western Pannonian Basin at that time.

6) Thermal modelling and sedimentation data allow two scenarios for the Miocene evolution of the crystalline highs: with and without Neogene sedimentary burial. In the first case the differential exhumation of the basement highs and sub-basins would only start after the Middle Miocene main rifting phase. In contrast, if no sediment burial of the basement highs is supposed, the W to E alternation of basement highs and intercalary basins were already forming during the Early Miocene.

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