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ORIGINAL PAPER

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Exhumation and relief history of the Southern Carpathians (Romania) as evaluated from apatite fission track chronology in crystalline basement and intramontane sedimentary rocks

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Abstract The combination of apatite fission track (FT) thermochronology from basement units and the FT age distributions of apatites in the Miocene intramontane sedimentary rocks allows describing the exhumation history of the central segment of the Southern Carpathians, Romania. Exhumation and cooling from the total track annealing temperature (>120°C) of the Cozia and Cibin massifs occurred in the Palaeocene–Early Eocene. Between the Eocene and Middle Miocene, there was a stagnation period concerning vertical displacement; the presently exposed part of the basement was buried in shallow depth. The present crests of the Cozia and Cibin Mountains were at temperatures around 80°C and 50°C, respectively. The second exhumation period occurred in Middle Miocene times. The magnitude of the Miocene vertical displacement is on the order of the present-day relief. The vertical apatite FT age distribution in the basement and the age clusters in the sedimentary rocks prove that the levels of the crests were already close to the surface in Palaeogene times. Therefore, the post-Palaeocene erosional removal from the crest zones is very limited.

Keywords Southern Carpathians · Exhumation · Fission track · Sediment · Tertiary

Introduction

Our paper focuses on the exhumation history of the central Southern Carpathians based on apatite fission track (FT) thermochronology in crystalline basement rocks and Late Oligocene to Middle Miocene basin sediments, which received material from adjacent basement regions (Fig. 1). Recent FT studies on zircon and apatite show fast Palaeocene cooling in the Romanian Southern Carpathians in response to Late Cretaceous nappe stacking (Bojar 1998; Sanders 1998; Sanders et al. 1999). Structural data from shear zones along the nappe contacts imply extension-related deformation during rock exhumation. They are interpreted in terms of the tectonic denudation of the Danubian half window since the Eocene (Schmid et al. 1998; Matenco and Schmid 1999; Fügenschuh and Schmid 2000) or since the latest Cretaceous (Willingshofer et al. 2001). We examine the low-temperature exhumation history of the Getic–Supragetic basement nappe as the hanging wall unit in the Southern Carpathian orogen by studying two elevation profiles in the Cibin and Cozia massifs (Fig. 2). FT data from the Late Oligocene to Middle Miocene clastic sediments of the Petrosani Basin give information about the exhumation history of the source areas.

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Geological setting

The Southern Carpathians are an important segment of the European Alpine orogen and situated in the central part of one of the most complex orogenic arc structures in the world (Fig. 1). The complex shape of the double-looped orogenic wedge was achieved during collision and block movements along orogen-parallel strike-slip systems including large-angle block rotations in the Tertiary (Pavelescu and Nitu 1977; Ratschbacher et al. 1993; Csontos 1995; Linzer et al. 1998; Zweigel 1998). The internal structure of the Southern Carpathians is characterized by a nappe stack, which is subdivided into three groups, i.e. from top to bottom (Fig. 2a): (1) the Supragetic–Getic nappe complex, (2) the Severin nappe and (3) the Danubian nappe complex (e.g., Murgoci 1905; Streckeisen 1934; Săndulescu 1984; Berza et al. 1983, 1994).

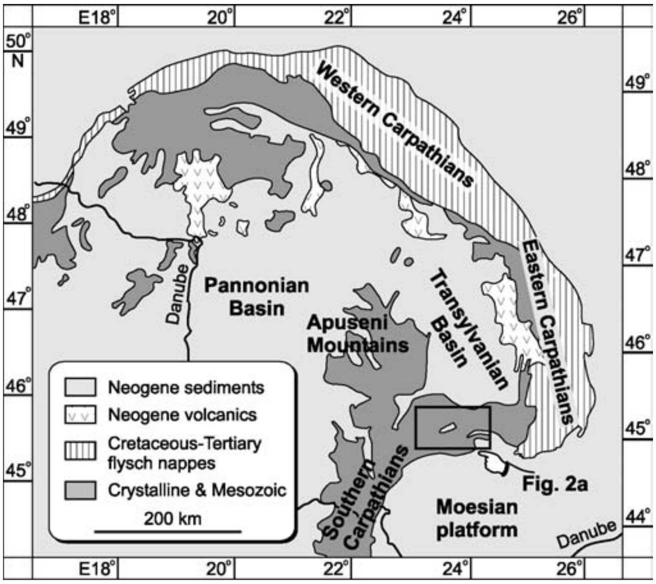


Fig. 1 Location of the study area within the Carpathian Mountains

The Supragetic–Getic nappes consist of predominantly medium-grade metamorphic rocks representing a polymetamorphic Variscan continental basement (e.g., Hârtopanu 1978, 1994; Conovici and Săbău 1993; Iancu and Măruntiu 1994). Their Upper Carboniferous to Upper Cretaceous sedimentary cover shows no metamorphic overprint. The Severin nappe consists of Upper Jurassic ophiolites and pelagic sediments and of Lower Cretaceous flysch deposits. They are interpreted as slices derived from an oceanic realm and thinned crust of the European continental margin (Săndulescu 1984). Rocks of the Severin nappe reveal subduction related Alpine metamorphism of prehnite–pumpellyite to pumpellyite–actinolite facies (Seghedi and Măruntiu 1995; Seghedi et al. 1996; Ciulavu et al. 2001). The Danubian nappe complex is exposed in a half window (Fig. 2) and consists of a Cadomian medium-grade metamorphic and granitic basement with Alpine greenschist facies overprint and mylonitization (Berza et al. 1984; Kräutner et al. 1988; Liégeois et al. 1996). Its cover consists of only locally preserved very-low to low-grade Silurian to Permian metasediments and Jurassic–Cretaceous sedimentary successions. The whole nappe stack is thrust towards the south-southeast onto the Moesian platform (Stefănescu 1988).

The Southern Carpathian nappe stack formed in two phases, (1) in late Early Cretaceous time and (2) around the Cretaceous/Tertiary boundary (Codarcea 1941; Săndulescu 1984). The deformation occurred mainly in the brittle regime. The first phase led to the stacking of several basement units in the Supragetic–Getic realm and their thrusting over the Severin unit. In Late Cretaceous times, the Supragetic–Getic and Severin nappe stack en bloc overthrust the Danubian units (Berza et al. 1994). Early Tertiary low-angle extensional faulting followed by dextral shearing and clockwise rotation

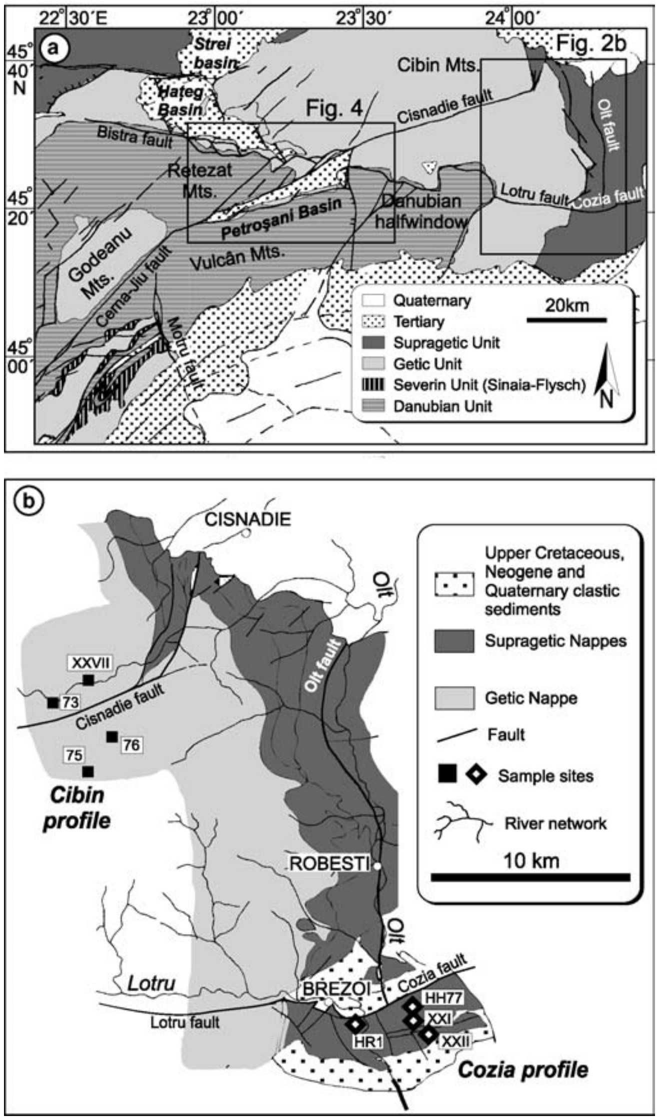


Fig. 2 **a** Overview map of the Central Southern Carpathians. **b** Geology of the Olt Valley region and sample locations in the Cibin and Cozia Mountains (compiled after Hann and Szász 1984; Hann 1995)

around the western end of the Moesian Platform (Berza 1997; Schmid et al. 1998; Willingshofer 2000; Moser 2001) dismembered the stack and thus changed the nappe geometry. Renewed foreland thrusting occurred during a Sarmatian compressional event (Stefănescu 1988).

Eocene tectonic denudation of the Danubian half window has been documented by Schmid et al. (1998), Bojar et al. (1998), Matenco and Schmid (1999) and Fügenschuh and Schmid (2000, 2003) with the aid of FT thermochronology. Tertiary tectonics mainly caused block faulting by strike-slip movements. A series of transtensive basin structures developed along the most important fault systems (Grubic 1967; Berza and Drăgănescu 1988; Pop 1993; Ratschbacher et al. 1993; Linzer et al. 1998; Moser 2001). In some basins, the subsidence was followed by folding and tectonic inversion (Matenco et al. 1997).

Geochronology and thermal evolution

Recent summaries of radiometric results from Southern Carpathian crystalline rocks are found in Stelea (1999) for the Supragetic–Getic nappes and in Willingshofer (2000) for the whole nappe stack. Within the Getic nappes, most K/Ar ages were determined in low pressure metamorphic pegmatites, which yielded Jurassic apparent ages. These ages were interpreted as ''rejuvenated'' Variscan ages, because the samples were collected from areas deformed in Alpine times (Soroiu et al. 1970; Grünenfelder et al. 1983). This interpretation is supported by Early Carboniferous U/Pb and Pb/Pb ages on zircon from pegmatites (Grünenfelder et al. 1983; Ledru et al. 1997). K/Ar ages on muscovites from low pressure metamorphic rocks in the range of 375–300 Ma indicate Variscan metamorphism (Mânzatu et al. 1975). Carboniferous $^{40}Ar/^{39}Ar$ ages from amphiboles and muscovites confirm the importance of the Variscan event (Dallmeyer et al. 1994, 1998). Alpine metamorphism was not penetrative and reached very low to incipient low grade. K/Ar isotope data show no Alpine recrystallization of muscovite in the Getic nappes (Ratschbacher et al. 1993). FT ages from the Getic Nappe range between 95 ± 6 Ma and 93 ± 12 Ma for sphene, between 128 ± 9 Ma and 50 ± 4 Ma for zircon, and between 82 ± 4 Ma and 9 ± 1 Ma for apatite (Fig. 3; Bojar et al. 1998; Schmid et al. 1998; Fügenschuh and Schmid 2000).

The K/Ar and Ar/Ar age determinations from the Danubian nappe complex reveal Late Precambrian to Early Cambrian ages (Grünenfelder et al. 1983; Liégeois et al. 1996; Dallmeyer et al. 1998) and reflect penetrative Cadomian tectonothermal activity. Furthermore, retrograde Variscan and Eoalpine (Late Cretaceous) events can be identified (summaries in Kräutner et al. 1988; Ratschbacher et al. 1993). FT ages show a wide range for zircon (from 220 ± 14 Ma to 21 ± 2 Ma) and apatite (from 94 ± 9 Ma to 8 ± 1 Ma) (Fig. 3; Bojar et al. 1998; Sanders 1998; Schmid et al. 1998; Fügenschuh and Schmid 2000).

The Cibin and Cozia basement massifs and sample locations

Metamorphic sequences of the Cibin Mountains belong to the Getic crystalline basement and are exposed with a thickness of ca. 2,000 m (Stelea 1999). On a regional scale, these metamorphic rocks form a tabular, subhorizontal structure, which is conformable with the Variscan foliation. The sequence contains four lithologically distinguished complexes, from bottom to top: (a) augen gneiss, (b) mica-rich gneiss, (c) quarz-feldspar gneiss and (d) micaschist (Hann et al. 1993). The samples were taken from complexes (b) and (d) in a profile from 800 m to 2,100 m a. s. l. (Fig. 2).

The Cozia Massif belongs to the Supragetic Nappes and experienced westward thrusting in Late Cretaceous times (later than Santonian, but sealed by Campanian-Maastrichtian sediments; Hann and Szász 1984; Balintoni et al. 1986; Hann 1995). The Cozia Massif consists of augen gneisses with subordinate paragneisses and amphibolites and reveals medium-grade metamorphism (Hann 1990). Twelve samples (Fig. 2b) were taken from the augen gneisses in a profile from 285 m to 1,688 m a. s. l. (Cozia Peak).

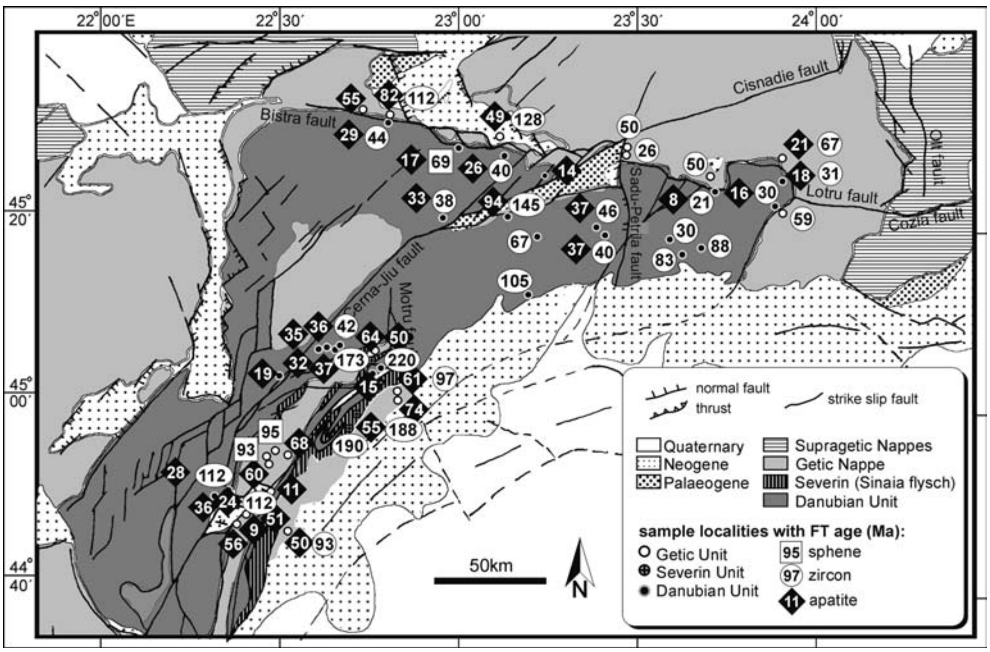
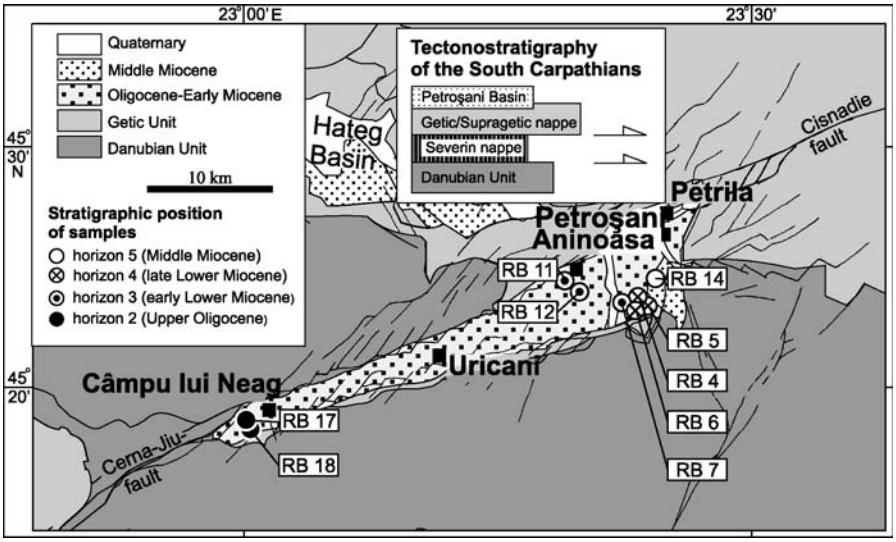


Fig. 3 Compilation of significant FT data of the Southern Carpathians (Bojar et al. 1998; Schmid et al. 1998; Fügenschuh and Schmid 2000)

Fig. 4 Localities of the Oligo–Miocene sedimentary samples of the Petrosani Basin



The Petrosani Basin and sample locations

The Tertiary Petrosani Basin is located ca. 50 km west of the Cibin and Cozia Mountains and has an elongated shape parallel to the Cerna-Jiu and the Cisnadie fault systems (Figs. 2a, 4). The sediment pile is up to 2,000 m thick (Pop 1993). The sediments show a transgressive contact with basement rocks of the Getic nappe, whereas contacts with the Danubian Unit are fault related.

The sedimentary succession of the Petrosani Basin is subdivided into five lithologic horizons, which are assigned to two sedimentary cycles (Moisescu 1981; Panaitescu 1991; Pop 1993). The older, Upper Oligocene to Lower Miocene deposits (horizons O1–O4) start with lacustrine and coarse-grained fluvial clastic sediments grading into pelitic- and coal-bearing strata of a brackish to marine facies (Moisescu 1980, 1981; Pop 1993). Aquitanian claystones and marls occur in the entire basin and indicate homogeneous sedimentation and basin subsidence. Renewed brackish sedimentation (O4) in Burdigalian time is restricted to the northeastern basin segment. The absence of the youngest, Burdigalian marine strata elsewhere can be interpreted as the beginning of uplift due to tectonic inversion, which is coeval with deformation processes and the formation of a foreland basin along the southern margin of the orogen (Moser 2001). Horizon O5 (Middle Miocene) forms the younger cycle and starts with fluvial high-energy fan deposits. They are characterized by fining-upward sequences towards the internal part of the Petrosani Basin. These sedimentary rocks are undeformed and restricted to the eastern basin area. They overlap the deformed strata of the older cycle.

The transgression of the sediments on basement rocks of the Getic nappe implies that the footwall nappe (Danubian unit) was not exposed to erosion before the Late Oligocene in the vicinity of the Petrosani Basin. Sixteen sandstone samples were taken for FT chronology from horizons O2–O5 in different locations of the Petrosani Basin (Fig. 4).

Apatite FT analysis

Fission track results of the basement samples

The details of the analytical procedure can be found in the Appendix. The basement rock samples of the Cibin and Cozia Massifs collected above 800 m yield a narrow range of apatite ages: from 50 ± 2.5 Ma to 58 ± 2.9 Ma (Fig. 5; Table 1). The Cibin profile shows no significant correlation with the altitude. The distribution of the track lengths and their averages also do not change significantly with the altitude. However, in the Cozia profile the lowest sample (HR 1, 285 m) has a significantly younger age than the others, and sample HH 77 (1,668 m) displays a broad track-length distribution with a higher proportion of shortened tracks (Fig. 5). The cooling histories of both profiles were modelled using the computer program AFTSolve (Ketcham et al. 2000). The modelling parameters and conditions that were applied are listed in the Appendix, and the modelling results of the two samples collected on the summits of the elevation profiles are presented on time–temperature plots (Fig. 6).

Fission track results of the sedimentary samples

The single-grain apatite FT ages of the Oligo-Miocene sandstone samples from the Petrosani Basin range mainly from Cretaceous to Oligocene (Fig. 7; Table 1). A preliminary study on the vitrinite reflexion data (Predeanu et al. 1987) suggests that these rocks never reached the partial annealing zone after deposition. We therefore treat the single-grain FT ages as an unbiased mirror of the cooling ages of the metamorphic rocks in the source area of the siliciclastic sediment. Sample RB 7 passed the χ^2-test ($P = 7\%$), indicating that the apatite grains derived from a homogeneous source, which can be characterized by a pooled age of 72.5 ± 7.9 Ma. All

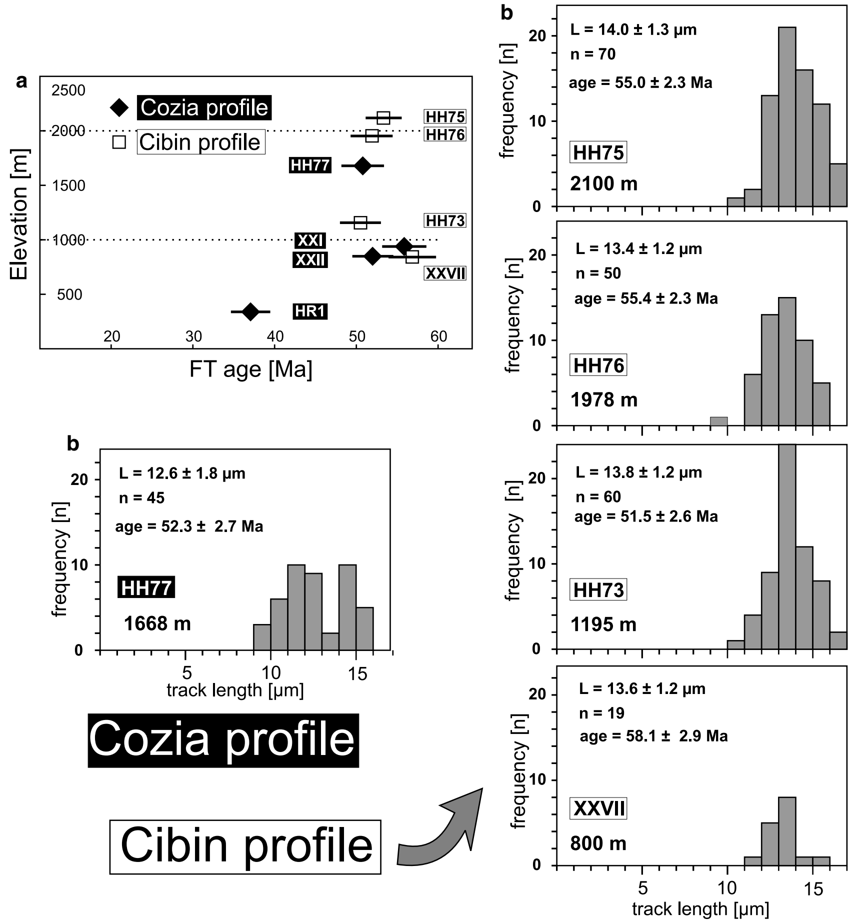


Fig. 5 **a** Apatite FT ages versus elevation from the Cozia and Cibin profiles. **b** Horizontal confined track-length distributions in the apatite samples

other samples failed the χ^2-test ($P < 5\%$); their single-grain age distributions are therefore the result of mixing from distinct sources (Galbraith 1981; Green 1981). These age distributions were treated as composite samples; the BinomFit (Brandon 1992; Brandon et al. 1998) and PopShare (Dunkl and Székely 2002) computer programs were used to identify the age components. The fitting procedures were applied supposing two components, an older (Cretaceous–Jurassic) and a younger one (Palaeocene–Eocene). This assumption (1) was necessary for both fitting algorithms, (2) it matches well with the observed single-grain age distributions of the samples and (3) the known cooling history of the crystalline areas can also be characterized by two cooling periods: a Cretaceous and a Palaeogene period (see above).

The BinomFit and PopShare fitting procedures are basically different. The first one determines best-fit peaks based on a binomial model described by Galbraith (1988) and Galbraith and Green (1990). The PopShare program uses the Simplex algorithm (Cserepes 1989). In this procedure, it is supposed that the components have Gaussian distributions, and fitting was optimised to the minimization of the root mean square; 300 iterations and multiple trials have been used. This is the first methodical survey, to our knowledge, that compares the two procedures; eight samples having composite age distributions were used for the comparative study. The mean ages of the identified components are listed in Table 2 and shown in Fig. 8. The mean ages of the younger components calculated by the two procedures match well, while the means of the older components show a broad scatter. The data of the old grains carry much larger errors than the grains of the younger groups; the old age clusters are rather loose, thus the different algorithms found different characteristic mean values for these populations.

According to the results of the two methods, it is obvious that the younger age components can be identified with a narrow confidence interval, and the two procedures usually resulted in coherent values. Thus, it is possible to express a distinct geological message from the component analysis of the single-grain age patterns. On the other hand, the older components are rather badly defined, and therefore geological conclusions from them can only be used with caution.

Discussion

Exhumation history of the basement

Except for the lowest sample in the Cozia profile, the age/elevation plots of the Cozia and Cibin Mountains are very similar (Fig. 5). The vertical age distributions

Table 1 Apatite FT results from the Southern Carpathians

Code	Latitude	Longitude	Elev. (m)	Cryst.	Spontaneous ρs (Ns)	Induced ρi (Ni)	Dosimeter ρd (Nd)	$P(\chi^2)$ (%)	Disp.	FT age[a] (Ma ± 1σ)	Track length SE (n) (µm)	Dpar (µm)
Cibin Massif (Getic basement, gneiss samples)												
HH 75	45° 32′ 16″	23° 54′ 25″	2,100	20	5.53 (1307)	7.82 (1847)	4.08 (12045)	26	0.06	53.7 ± 2.2	14.0 ± 1.3 {0.15} (70)	2.1 ± 0.4
HH 76	45° 33′ 08″	23° 55′ 31″	1,978	25	6.19 (1385)	9.08 (2034)	4.08 (12045)	4	0.11	51.9 ± 2.4	13.4 ± 1.2 {0.17} (50)	1.7 ± 0.3
HH 73	45° 35′ 17″	23° 54′ 54″	1,195	26	3.92 (797)	5.91 (1203)	4.08 (12045)	96	0.00	50.3 ± 2.5	13.8 ± 1.2 {0.16} (60)	2.2 ± 0.3
XXVII	45° 35′ 30″	23° 55′ 12″	800	22	5.25 (768)	8.40 (1230)	4.97 (12211)	47	0.04	57.7 ± 2.9	13.6 ± 1.2 {0.26} (19)	1.5 ± 0.2
Cozia Massif (Supragetic basement, gneiss samples)												
HH 77	45° 18′ 58″	23° 19′ 28″	1,668	25	4.68 (789)	6.95 (1172)	4.08 (12045)	28	0.08	51.1 ± 2.6	12.6 ± 1.8 {0.27} (45)	2.1 ± 0.3
XXI	45° 18′ 45″	23° 18′ 59″	950	25	5.61 (838)	9.24 (1381)	4.97 (12211)	47	0.07	56.0 ± 2.7		
XXII	45° 18′ 12″	23° 19′ 15″	800	20	6.14 (825)	10.8 (1461)	4.97 (12211)	49	0.01	52.2 ± 2.5		
HR 1	45° 18′ 45″	23° 17′ 08″	285	21	4.74 (385)	9.73 (790)	4.08 (12045)	14	0.19	37.0 ± 2.4		
Petrosani Basin (Oligo-Miocene sandstone samples)												
RB 14	45° 23′ 16″	23° 25′ 00″	900	74	3.5 (1107)	8.0 (2519)	5.1 (4938)	4	0.15	46.2 ± 5.2		
RB 4	45° 23′ 20″	23° 24′ 02″	700	100	4.8 (2208)	7.7 (3538)	5.1 (4938)	0	0.31	62.5 ± 7.1		
RB 5	45° 23′ 11″	23° 23′ 51″	640	90	4.9 (1424)	8.4 (2438)	5.1 (4938)	0	0.36	61.2 ± 7.2		
RB 6	45° 23′ 12″	23° 23′ 35″	620	97	5.0 (2436)	7.2 (3479)	5.1 (4938)	0	0.23	76.6 ± 3.7		
RB 7	45° 23′ 27″	23° 23′ 11″	660	99	5.5 (1580)	7.9 (2285)	5.1 (4938)	7	0.18	72.5 ± 7.9		
RB 11	45° 23′ 52″	23° 19′ 16″	580	100	4.6 (2213)	7.1 (3533)	5.1 (4938)	0	0.24	64.2 ± 7.1		
RB 12	45° 23′ 52″	23° 19′ 16″	580	100	4.1 (1891)	7.2 (3291)	5.1 (4938)	0	0.27	61.8 ± 7.0		
RB 17	45° 18′ 19	23° 01′ 30″	820	90	4.1 (1117)	7.2 (1994)	5.1 (4938)	0	0.31	58.7 ± 6.9		
RB 18	45° 18′ 50	23° 01′ 37″	780	100	5.1 (2302)	8.9 (4028)	5.1 (4938)	0	0.28	59.4 ± 6.6		

Note that nearly all sedimentary samples fail the χ^2 test. The central ages indicated have no definite meaning because the samples contain more than one apatite population (for evaluation, see text and Table 2)

Cryst: number of dated apatite crystals. Track densities (ρ) are as measured ($\times 10^5$ tr/cm^2); number of tracks (N) counted shown in brackets. $\boldsymbol{P}(\chi^2)$: probability obtaining χ^2 value for n degrees of freedom (where n = no. crystals-1). *Disp.*: Dispersion, according to Galbraith and Laslett (1993)

[a]Ages measured in crystalline rocks by I.D. and calculated using $\zeta_{CN5} = 373 \pm 7$; ages in the sedimentary samples were dated by F.M. and calculated using $\zeta_{CN5} = 415 \pm 12$. At the track-length data the standard deviation, the standard error (SE) and the number of measurements (n) are indicated; Dpar = kinetic parameter

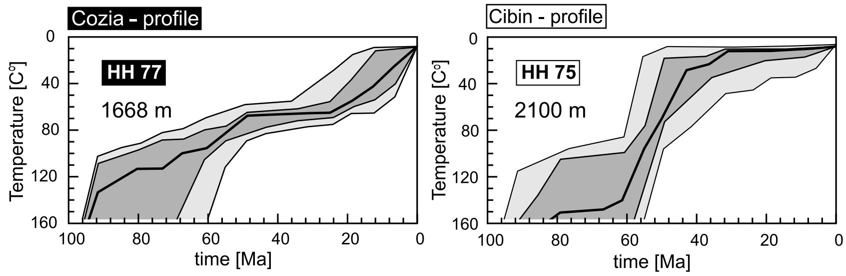


Fig. 6 Modelled cooling paths of the samples derived from the highest points of the Cozia and Cibin elevation profiles. *Dark grey* envelope of the tT paths with good fitting; *light grey* acceptable fitting (for details, see Ketcham et al. 2000). Only a starting point (100 Ma; 160°C) and the present-day point (0 Ma; 9°C) were applied, no further time–temperature constraints were considered at the modelling

indicate that the crystalline blocks represented by the samples between 800 m and 2,100 m were exhumed all the way from the total annealing zone during the Palaeocene–Eocene. Both the age profiles and thermal modelling of individual samples indicate that the apparent ages formed during a distinct cooling event in Palaeocene–Early Eocene (Fig. 6). This event postdates the Late Cretaceous deformation, and resulted in exhumation of at least 2–3 km. The very rapid exhumation together with the appearance of coarse clastic conglomerates in the Hateg (Stancu et al. 1980; Grigorescu 1983) and Titesti-Brezoi Basins (Szász 1976) at the same time or slightly earlier (Maastrichtian–Palaeocene) indicates a significant increase in the relief between the end of the Cretaceous and Early Eocene times. We conclude that fast exhumation following nappe stacking was accompanied by surface uplift and river incision.

The samples (HH 75-HH 77) from the summits of the two blocks have different mean track lengths and length distributions. Thermal modelling of samples HH 55 and HH 77 indicates slightly different Tertiary cooling histories (Fig. 6). After the Late Cretaceous–Early Tertiary cooling event, the apatites from the top of the Cozia profile were still in the zone of partial track stability. For the Eocene and Oligocene, the modelling results indicate stagnation (no or very low rate of exhumation). Final cooling started in Early Miocene times, which matches the known structural evolution of the area (see above). The top sample of the Cibin profile (HH 75) was in a much shallower, near-surface position in Late Eocene times. The amount of exhumation has been very minor since then.

The youngest Cozia apatite FT age (HR 1) at the altitude of 285 m stayed in the partial annealing zone between the Eocene and Miocene. This created a downward decrease in apparent ages. Figure 9 presents the computed vertical age distribution. Due to rapid exhumation and tectonic denudation of the Danubian half window (Schmid et al. 1998), we argue for an elevated geothermal gradient during this period. Because of the uncertainty, the modelling runs were performed using two different values, 30 and 40°C/km. The FT age profile is not complete, therefore a direct fitting of the data points to the modelled age profile cannot be done, but we can roughly estimate the eroded thickness. The elevation range between 2,100 m and 800 m fits to the upper, steep part of the calculated age profile, where the FT ages are between 50 Ma and 58 Ma. The lowermost sample offers a fitting point with a calculated apparent age around 37 Ma. The Δ_1 and Δ_2 values (900 and 200 m, respectively) are coarse estimates of the thickness of the removed material since the Palaeocene–Eocene cooling event. This approximation supposes horizontal paleo-isotherms and neglects some factors (e.g., slow erosion during the Late Palaeogene, vertical variation of thermal conductivity and fluctuation of the heat flow), but indicates that the integrated post-Palaeogene erosion was relatively low. The thickness of the rocks removed from above the top of the profiles is in the range of a few hundred metres to a maximum of 1 km.

Both structural and stratigraphic works (Ratschbacher et al. 1993) and thermal modelling of the new FT data show that the Cozia crystalline block was again exhumed during Miocene time, but the vertical displacement of the Cibin block is below the sensitivity of the apatite FT thermochronology. The Neogene vertical displacement is in the range of the recent relief of the mountains or only slightly more. Sanders (1998) and Bojar et al. (1998) also found Palaeocene apparent apatite FT ages in the Făgăras Mountains and in the Parâng, Vulcan, Godeanu and Cerna Mountains south and southwest of our study area (Fig. 3). We conclude that very limited Neogene erosion is a characteristic feature of the Southern Carpathians.

Fission track age provenance of the Petrosani Basin

For FT age-provenance studies, usually zircon ages are used, because zircon crystals contain more spontaneous tracks, their dating yields narrow age clusters, and moreover zircons are less sensitive to low-temperature overprint (Carter 1999). In this study, however, we aimed to combine the detrital apatite FT ages of the intramontane sediments, which were not thermally overprinted, with the cooling pattern of the neighbouring crystalline areas, which are the nearest possible source areas of the siliciclastic sediments.

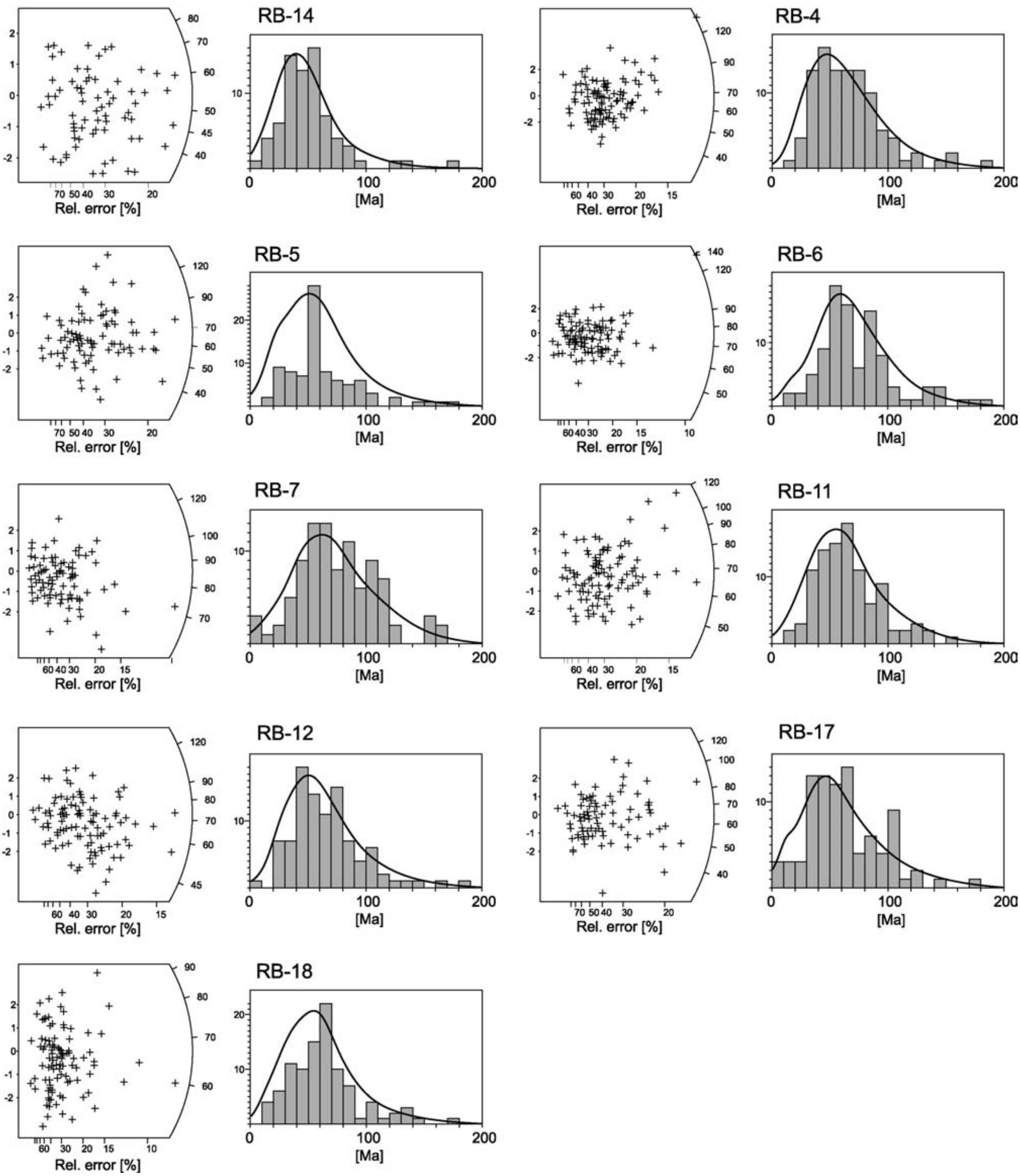


Fig. 7 Apatite FT single-grain ages in the sandstone samples presented on radial plots and age spectra

The single-grain apatite FT ages from the Petrosani Basin indicate multiple sources (Table 2). We have no evidence for the existence of more than two age clusters; thus, the analyses were performed to search for two components (see above). The younger one is usually represented by 60–70% of the grains (see %c1 values in Table 2). The two different modelling methods yield more coherent results for the younger clusters. In the following paragraphs, we will attribute much more meaning to the younger age components, because they are much better constrained by the high proportion of single-grain ages.

Age distributions of crystalline and sedimentary samples plotted in a diagram visualize the usability of the age-provenance method (Fig. 10a). The apatites in the sandstones have similar character (uranium content and proportion of datable grains) as the accessory apatite crystals of the gneisses from the elevation profiles. Thus, the two data sets can be directly compared.

Both age distributions yield their maxima around 50 Ma. The sedimentary samples, however, show a significantly broader distribution with a well-developed right-hand asymmetry. The most characteristic single-grain ages in the oldest sedimentary samples correspond to the ages of the highest crystalline samples. This suggests that ca. 25 Ma ago (the age of the sedimentation), a layer of limited thickness above the recent summit level was eroded, and this material supplied the Petrosani Basin (shown in Fig. 10b). This supports the validity of the calculation on the eroded thickness presented above.

A part of the single-grain ages in the sedimentary samples is younger than the characteristic ~50 Ma. Modelling of the amalgamated grain population by the PopShare program into three components yields a weak evidence for the presence of a second-order age component around 37 Ma. This youngest cluster of single-grain ages shows that at the time of the deposition of horizon O2, a significant relief had been developed in the Southern Carpathians. The erosion reached deeper levels, thus younger apatites of the former partial annealing zone were transported into the basin. This means that the Eocene/Oligocene boundary corresponds to the apparent age of the lowest sample of the Cozia profile. From this we can estimate a relief of 2 km or slightly more at the time of sedimentation of horizon O2 in the Petrosani Basin. The amount of younger grains is necessarily less than that of the 50–55 Ma age cluster, which is explained from the geometry of the eroded masses (Fig. 10b).

There are numerous isolated single-grain ages or even-age components, which are older than the Late Cretaceous–Palaeocene metamorphism in the surroundings of the Petrosani Basin (Table 2). These ages indicate the presence of structural blocks in the source area, which were not affected by this thermal overprint and which are completely eroded today, because base-

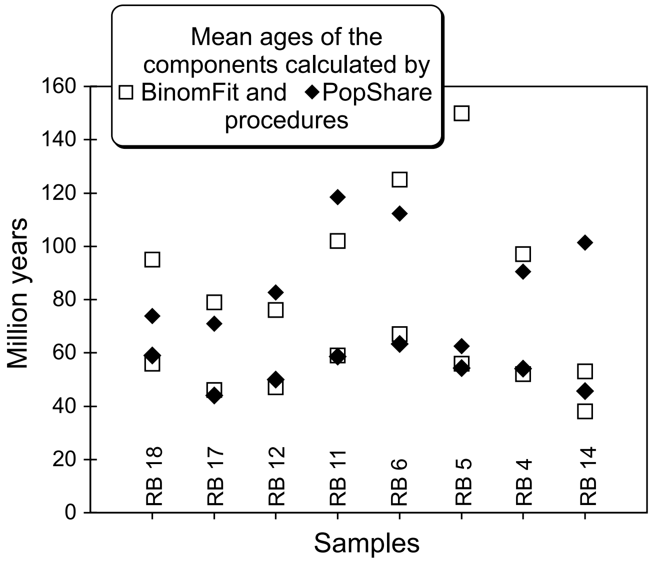


Fig. 8 Mean ages of the components from clastic apatite determined by two different fitting procedures. The younger values are consistent, but the older clusters show different means (see text for Discussion). The error bars are not presented for simplicity, but more details can be found in Table 2

ment areas with pre-Maastrichtian apatite FT ages are neither known from the Apuseni Mountains, nor from the Southern or Eastern Carpathians (Sanders 1998; Schmid et al. 1998; Bojar et al. 1999; Fügenschuh and Schmid 2000).

In the younger components of the five youngest samples, there is a clear trend towards lower FT ages with decreasing depositional age (Fig. 11). This trend reflects progressive exhumation of the source area supplying these Lower to Middle Miocene sedimentary rocks. These samples derived from a small area south of Aninoasa (Fig. 4), and it is likely that they were supplied from the same source area.

The trend of decreasing age is not visible in the older samples (e.g. RB 17 and RB 18). The scatter in the ages of the younger-age component can be the consequence of sediment supply by different river systems.

Table 2 Result of component identification using BinomFit (Brandon 1992; Brandon et al. 1998) and PopShare (Dunkl and Székely 2002) programs

	Cryst.	Fitting by PopShare					Fitting by BinomFit				
		M1	SD1	%c1	**M2**	SD2	**M1**	CI1	%c1	**M2**	CI2
RB 14	74	**46**	17	88	**101**	53	**39**	7	47	**54**	6
RB 4	100	**54**	20	70	**91**	31	**53**	4	72	**98**	9
RB 5	90	**54**	3	22	**63**	35	**56**	3	91	**150**	22
RB 6	97	**63**	20	75	**112**	43	**67**	4	92	**125**	17
RB 11	100	**59**	20	87	**118**	22	**59**	3	84	**102**	9
RB 12	100	**50**	16	49	**83**	32	**47**	4	45	**76**	6
RB 17	90	**44**	15	30	**71**	35	**46**	5	63	**80**	10
RB 18	100	**59**	17	68	**74**	62	**56**	3	85	**95**	11

The fitting was performed to search for two components. The initial estimates were according to the actual single-grain age distributions of the samples, usually around 60 and 100 Ma

Cryst. number of dated apatite crystals, *M1* and *M2* mean values of the components (Million years), *SD1* and *SD2* standard deviations of the components; %c1 fraction of the younger component, *CI1* and *CI2* confidence interval of the estimated means

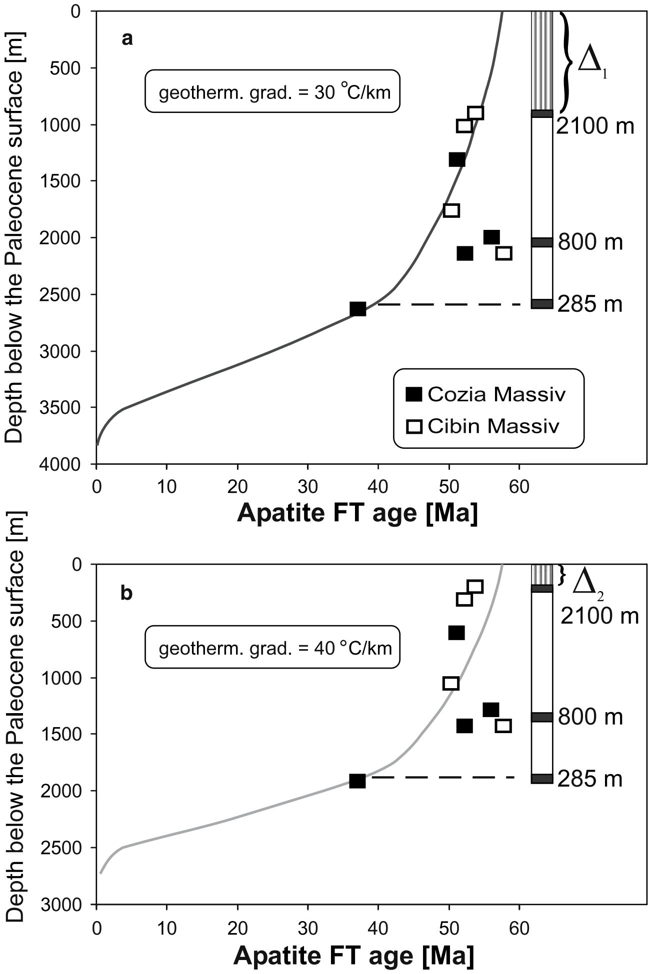


Fig. 9 Measured (*squares*) and modelled (*line*) vertical apatite FT age profile in the topmost section of the Getic and Supragetic basement. The modelled profile was computed by the AFTSolve program of Ketcham et al. (2000) using the annealing model of Ketcham et al. (1999), supposing rapid cooling around 60 Ma and negligible erosion since the Eocene. **a**, **b** show the computed age distribution supposing lower and higher geothermal gradients (30 and 40°C/km, respectively). The *vertical bars* represent the elevation profiles with the key samples (285 m = sample from the post-Palaeocene partial annealing zone; 800 m = samples from around the "break in slope"; 2,100 m = topmost samples). Δ_1 and Δ_2 represent coarse estimates of the thickness of eroded material from above the present summits since the Palaeocene

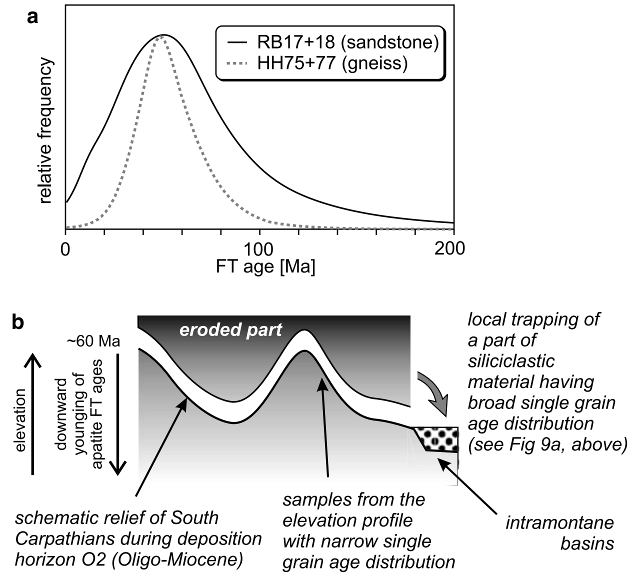


Fig. 10 **a** Age spectra computed from single-grain age distributions using the method of Hurford et al. (1984). The HH 75 + 77 distribution contains the amalgamated data (45 crystals) from the two samples collected from the highest elevations of the crystalline profiles. The RB 17 + 18 distribution is amalgamated from the two oldest sedimentary samples (190 crystals). The sedimentary samples show broader scatter, because the apatite crystals derived from different elevations having different cooling ages, while the HH 75 + 77 gneiss samples represent a given level. **b** Sketch showing the erosional removal of crystalline material and the trapping of a part of the detritus in the intramontane basins in Late Oligocene times

Conclusions

1) The elevation profiles of the Cozia and Cibin Mountains contain a vertical interval between 800 and 2,100 where the apparent apatite FT ages are very similar (ranging between 58 ± 3 Ma and 50 ± 2.5 Ma). This low age gradient section was formed by rapid cooling through the apatite total annealing zone (120–60°C) during Palaeocene exhumation. The sample with the lowest elevation (285 m) shows a considerably younger FT age (37 ± 2.4 Ma). This level remained in the deeper part of the partial annealing zone after the Palaeocene–Eocene cooling event.
2) The Palaeocene–Eocene exhumation reflected in the FT ages is in agreement with the deposition of coarse clastic sediments in the Hateg and Titesti-Brezoi Basins at the same time. This indicates a mountainous relief at the beginning of Tertiary.
3) Between Eocene and Miocene, there was stagnation with respect to exhumation. The crest levels of the Cozia and Cibin Mountains were in a shallow position in the crust, at slightly different thermal conditions, around 80°C and 50°C, respectively.
4) Thermal modelling indicates that there is a second Miocene cooling event in the Cozia basement, while this exhumation phase made no detectable trace in the FT thermochronology in the Cibin basement. This exhumation event has created the present topography.
5) Erosion since the Palaeocene–Eocene exhumation event was very limited. The integrated removal is less than 0.8 km since Eocene times.
6) The ages of the detrital apatite grains from the Oligo-Miocene siliciclastic sedimentary rocks conform to the provenance from the Getic and Supragetic nappes. The Danubian half window was not exposed to

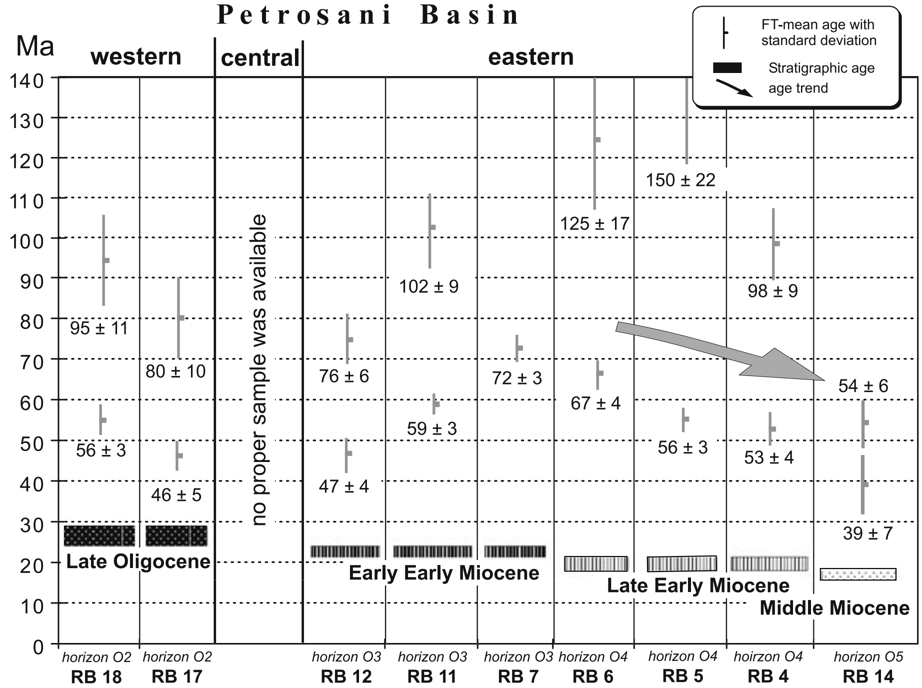


Fig. 11 Stratigraphic age of the sandstone samples from the Petrosani Basin and the mean values of the components of the apatite FT age distributions

the surface at that time. The characteristic age component in the sedimentary rocks is Palaeocene, very similar to the ages in the uppermost basement units.

7) In the Early and Middle Miocene sandstone samples, the means of the Palaeocene age components decrease with decreasing stratigraphic age. This indicates syn-sedimentary exhumation of the source area.
8) The older, less constrained age components of the sandstone samples from the intramontane basin are mainly Late Cretaceous, but indications of older-age components are also found. Crystalline areas with such old apatite FT ages do not exist any more in the Southern Carpathians. These ages therefore indicate total erosion of crystalline volumes, which remained nearly unaffected by the Cretaceous thermal event.
9) The formation and preservation of the Oligo–Miocene intramontane basins and the rather old FT ages of detrital apatites in the Southern Carpathians show similarities to the Eastern Alps (Hejl 1997; Frisch et al. 1999). The two areas are now separated by the Pannonian Basin, but the Tertiary evolution and especially the very limited exhumation and erosion of the crystalline areas during Neogene times show striking similarities.

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Appendix: Analytical procedure

A total of 2–5 kg unweathered material was sampled from each locality and treated with crushing, sieving, heavy liquid and magnetic separation processes. The apatite crystals were embedded in epoxy resin; 1% nitric acid was used with 2.5–3 min etching time at 21°C (Burchart 1972). In addition to the dated apatite crystal mounts, separate mounts were prepared for Dpar measurements. These crystal fractions were etched by 5.5 N HNO_3 for 20 s at 21°C, according to Donelick et al. (1999). The samples, age standards and CN-5 dosimeter glasses were irradiated in the thermal channel of the RISø reactor in Denmark. The external detector method was used (Gleadow 1981). After irradiation the induced FTs in the mica detectors were etched by 40% HF for 40 min at 21°C. Track counts were made with a Zeiss Axioskop microscope—computer-controlled stage system (Dumitru 1993), with a magnification of 1,000. FT ages were calculated using the standard FT age equation (Hurford and Green 1982) with a geometry factor of 0.5 (Gleadow and Lovering 1977) using the zeta calibration (Hurford and Green 1983; Green 1985; Hurford 1990). The FT ages are presented as 'pooled ages' if the sample passed the χ^2-test (Green 1981). When the χ^2-test failed ($P < 5\%$), central age was computed (Galbraith and Laslett 1993). Calculations and plots were made by the TRACKKEY computer program (Dunkl 2002). Track-length analyses in apatites were carried out on horizontal confined tracks (Bhandari et al. 1971).

To model the thermal histories, we used the computer program AFTSolve (Ketcham et al. 2000) applying the annealing model of Ketcham et al. (1999). An initial track length of 15.3 µm was applied and kinetic parameter of 2.1 µm Dpar was considered (see Table 1). We have performed the thermal modelling with several trials applying different time–temperature constraints, but the unsupervised modelling runs resulted in the most reliable thermal histories. In these cases, we did not force the searching algorithm by time–temperature constraints that can have a significant influence on the results of thermal modelling (R. Jonckheere, personal communication, 2000). Only the initial 160°C (100 Ma) and the present 9°C (0 Ma) points were fixed. Neither maximum cooling rate nor monotony was enforced. We have used 14°C paleo-surface temperature for the modelling runs.

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