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Age and significance of core complex formation in a very curved orogen: Evidence from fission track studies in the South Carpathians (Romania)

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Abstract

Twenty-four new zircon and apatite fission track ages from the Getic and Danubian nappes in the South Carpathians are discussed in the light of a compilation of published fission track data. A total of 101 fission track ages indicates that the Getic nappes are generally characterized by Cretaceous zircon and apatite fission track ages, indicating cooling to near-surface temperatures of these units immediately following Late Cretaceous orogeny.

The age distribution of the Danubian nappes, presently outcropping in the Danubian window below the Getic nappes, depends on the position with respect to the Cerna-Jiu fault. Eocene and Oligocene zircon and apatite central ages from the part of the Danubian core complex situated southeast of this fault monitor mid-Tertiary tectonic exhumation in the footwall of the Getic detachment, while zircon fission track data from northwest of this fault indicate that slow cooling started during the Latest Cretaceous. The change from extension (Getic detachment) to strike-slip dominated tectonics along the curved Cerna-Jiu fault allowed for further exhumation on the concave side of this strike-slip fault, while exhumation ceased on the convex side. The available fission track data consistently indicate that the change to fast cooling associated with tectonic denudation by core complex formation did not occur before Late Eocene times, i.e. long after the cessation of Late Cretaceous thrusting.

Core complex formation in the Danubian window is related to a larger-scale scenario that is characterized by the NNW-directed translation, followed by a 90° clockwise rotation of the Tisza-Dacia “block” due to roll-back of the Carpathian embayment. This led to a complex pattern of strain partitioning within the Tisza-Dacia “block” adjacent to the western tip of the rigid Moesian platform. Our results suggest that the invasion of these southernmost parts of Tisza-Dacia started before the Late Eocene, i.e. significantly before the onset of Miocene-age rollback and associated extension in the Pannonian basin.

Keywords: Fission track analysis; Exhumation; Core complex; Arc formation; South Carpathians; Danubian window

1. Introduction

The South Carpathians form the E–W trending segment within the highly arcuate Carpathian–Balkan

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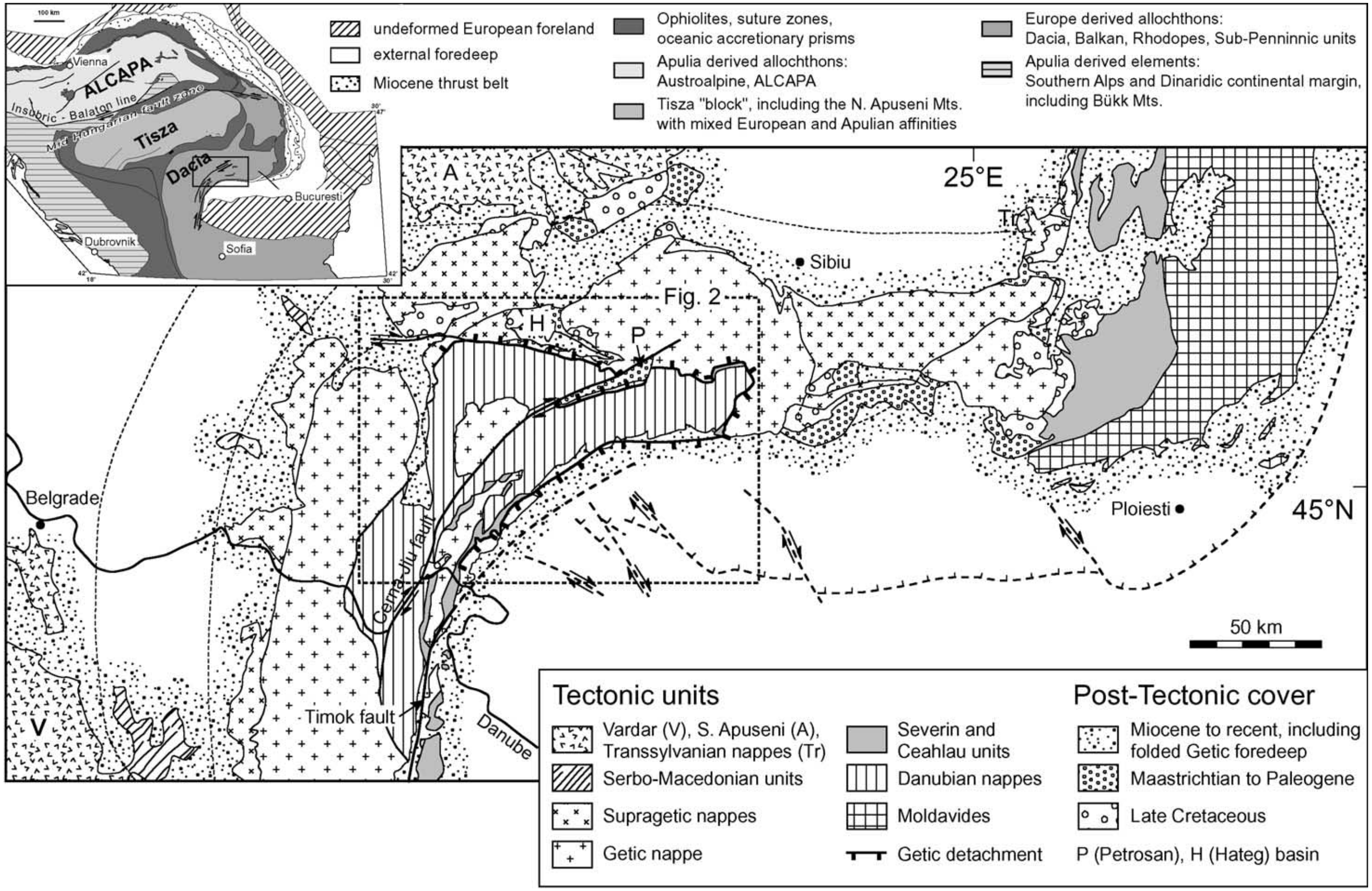

Fig. 1. Tectonic map of the Southern Carpathians, based on the Geological Map of Romania, 1:1 000 000 (Sandulescu et al., 1978) and on a tectonic map by Balintoni et al. (in: Berza et al., 1994a). The structures in the Getic foredeep are after Matenco et al. (1997), subsurface continuation of the Timok fault roughly after Visarion et al. (1988). A: South Apuseni mountains; H: Hateg basin; Tr: Transylvanian nappes; P: Petrosani basin; V: Vardar zone. The inset depicts the location of the map in the framework of the entire Alps–Carpathians–Dinarides system.

fold and thrust belt (inset of Fig. 1). The eastward convex part of this belt, the Eastern Carpathians, are generally believed to have resulted from the roll-back of a former oceanic embayment (e.g. Royden and Burchfiel, 1989) during the Neogene, coupled with E-directed movement and soft-collision of the Tisza-Dacia and Alcapa blocks, pre-structured during Cretaceous orogeny, with the East European foreland (e.g. Balla, 1987; Zweigel et al., 1998; Csontos and Vörös, 2004). In contrast, the westward convex arc, linking South Carpathians and Balkan mountains, probably formed by oroclinal bending in front of the rigid Moesian platform, welded to the European craton since Early Cretaceous times and thereby exerting a "corner effect" during the translation and rotation of the Tisza-Dacia block (Ratschbacher et al., 1993). This led to an arcuate structure that is associated with the rotation of a pre-existing structural grain (e.g. Marshak, 1988). Although the Southern Carpathians occupy a key position, linking these two arcs, a number of questions regarding their deformation during the Tertiary, i.e. immediately before and during invasion of Tisza-Dacia into the Carpathian embayment around the Moesian corner, remained controversial and/or unknown. This paper re-evaluates published zircon and apatite fission track data from the South Carpathians in the light of new data and attempts to solve a series of questions, that can only be answered by combining the results of fission track dating with structural evidence.

Firstly, the age of core complex formation leading to extensional unroofing of the deepest structural level exposed within the South Carpathians, the Danubian nappes (Fig. 1), is still disputed (Late Cretaceous vs. Tertiary). Solving this question is of relevance since; in case it is of Tertiary age (Schmid et al., 1998), this extension may be linked to contemporaneous oroclinal bending.

Secondly, this paper demonstrates that samples which display a large scatter in zircon fission-track single-grain age distributions may bear valuable and interpretable information in the context of structural investigations. Samples displaying a high dispersion are observed in parts of the South Carpathians and in many other areas that did not quickly cool across the fission track annealing window.

A third question relates to mechanisms of extension in orogens. While orogen-perpendicular extension is almost invariably induced by some sort of gravitational collapse during accretion (e.g. Platt, 1986) or during the final stages of convergence (e.g. Vanderhaeghe et al., 1999), orogen-parallel extension, as postulated for the South Carpathians by some (e.g. Schmid et al., 1998) but not all authors, is often directly linked to, and contemporaneous with orogen-perpendicular shortening (Mancktelow, 1992; Fügenschuh et al., 1997). A number of tectonic settings, ranging from lateral extrusion within a channel bound by strike-slip faults (Ratschbacher et al., 1991) to arc-parallel stretch during oroclinal bending (i.e. Marshak, 1988; Zweigel et al., 1998), may lead to orogen-parallel stretching.

Finally, this paper attempts to shed more light on the question as to what kind of structural features accommodated Tertiary-age emplacement of the Tisza-Dacia block around the Moesian corner, and when exactly this emplacement initiated. So far, primary attention was either given to the role of Miocene-age dextral strike-slip motions along E–W-striking strike-slip faults across the South Carpathians (e.g. Linzer, 1996; Decker and Peresson, 1996), or alternatively, to Oligocene-age dextral strike-slip faulting along curved faults within the South Carpathians (Berza and Draganescu, 1988; Ratschbacher et al., 1993), both in combination with dextral transpression within the southern (Getic) foredeep that is adjacent to the South Carpathians (Matenco et al., 1997). However, there is increasing evidence for a complex pattern of strain partitioning in space and time that also allows for orogen-parallel stretch within the South Carpathians and their foredeep (Schmid et al., 1998; Matenco and Schmid, 1999).

2. Regional geological setting

The South Carpathians extend from the arcuate junction zone with the East Carpathians near the Prahova valley (north of Ploiesti) westwards to the Timok valley in eastern Serbia, where they pass into the Balkans of Bulgaria (Kräutner et al., 1988; Sandulescu, 1984; Kräutner, 1996; Fig. 1). During the Alpine tectonic evolution, four major tectonic units were stacked (Sandulescu, 1994; Berza et al., 1994a). These are, from bottom to top: (1) the autochthonous Moesian platform; (2) the Danubian nappes (Marginal Dacides), outcropping in a window, and consisting of basement and sedimentary cover sequences of Carboniferous to Late Cretaceous age; (3) the Severin nappe (Outer Dacides, corresponding to the Ceahlau nappe of the East Carpathians), made up of Jurassic ophiolites, covered by Tithonian–Lower Cretaceous flysch and representing an oceanic suture; and (4) the Getic and Supragetic nappes (Median Dacides).

Three stages of convergence and collision have been distinguished in the East and South Carpathians (e.g. Sandulescu, 1984, 1994). Mid-Cretaceous orogeny ("Austrian" phase of the local literature) led to the suturing of the oceanic Severin and Ceahlau units to the overlying Getic nappes. Albian–Cenomanian post-tectonic sediments seal nappe contacts attributed to this phase. Late Cretaceous orogeny ("Laramian" phase of the local literature) involved the thrusting of the Mid-Cretaceous nappe stack (Severin-Ceahlau units and Getic nappe) over the Danubian nappes. The oldest post-tectonic sediments, that post-date Late Cretaceous thrusting, are Maastrichtian in age. Late Oligocene to Pliocene E-directed folding and thrusting during a third stage primarily affected flysch nappes (Moldavides) and foredeep of the Eastern Carpathians (Morley, 1996; Matenco and Bertotti, 2000). However, the foreland of the South Carpathians, the Getic depression, affected by dextral transtension, followed by dextral transpression (Matenco et al., 1997, 2003), does not represent the continuation of the Moldavide Flysch belt.

The timing constraints provided by the age of post-tectonic cover series (Sandulescu, 1984, 1994) are supported by a very limited amount of isotopic dating (e.g. Grünenfelder et al., 1983; Ratschbacher et al., 1993; Dallmeyer et al., 1994, 1996). Given the relatively low grade of Alpine-age metamorphism (some 350–400 °C were reached only locally and within the Danubian window; Ciulavu et al., 2001, in press) fission track studies, aiming to reveal the cooling and exhumation history of the Getic, Severin and Danubian nappes provide most valuable additional timing constraints. So far, such studies are available from three areas (see Fig. 2).

A combined structural and fission-track analysis of the easternmost Danubian nappes (Paring mountains; Schmid et al., 1998), revealed evidence for the existence of a normal fault (Getic detachment) that reactivated the former basal thrust of the Getic nappes. This locally led to the tectonic omission of the intervening Severin unit above a core complex formed by the Danubian nappes. Normal faulting occurred by top to the ENE pervasive shearing and mylonitisation in deeper tectonic levels, abruptly terminating upwards along a brittle detachment at the base of the Getic nappe. According to these authors the metamorphic core complex outlined by the outcropping area of the easternmost Danubian window (Fig. 1), characterized by anchi- to epizonal metamorphism (Ciulavu et al., in press) formed during Eocene times, obliterating most Cretaceous-age structures. Late Cretaceous top to the SSE (in present-day coordinates) mylonitic shearing is only preserved in a few places.

Fission-track data are also available from a second study (Bojar et al., 1998; see also Nicolescu et al., 1999; Sanders, 1998) in the south-western part of the Danubian window, where klippen of the Getic nappes are preserved (Fig. 1) and grade of metamorphism is lower within the Danubian units (anchizonal conditions were reached only in the eastern part of this area according to Ciulavu et al., in press). Bojar et al. (1998) proposed a first stage of exhumation linked to core complex formation during the Late Cretaceous, i.e. immediately after Laramian nappe stacking and they related a second stage of exhumation to Late Oligocene to Miocene thrusting of the South Carpathians onto the Moesian platform.

A third zircon fission track study (Willingshofer, 2000; Willingshofer et al., 2001) is available for the area of the northern Danubian window (Tarcu-Retezat area, north-west of the Cerna-Jiu fault, see Fig. 1), characterized by roughly the same degree of metamorphism (anchi- to epizonal, Ciulavu et al., in press) found in the easternmost Danubian window. These authors postulated Late Cretaceous to Paleocene age top-NE simple shearing in the context of extensional unroofing of the northern margin of the Danubian window, immediately following the Cretaceous-age top-NE shearing, also postulated by Ratschbacher et al. (1993). Thereby Paleogene cooling in the Danubian window would simply represent a follow on of core complex formation that occurred during Late Cretaceous times.

Two additional fission track studies dealt with detrital grain analyses from two intramontane basins within and north of the Danubian window (Fig. 1): the Hateg (Willingshofer, 2000; Willingshofer et al., 2001) and Petrosan basins (Moser, 2001), respec-

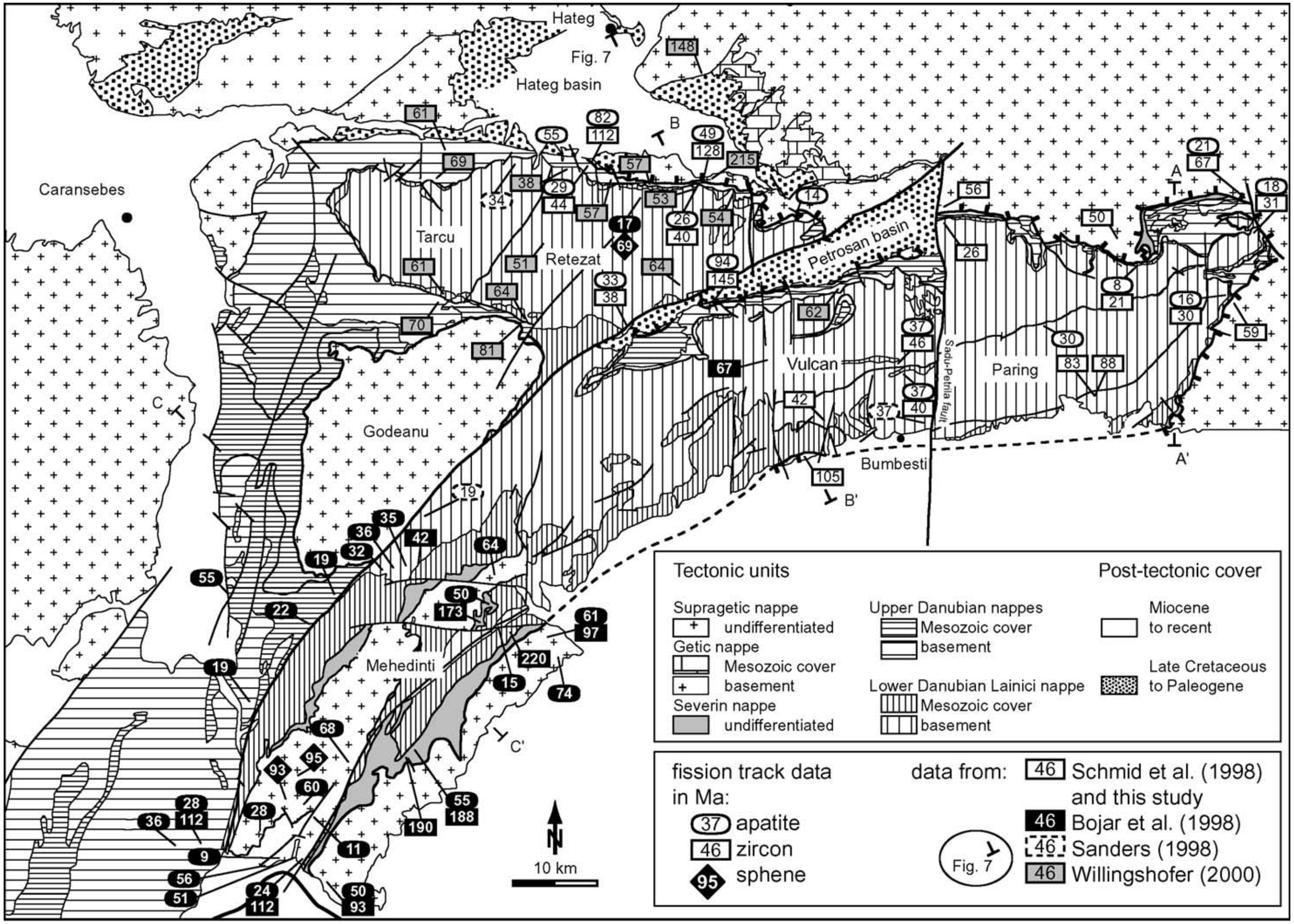

Fig. 2. Simplified structural map of the South Carpathians depicting new zircon and apatite fission track central ages, as well as central ages compiled from the literature. Note, however, that detrital fission track data by Willingshofer et al. (2001) from the Hateg basin and by Moser (2001) from the Petrosan basin are not included in this compilation. Base map is redrawn after Berza et al. in Berza and Iancu (1994).

tively. Willingshofer et al. (2001) even postulated that the Danubian lower plate was exhumed and eroded during the late Maastrichtian adjacent to the Hateg basin, based on the perhaps erroneous assumption (see Berza, 2004 for an alternative view) that the Danubian basement served as a source of detritus for sedimentation during the upper Maastrichtian ("Sinpetru formation"). Indeed, investigations of upper Oligocene to middle Miocene sediments in the Petrosan basin indicate that the Danubian units were not exposed to the earth's surface before the early Miocene (Moser, 2001).

Hence, apparently there are substantial discrepancies concerning the timing of extensional unroofing of the Danubian units (Late Cretaceous vs. Eocene), as well as the kinematics of movement during Late Cretaceous nappe stacking (top-SSE vs. top-NE) While the rather continuous outcrop pattern of the Danubian window makes substantial differences in the age of extensional unroofing of the various subareas rather unlikely, subsequent overprinting by faulting (i.e. along the Cerna fault) may have modified a pre-existing cooling pattern. This contribution will address these problems primarily by the aid of new zircon and apatite fission track data. These will be discussed together with literature and structural data.

3. New results on fission track dating

Seven samples from the Getic and 10 from the Danubian units yielded 10 apatite and 14 zircon ages. Seven samples yielded both zircon and apatite data. Analytical results, obtained by a procedure

Table 1
Fission-track data

Sample	Altitude (m)	*X* coordinate	*Y* coordinate	Number of grains counted	Standard track densities $\times 10^4$ cm^{-2} (counted)	ρs $\times 10^4$ cm^{-2} (counted)	ρi $\times 10^4$ cm^{-2} (counted)	$P(\chi^2)$ %	Age (Ma) ± 1σ
96-16 Z	680	23.44.41	45.12.56	16	17.08 (1292)	1246 (1403)	437.7 (493)	12	83.4 ± 5.7
96-20 A	1150	23.35.39	45.17.56	20	14.80 (2167)	415.4 (297)	3659 (2616)	95	29.9 ± 1.9
97-11 A	1300	23.45.00	45.21.43	11	171.1 (1879)	17.81 (68)	468.7 (1790)	64	7.9 ± 1.0
97-11 Z				16	10.6 (2605)	817.5 (670)	702.8 (576)	97	21.4 ± 1.3
97-13 Z	570	23.40.15	45.13.16	12	10.41 (2605)	1040 (1448)	203.6 (283)	< 5	88.3 ± 8.5
97-17 Z	1900	23.43.23	45.22.40	20	10.22 (2605)	958.0 (915)	337.1 (322)	99	50.3 ± 3.4
97-18 Z	900	23.26.55	45.24.52	20	10.03 (2605)	849.9 (618)	579.0 (421)	93	25.6 ± 1.7
97-20 Z	900	23.27.09	45.25.30	20	14.72 (2282)	811.0 (2124)	371.2 (972)	81	55.7 ± 2.5
97-23 A	800	23.13.14	45.25.21	20	115.5 (1879)	20.05 (187)	289.1 (2697)	75	14.3 ± 1.1
97-24 A	1050	22.56.23	45.16.38	11	99.04 (3089)	128.3 (78)	677.8 (412)	98	33.4 ± 4.2
97-24 Z				7	14.83 (2282)	632.9 (312)	434.1 (214)	58	37.5 ± 3.4
97-25 A	950	23.05.21	45.18.55	20	113.8 (1879)	173.1 (1988)	369.0 (4237)	< 5	94.0 ± 5.0
97-25 Z				9	14.61 (2282)	1219 (1315)	211.4 (228)	81	145 ± 10.8
97-26 A	600	22.49.38	45.29.11	20	112.2 (1879)	207.5 (1718)	763.2 (6320)	< 5	55.4 ± 3.0
97-27 A	700	22.53.49	45.28.06	20	120.2 (2400)	15.34 (242)	114.8 (1812)	95	28.6 ± 2.0
97-27 Z				15	14.49 (2282)	471.7 (593)	269.7 (339)	85	44.0 ± 3.1
97-30 A	700	22.54.35	45.28.19	20	98.72 (3089)	546.3 (1197)	1167 (2556)	80	82.0 ± 3.2
97-30 Z				17	14.38 (2282)	1356 (1253)	299.7 (277)	74	112 ± 7.9
97-31 A	600	23.03.36	45.26.51	20	140.4 (2167)	199.8 (239)	1899 (2271)	82	26.3 ± 1.9
97-31 Z				13	14.26 (2282)	915.6 (1433)	545.0 (853)	7	39.8 ± 2.5
97-33 A	600	23.03.23	45.27.10	15	98.41 (3089)	57.53 (257)	204.6 (914)	81	49.2 ± 3.6
97-33 Z				20	14.15 (2282)	1201 (2065)	228.0 (392)	91	128 ± 7.6
97-34 Z	450	23.15.46	45.12.17	6	14.04 (2282)	455.2 (216)	265.6 (126)	74	41.7 ± 4.8
97-36 Z	400	23.13.46	45.09.21	15	13.92 (2282)	1409 (1268)	321.2 (289)	20	105 ± 8.0

Apatite (A) and zircon (Z) fission-track data. All samples have been treated using the external detector method. First and second column refer to sample number and altitude, respectively. Number of grains counted is given in column 5. Standard, spontaneous (ρs) and induced (ρi) track densities are shown in columns 6, 7 and 8, respectively. Number of counted tracks is given in parenthesis. (χ^2) test (Galbraith, 1981). Zircon ages were calculated with a zeta value of 348 for dosimeter glass SRM612. Apatite ages were calculated with a zeta value of 357 for dosimeter glass CN5. All ages are "Central ages" (Galbraith and Laslett, 1993), errors are quoted as 1σ.

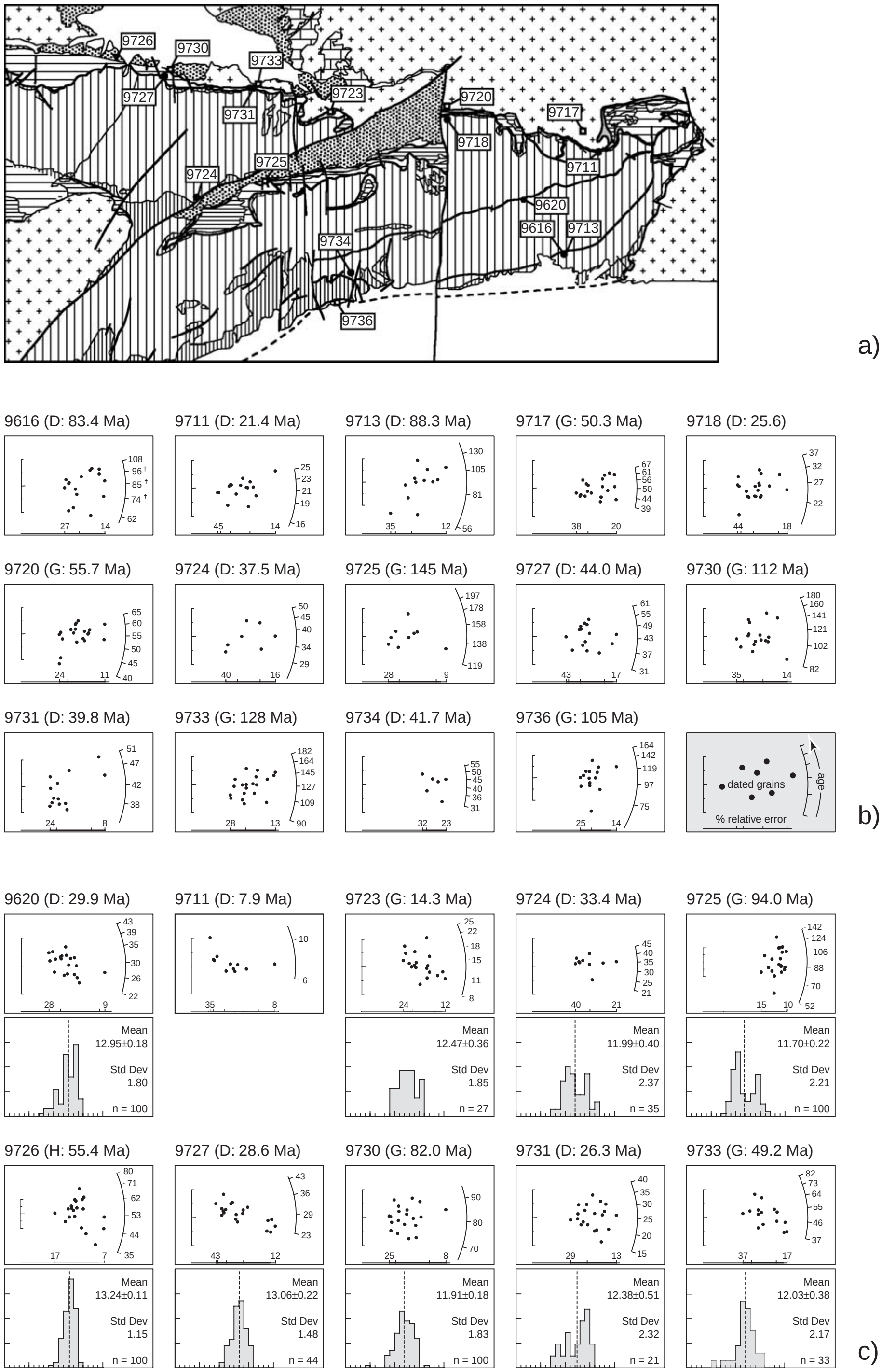

Fig. 3. New fission track data from the South Carpathians. Please note that the same data are also included in Fig. 2. (a) Sample localities (open squares: Getic samples; full squares: Danubian samples). In (b) and (c) provenance (D: Danubian nappes; G: Getic nappe) and central ages are given in brackets behind the specimen number. (b) Radial plots of zircon fission track data. (c) Apatite fission track data in the form of radial plots and with histograms of confined horizontal track lengths.

briefly described in Appendix A, are given in Table 1. Fig. 2 shows a compilation of the available literature data, together with the newly analysed samples. Fig. 3 displays radial plots and track length histograms of the newly analysed samples listed in Table 1.

The sampling strategy was to follow the trace of the Getic detachment further to the west, both along the northern and southern margins of the Danubian window delimited by this normal fault, respectively (Fig. 3a). It was felt necessary to complement earlier published data from the easternmost Danubian window (Schmid et al., 1998) (Fig. 2) in order to test the working hypothesis that this detachment extends westwards for a considerable distance along its southern and south-dipping margin, as well as along its northern and north-dipping margin (adjacent to the Hateg basin; see Fig. 2). The mylonites below the detachment all along these contacts revealed ENE–WSW oriented stretching lineations, indicating that exhumation was indeed top-ENE (and not top-NE as postulated by Ratschbacher et al., 1993; Willingshofer, 2000), provided that these lineations are indeed related to extensional unroofing rather than to Cretaceous nappe stacking. Note that the northern parts of the Danubian window are offset by the Cerna-Jiu fault while the southern margin is locally on-lapped by post-tectonic Neogene sediments of the Getic foredeep (Fig. 2).

Most zircon central ages (Fig. 3b) from the Danubian nappes range between 21.4 and 44 Ma, while two exceptionally old samples yielded 83.4 ± 5.7 (9616) and 88.3 ± 8.5 Ma (9713). These two samples, taken at the same locality in the southern Paring mountains, are also characterized by a low Chi-square probability, contrasting with the generally high $P(\chi^2)$ percentages for the "younger" zircon samples. Hence, these central ages cannot simply be interpreted as cooling ages. Apatite central ages from the Danubian basement range between 7.9 and 33.4 Ma and all these samples pass the Chi-square test. Track length distributions of confined horizontal tracks (Fig. 3c) mainly exhibit a negative skewness and a relatively small range in mean track lengths between 12 and 13.1 μm.

Samples from the Getic nappe yielded a range of zircon central ages between 50.3 and 145 Ma, while apatite ages range between 14.3 and 94 Ma. Track length distributions for the Getic samples are mostly unimodal with mean lengths between 11.9 and 13.2 μm (Fig. 3c). Sample 9725 is clearly bimodal and yielded a mean length of 11.7 μm.

4. Compilation of new results and literature data

All central ages available for the area of the Danubian window are compiled in Fig. 2. Neither Danubian nor Getic samples do display a correlation of age with altitude (Fig. 4a).

Zircon ages vary between 21 and 112 Ma in the Danubian nappes, and between 50 and 215 Ma in the Getic nappes. No apatite ages older than 37 Ma are found in the Danubian nappes, except for one specimen, which yields an age of 55 Ma (Bojar et al., 1998). Note that this specimen was taken from the westernmost part of the Danubian window. This documents a general trend towards relatively younger ages in the Danubian window, as compared to the Getic nappes. This is consistent with considerable age jumps

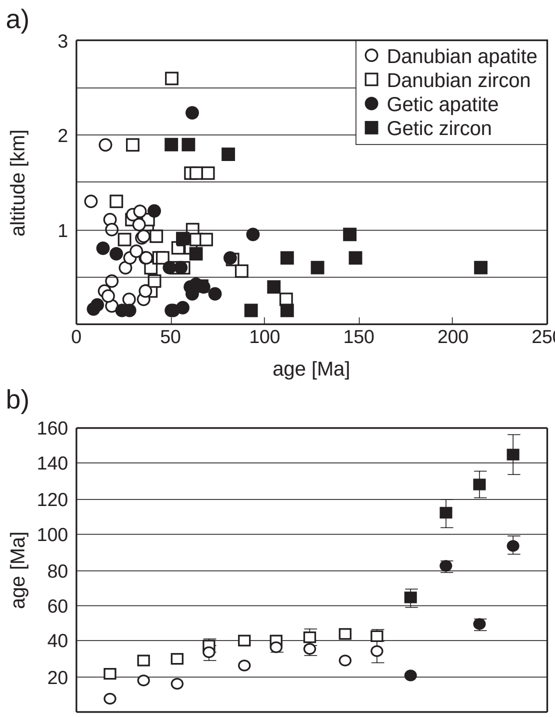

Fig. 4. (a) Age vs. altitude diagram for Danubian and Getic samples, samples and corresponding references are the same as in Fig. 2. (b) Available zircon/apatite pairs for Danubian and Getic samples sorted by ascending zircon ages.

across the Getic detachment, as is frequently observed all along the detachment (see Fig. 2). However, the ranges in zircon and apatite ages measured so far in the area depicted in Fig. 2 exhibit very considerable overlap (Fig. 4a).

The very distinct cooling histories of Getic nappe and Danubian window become more evident by plotting all available zircon–apatite age pairs obtained from one and the same sample (Fig. 4b). The age difference between apatite and zircon ages is systematically larger for the Getic samples, when compared to the samples from the Danubian nappes. Although central ages do not always simply reflect ages of cooling through a given temperature, these systematics clearly indicate very different cooling rates for the two units. These are somewhere between 2 and 5 °C/Ma in case of the Getic nappes, and between 10 and 45 °C/Ma for the Danubian nappes, respectively.

5. Discussion of all available fission track data

The compilation of all available data may be summarised as follows. Firstly, Danubian and Getic units display distinct cooling and exhumation histories. Secondly, different regions of the South Carpathians apparently display major differences concerning their cooling histories. In particular, the tectonic position below or above the Getic detachment (i.e. Danubian vs. Getic) alone does not adequately explain the data. Hence, the significance of the data with respect to their exact geographical position also needs to be discussed.

Three different regional domains roughly coincide with the areas investigated by the various authors (Fig. 2): The Paring and Vulcan mountains in the northeast (Schmid et al., 1998 and this work), the klippen area to the southwest (Bojar et al., 1998) and the Tarcu-Retezat mountains in the northwest (Willingshofer, 2000; Willingshofer et al., 2001 and this work). While the first two areas are located south and southeast of the Cerna-Jiu fault, the latter is located northwest of this important dextral strike-slip fault.

5.1. The eastern part of the Danubian window: Paring and Vulcan mountains

The area of the easternmost Danubian window (Paring mountains) is characterized by the youngest zircon and apatite fission fission-track ages. This holds for the Danubian as well as for the Getic units. In spite of the overall young cooling ages a clear age jump can be observed: zircon cooling-ages differ by about 30 Ma across the tectonic contact between Getic (Late Cretaceous/Paleocene cooling ages) and Danubian units (Oligocene cooling ages). According to previously published structural evidence (Schmid et al., 1998), and based on new structural observations made along the westward continuation of the Getic detachment, this change in cooling ages is interpreted to be related to top to the ENE directed normal faulting across the Getic detachment. This detachment brings the greenschist and subgreenschist facies mylonites derived from the Danubian core complex (Ciulavu et al., in press) in contact with the brittlely deformed Getic unit during Eocene times (Schmid et al., 1998).

The Danubian units further west (Vulcan mountains) exhibit Eocene zircon and apatite fission-track cooling ages, while two Cretaceous zircon ages could be determined for the Getic nappe. With respect to the area of the easternmost Danubian window, both the central ages of Danubian and Getic units, as well as the age jump between zircon and apatite central ages increase. This change occurs across a N–S trending fault, locally known as Sadu-Petrila fault (Berza et al., 1994a). Matenco and Schmid (1999) reported normal faulting along this fault, followed by sinistral reactivation during the Miocene.

Fig. 5a shows zircon fission track data from the Danubian and Getic units, plotted onto an E–W profile across the Sadu-Petrila fault, while Fig. 5b illustrates the present-day geometry of the eastern Danubian window in a simplified block diagram. Isochrones of zircon fission track central ages for the Danubian and Getic units, respectively, assumed to be horizontally oriented, are superimposed onto the block diagram of Fig. 5b. These isochrones were deduced as follows. In a first step, and based on the available zircon/apatite age pairs discussed earlier (Fig. 4b), mean cooling rates of roughly around 15°/Ma and 3°/Ma may be assumed for the Danubian and Getic units, respectively. In a second step, these estimates were converted into the depth distributions of zircon fission track ages expected after cessation of movements along the Getic detachment. This simple construction shows

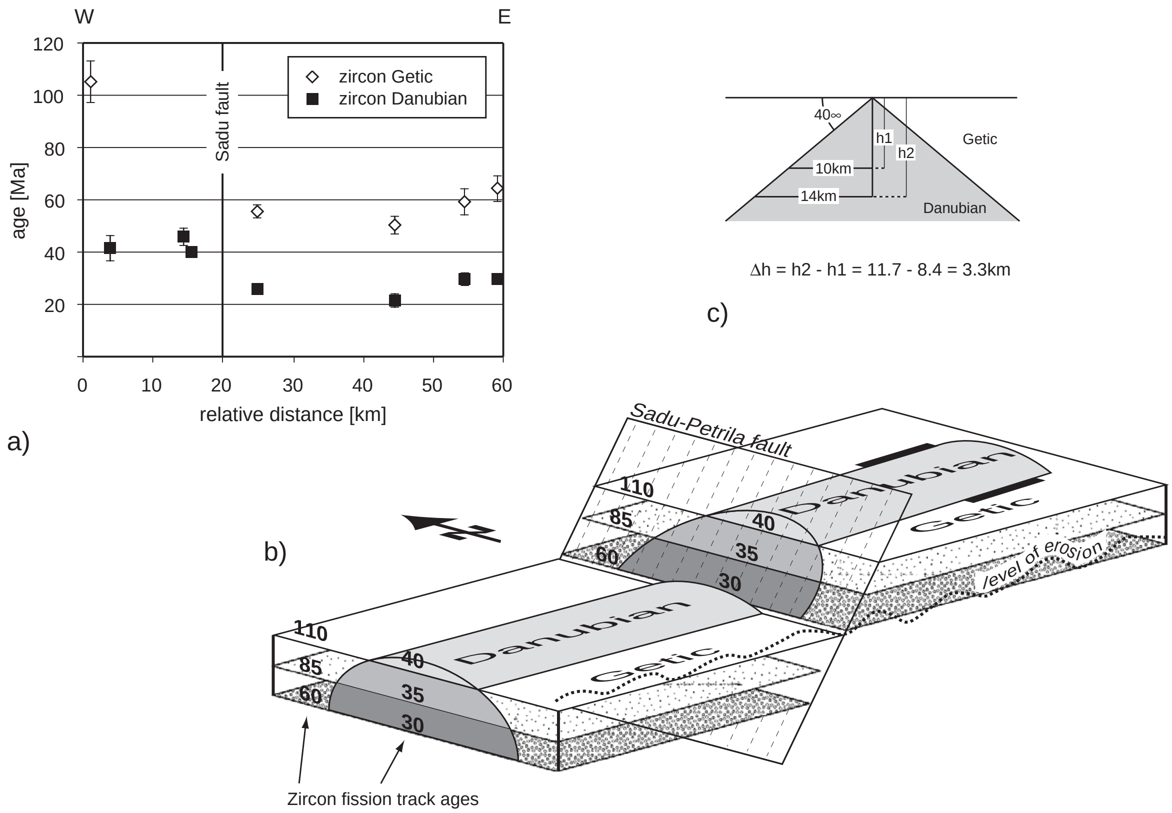

Fig. 5. (a) Zircon and apatite fission track data along an E–W trending section through the Sadu-Petrila fault. (b) Schematic block diagram illustrating the zircon fission track isochrones of the Danubian and Getic unit to either side of the Sadu-Petrila fault. (c) Geometric construction to illustrate the calculation of the vertical offset along the Sadu-Petrila fault using the different outcrop widths of 10 and 14 km, respectively.

that, east of the Sadu-Petrila fault, the present level of erosion exposes the 60 Ma isochrone for the Getic unit, and the 30 Ma isochrone for the Danubian window, respectively. West of this fault, on the other hand, the 110 Ma (Getic) and 40 Ma (Danubian) zircon cooling age isochrones are presently exposed at the earth's surface. Based on the simplified assumptions discussed above, and assuming the activity along the Sadu-Petrila fault to post-date the cooling ages (i.e. post-dating 20 Ma), a vertical offset on the order of 5 km can be estimated for this fault. The amount of vertical displacement can be independently estimated by geometrical considerations. As seen from Fig. 2 the width of the Danubian window differs east and west of the Sadu-Petrila fault, when looked at in map view. To the east, the width of the Danubian antiform is on the order of 28 km (e.g. Balintoni et al., 1994; Berza et al., 1994b), while only 20 km are exposed to the west. Given the average dip angle of 40° for the tectonic contact between the Getic and the Danubian units (Berza et al., 1994b) a vertical offset of 3.3 km is calculated for the Sadu-Petrila fault according to the construction illustrated in Fig. 5c.

Keeping the considerable uncertainties in mind, the western compartment of the Sadu-Petrila fault must have been downthrown by 3 to 5 km with respect to the eastern compartment. This normal faulting affected the previously formed antiform of the Danubian core and, assuming the above interpretation to be correct, did offset zircon and apatite fission track isochrones in both tectonic units (i.e. Getic and Danubian). This is compatible with the estimated age of activity along this fault (post-Early Burdigalian according to Matenco and Schmid, 1999).

5.2. The south-western part of the Danubian window: Mehedinti Klippen area

Bojar et al. (1998) studied this region in great detail. Interpreting numerous fission track data on sphene, zircon and apatite these authors conclude that the Getic and Danubian basement units were exhumed in two stages, i.e. during the Late Cretaceous and the Late Oligocene/Early Miocene, respectively. In comparison with two other profiles situated further to the east (Fig. 6a and b) the profile through this area (Fig. 6c) exhibits the same characteristics. All data plotted along the profile of Fig. 6c, taken from Bojar et al. (1998), confirm the distinct cooling histories deduced above for the Getic and the Danubian units, respectively. The Danubian core is again characterized by Eocene to Oligocene zircon and apatite fission track ages. The short time interval between cooling through the zircon partial annealing zone and the apatite partial annealing zone again asks

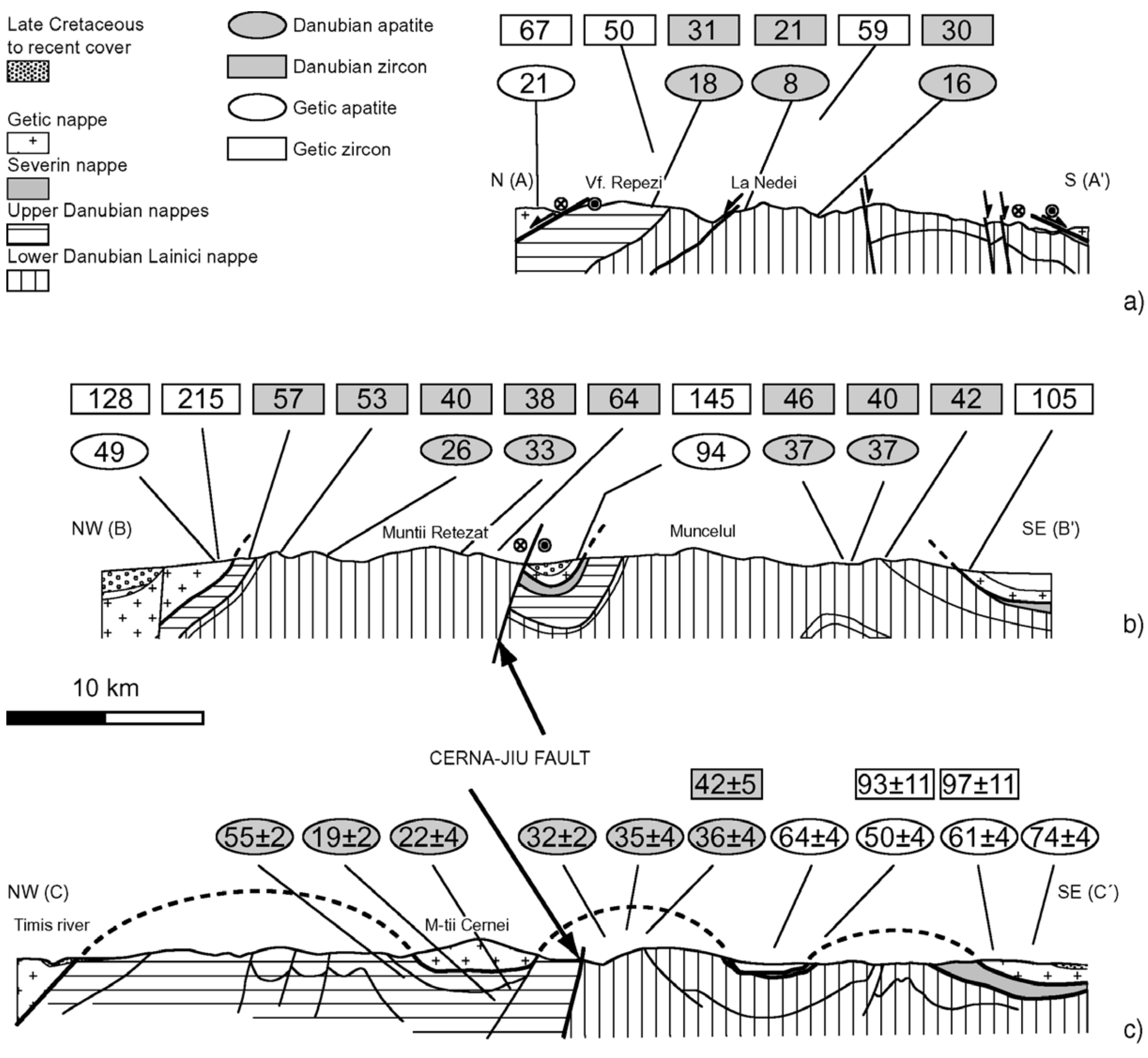

Fig. 6. Zircon and apatite fission track data along schematic cross sections through the Danubian window; trace of profiles indicated in Fig. 2. (a) Cross section redrawn after Schmid et al. (1998). (b) Redrawn after Stefanescu et al. (1988). Please note that data from the Hateg basin are not included. (c) Redrawn after Geological map of Romania 1:200000, sheet 32.

for enhanced cooling of the Danubian units during the late Eocene. Note, however, that the southwesternmost parts of the Mehedinti Klippen area exhibit a very low grade of metamorphism only (anchizone according to Ciulavu et al., in press). This, together with an exceptionally old apatite central age of 55 Ma from the westernmost Danubian window (Bojar et al., 1998), indicates that Eocene-age exhumation is considerably less in the Mehedinti Klippen area, situated at the south-western margin of the Tertiary-age Danubian core complex.

We conclude that fission track data from both areas within the Danubian window located south of the Cerna-Jiu fault, with the exception of the southwesternmost Mehedinti Klippen area, indicate enhanced cooling in the late Eocene. Hence, Mid-Tertiary Danubian core complex formation postulated for the eastern Danubian window (Schmid et al., 1998) did also affect most of the Mehedinti Klippen area.

5.3. The northern part of the Danubian window: Tarcu-Retezat Mountains

Fission-track data from this area (Willingshofer, 2000; Willingshofer et al., 2001; Bojar et al., 1998; Sanders, 1998), located north and northwest of the Cerna-Jiu fault, were complemented by new data (Fig. 2 and Table 1). The available zircon fission track data (Willingshofer, 2000 and this study) display a large range of zircon fission track central ages bracketed between 70 and 38 Ma (Fig. 2 and northern part of Fig. 6b). Radial plots of zircon fission track data, (Figs. 3b and 7a, b and c) reveal that only those samples which yielded relatively young central ages display a small scatter in single grain ages. Samples yielding older central ages, however, exhibit considerable scatter in single grain ages, as is also expressed by a higher dispersion. According to the oldest single grain ages, slow cooling must locally have started in the Late Cretaceous (i.e. around 90 Ma) in this northern part of the Danubian window.

This Late Cretaceous cooling is in line with the early stages of the evolution of the neighbouring Hateg basin, where Late Cretaceous sediments were deposited unconformably over a reduced thickness of a previously eroded part of the Getic nappe (Fig. 6b). According to Willingshofer et al. (2001) the Hateg basin represents a Late Cretaceous piggyback basin during Late Cretaceous thrusting. This first stage of the evolution of the Hateg basin ends with a drastic facies change and with the arrival of course detritus during the Late Maastrichtian to Early Paleocene (Sinpetru formation; Willingshofer et al., 2001).

The large portion of rather old central ages, together with the large spread in single grain ages observed in the specimens (Fig. 7b and c) indicates that cooling, as recorded by the zircon fission track data, started much earlier than in the rest of the Danubian window. However, this initial phase of cooling was rather slow, as can be inferred from the large spread in single grain ages in a great part of the samples (Fig. 7b and c). As noted by Willingshofer (2000), there is a weak tendency of samples originating from the Upper Danubian nappes towards relatively older ages, when compared to samples from the Lower Danubian nappes (compare Fig. 7b and c, respectively). We also agree with this author that thermal overprint in the Danubian units originally exceeded the upper temperature limit of the zircon partial annealing zone (about 300 °C after Tagami et al., 1998).

Willingshofer (2000) interpreted the youngest age of 38 Ma (i.e. the sample with the lowest dispersion, Fig. 7a) to be of local significance only and concluded, that the major phase of exhumation occurred during the late Cretaceous to Paleocene. However, we do not regard the older central ages to be meaningful in terms of ages of rapid cooling because of the large scatter in single grain ages. Moreover, the youngest single grains in all samples are (middle) Eocene in age, irrespective of central age and tectonic position (Upper or Lower Danubian nappes). This, together with the samples indicating rapid cooling (e.g. HA 16 in Fig. 7), indicates that enhanced cooling rates started during the Eocene also in this part of the Danubian window.

Based on all available data from this area, the large spread of zircon fission track ages recorded in the Danubian units north of the Cerna-Jiu fault is best interpreted in terms of overall slow cooling during the Late Cretaceous to early Tertiary. However, the data do not provide direct evidence for a phase of enhanced exhumation of the Danubian window due to extensional unroofing during the Maastrichtian to early Paleocene, as postulated by Willingshofer et al. (2001). Instead we propose that the cooling history

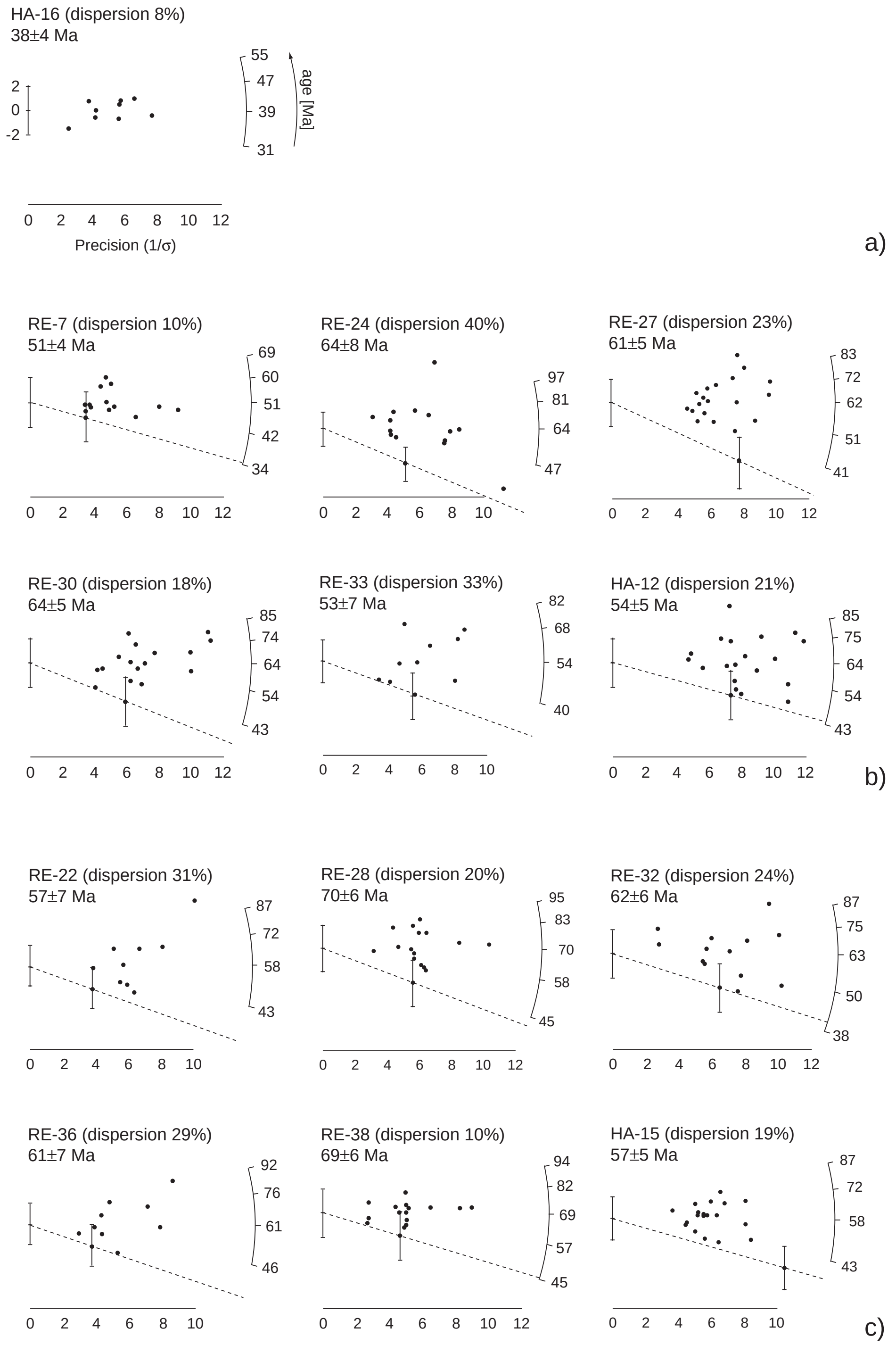

Fig. 7. Radial plots of zircon fission track data from the Tarcu-Retezat mountains, all data are from Willingshofer (2000). (a) Sample HA 16, displaying a very small spread in single grain ages (dispersion 8%) and yielding the youngest central age of 38 Ma. Notation of radial plot axes given in (a). (b) Samples from lower Danubian nappes. (c) Samples from upper Danubian nappes. Stippled lines in (b) and (c) indicate youngest single grains.

of the northern Danubian units (Tarcu-Retezat Mountains) is similar, although not identical, to that of the other parts of this window. The cooling ages given in Figs. 3b and 7a, as well as the youngest single grain ages given in Fig. 7b and c, document a phase of enhanced unroofing due to tectonic exhumation starting in the Eocene.

The few apatite fission track data available from the northern Danubian units yielded Oligocene cooling ages. Hence, based on all available fission track ages, it is proposed that a phase of enhanced cooling of the Danubian units during the Eocene to Oligocene did also occur in this part of the Danubian window. This conclusion is supported by structural observations, which indicate that the Getic detachment, responsible for fast exhumation and cooling, can be followed westwards all along the northern rim of the Danubian window into the area north of the Tarcu Mountains. Also in this area, analogous to the observations made in the Paring mountains (Schmid et al., 1998), the lineations and associated senses of shearing recorded within a mylonitic belt indicate top-ENE shearing along this E–W-striking part of the Getic detachment, offset by the Cerna-Jiu fault (Fig. 2). Hence, top-ENE shearing is related to Eocene-age core complex formation, while Late Cretaceous nappe stacking was top-SSE, as postulated by Schmid et al. (1998), and not top-ENE as reported by Ratschbacher et al. (1993) and Willingshofer (2000). In summary, there is evidence that slow cooling by erosional unroofing started during the Late Cretaceous. By late Maastrichtian times parts of the Danubian units were already exhumed in the northern Danubian window (Willingshofer et al., 2001; Moser, 2001). Exhumation by tectonic unroofing started at around 40 Ma, and in the context of top-ENE tectonic exhumation along the Getic detachment. This led to mid-Tertiary core complex formation in the Danubian units to both sides of the Cerna-Jiu fault. However, the cooling history of this northern part of the Danubian window differs from that of the rest of the Danubian units situated south of the Cerna-Jiu fault in that slow cooling commenced earlier and in the context of Late Cretaceous to early Tertiary exhumation, probably by erosion. Hence, at the onset of Late Eocene to Oligocene core complex formation, shallower crustal levels were exposed in this area as compared to the eastern and southwestern parts of the Danubian window.

5.4. The role of the Cerna-Jiu fault during exhumation of the Danubian window

The Cerna-Jiu fault system (Berza and Draganescu, 1988) is the most prominent structural feature that separates the two parts of the Danubian window characterized by a slightly different cooling history, as was described above. The most important component of displacement across this fault system is dextral strike-slip by some 35 km (Berza and Draganescu, 1988; Ratschbacher et al., 1993; Moser, 2001). The formation of the Oligocene to lower Miocene Petrosan basin (e.g. Pop, 1993), interpreted to be directly related to this dextral strike-slip motion (Ratschbacher et al., 1993; Moser, 2001), dates its activity to have taken place in Oligocene to Early Miocene times.

Although the Cerna-Jiu fault system offsets the Getic detachment, a direct link between dextral strike-slip motion along the Cerna-Jiu fault and the very latest stages of core complex formation in the Danubian units is likely, because the age of deposition of the oldest strata in the Petrosan basin (Rupelian) is still within the range of the apatite fission track cooling ages in the area. The Chattian strata in the Petrosan basin discordantly overlie thin slivers of the Getic nappe (Fig. 6b). The detrital apatite fission track ages obtained from this basin indicate a Getic source area, with no evident input from Danubian units (Moser, 2001). All this indicates that dextral strike-slip movements along the Cerna-Jiu fault, and associated formation of the Petrosan basin, commenced during the latest stages of extensional unroofing of the Danubian window but significantly outlasted it, as is evident from the dextral offset of the Getic detachment by some 35 km (Figs. 1 and 2).

6. Summary of the exhumation history of the Danubian units in the South Carpathians

An early stage of exhumation of the northern parts of the Danubian window, presently located north of the Cerna-Jiu fault, starts during Late Cretaceous nappe stacking. However, this first stage of exhumation and cooling was by erosional denudation rather than by extensional unroofing. Exhumation north of the Cerna-Jiu fault is also synchronous with sedimentation in the Hateg piggyback basin, positioned within the Getic nappe immediately north of the Danubian window (Fig. 8). Due to the overthrusting by the Getic nappes towards the SSE (in present-day orientation) the underlying northernmost parts of the Danubian window were subjected to medium grade metamorphic overprint. According to Ciulavu et al. (2001, in press) an increase in metamorphism from anchizonal conditions in the south to epizonal conditions (about 350° to 400 °C, 3.5 kb) in the north can be observed on either side of the Cerna-Jiu fault.

The fact that this first stage of cooling is only observed north of the Cerna-Jiu fault is best explained by internal top-SSE thrusting (in present-day coordinates) within the Danubian units that consist of several nappes (Fig. 8). Unroofing of the northernmost Danubian units (Tarcu-Retezat area) was associated with slow cooling rates (in the order of 2–5°/Ma based on the zircon–apatite age pairs from the Getic units, see Fig. 4) during the Late Cretaceous. Late Cretaceous thrusting ceased by Maastrichtian times, as is also documented by the overstepping of the Danubian–Getic nappe stack by "Late Senonian" to Paleogene sediments in the Getic foredeep (Fig. 8 and Stefanescu et al., 1988). The Danubian nappes in the Paring–Vulcan area south of the Cerna-Jiu fault, and situated deeper below the Late "Senonian" unconformity, however, remained close to peak metamorphic conditions until the onset of tectonically induced exhumation by a second stage of cooling, related to Eocene–Oligocene core complex formation and activity of the Getic detachment (Schmid et al., 1998).

In summary, it appears that the northern parts of the Danubian window adjacent to the Hateg basin had already cooled to temperatures within the zircon partial annealing zone before Eocene core complex formation. Meanwhile, temperatures still allowed for "instantaneous" annealing of fission tracks in zircon further south (Paring–Vulcan mountains). According to the kinematic reconstruction discussed in Schmid et al. (1998) this first stage of Cretaceous to Paleocene exhumation pre-dating core complex formation took place far from the present-day position of the Danubian window, as is sketched in Fig. 9a.

The second stage of exhumation started in the Eocene with tangential stretching and tectonically controlled exhumation of the Danubian core (Fig. 9d). Structurally, this phase of rapid cooling (around 15°/Ma) finds its expression in a continuous evolution from mylonitic deformation under greenschist facies conditions to cataclastic faulting along the Getic detachment (Schmid et al., 1998). Fission track data from all parts of the Danubian basement well constrain the timing of the main period of core complex formation as Late Eocene. Core complex formation was primarily associated with very prominent SW–NE stretching (Fig. 9d), accompanied by minor orogen-perpendicular shortening. Hence, the large-scale antiformal structure of the Danubian window (Fig. 8) is the result of Eocene to Early Oligocene core complex formation, rather than that of Miocene-age thrusting onto the Getic foredeep. There shortening during the Miocene is very minor (Fig. 8). This is in contrast to

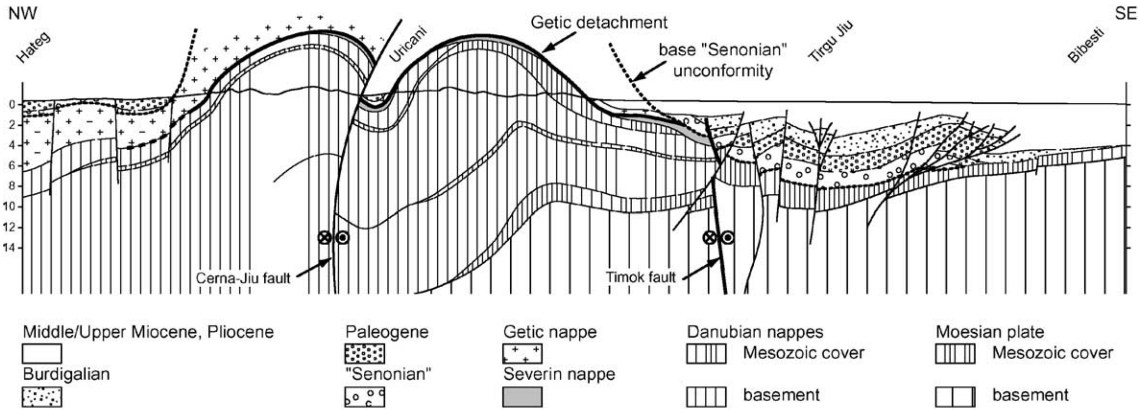

Fig. 8. Synthetic profile through South Carpathians and Getic depression. Surface-near geology redrawn after Stefanescu et al. (1988) and Matenco et al. (1997). The trace of the profile, indicated in Fig. 2, includes that of Fig. 6b.

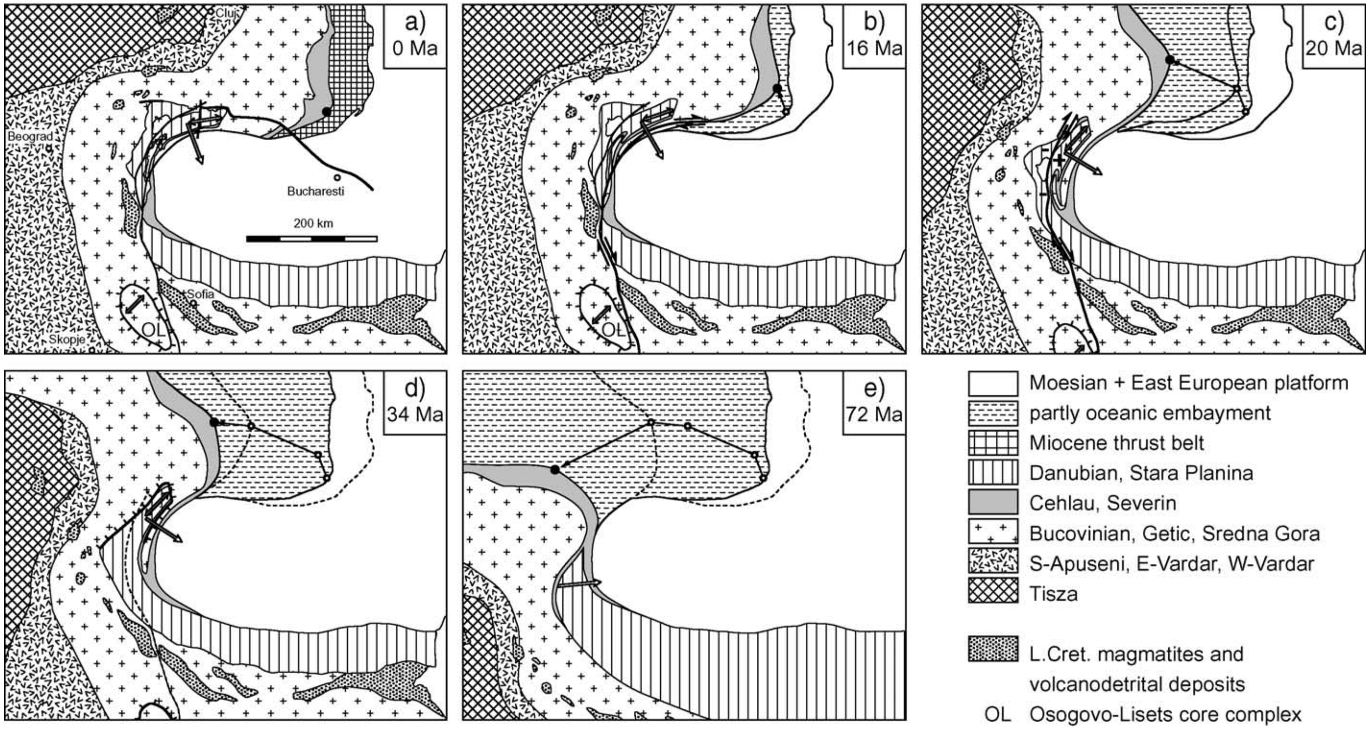

Fig. 9. Step-wise retro-deformation of oroclinal bending in the South Carpathian–Balkan mountain system in order to depict the situation during (d) and before (e) core complex formation in the South Carpathians. The white arrows indicate the orientations of Late Cretaceous thrusting (single arrow) and Eocene extension (double arrow), respectively. Present-day exposures of late Cretaceous magmatites and volcanodetrital deposits ("banatites") are also shown (a). Note that they align along a straight NW–SE trending corridor after retro-deformation. (a) Present-day situation (after Sandulescu et al., 1978; Berza and Iancu, 1994; Kräutner and Krstic, 2003). (b) Middle Miocene: retro-deformation of 12 km dextral strike slip movement along the Intra-Moesian fault, associated with normal faulting across the Sadu-Petrila normal fault, and additionally, Sarmatian-age top-SSE thrusting along the Getic foredeep (Matenco et al., 1997, 2003), assumed to have increased from 0 to 40 km, from W to E, respectively, resulting in a 9° counter-clockwise retro-rotation of the area around the Danubian window. (c) Lower Miocene: retro-deformation of 65 km dextral strike-slip along the curved northern segment of the Timok fault (after Moser, 2001; Kräutner and Krstic, 2003), amounting to 29° counter-clockwise retro-rotation of the Danubian window; areas labelled with a (+) sign were exhumed relative to areas labelled (−) as a result of dextral movement along the Cerna-Jiu fault. (d) Situation during core complex formation at the end of the Eocene; note that the original stretching direction was NE–SW-oriented, i.e. parallel to the stretch presently observed in the Osogovo-Lisets core complex further to the south and assumed to not have undergone rotation (Kounov et al., 2004): retro-deformation of 35 km dextral strike-slip along the curved Cerna-Jiu fault (after Berza and Draganescu, 1988), amounting to 13° counter-clockwise retro-rotation of the area N of the Cerna-Jiu fault. (e) Situation at the end of Late Cretaceous thrusting which originally was top-ENE (top SSE in present-day coordinates): further counter-clockwise retro-rotation of the Late Cretaceous nappe stack by 39°, such as to allow for a total of 90° clockwise rotation, indicated by paleomagnetic data for the area of the Tisza-Dacia block situated north of the Cerna-Jiu fault (i.e. Balla, 1987; Patrascu et al., 1994). Note, however, that much of this 90° rotation, generally reported to entirely be of Miocene age, pre-dates the Miocene according to our reconstruction.

the East Carpathians, as was emphasised by Matenco et al. (1997, 2003).

The onset of late Early Oligocene dextral strike-slip movements along the curved Cerna-Jiu fault coincides with the transition into a third stage of the exhumation history (Fig. 9c). Enhanced exhumation ceased on the convex side of this fault, i.e. in the northernmost Danubian window (Tarcu-Retezat mountains). In the areas located on the concave side of the Cerna-Jiu fault (Paring–Vulcan mountains and Mehedinti Klippen area), however, tectonic unroofing continued. We interpret this distinct evolution of two parts of the Danubian window to be induced by the curvature of the Cerna-Jiu fault. As demonstrated by Schultz and Aydin (1990) the mean stress is reduced along the convex side of a curved fault but increased along the concave side. Applied to the Cerna-Jiu fault this induces subsidence in the Tarcu-Retezat area and uplift in the southerly adjacent Paring–Vulcan mountains (Fig. 9c). Ratschbacher et al. (1993) already proposed that the Petrosan basin formed in this way. According to the youngest presently exposed zircon fission track ages rapid exhumation by extension ended by late Oligocene times, when most of the 35 km dextral offset along the Cerna-Jiu fault, that offsets the Getic detachment, occurred. Post 20-Ma normal faulting along the Sadu-Petrila fault (Fig. 5) terminates orogen-parallel extension, as well as dextral strike-slip motion along the Cerna-Jiu fault.

In the Middle Miocene (Fig. 9b) the stress field changed to transpression affecting both South Carpathians and the Getic foredeep (Ratschbacher et al., 1993; Matenco and Schmid, 1999). This led to a change back to slow and erosion-controlled cooling during a fourth stage associated with very minor exhumation and recorded by few apatite central ages only. However, this period of dextral transpression that leads to the reactivation of Paleogene normal faults in the Getic foredeep (Matenco et al., 1997; Matenco and Schmid, 1999), must have been associated with very substantial strike-slip movements along another curved fault, outcropping in Bulgaria and eastern Serbia, the Timok fault (Moser, 2001; Kräutner and Krstic, 2003), as will be discussed below.

A final stage of the tectonic evolution during Sarmatian to Late Pliocene times led to the present-day situation (Fig. 9a). It was associated with dextral strike-slip faulting across the South Carpathians (Ratschbacher et al., 1993; Matenco and Schmid, 1999), and probably, with normal faulting across the Sadu-Petrila fault.

7. Discussion

We now discuss a series of questions, raised by the interpretation based on the available fission track and structural data presented above.

Firstly, the question arises as to weather the curved geometry of the Getic detachment in profile view (Fig. 8) is directly linked to core complex formation, being induced by minor amounts of orogen-perpendicular shortening that would be contemporaneous with orogen-parallel stretching (see discussion in Mancktelow, 1992) during Eocene to Early Miocene times. Alternatively, this folding could also be interpreted as a passive one, the antiformal Danubian dome representing a ramp fold related to Miocene thrusting onto the Getic foredeep, post-dating core-complex formation. Since the data demonstrate normal faulting to also have occurred across the S-dipping parts of the Getic detachment, and because this detachment reactivates a former thrust with an original dip to the north (in present-day coordinates), the reorientation of this Late Cretaceous top-S thrust must have taken place during core complex formation, as was argued by Matenco and Schmid (1999), and contemporaneous with very moderate amounts of orogen-perpendicular compression (Fig. 8).

The second question concerns the spatial extent of core complex formation and the amount of associated stretching. Our interpretation of the available data indicates that the Getic detachment can be followed as far east as the Hateg basin along its north-dipping branch and almost all the way to the Danube river along its south-dipping branch (Fig. 1). After retro-deforming early Oligocene to Miocene deformations, particularly the displacements along the Cerna-Jiu and Timok curved faults amounting to a total of 100 km (Fig. 9a,b,c), this core complex appears as a fairly narrow (some 30 km) and elongate (some 140 km) extensional corridor (Fig. 9d). The original stretching direction was SW–NE-oriented, as is the case for the present-day orientation of another core complex situated in Western Bulgaria (the Osogovo-Lisets core complex, Kounov et al., 2004). The exact amount of orogen-parallel extension remains unknown due to the poorly constrained geometry of the asymmetrical detachment in an orogen-parallel section. A horizontal stretch between 10 and 20 km is calculated when assuming a dip of the originally NE-dipping master-detachment between 45° and 27°, respectively, and 10 km omission (allowing for rapid cooling from peak metamorphic temperatures of around 300 °C). This by far exceeds the contemporaneous orogen-perpendicular shortening which results in a curved geometry of the Getic detachment in profile view perpendicular to the stretching direction (Fig. 8).

This immediately leads to the question after the significance of core complex formation in the South Carpathians. Obviously, local extension affected a relatively narrow corridor within the Tisza-Dacia block, situated immediately adjacent to the Moesian platform (Fig. 9d). According to our reconstruction this extension occurred during an intermediate stage of the long-lasting invasion of the Tisza-Dacia block into the Carpathian embayment and around the curved Moesian corner (Fig. 9), that started after the deposition of the "post-orogenic" deposits in the Latest Cretaceous (Fig. 9e) and which terminated by the Late Miocene to recent top-SSE thrusting in the bend-area north of Bucarest (Fig. 9a). The kinematic restoration proposed in Fig. 9 suggests that this invasion is associated with oroclinal bending of a pre-existing nappe stack of Late Cretaceous age, associated with dextral strike-slip faulting that results in core complex formation (Danubian window) and/or transtension (Petrosan basin) during the Late Eocene to Earliest Miocene, followed by transpression in the Getic foredeep from the Miocene (Late Burdigalian) onwards, as previously postulated by Matenco et al. (2003).

Exact cause and mechanism of core complex formation in the Danubian window still remain enigmatic to some extent. However, orogen-perpendicular extension by gravitational collapse during accretion or during the final stages of convergence certainly does not apply in the case of the Danubian window since extension clearly is orogen-perpendicular and directly linked to, and contemporaneous with, orogen-perpendicular shortening. However lateral extrusion within a channel bound by strike-slip faults (Ratschbacher et al., 1991) does not apply either since no such strike-slip is documented for the northern margin of the Danubian window (except for the Late Miocene stage indicated in Fig. 9a). Arc-parallel stretch during oroclinal bending, e.g. in front of an indenter (Marshak, 1988; Zweigel et al., 1998), or in our case, adjacent the circular-shaped western corner of the rigid Moesian block (Ratschbacher et al., 1993; Fig. 9) may lead to orogen-parallel stretching. However, at first sight it is hard to understand why this stretch did primarily occur along the inner arc of the Carpathians–Balkan Mountains orocline. Note however, that according to our reconstruction in Fig. 9 the curved northern segments of the Timok and Cerna-Jiu faults are kinematically linked to a straight and NNW–SSE striking system of dextral strike-slip faulting along the southern extension of the Timok fault and its probable continuation further south and into northern Greece (Strymon fault system, Ricou et al., 1998).

Hence it appears that the former western extension of the Late Cretaceous nappe stack of northern Bulgaria (Stara Planina and Sredna Gora, corresponding to the Danubian and Getic nappes of southern Romania, respectively, see Fig. 9a), after having moved past the western tip of the Moesian corner by dextral strike-slip (Fig. 9e) was affected by stretching and pene-contemporaneous dextral strike-slip along a precursor of the Timok fault. This extension of the innermost part of the non-rigid Tisza-Dacia "block" occurred as this "block" was about to invade the Carpathian embayment (Fig. 9d), and it was followed by the sequential development of strike-slip faulting along the Timok and Cerna-Jiu faults (Fig. 9c,b). We speculate that two driving forces are responsible for extension of the Late Cretaceous orogen and associated dextral strike-slip faulting along the curved Timok and Cerna-Jiu faults: Firstly NNW-directed push of the Adriatic promontory, delimited by NW–SE-striking systems of dextral strike-slip faulting at its eastern edge, i.e. along the southern Timok and Strymon strike-slip system (and along the Vardar strike-slip zone further to the west; Morley, 1996), and secondly, by the east-directed gravitational forces exerted by slab retreat of a partially oceanic slab that occupied the former Carpathian embayment (e.g. Balla, 1987; Wortel and Spakman, 2000).

8. Conclusions

We conclude that

1. All available fission track data consistently indicate that the change to fast cooling associated with tectonic denudation by core complex formation did not occur before Late Eocene times, i.e. long after the cessation of Laramide thrusting during the Campanian to Maastrichtian.
2. Single grain age distributions yield reliable information regarding the timing of rapid cooling and exhumation in an area characterized by a large scatter of fission track central ages. Zircon samples from the Tarcu-Retezat area started to cool from peak temperatures situated near the upper temperature bound of the annealing window (Tagami et al., 1998). Cooling occurred in two stages, i.e. during the Late Cretaceous due to erosional denudation and during the Late Eocene to Oligocene due to extensional unroofing.
3. Arc-parallel stretch during oroclinal bending in front of the western edge of the rigid Moesian block led to local orogen-parallel stretching in the inner arc of the Carpathian–Balkan Mountains orocline, as the Tisza-Dacia block was about to invade the Carpathian embayment.
4. Translation and clockwise rotation of the Tisza-Dacia "block" occurred in a complex pattern of strain partitioning in space and time that led to core complex formation and was associated with transtension, followed by transpression along curved strike-slip faults with a total offset of some 100 km. This invasion of the southernmost parts of the Tisza-Dacia "block" started before the Late Eocene, i.e. significantly before the onset of roll-back and associated extension in the Pannonian basin, and the contemporaneous invasion of the ALCAPA "block", reported to have started at around 20 Ma, i.e. during the Lower to Middle Miocene (Balla, 1987; Royden and Horvath, 1988).
5. The combined effects of E-directed gravitationally induced roll-back of the Carpathian embayment, combined with the NNW-directed plate movement of the Adriatic promontory led to the relative displacement and rotation of the South Carpathians from a southern position around the Moesian corner into their present position as proposed by, e.g. Burchfiel (1980), Balla (1987) and Royden (1988) and supported by paleomagnetic data (Balla, 1987; Patrascu et al., 1994).

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Appendix A. Technique used

After conventional mineral separation (crushing, sieving, magnetic and heavy liquid separation) samples were mounted in epoxy resin (apatite) and PFA® Teflon (zircon), respectively. Revelation of fossil tracks was achieved by etching polished zircon mounts in a NaOH-KOH eutectic melt at 210 °C. Apatite mounts were etched in 5 N HNO_3 at 20 °C for 20 s. Induced tracks in external detector muscovites were etched in 40% HF for 45 min at 20 °C. Irradiation of both, zircon and apatite, was carried out at the HIFAR reactor in Australia. Neutron flux was monitored using CN5 and SRM 612 dosimeter glasses. Fission tracks were counted at 1250× (apatite) and 1600× (zircon) magnification in crystallographic prism faces. Track lengths of horizontal confined tracks in apatite were measured at 1250× magnification. All samples have been analysed using the external detector method as described by Gleadow (1981). Ages were calculated using the zeta calibration method (Hurford and Green, 1983) with a zeta factor of 348 ± 9 (zircon, SRM 612 glass) and 357 ± 15 (apatite, CN 5 glass).

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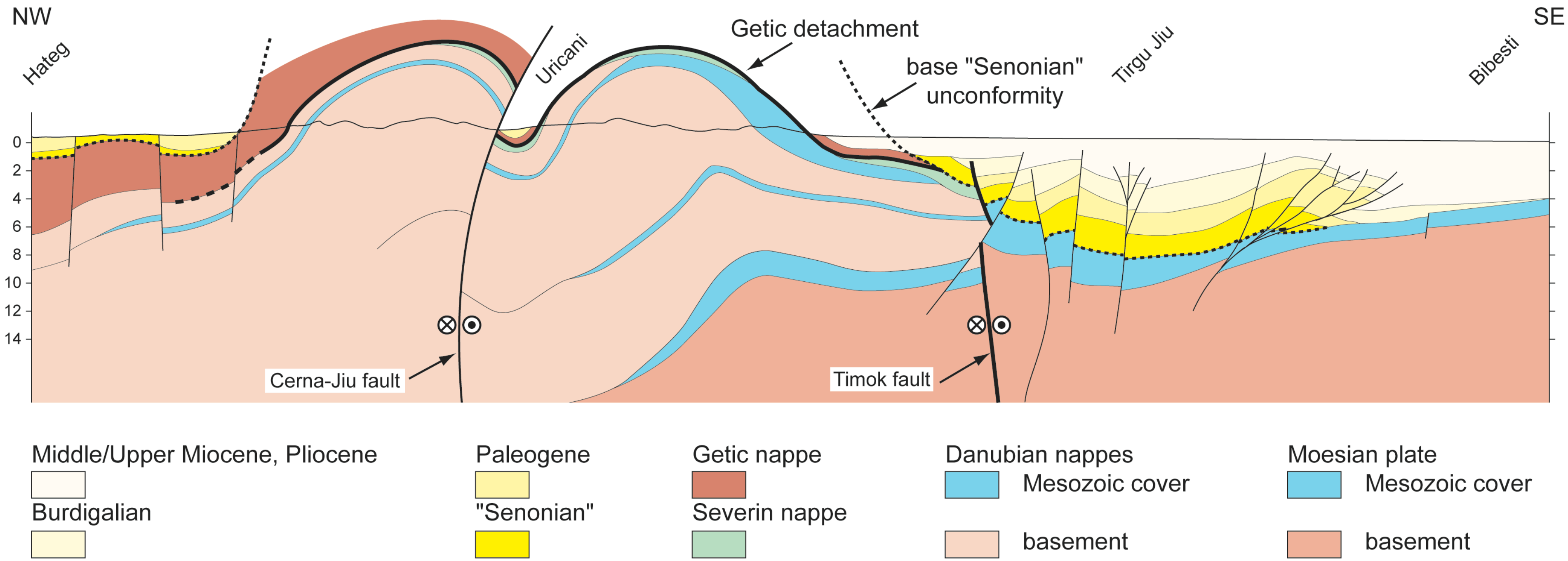
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Timok fault
Middle/Upper Miocene, Pliocene
Burdigalian
Paleogene
"Senonian"
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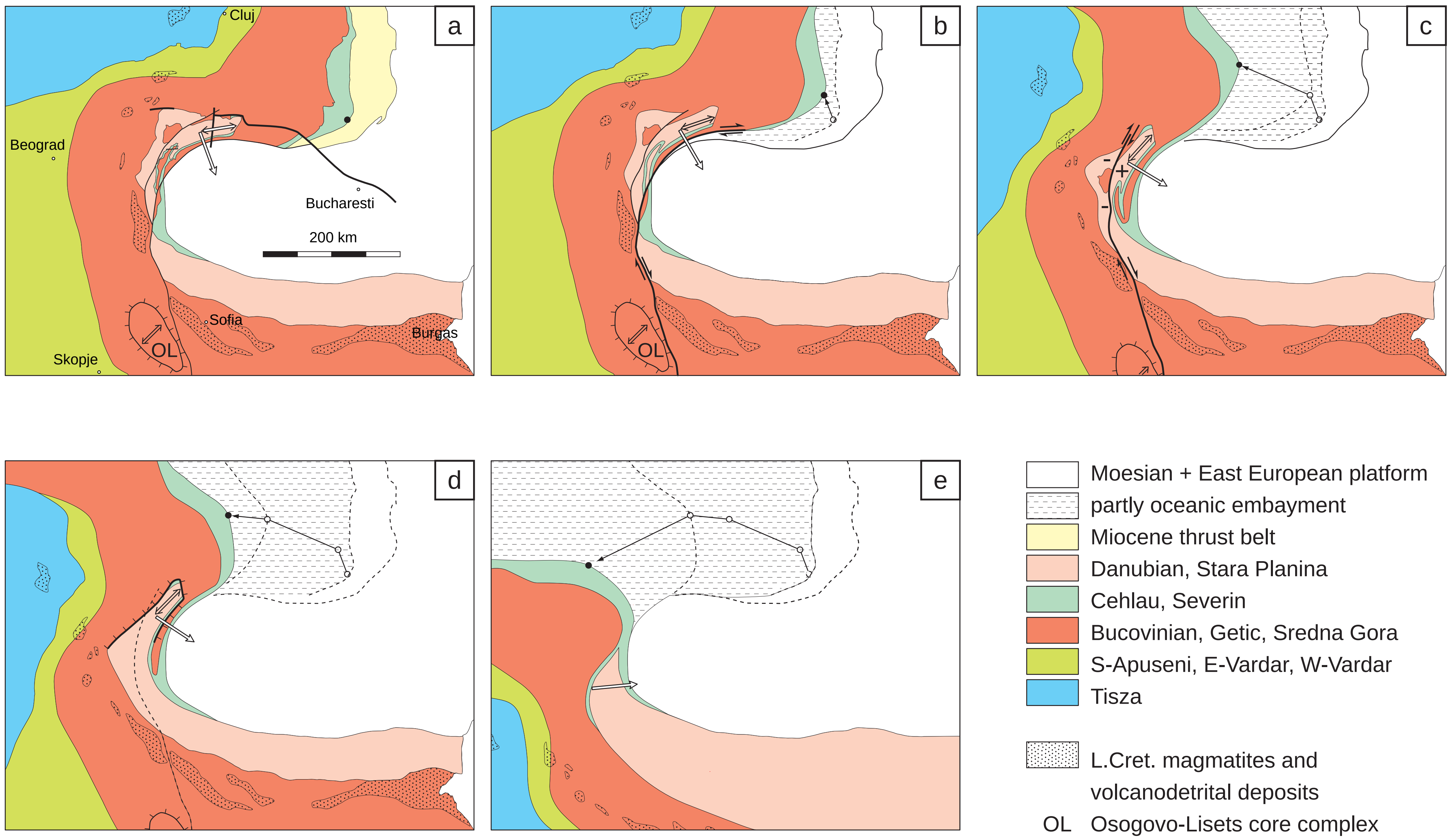
Mesozoic cover
basement

Fig. 8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Moesian + East European platform
partly oceanic embayment
Miocene thrust belt
Danubian, Stara Planina
Cehlau, Severin
Bucovinian, Getic, Sredna Gora
S-Apuseni, E-Vardar, W-Vardar
Tisza
L.Cret. magmatites and
volcanodetrital deposits
OL Osogovo-Lisets core complex