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Thermal history of the Maramureş area (Northern Romania) constrained by zircon fission track analysis: Cretaceous metamorphism and Late Cretaceous to Paleocene exhumation

HEIKE R. GRÖGER[1], MATTHIAS TISCHLER[1], BERNHARD FÜGENSCHUH[2] and STEFAN M. SCHMID[3]

[1]Statoil ASA, Forusbeen 50, 4035 Stavanger, Norway; heigr@statoil.com
[2]Institut für Geologie und Paläontologie, Universität Innsbruck, Innrain 52, Bruno Sander Haus, 6020 Innsbruck, Austria; bernhard.fuegenschuh@uibk.ac.at
[3]Institute of Geophysics, ETH, CH-8092 Zürich, Switzerland; stefan.schmid@erdw.ethz.ch

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Abstract: This study presents zircon fission track data from the Bucovinian nappe stack (northern part of the Inner Eastern Carpathians, Rodna Mountains) and a neighbouring part of the Biharia nappe system (Preluca massif) in order to unravel the thermal history of the area and its structural evolution by integrating the fission track data with published data on the tectonic and sedimentary evolution of the area. The increase of metamorphic temperatures towards the SW detected by the zircon fission track data suggests SW-wards increasing tectonic overburden (up to at least 15 km) and hence top NE thrusting. Sub-greenschist facies conditions during the Alpine metamorphic overprint only caused partial annealing of fission tracks in zircon in the external main chain of the Central Eastern Carpathians. Full annealing of zircon points to at least 300 °C in the more internal elements (Rodna Mountains and Preluca massif). The zircon fission track central and single grain ages largely reflect Late Cretaceous cooling and exhumation. A combination of fission track data and stratigraphic constraints points to predominantly tectonic differential exhumation by some 7–11 km, connected to massive Late Cretaceous extension not yet detected in the area. Later events such as the latest Cretaceous ("Laramian") juxtaposition of the nappe pile with the internal Moldavides, causing exhumation by erosion, re-burial by sedimentation and tectonic loading during the Cenozoic had no impact on the zircon fission track data; unfortunately it prevented a study of the low temperature part of the Late Cretaceous exhumation history.

Key words: Cretaceous, Eastern Carpathians, Romania, Rodna Mountains, Alpine metamorphism, thermochronology, zircon fission track analysis.

Introduction

The highly arcuate external Miocene thrust belt of the Carpathians and its foredeep (Fig. 1) formed in Miocene times (Matenco et al. 2003, 2007, 2010). Continental blocks of different provenance referred to as Mega-Units (ALCAPA, Tisza, Dacia; see Csontos & Vörös 2004; Schmid et al. 2008 and references therein) are presently located between the Bohemian and Moesian promontories (Fig. 1), in an area that was, until Mid-Miocene times, occupied by the so-called Carpathian embayment, probably partly underlain by old oceanic lithosphere (Balla 1987; Csontos & Vörös 2004; Ustaszewski et al. 2008). Before their final emplacement into the Carpathian embayment these three Mega-Units underwent Cretaceous orogeny. Our area of investigation is located in the internal Eastern Carpathians that are a part of the Dacia Mega-Unit. Cretaceous orogeny in the Eastern Carpathians propagated eastwards until Paleogene times (Matenco et al. 2003). In the Miocene the Eastern Carpathians, including partly oceanic accretionary prisms accreted in Cretaceous times (e.g. the Ceahlau and Black Flysch Nappes of Fig. 2; Săndulescu 1975), collided with the European foreland, thereby closing the Carpathian embayment and forming the external Miocene-age flysch belt (Matenco et al. 2010).

A number of publications investigating the invasion of these continental blocks into the Carpathian embayment (e.g. Balla 1987; Royden & Báldi 1988; Ratschbacher et al. 1991a,b; Csontos et al. 1992; Csontos 1995; Fodor et al. 1999; Sperner et al. 2005; Schmid et al. 2008; Ustaszewski et al. 2008) considerably improved our understanding of the Tertiary tectonic evolution. In contrast, the Cretaceous and Early Paleogene history of the Tisza and Dacia Mega-Units themselves, forming the backbone of the Carpathian arc (Burchfiel 1980; Săndulescu 1988, 1994; Csontos 1995; Csontos & Vorös 2004; Schmid et al. 2008), is still ill constrained.

In the area of investigation the Dacia Mega-Unit consists of the so-called Bucovinian nappe stack (Fig. 2). This nappe stack is built up, from bottom to top, by the Infrabucovinian Nappe, followed by the Subbucovinian and Bucovinian Nappes (Săndulescu 1994). These Cretaceous-age nappes that constitute the internal parts of the Eastern Carpathians are the lateral equivalents of the Getic and Supragetic Nappes of the Southern Carpathians that can be followed into the Sredna Gora and Serbo-Macedonian Units of the

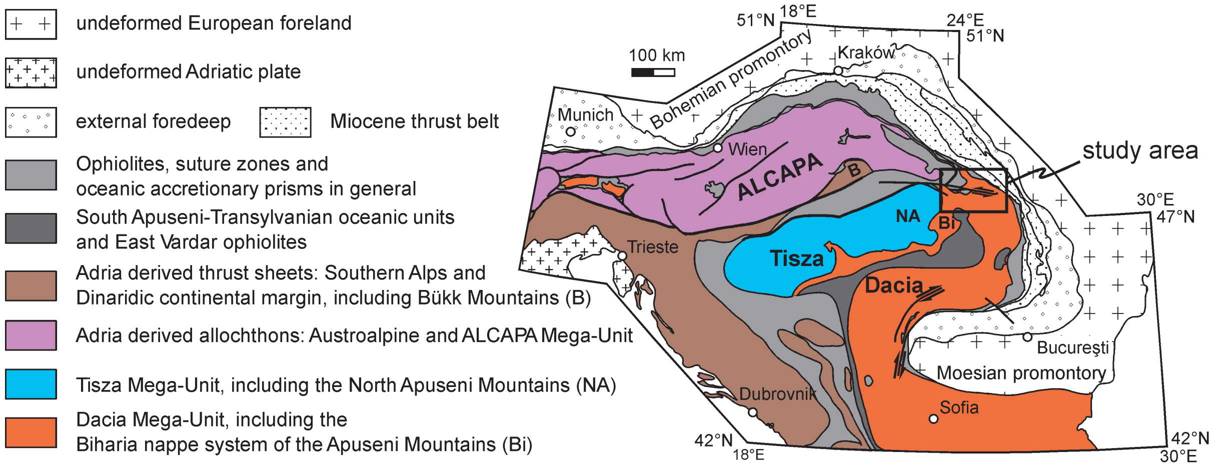

Fig. 1. Tectonic overview of the Alpine-Carpathian-Pannonian area (after Schmid et al. 2008); rectangle indicates the location of the study area at the northern edge of the Dacia Mega-Unit.

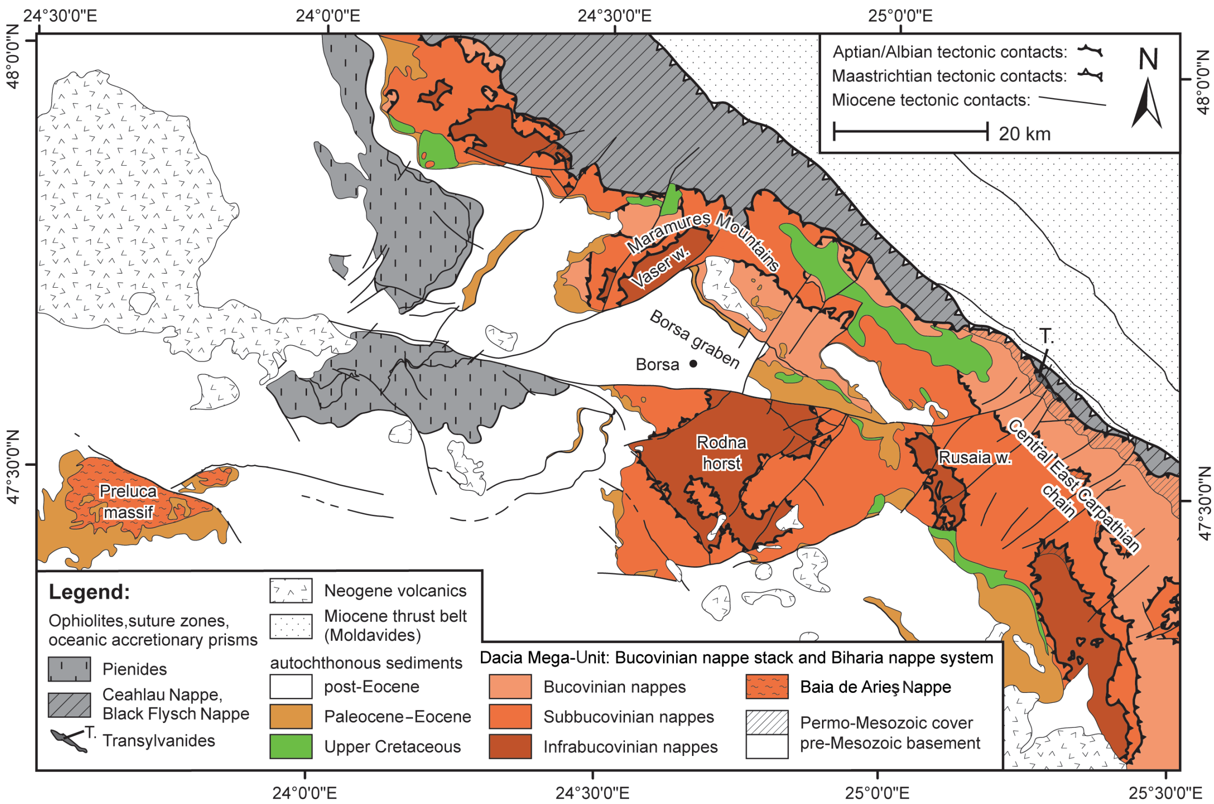

Fig. 2. Tectonic map of the study area. The map is compiled after Giusca & Radulescu (1967), Raileanu & Radulescu (1967), Ianovici & Dessila-Codarcea (1968), Ianovici & Radulescu (1968), Ianovici et al. (1968), Raileanu & Saulea (1968), Kräutner et al. (1978, 1982, 1983, 1989), Borcos et al. (1980), Dicea et al. (1980), Săndulescu (1980), Săndulescu & Russo-Săndulescu (1981), Săndulescu et al. (1981, 1991), Rusu et al. (1983) and Aroldi (2001).

Carpatho-Balkan orogen (Săndulescu et al. 1981). Therefore, these units are also part of the Dacia Mega-Unit (Csontos et al. 1992; Csontos & Vörös 2004; Schmid et al. 2008).

A similar Cretaceous-age nappe stack outcrops in the neighbouring Apuseni Mountains, which are classically attributed to the Tisza Mega-Unit (e.g. Haas & Péró 2004). Their thermal history has recently also been investigated by fission track studies (Merten et al. 2011; Kounov & Schmid 2013). Particularly the highest nappe system of the North Apuseni Mountains, the Biharia nappe system shows close similarities with the Bucovinian nappe stack of our working area and has been proposed to be a part of the Dacia Mega-Unit (Schmid et al. 2008; Matenco et al. 2010; Kounov & Schmid 2013).

The juxtaposition of the Tisza and Dacia Mega-Units started during the Late Jurassic and Early Cretaceous orogeny also affecting the Central Eastern Carpathians, leading to the obduction and closure of the intervening South Apuseni–Transylvanian oceanic units (Transylvanides — Săndulescu 1988; Vardar-Mureş zone — Csontos & Vorös 2004). The Transylvanides, consisting of Middle Triassic to Middle/Upper Jurassic ophiolites (Săndulescu 1994), were obducted and subsequently thrusted onto the Bucovinian nappe pile (Săndulescu 1988, 1994).

The pre-Alpine metamorphic evolution of the Bucovinian nappes in the study area and that of the similar Biharia nappe system of the Apuseni Mountains is quite well established (Kräutner 1988, 1991; Pană & Erdmer 1994; Voda & Balintoni 1994; Strutinski et al. 2006; Balintoni et al. 2010; Balintoni & Balica 2013). The grade and age of Alpine metamorphic overprint, however, is still ill constrained (Săndulescu et al. 1981; Pană & Erdmer 1994; Dallmeyer et al. 1996, 1998; Strutinski et al. 2006; Culshaw et al. 2012). The low degree of metamorphism of Permian to Lower Cretaceous sedimentary units separating the individual nappes (Fig. 2) led to the view that late Early Cretaceous (Aptian/Albian) nappe stacking occurred under sub-greenschist metamorphic conditions (Săndulescu et al. 1981). Later publications revealed Alpine-age greenschist facies metamorphic overprint (Pană & Erdmer 1994; Dallmeyer et al. 1996, 1998; Balintoni et al. 1997; Strutinski et al. 2006; Culshaw et al. 2012). An Alpine-age metamorphic overprint is particularly well documented for the so-called Rodna horst (Fig. 2), exposing the Infrabucovinian nappes (Dallmeyer et al. 1998; Strutinski et al. 2006; Culshaw et al. 2012). The same holds for the Preluca massif in the SW corner of our area of investigation classically assigned to the Biharia nappe system (Fig. 2; Rusu et al. 1983; Strutinski et al. 2006) and the bulk of the Biharia nappe system in the Apuseni Mountains located further to the SW (Fig. 1; Dallmeyer et al. 1996; Strutinski et al. 2006; Kounov & Schmid 2013).

This zircon fission track study complements structural (Tischler et al. 2007), sedimentological (Tischler et al. 2008), paleomagnetic (Márton et al. 2007) and apatite fission track (Gröger et al. 2008) investigations in the Maramureş area of northern Romania. In Gröger et al. (2008) the zircon fission track data has been used combined with apatite fission track data to constrain the Tertiary exhumation and final emplacement of the Tisza-Dacia block in the Eastern Carpathians. This study offers a new interpretation of the data in combination with published metamorphic information. Firstly, the zircon fission track data allow us to discuss the degree and age of Alpine metamorphism. Secondly, the zircon data also provide information on the subsequent exhumation of the Bucovinian nappe stack of the Eastern Carpathians (Fig. 2) in Cretaceous times since zircon fission tracks were not annealed during subsequent burial in Cenozoic times; this was the case for the apatite fission tracks (Gröger et al. 2008). A third target concerns the comparison of the Bucovinian nappe stack with basement units of the neighbouring Biharia nappe system exposed in the North Apuseni Mountains, classically attributed to the Tisza Mega-Unit (e.g. Haas & Péró 2004).

Since annealing of fission tracks in zircon occurs in a temperature range of 200–350 °C (Hurford 1986; Yamada et al. 1995; Tagami et al. 1996) our results will be discussed in the context of published geochronological data from the Bucovinian nappe stack that record the higher temperature history (K-Ar and $^{40}Ar/^{39}Ar$ thermochronology — Dallmeyer et al. 1998; Strutinski et al. 2006; Culshaw et al. 2012). Since apatite fission tracks have been fully annealed during post-Cretaceous burial (Gröger et al. 2008), we also will use stratigraphic data (Szasz 1973; Kräutner et al. 1978, 1983; Săndulescu et al. 1991) to further constrain the Late Cretaceous to Early Paleogene exhumation history of the area.

Geological setting

The Infrabucovinian Nappe is the tectonically deepest unit of the Bucovinian nappe stack and laterally corresponds to the Getic Nappe of the Southern Carpathians (Schmid et al. 2008). It is exposed in a series of windows (Fig. 2). The window in the Rodna horst (Kräutner 1988), surrounded by the Subbucovinian Nappe, is one of the largest. The tectonically highest Bucovinian Nappe is found in the most external, meaning the northeastern part of the Eastern Carpathians (Fig. 2). The bulk of the Bucovinian nappe stack consists of pre-Mesozoic basement, the Mesozoic cover being thin and only sporadically preserved, particularly in the case of the Infrabucovinian and Subbucovinian Nappes. The pre-Mesozoic basement of the Preluca massif (SW corner of Fig. 2) is attributed to the Baia de Arieş Nappe of the Biharia nappe system (Rusu et al. 1983; Strutinski et al. 2006). Its Mesozoic cover is not preserved.

A Precambrian amphibolite facies basement, derived from Proterozoic sediments (Rebra, Negrisoara and Bretila series; Kräutner 1938, 1988) predominates within the Bucovinian nappe pile. In addition, the Subbucovinian and Bucovinian Nappes feature a series composed of Cambrian sediments and eruptive rocks (Tulghes series) whose greenschist facies metamorphic overprint has been dated by K-Ar methods as Ordovician (450–470 Ma; Kräutner 1988, 1991, and references therein). According to Kräutner (1991), the Variscan and Alpine orogenies only locally caused greenschist facies overprint.

The Infra- and Subbucovinian Nappes also feature a post-Caledonian sedimentary cover (Repedea, Rusaia and Cimpoiasa series — Kräutner 1991; Rodna series — Voda & Balintoni 1994). Palynological data indicate a Silurian to Mississippian depositional age of these series (Săndulescu et al. 1981; Kräutner 1988, 1991, and references therein). A Variscan prograde greenschist facies metamorphic overprint has been dated by K-Ar age data as Pennsylvanian (310 Ma; Kräutner 1991). However, in the case of the Rodna horst, Balintoni et al. (1997) proposed the greenschist facies overprint to be Alpine in age. Moreover, Balintoni et al. (1997) interpreted the so-called "Rodna series" to represent post-Variscan Jurassic cover, due to similarities in structural position and lithology with metamorphosed Jurassic cover units exposed in the Vaser window.

A post-Variscan Permian to Lower Cretaceous cover, with highly variable facies types, characterizes the different nappes, except for the basement of the Rodna horst that lacks non-metamorphic Permo-Mesozoic cover (Săndulescu et al. 1981; Săndulescu 1994). Common to all tectonic units are Middle Triassic dolomites, an Upper Triassic hiatus and

Middle Jurassic siliciclastic marls (Săndulescu 1994). While sedimentation is only documented until the end of the Barremian in the case of the Subbucovinian and Infrabucovinian Nappes, the Bucovinian nappes also carry a Barremian to Aptian (or even Albian — Kräutner et al. 1975) wildflysch, separating the Bucovinian nappe stack from the overlying Transylvanian nappes that contain relics of the South Apuseni–Transylvanian oceanic units (Höck et al. 2009).

Alpine thrusting within the Bucovinian nappe pile is of Early Cretaceous age according to stratigraphical constraints (so-called "Austrian" phase of Săndulescu 1982). Thrusting during this Austrian phase was top-E to NE (in present day coordinates) as inferred from the regional compilations within and around the Transylvanian Basin provided by Săndulescu (1994), Schmid et al. (2008) as well as Kounov & Schmid (2013). However, mesoscopic kinematic data on the exact transport direction are still missing in our working area. In the area of the Rodna horst stretching lineations are NW-SE-oriented (Culshaw et al. 2012) but these authors do not provide kinematic data. Later, the nappe pile became folded around SE to SSE-striking fold axes, as suggested by the strike of the windows exposing the Infrabucovinian units (Fig. 2) and as indicated by related metamorphic lineations (NW–SE in the Rodna horst — Balintoni et al. 1997; Culshaw et al. 2012; NNW–SSE further to the east — Balintoni & Baier 2001). This post-nappe folding is probably contemporaneous with the late "Austrian" juxtaposition (Săndulescu 1982) of the Bucovinian nappe stack onto the Black Flysch and Ceahlau Nappes. The Early Cretaceous nappe contacts all the way down to the Infrabucovinian units (e.g. in the Rusaia window, Fig. 2) are sealed by unconformably deposited (Upper?) Cenomanian sediments (Ianovici et al. 1968; Săndulescu et al. 1981).

The pre-Cenomanian "Austrian" orogeny is often considered to have taken place under sub-greenschist facies condi-

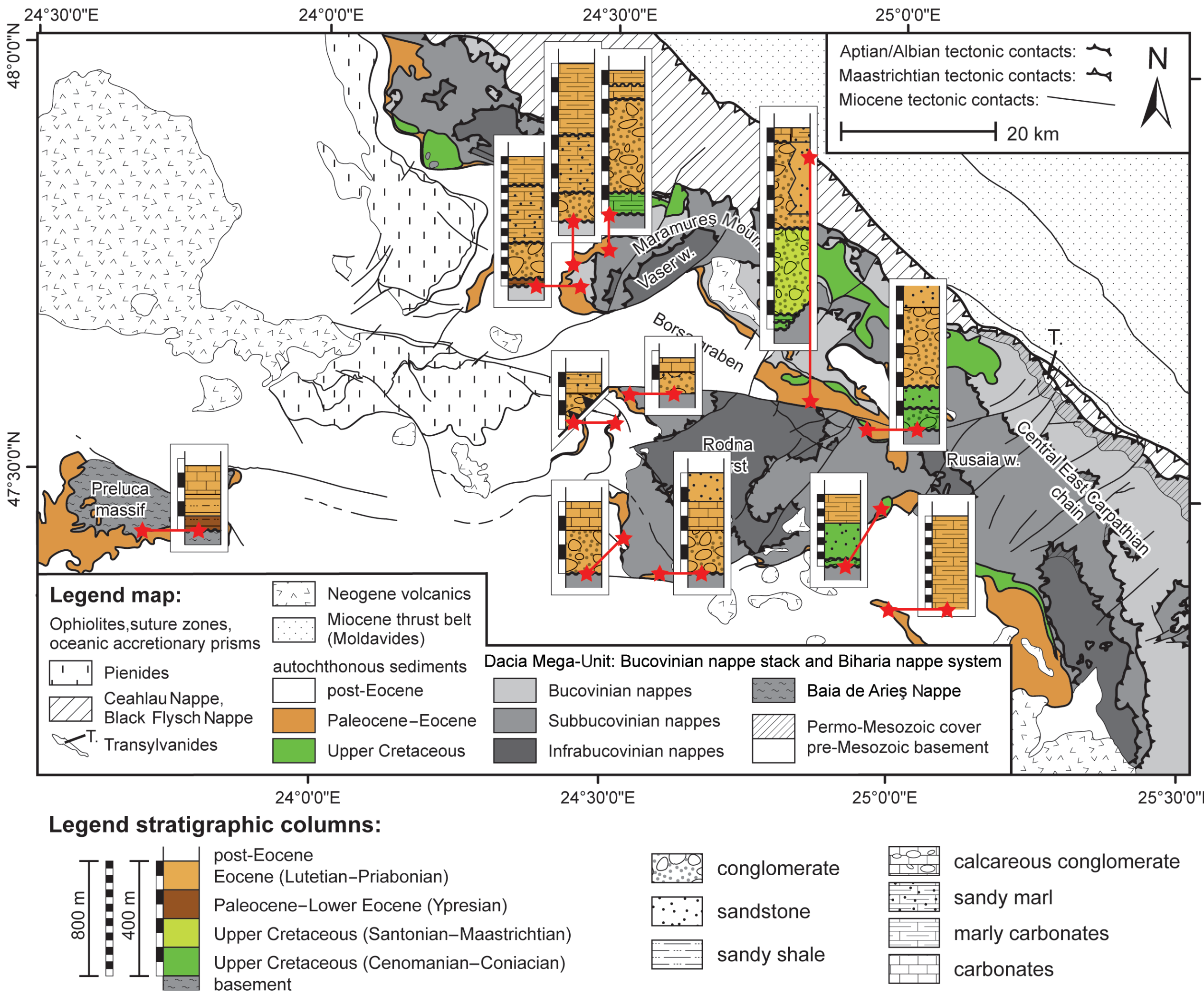

Fig. 3. Schematic stratigraphic columns — to illustrate the Upper Cretaceous (green) and Paleogene–Eocene (brown) sedimentary cover. The Upper Cretaceous deposits are only preserved as small remnants because of an erosional event during the latest Maastrichtian to earliest Paleocene following "Laramian" (Early Maastrichtian) thrusting. Note that, due to this same erosional event the basement of the Preluca massif is directly overstepped by Paleocene deposits. Stratigraphic columns after Kräutner et al. (1978, 1982, 1983, 1989), Rusu et al. (1983) and Săndulescu et al. (1991).

tions (i.e. Săndulescu et al. 1981). However, syntectonic greenschist facies metamorphism in the vicinity of nappe contacts was locally described, especially in the case of the Rodna horst (Kräutner et al. 1978, 1982, 1983, 1989; Dallmeyer et al. 1998; Strutinski et al. 2006; Culshaw et al. 2012) and in the case of the Vaser window (Balintoni et al. 1997).

The post-tectonic (with respect to the "Austrian" phase) Upper Cretaceous cover (Figs. 2, 3) includes Cenomanian-Turonian conglomerates and sandstones, discordantly overlain by Turonian–Coniacian (silty) marls (Kräutner et al. 1978, 1983; Săndulescu et al. 1991). Within the Borsa graben Santonian to Maastrichtian conglomerates are documented above a second unconformity (Szasz 1973; Kräutner et al. 1983). Similar Cenomanian to Maastrichtian deposits are widespread within and at the rims of the Transylvanian Basin and are generally interpreted to have been deposited during crustal extension (e.g. Krézsek & Bally 2006).

Thrusting resumed in the Late Maastrichtian when the exhumed "Austrian" nappe-pile and its post-tectonic Late Cretaceous cover thrusted the underlying Black Flysch and Ceahlau Nappes ("Laramian" phase; Săndulescu 1982, 1994; Matenco et al. 2003). This thrusting is contemporaneous with the formation of the Danubian nappes in the Southern Carpathians (Schmid et al. 1998; Matenco & Schmid 1999). The Maastrichtian collisional event was also followed by uplift and erosion in the Central East Carpathian chain, leading to a paleo-relief, for example, associated with a basement high in the area of the Rodna horst (Săndulescu et al. 1991; Tischler et al. 2007; Gröger et al. 2008). During the Paleocene erosion dominates within most of the study area (Fig. 3). Only west of the Borsa graben and in the Preluca massif are Paleocene continental deposits, namely the shales and sandstones of the Jibou Formation, seen to unconformably overlie the basement (Rusu et al. 1983; Săndulescu et al. 1991; see Figs. 2 and 3).

Post-"Laramian" Paleogene sedimentation started with typically terrestrial conglomerates of Ypresian (in case of the Borsa graben — Kräutner et al. 1983) to Lutetian age (Prislop conglomerate). These are followed by lithologically variable Lutetian to Priabonian marine sediments (Fig. 3) deposited in sag basins (Krézsek & Bally 2006). Platform carbonates are preserved in the Rodna horst and in the southern and eastern parts of the study area (Iza limestone — Dicea et al. 1980; De Brouker et al. 1998; Sahy et al. 2008). Deepening towards the northwest is indicated by a change from platform carbonates towards marls and distal turbidites (Vaser and Viseu Formations — Săndulescu et al. 1991). The maximum thickness of the Eocene sediments in the study area (around 1000 m) is found immediately west of the Borsa graben (Fig. 3). The existence of an Eocene paleorelief is also supported by the observation that Oligocene sediments locally directly overlie the basement units of the Rodna horst (Kräutner et al. 1982).

Deposition of thick siliciclastic flysch ("Transcarpathian flysch") started in the Early Oligocene, reflecting flexural bending at the onset of convergence between ALCAPA and the Tisza–Dacia Mega-Units (Tischler et al. 2008) and leading to considerable burial of all underlying units (Dicea et al. 1980). Final exhumation of the pre-Mesozoic basement units is the result of Miocene brittle tectonics and erosion during the final stages of juxtaposition of the Tisza–Dacia Mega-Units against the European margin (Tischler et al. 2007, 2008; Márton et al. 2007; Gröger et al. 2008).

Method — zircon fission track analysis

Fission track (FT) analysis (overview in Wagner & van den Haute 1992) is a radiometric dating procedure. The samples in this study are analysed using the external detector method, calculating single grain ages (Gleadow 1981). The age is calculated from the ratio between spontaneous fission tracks (Ns), counted on a defined square on the grain, and tracks induced by thermal neutrons (Ni), counted on the equal square on a uranium-free external detector (Fig. 4).

Latent fission tracks are only stable below a critical temperature range, namely the partial annealing zone, wherein tracks start to anneal and finally fade. The zircon partial annealing zone (ZPAZ) has been addressed in experimental (e.g. Yamada et al. 1995) and empirical studies (e.g. Hurford 1986; Tagami et al. 1996; Tagami & Shimada 1996). While the lower temperature limit at ~200 °C (Tagami et al. 1996) is generally agreed, the upper temperature limit is still a matter of debate, ranging between 300 and 400 °C (Yamada et al. 1995). Indeed this large temperature range might at least partly be related to different geodynamic settings (fast exhuming/high-grade rocks vs. deposition/burial/slow exhumation) and the effect of a-recoil damage (Rahn et al. 2004; Timar-Geng et al. 2006). For our interpretations we take a temperature range of 240±50 °C (Hurford 1986), which is, within error bars, in accordance with other authors (Zaun & Wagner 1985; Tagami et al. 1996).

Samples have been processed using conventional crushing, sieving, magnetic and heavy liquid separation (bromoform, methylene iodide). Zircon grains were mounted in PFA® Teflon, polished and etched for 12–24 hours in an eutectic melt of NaOH/KOH (relation 16/23 g) at 225 °C to reveal the ^{238}U fossil fission tracks. Irradiation was carried out at the High Flux Australian Reactor (HIFAR) at Lucas Heights, New South Wales with neutron fluxes monitored in CN1. Muscovite was used as an external detector and etched

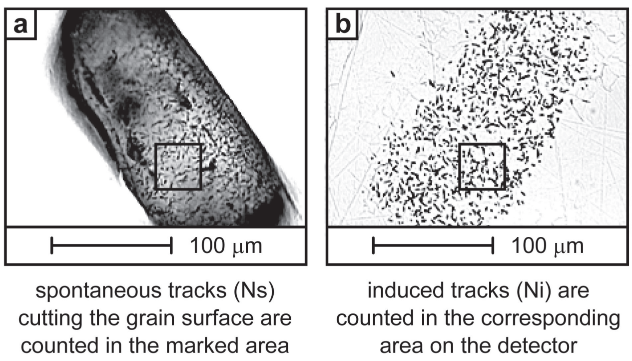

Fig. 4. Zircon fission track ages are calculated based on the ratio of spontaneous tracks (Ns) counted on the grain (**a**) and induced tracks (Ni) counted on a uranium free mica detector (**b**).

for 40 minutes at room temperature in 40% HF to reveal the ^{235}U induced tracks.

Fission tracks were counted on a Zeiss® Axiotron-S microscope in transmitted light with a computer-controlled scanning stage ("Langstage" — Dumitru 1993) at magnifications of ×1600 (dry). The ages are calculated using the ξ-calibration method (Hurford & Green 1983) using a ξ value of 141.40 ± 6.33 (fish canyon tuff standard, CN1) for zircon

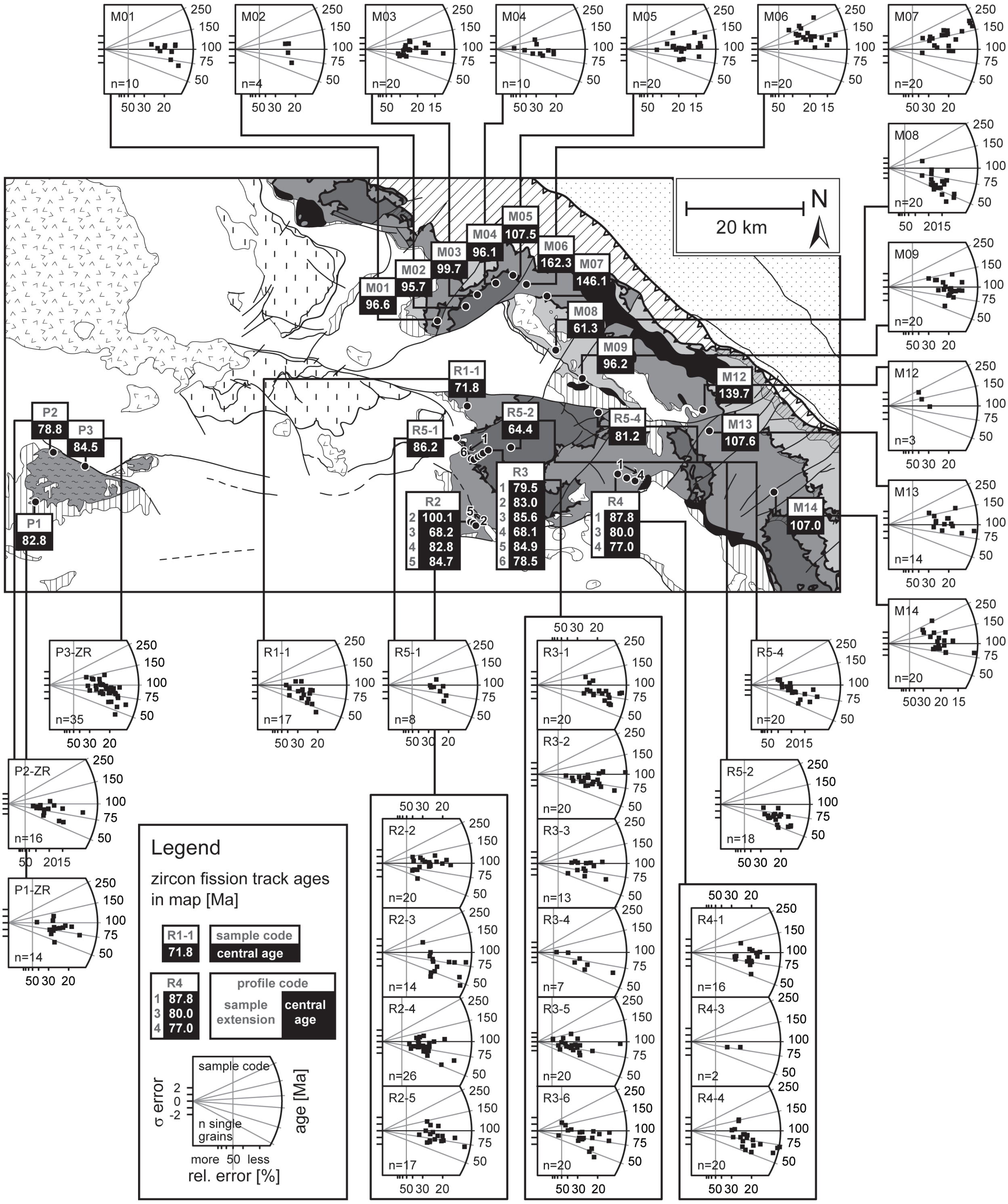

Fig. 5. Results of zircon fission track analyses. All radial plots depicting the single grain ages are equally scaled (Galbraith 1990) to allow for direct comparison. The central ages (Galbraith & Laslett 1993), given in the black fields are the weighted mean of the single grain ages. See legend integrated in the figure for further details.

with the aid of the windows software TrackKey (Dunkl 2002). All ages mentioned are central ages (Galbraith & Laslett 1993) and errors are quoted at the 1σ level.

Results

Location of samples and list of zircon fission track data

All zircons analysed were taken from samples of the pre-Permo-Mesozoic basement. Most samples were taken in close contact to the autochthonous sedimentary cover of the basement in order to provide independent stratigraphic and thermal control. Fig. 5 shows their location on a geological map and depicts the central ages and radial plots, Table 1 lists the results of the 32 samples analysed.

Samples M01-09 and M12-M14 were taken along a horizontal strike-parallel profile going from the Maramureş Mountains in the NW to the Central East Carpathian chain in the SE (see Figs. 2 and 5). The area of the Rodna horst (Fig. 2) was sampled in greater detail (Fig. 5). The samples collected there include three vertical profiles: two across the Subbucovinian Nappe (R2 with 4 samples and R4 with 3 samples) and one across the Infrabucovinian Nappe (R3 with 6 samples). These are complemented by four samples from the northern part of the Rodna horst (R1-1 from the Subbucovinian Nappe; R5-1, R5-2, R5-4 from the Infrabucovinian Nappe and covering a WSW-ENE profile). Three samples derive from the Preluca massif in the SW (P1–P3; Fig. 5).

Zircon fission track data

All central ages (except for that of M08), found along the horizontal profile from the Maramureş Mountains to the Central East Carpathian chain (Fig. 5; Table 1, row 1–12) scatter between Late Jurassic and Cenomanian (162.3–96.1 Ma). Some of these samples (M01–M04, M09), all located more to the SW, show Cenomanian central ages (99.7–96.1 Ma) and pass the Chi-Square test ($\chi^2 > 5$ %; Table 1, column 12). Hence this group of samples indicates Cenomanian cooling after full annealing of the zircon fission tracks. Central ages

Table 1: Zircon fission track data. All samples have been analysed using the external detector method (Gleadow 1981) with a zeta value (Hurford & Green 1983) of 141.40±6.33 (Fish Canyon Tuff standard, CN1). Code — sample code; Locality X — Latitude in decimal degrees; Locality Y — Longitude in decimal degrees; Loc. Z [m] — altitude above sea level; No. Grains — number of grains counted; Ps [$\times 10^6 cm^{-2}$] — spontaneous track density; Ns — number of spontaneous tracks counted; Pi [$\times 10^6 cm^{-2}$] — induced track density; Ni — number of induced tracks counted; Pd [$\times 10^6 cm^{-2}$] — standard track density; Nd — number of standard tracks counted; χ^2 [%] — Chi-Square probability (Galbraith 1981). Central Age ±1σ [Ma] — zircon fission track central age (Galbraith & Laslett 1993).

Code	Locality X	Locality Y	Locality Z [m]	No. Grains	Ps [$\times 10^6$ cm^{-2}]	Ns	Pi [$\times 10^6$ cm^{-2}]	Ni	Pd [$\times 10^6$ cm^{-2}]	Nd	χ^2 [%]	Central Age ±1σ [Ma]
M01	24.496670	47.729790	540	10	17.637	1291	4.932	361	0.385	3065	34	96.6±7.6
M02	24.560710	47.753720	580	4	10.939	367	3.010	101	0.377	3065	13	95.7±13.5
M03	24.586640	47.772540	630	20	8.688	1468	3.545	599	0.580	3605	81	99.7±6.8
M04	24.628100	47.791450	680	10	7.007	436	3.054	190	0.597	3605	84	96.1±9.5
M05	24.667090	47.804300	745	20	9.844	2366	3.720	894	0.586	3605	<5	107.5±7.4
M06	24.698590	47.790850	790	20	12.907	2543	3.335	657	0.591	3605	<5	162.3±13.0
M07	24.736840	47.773640	835	20	8.663	2193	2.501	633	0.614	3605	10	146.1±10.5
M08	24.770543	47.690263	820	20	12.309	2703	5.232	1149	0.369	3065	<5	61.3±4.7
M09	24.833619	47.647505	1660	20	12.615	2501	3.218	638	0.350	3065	22	96.2±6.5
M12	25.112014	47.603497	985	3	13.443	164	2.541	31	0.377	3065	21	139.7±29.5
M13	25.128220	47.571246	930	14	25.389	1812	5.871	419	0.354	3065	23	107.6±8.5
M14	25.279510	47.478662	850	20	13.767	2830	3.060	629	0.338	3065	<5	107.0±9.1
P1	23.574760	47.430957	315	14	7.960	1010	2.522	320	0.373	3065	55	82.8±6.6
P2	23.628772	47.509842	215	16	15.574	1919	4.740	584	0.342	3065	38	78.8±5.6
P3	23.686807	47.488712	610	35	12.838	3336	4.087	1062	0.381	3065	<5	84.5±5.5
R1-1	24.559360	47.597860	1550	17	9.173	996	3.113	338	0.346	2967	25	71.8±6.1
R2-2	24.597260	47.414920	1105	20	8.041	981	3.238	395	0.574	3605	78	100.1±7.6
R2-3	24.595860	47.415710	885	14	9.881	1326	3.622	486	0.357	2967	<5	68.2±6.4
R2-4	24.590430	47.419300	705	26	11.520	2312	3.443	691	0.352	2967	12	82.8±5.9
R2-5	24.583480	47.421240	600	17	12.109	1625	3.368	452	0.335	2967	49	84.7±6.1
R3-1	24.620652	47.533782	2020	20	18.830	2550	5.568	754	0.335	3065	47	79.5±5.1
R3-2	24.582850	47.423290	1465	20	7.415	1642	3.902	864	0.625	3605	62	83.0±5.5
R3-3	24.608990	47.528930	1310	13	7.626	842	3.877	428	0.620	3605	37	85.6±6.8
R3-4	24.604450	47.526330	1155	7	9.477	607	6.011	385	0.614	3605	50	68.1±5.5
R3-5	24.597630	47.523200	1005	20	11.482	1751	5.705	870	0.608	3605	14	84.9±5.9
R3-6	24.587980	47.518690	945	20	9.224	934	4.977	504	0.603	3605	11	78.5±6.4
R4-1	24.920150	47.500800	1638	16	7.516	1710	2.193	499	0.366	3065	28	87.8±6.3
R4-3	24.941010	47.494710	980	2	11.694	107	3.716	34	0.362	3065	86	80.0±16.2
R4-4	24.960230	47.490430	700	20	13.472	1923	4.589	655	0.369	3065	<5	77.0±5.8
R5-1	24.546451	47.552021	1150	8	20.411	635	5.754	179	0.346	3065	47	86.2±8.4
R5-2	24.449131	47.460078	1245	18	15.094	1556	5.345	551	0.324	2967	90	64.4±4.5
R5-4	24.872870	47.596160	1270	20	16.118	2517	5.033	786	0.358	3065	10	81.2±5.5

from locations more to the NE, i.e. towards the present-day erosional front of the Bucovinian nappe stack, are older and range between Late Jurassic and Early Cretaceous (162.3–107.0 Ma; M05–M07, M12–M14). The large spread in central ages from this external sub-group reflects the observed scattering of single grain ages between Late Cretaceous and Paleozoic (oldest single grain: 310 Ma, M06); most of them fail the Chi-square test (χ^2<5 %; Table 1, column 12). Consequently the zircons from this sub-group are interpreted as having been partially annealed prior to Cenomanian cooling. The Paleocene central age obtained for M08 (61.3 Ma) forms an exception. Its extraordinarily young age is most likely the result of hydrothermal overprint inducing partial annealing, caused by a Miocene volcanic body nearby (Pécskay et al. 1995). Consequently, sample M08 will be excluded from further discussions.

All zircon FT central ages taken from the Preluca massif (Fig. 5; Table 1, row 13–15) and the Rodna horst (Fig. 5; Table 1, row 16–32) show a spread between 100.1–64.4 Ma, a time interval that covers the entire Late Cretaceous period. Most of the zircon FT central ages from the Rodna horst are of Coniacian to Campanian (89.3–70.6 Ma) age and most of them pass the Chi-Square test (χ^2>5 %; Table 1, column 12), which indicates full annealing prior to Late Cretaceous cooling.

Figure 6 presents the distribution of zircon single grain ages for specified groups of samples and compares this distribution with the spread in nominal central ages for the same groups of specimens in order to better assess the degree of annealing that occurred during Early Cretaceous metamorphism. In the Maramureş Mountains and the Central East Carpathian main chain (Fig. 6a,b) differences depending on the structural position within the Early Cretaceous nappe pile are apparent. In the case of the Bucovinian and Subbucovinian Nappes (Fig. 6a) no clear peak is discernable in the single grain age distribution, suggesting only partial annealing during the Early Cretaceous orogeny. Samples from the tectonostratigraphically lowest Infrabucovinian Nappe, however, show a relatively well-defined peak at around 100 Ma, coinciding with the small spread in central ages (Fig. 6b), suggesting full Cretaceous-age annealing.

Within the Rodna horst both structural units appear to be fully annealed (Fig. 6c,d). The distributions of the single grain ages as well as the spread of the central ages are very similar regardless of tectonic position. Moreover, no age vs. altitude relation was detected in the case of the vertical profiles in the Rodna horst (Fig. 5). The three samples from the Preluca massif show single grain age distribution similar to that of the Rodna horst (Fig. 6e), suggesting full annealing again, though testified by far less single grains.

In order to evaluate the geological significance of the surprisingly large spread of central ages found in the Rodna horst, vertical profile R2 is examined in more detail. Fig. 7a–b shows two neighbouring samples from this profile that reflect a large difference in central age (R2-2: 100.1 ± 7.6 Ma; R2-3: 68.2 ± 6.4 Ma) but at the same time shows a similar spread of single grain ages. Note that this overall spread of single grain ages is roughly the same as that observed when looking at all the samples taken from the Rodna horst (Fig. 7c). This indicates that the differences in central ages observed in the Rodna

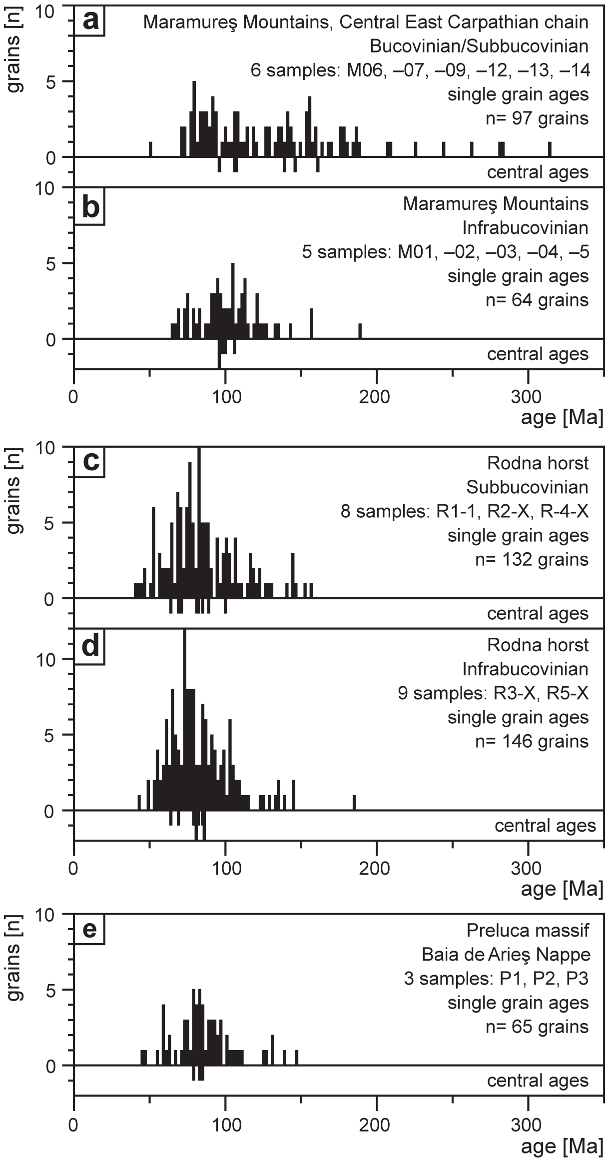

Fig. 6. Age distribution of the single grain zircon FT ages and spread in the calculated central ages from groups of specimens. **a** — ages from the Bucovinian and Subbucovinian Nappes of the Maramureş Mountains and Central East Carpathian chain; **b** — ages from the Infrabucovinian nappes of the Maramureş Mountains; **c** — ages from the Subbucovinian nappes in the Rodna horst; **d** — ages from the Infrabucovinian nappes in the Rodna horst; **e** — ages from the Preluca massif.

horst have no geological significance and are merely of statistical relevance. A large spread in single grain ages such as shown in Fig. 7a,b can be aggravated by inhomogeneous annealing behaviour, resulting in shifts of single grain age distributions within one sample. Apart from cooling, alpha radiation damage is another important factor influencing the annealing behaviour of zircon grains (Gleadow 1981; Kasuya & Naeser 1988; Rahn et al. 2004). The alpha radiation damage accumulates in relation to the entire grain age and uranium content of the grain (Gleadow 1981; Timar-Geng et al. 2006). Strong reduction of alpha radiation damage requires

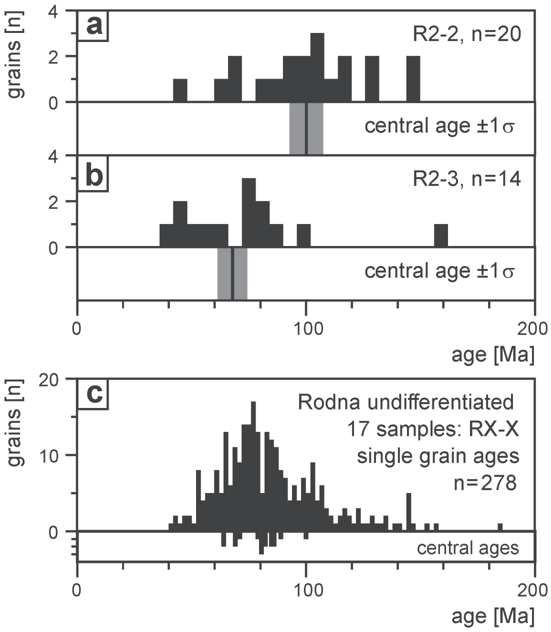

Fig. 7. a,b — Comparison between the zircon FT single grain and central ages of neighbouring samples R2-2 (a) and R2-3 (b) taken from the Subbucovinian nappes in the Rodna horst. Note that both samples show a similar spread in single grain ages, although the central ages are rather different. In these cases the two central ages merely indicate the position of the most pronounced peaks within that spread. **c** — Histogram of single grain ages assembled for all samples from the Rodna horst. The peak in the Campanian approximates the time when these samples cooled through the ZPAZ.

higher temperatures than those needed for FT annealing (Rahn et al. 2004 and therein). Due to these considerations, the zircon central ages in the Rodna horst will not be geologically interpreted individually. On the other hand, the clear peak of the single grain age distribution in Campanian, as seen in Fig. 7c, assembling all the samples from the Rodna horst, is interpreted as documenting the approximate time when the samples from the Rodna horst cooled through the ZPAZ.

In summary, the new zircon FT data indicate a significant metamorphic imprint during Early Cretaceous nappe stacking, followed by Late Cretaceous cooling and exhumation. Full annealing during this event is indicated for (1) the Infrabucovinian Nappe of the Maramureş Mountains and the Central East Carpathian chain, (2) the Infrabucovinian and Subbucovinian Nappes exposed in the area of the Rodna horst and (3) the Biharia nappe system (Baia de Arieş Nappe) exposed in the Preluca massif. Hence metamorphic temperatures must have exceeded 300 °C (upper limit of ZPAZ; Hurford 1986; Yamada et al. 1995) in these areas. Cooling and exhumation is of Late Cretaceous age within the entire studied area. In the case of the Rodna horst cooling across the ZPAZ occurred in Campanian times (Fig. 7c). However, the rather tight clustering of central ages in the case of samples M01–M04 and M09 from the more internal (SE) parts of the Maramureş Mountains and the Central East Carpathian chain, and the Cenomanian age of the post-tectonic cover, are evidence that cooling started earlier, namely during the Cenomanian in these areas. Apatite fission tracks have been fully annealed during renewed burial in the Miocene (Gröger et al. 2008) that occurred in the context of thrusting of the easternmost tip of ALCAPA (Pienides) over Tisza–Dacia (Tischler et al. 2007) and related flysch sedimentation (Tischler et al. 2008). Hence, they cannot provide additional information regarding the Cretaceous exhumation history.

Interpretation and discussion

Combination of zircon FT data with other constraints on Cretaceous metamorphism and cooling of the Bucovinian nappe stack

The combination of the zircon FT central age data with a compilation of K-Ar (Strutinski et al. 2006) and $^{40}Ar/^{39}Ar$ data (Dallmeyer et al. 1998; Culshaw et al. 2012) data from the same area enables better estimation of the maximum temperatures reached during the Cretaceous. Fig. 8 provides temperature estimates based partly on the upper limit of the ZPAZ (at least 300 °C; Hurford 1986; Yamada et al. 1995) and partly on widely accepted temperatures for argon retention in muscovite (400 ± 25 °C; von Blanckenburg et al. 1989; Hames & Bowring 1994). The same Fig. 8 also summarizes available age constraints. Note that, in the case of the Rodna horst, zircon central ages, which failed the Chi-Square test ($\chi^2 < 5$ %), and so do not represent cooling ages (R2-3 and R4-4), are omitted. Note that the colour coding of the ages in Fig. 8 is not identical for all data since some of the sources for radiometric ages only provide age groups and not individual ages.

The data indicate that metamorphic temperatures increase from NE to SW. Along the north-easternmost rim of the study area sub-greenschist facies metamorphic conditions (200–300 °C) are indicated by (1) the partial annealing of zircon fission tracks, (2) sub-greenschist facies metamorphic grade of Permian to Lower Cretaceous sedimentary cover and (3) undisturbed pre-Alpine K-Ar and $^{40}Ar/^{39}Ar$ mica ages (Dallmeyer et al. 1998; Strutinski et al. 2006). Temperatures between 300–400 °C are inferred further to the SW based on (1) fully annealed zircon fission tracks and (2) pre-Alpine K-Ar and $^{40}Ar/^{39}Ar$ ages (Dallmeyer et al. 1998; Strutinski et al. 2006). In the area of the Rodna horst still further SW both pre-Alpine and Cretaceous-age K-Ar and $^{40}Ar/^{39}Ar$ ages are found (Dallmeyer et al. 1998; Strutinski et al. 2006; Culshaw et al. 2012). The Cretaceous muscovite $^{40}Ar/^{39}Ar$ ages group around 95 Ma (Cenomanian) and only occur close to Alpine nappe contacts. This implies temperatures of around 400 °C during Cretaceous nappe stacking, which is corroborated by the greenschist facies microstructures found in Alpine-age tectonites (Culshaw et al. 2012).

Nearby age data were projected onto a schematic cross-section across the Rodna horst (Fig. 8). The contact between Infrabucovinian and Subbucovinian Nappes is openly folded with NW-SE striking fold axes. Fold axial planes dip 80° towards the NE. Note that the Borsa graben is delimited by Miocene age faults (Tischler et al. 2007). Assuming a geothermal gradient of 25 °C/km and a surface temperature of 25 °C the observed temperatures along the Central East Carpathian chain (200–300 °C) and in the south-westernmost corner of

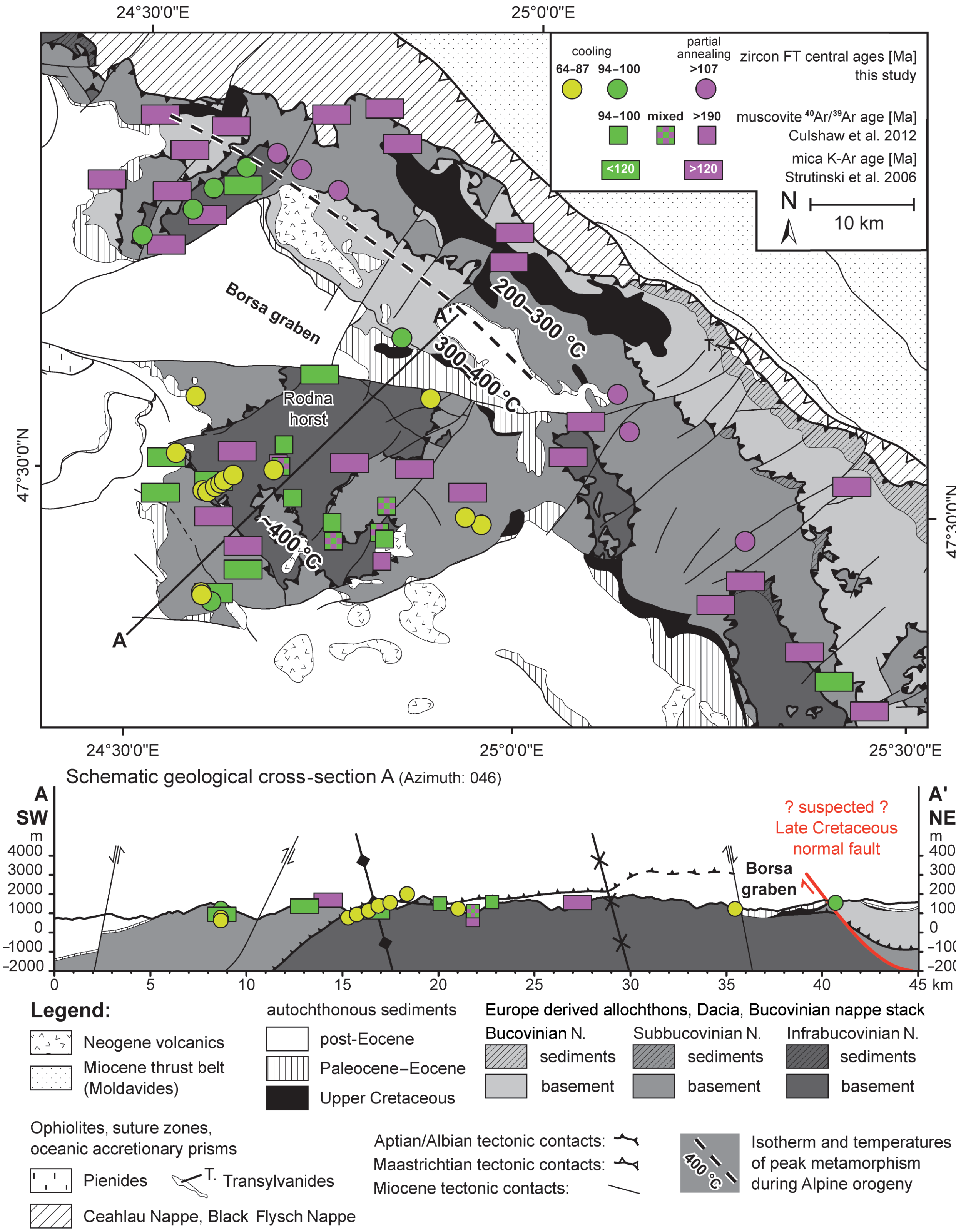

Fig. 8. Map and profile displaying estimates of maximum temperature reached during Early Cretaceous metamorphism based on the zircon fission track data of this study combined with estimates based on K-Ar- and ^{40}Ar/^{39}Ar-data compiled by Strutinski et al. (2006) and Culshaw et al. (2012). The compilation suggests increasing temperatures towards the SW. Sub-greenschist facies conditions prevailed along the NE part of the Maramureş Mountains and the Central East Carpathian chain where partial annealing of zircon is observed while Cretaceous-age greenschist-facies prevailed within the Rodna horst and in the Preluca massif (ESE of Fig. 8). There is an overall but rather unsystematic tendency towards younger isotopic as well as zircon fission track towards the SE, suggesting later cooling in the more internal, i.e. SE, areas.

the Rodna horst (~400 °C) correspond to former overburdens of 7–11 km and ~15 km, respectively. This overburden was largely removed during the Late Cretaceous since Upper Cretaceous and Paleogene sediments are locally preserved at the surface along this same profile (see also map of Fig. 8 and compilation of sedimentary ages of these post-metamorphic deposits in Fig. 9). This former overburden was partly provided by the South Apuseni–Transylvanian oceanic units including their Jurassic cover (part of the Eastern Vardar ophiolites — Schmid et al. 2008). Their former thickness is estimated as some 8 km in the Apuseni Mountains based on fission track evidence (Kounov & Schmid 2013). They were largely eroded, however, in Late Cretaceous times also in the subsurface of the central and eastern Transylvanian Basin (see profiles in Matenco et al. 2010). These oceanic units are, however, still preserved in the subsurface of the western Transylvanian Basin (De Broucker et al. 1998; Matenco et al. 2010) as klippen above the Biharia nappe system in the Apuseni Mountains (Matenco et al. 2010; Kounov & Schmid 2013) and very sporadically as klippen on the Bucovinian Nappe in the Eastern Carpathians (Höck et al. 2009).

Early Cretaceous nappe stacking ("Austrian" phase)

The compilation of all the zircon FT ages and the stratigraphical constraints regarding the Late Cretaceous post-tectonic cover (Fig. 9) show that pre-Cenomanian Early Cretaceous nappe stacking led to at least partial annealing of

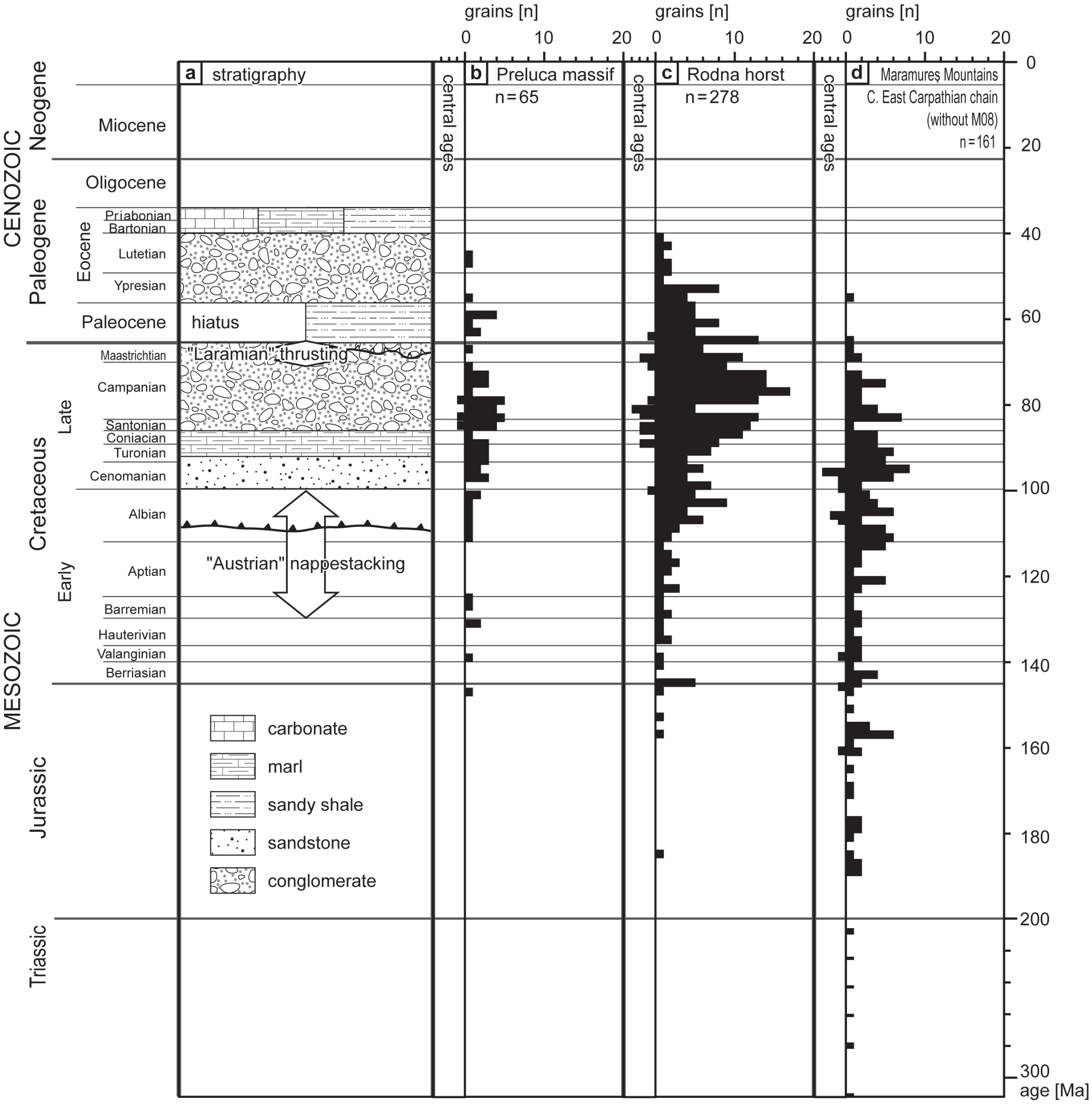

Fig. 9. Diagram comparing tectonic events and the stratigraphic record (**a**) with the spectrum of zircon fission track ages (b,c,d). Campanian cooling and exhumation in the Preluca massif (**b**) and the Rodna horst (**c**) is contemporaneous with the deposition of Upper Cretaceous conglomerates. Zircon FT ages indicate only partial annealing and Cenomanian cooling in the Maramureș Mountains and the Central East Carpathian chain (**d**).

fission tracks in zircon, followed by Late Cretaceous cooling and exhumation. Fig. 9, also clearly shows, together with Fig. 8, that degree of annealing and thus metamorphic grade increase from the area of the Maramureş Mountains and the Central East Carpathian chain in the NE towards the Rodna horst and the Preluca massif located more to the SW. This, together with the observation that the degree of annealing also depends on the position within the Bucovinian nappe stack (Fig. 6a–b), provides clear evidence that (1) this annealing is the consequence of nappe stacking during the Early Cretaceous orogeny, (2) that nappe stacking was most probably top NE and (3) that the Preluca massif attributed to the Biharia nappe system and whose annealing behaviour is similar to that of the Rodna horst area is also very probably part of this same nappe stack. The southwestward increasing tectonic overburden provided by the overriding South Apuseni–Transylvanian oceanic units provided the necessary overburden for Early Cretaceous metamorphism that reached greenschist facies conditions in the internal parts of our working area. SW-NE oriented Early Cretaceous shortening is also indicated by the NW-SE trending fold axes and predominant metamorphic lineations (Balintoni et al. 1997; Culshaw et al. 2012) associated with pre-Cenomanian folding of the Austrian nappe pile (profile of Fig. 8). Secondary ENE-WSW-oriented lineations of Culshaw et al. (2012) possibly reflect top ESE transport during Late Cretaceous extension (see below).

The available thermochronological data in the working area (Dallmeyer et al. 1998; Strutinski et al. 2006; Culshaw et al. 2012) do not allow us to precisely constrain the age of this Early Cretaceous metamorphic overprint. On the scale of the entire Biharia nappe system–Transylvanian Basin–Eastern Carpathians orogenic system (see Schmid et al. 2008 and Matenco et al. 2010 for a larger scale overview), and based on biostratigraphic evidence (Săndulescu 1975, 1984) the Early Cretaceous orogeny started during the Hauterivian to Barremian, which means about 130 Ma (Fig. 9a), with the onset of syntectonic sedimentation recorded in the South Apuseni–Transylvanian Nappes (Feneş Formation) and at the base of the Transylvanian klippen, on top of the Bucovinian nappe stack, in the Eastern Carpathians (Săndulescu 1984; Kounov & Schmid 2013).

During the latest stages of the Early Cretaceous orogeny the Bucovinian nappe pile became gently folded and juxtaposed against the more external Black Flysch and Ceahlau Nappes. The end of the Early Cretaceous orogeny is dated by Cenomanian and Turonian conglomerates and sandstones that overstep the folded nappe contacts (Ianovici & Dessila-Codarcea 1968). Cenomanian or even older (Aptian) post-tectonic cover is also known to overstep the contact of the Bucovinian–Getic nappe system with the underlying Ceahlau Unit in the southern part of the Eastern Carpathians (Bucegi Conglomerate — Stanley & Hall 1978). In our working area timing of the end of Early Cretaceous nappe stacking in the Cenomanian roughly coincides with Cenomanian zircon FT central ages (samples M01–M04 and M09 from the more internal parts of the Maramureş Mountains) and with Cenomanian $^{40}Ar/^{39}Ar$ muscovite ages (Dallmeyer et al. 1998; Culshaw et al. 2012) documenting cooling below 400 °C.

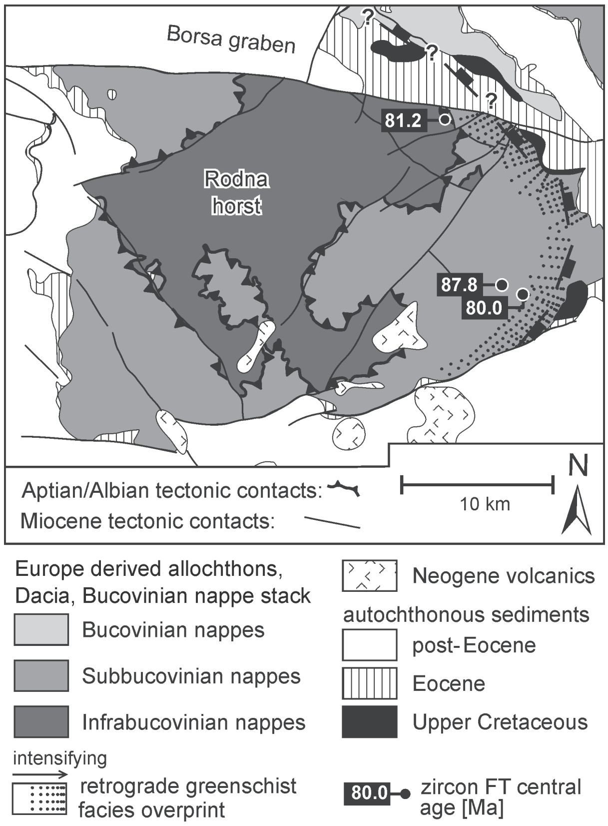

Fig. 10. Sketch map showing a belt with retrograde greenschist facies metamorphic overprint (Kräutner et al. 1978, 1983) running sub-parallel to parallel to the base of the Upper Cretaceous sediments on the eastern margin of the Rodna horst. This belt may serve as a normal fault that would explain the finding of zircon FT central ages (Coniacian to Campanian) that are younger than the age of deposition of the neighbouring Upper Cenomanian sediments.

However, Coniacian to Campanian zircon FT central ages from the Rodna horst and the Preluca massif indicate that these more internal areas cooled slowly and were still within the ZPAZ (i.e. 200–300 °C) in Cenomanian times. The close spatial neighbourhood of Coniacian to Campanian zircon FT central ages and Cenomanian sediments in the eastern part of the Rodna horst (Fig. 10) thus indicates 7–11 km differential exhumation between the internal area of the Rodna horst and the more external Maramureş Mountains and Central East Carpathian chain since the Cenomanian, assuming again a geothermal gradient of 25 °C/km and a surface temperature of 25 °C.

Late Cretaceous extension and exhumation

The Coniacian to Campanian zircon FT central ages (Figs. 5 and 6c–d) and the single grain zircon FT ages peaking in the Campanian (Fig. 7c) from the internal areas of the Rodna horst and the Preluca massif (Fig. 9b–c) indicate substantial Late Cretaceous cooling and exhumation, responsible for much of the 7–11 km differential exhumation between the internal area of the Rodna horst and the more external Maramureş Mountains and Central East Carpathian chain mentioned earlier. Most of this differential exhumation probably occurred mainly by extension, although distinct Upper Cretaceous structures have not yet been mapped in the area. On the other hand a broad zone of greenschist facies retromorphism in the Subbucovinian basement, running parallel to the contact with the Upper Cretaceous sedimentary cover (Kräutner et al. 1978, 1983) has been mapped and possibly marks a low angle top E shear zone of Late Cretaceous age, allowing for the exhumation of the basement units of the Rodna horst (Fig. 10). A possible continuation of this feature into the area of the Borsa graben (Figs. 8 and 10), which is bounded by Miocene-age faults (Tischler et al. 2007) and unfortunately overprints Cretaceous structures, could explain the presence of syntectonic Santonian to Maastrichtian conglomerates in the area of this graben (Szasz 1973) as well as the presence of Infrabucovinian and Bucovinian Nappes at similar altitudes south and north of the Borsa graben, respectively (Fig. 8).

Late Cretaceous extension leading to the exhumation of metamorphic domes and contemporaneous sedimentation is widespread within the ALCAPA (e.g. Neubauer et al. 1995) and Tisza–Dacia Mega-Units (e.g. Willingshofer et al. 1999; Schuller et al. 2009). Although the exact timing and geodynamic context of Late Cretaceous basins may be different in different parts of the ALCAPA and Tisza–Dacia Mega-Units such Late Cretaceous basins are often collectively coined with the term "Gosau" or "Gosau-type" basins (see discussion by Willingshofer et al. 1999). The term "Gosau" was originally defined in the Eastern Alps and used for piggy-back basins interpreted to have formed in the upper plate of an active margin related to the subduction of the South Penninic Ocean ("external" Gosau of the Northern Calcareous Alps — e.g. Wagreich & Faupl 1994), and/or, for basins that are believed to have formed due to massive extension and associated exhumation of metamorphic rocks within over-thickened crust ("internal" Gosau of the internal upper Austroalpine basement nappes — e.g. Neubauer et al. 1995).

Late Cretaceous sedimentary basins within the Tisza and Dacia Mega-Units have some similarities with the "internal" Gosau of the Eastern Alps in that they post-date Cretaceous-age nappe stacking and are associated with the exhumation of previously stacked nappe piles. However, we do not regard the term "Gosau" for such Late Cretaceous sediments within the Tisza and Dacia Mega-Units as particularly useful since there appear to be two periods of Late Cretaceous extension in these Mega-Units: (1) a first one affects units attributed to the Dacia Mega-Unit and starts in Late Albian to Cenomanian times (basal siliciclastics of our working area; Fig. 9a), roughly contemporaneous with the sedimentation of the Bucegi Conglomerate of the Eastern Carpathians and the Valea lui Paul Formation of the Biharia nappe system in the Apuseni Mountains (Bleahu & Dimian 1967; Kounov & Schmid 2013). (2) A second period of extension and sedimentation lasted from Turonian to Maastrichtian times ("Gosau" deposits of the northern Apuseni Mountains attributed to the Tisza Mega-Unit — e.g. Săndulescu 1994; Schuller et al. 2009; Kounov & Schmid 2013). In the case of the Apuseni Mountains zircon FT central ages from the South Apuseni Mountains indicate that cooling of parts of the Biharia nappe system (Vidolm Nappe), a part of the Dacia Mega-Unit, started already in Albian–Cenomanian (112–96 Ma) times (Kounov & Schmid 2013). Zircon FT central ages from the Baia de Arieş Nappe of the Biharia nappe system of the Apuseni Mountains yielded central ages between (101–69 Ma; Kounov & Schmid 2013). This age range is very similar to that found in the Preluca massif of our working area, supporting correlation of the basement of the Preluca massif with that of the Baia de Arieş Nappe in the Apuseni Mountains (Rusu et al. 1983; Strutinski et al. 2006), both being part of the Dacia Mega-Unit. The most prominent time of extension and contemporaneous sedimentation of Late Cretaceous deposits in the Tisza Mega-Unit of the North Apuseni Mountains occurred, however, in Turonian to Maastrichtian times (94–65 Ma; Schuller 2004); zircon FT central ages in this part of the Apuseni range between 89–71 Ma (Kounov & Schmid 2013).

The geodynamic scenario for Late Cretaceous extension in the Tisza and Dacia Mega-Units is a matter of debate. Some authors proposed in situ orogenic wedge collapse following thickening of the continental crust (e.g. Willingshofer et al. 1999). Others related the deposition of Upper Cretaceous sediments to a fore-arc basin scenario (Schuller 2004; Schuller et al. 2009). Extension related to the formation of the Late Cretaceous Apuseni–Banat–Timok–Sredna Gora magmatic belt (von Quadt et al. 2005) behind the N-directed subduction of the Neotethys in the Aegean area is yet another possibility. Our data document long-lived and surprisingly large amounts of Late Cretaceous extensional unroofing of the Bucovinian nappe stack in Cenomanian to Campanian times. This makes a fore-arc scenario rather unlikely and favours the orogenic wedge collapse model proposed by Willingshofer et al. (1999).

Latest Cretaceous thrusting ("Laramian"phase) and Paleocene exhumation

During the "Laramian" phase in the Maastrichtian, the Ceahlau and Black Flysch Units were thrusted onto the most internal nappes of the Moldavides, carrying the mid-Cretaceous Bucovinian nappe stack along in "piggy-back" fashion. This thrusting caused exhumation by erosion in the more external part of the study area, expressed by the erosion of much of the Upper Cretaceous cover and a period of non-deposition during the Paleocene in much of the working area (Figs. 3 and 9). In the Preluca massif, however, continental shales and sandstones (Jibou Formation) were deposited directly onto the pre-Mesozoic basement during the Paleocene, which requires erosion of all former Cretaceous-age cover sometime during the latest Maastrichtian and/or Early Paleocene. We found no Paleocene-age central ages (with the exception of M09 for which hydrothermal overprint is invoked). The apatite fission track and (U-Th)/He thermochronology available from the Apuseni Mountains (Merten et al. 2011; Kounov & Schmid 2013) and the Eastern Carpathians (Merten et al. 2010), however, provide evidence for considerable amounts of latest Cretaceous to Paleogene exhumation that must also have affected our working area in a temperature range below some 200 °C that we could not explore due to later re-heating.

Eocene burial and Miocene exhumation

Renewed burial started in the Eocene with the sedimentation of conglomerates, followed by marls and platform carbonates (Fig. 9a). It continued in Oligocene times with flysch sedimentation, starting with fine-grained siliciclastics coarsening into sand dominated flysch units. Our data show that related burial metamorphism did not even reach temperatures to allow for partial annealing of zircon fission tracks, as indicated by the complete lack of zircon FT single grain ages younger than Eocene (Fig. 9). As a consequence of erosion after Miocene shortening and strike-slip faulting the basement units of the Preluca massif and the Bucovinian nappe stack only underwent minor differential exhumation (Gröger et al. 2008). This indicates that Miocene-age differential exhumation was modest in the area and did not exceed some 2 km. The total amount of Miocene-age exhumation in the Eastern Carpathians is in the order of 5–7 km (Gröger et al. 2008; Merten et al. 2010), which is substantially less than that reported for Late Cretaceous times by the present study, which must substantially exceeds 10 km in view of our estimate for 7–11 km differential exhumation alone.

Conclusions

Our zircon FT study provides two major constraints regarding the Cretaceous history of the Bucovinian nappe stack of the Eastern Carpathians:

(1) Early Cretaceous ("Austrian") nappe stacking is inferred to have been top to the NE. While only sub-greenschist facies were reached in the main Maramureş Mountains and Central East Carpathian chain (Fig. 9d), temperatures of about 400 °C are documented for the areas of the more internal Rodna horst (Fig. 9c) and the Preluca massif (Fig. 9b) attributed to the Biharia nappe system of the Apuseni Mountains. This temperature gradient is interpreted as the result of increasing tectonic overburden (up to about 15 km) towards more internal units, partly provided by the South-Apuseni–Transylvanian nappe stack within the Dacia Mega-Unit, comprising both the Biharia nappe system and the Bucovinian nappe stack.

(2) The zircon FT central and single grain ages largely reflect Late Cretaceous cooling and exhumation. Differential exhumation by some 7–11 km, indicated by a combination of FT data and stratigraphic constraints, point to massive amounts of Late Cretaceous extension accompanied by predominantly tectonic exhumation that must have substantially exceeded 10 km. Due to the lack of structural data this massive extension is documented for the first time.

Later events such as the latest Cretaceous ("Laramian") juxtaposition of the nappe pile with the internal Moldavides, causing exhumation by erosion, re-burial by sedimentation and tectonic loading during the Cenozoic had no impact on the zircon FT data but prevented a study of the low temperature part of the Late Cretaceous exhumation history. The presence of Upper Cretaceous sediments deposited on exhumed pre-Permian basement indicates exhumation of parts of the basement of the Bucovinian nappe stack to the earth's surface in Late Cretaceous times.

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