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ALPINE UPLIFT HISTORY OF THE CENTRAL WESTERN CARPATHIANS: GEOCHRONOLOGICAL, PALEOMAGNETIC, SEDIMENTARY AND STRUCTURAL DATA

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Abstract: The mid-Cretaceous onset of the Alpine uplift of previously burried pre-Tertiary basement and cover rock units is recorded in the southern Central West Carpathian zones in the Veporic superunit. The Meso-Cenozoic collisional processes gradually continued by the uplift of more external Tatric units during the Paleogene, Neogene and Quaternary. Based on the paleo-Alpine values of Rb - Sr, Ar - Ar, K - Ar and FT datings, the south to north Veporic and southernmost Tatric (Nízke Tatry Mts.) zones began to be uplifted from the depth levels of ca. 20 km (T = 350 - 450 °C) 120 - 90 Ma ago. They reached ca. 100 °C 90 - 55 Ma ago which indicates an average uplift rate of about 0.5 mm/year. To the contrary, the Tatric pre-Alpine complexes have been not buried deeper than 12 km (ca. 250 °C) after the Permian. Their uplift is documented by zircon and apatite FT data. It started from depths of 10 - 11 km (225 °C) about 70 - 50 Ma ago and reached the 5 km (100 °C) depth level 30 - 15 Ma ago. Accordingly, the average uplift rate was 0.1 - 0.2 mm/year. Besides the time differences, the dynamic background of uplift in the Veporic and Tatric zone was also apparently different. The impacts of distinct tectonic regimes on the modes of uplift, namely the tectonic unroofing of metamorphic domes vs. block rotation in wrench zones, are briefly discussed.

Key words: Central Western Carpathians, pre-Tertiary basement, Meso-Cenozoic, uplift history, FT data.

Introduction

The polarity of orogenic processes within the Western Carpathian mountain belt is reflected in the migration of geological processes, generally from south to north. The migration affected manifestations of Mesozoic rifting and lithospheric extension, subsidence and sedimentation, compression with progradation of individual deformation stages as well as post-collision uplift, tectonic denudation and erosion.

Rock uplift is an integral component of tectonic evolution of the elevated zone. It is documented by cooling ages of different mineral phases, by the structural regimes in ductile and later in brittle deformation field, as well as by the sedimentary record of the adjoining basins with the presence of clastic material derived from uplifted sources.

The aim of the paper is to discuss isotope K - Ar, Ar - Ar and Rb - Sr, as well as fission track (FT) geochronological data obtained from the Central Western Carpathian (CWC) granitic and metamorphic rocks. The presented model summarizes the cooling history of the individual crystalline complexes and the Alpine burial and uplift history of the Central Western Carpathians from the Cretaceous to Quaternary.

Cooling ages

Our interpretations of rock uplift in the Central Western Carpathians are based on the results of Rb - Sr, Ar - Ar, K - Ar and FT geochronologic methods. These are mentioned mainly in Burchart et al. (1987), catalogue of Cambel et al. (1990), Bibikova et al. (1990), Hurai et al. (1991), Dallmeyer et al. (1993a, b) and Maluski et al. (1993).

All above mentioned geochronologic methods are based on measurements of radioactive and their daughter radiogenic isotopes and/or their ratios (^{87}Rb - ^{87}Sr, ^{40}Ar - ^{39}Ar, ^{40}K - ^{40}Ar) in different minerals (muscovite, biotite, feldspar) or fission tracks in apatites and zircons (FT method). An accumulation of daughter isotopes in these minerals usually begins in temperatures below these in plutonic and/or metamorphic events. The ages represent the time when rocks cooled to blocking temperature, different for different parent - daughter pairs.

Besides the magmatic crystallization and tectonometamorphic events, the uplift or cooling of magmatic and metamorphic rocks is one of the most prominent geological processes, which are recorded in some rock-forming or accessory minerals, e.g. in micas, amphiboles, feldspars, zircon or apatite. The accumulation rate of daughter isotopes (or fission tracks) strongly depends on the temperature of the system: if temperatures overstep a certain critical value, their loss or annealing would prevail over production from parental radioactive isotopes and, consequently, ages measured from parental/daughter isotopic ratios or FT density will be younger than primary magmatic or metamorphic age of the studied rock. Only after cooling below this critical, i.e. blocking or closing temperature, the system closes and can provide the age of the cooling.

The blocking temperatures vary for individual systems and minerals and, in addition, they depend on many other factors (e.g. rate of crystallization, chemical composition of minerals).

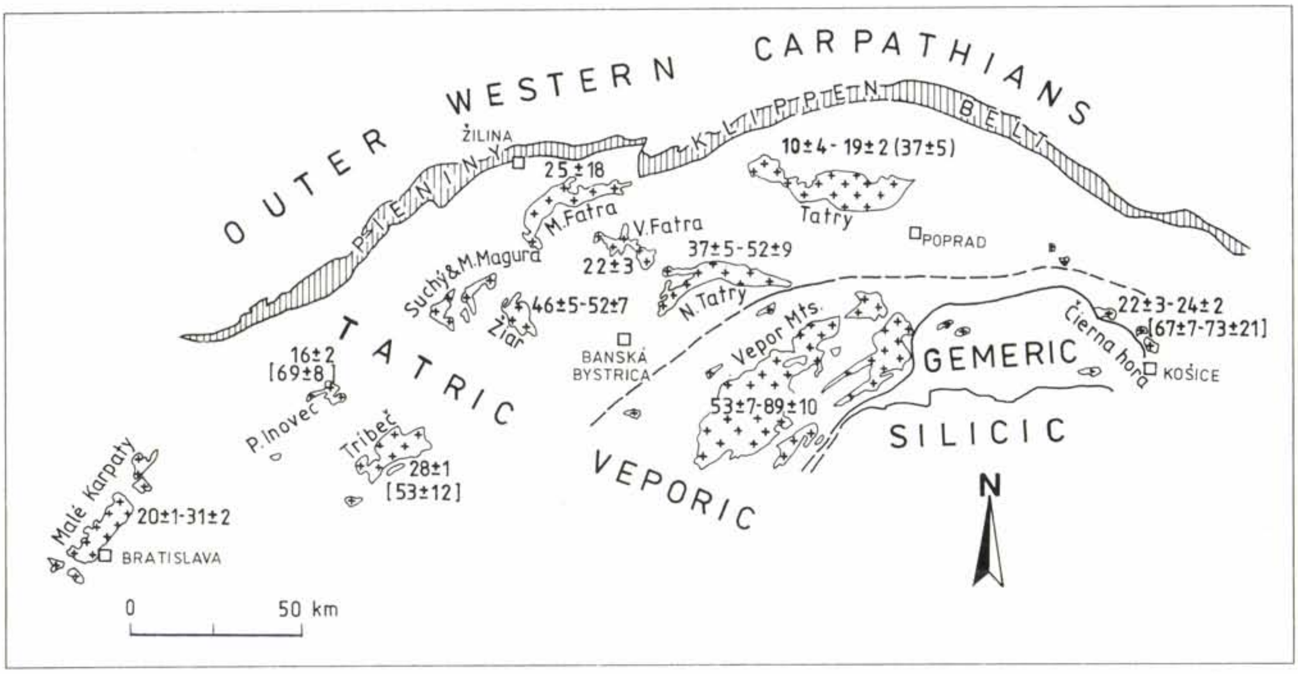

Fig. 1. The Western Carpathian Variscan granitoid massifs with apatite and zircon (in brackets) FT cooling ages in Ma. Taken from Burchart (1972), Kráľ (1977), Cambel et al. (1990) and the present work (Tab. 1).

In our calculations, we are using mostly the intermediate values with errors of ca. 20 - 50 °C, as recommended in recent literature: ca. 500 °C for amphibole in K - Ar system (Harrison et al. 1979; Hunziker et al. 1992, Neubauer et al. 1992), 400 °C for muscovite in Ar - Ar system (Neubauer et al. 1992; Dallmeyer 1993 - oral comm.), 350 °C for muscovite in K - Ar system (Purdy & Jäger 1976; Burchart et al. 1987), 300 °C for biotite in Rb - Sr system (Neubauer et al. 1992), 270 °C for biotite in K - Ar system (Burchart et al. 1987; Cambel et al. 1990), 225 °C for FT in zircons (Hurford 1986; Neubauer et al. 1992), 150 °C for K-feldspar in K - Ar system (Harrison & McDougall 1980) and 100 °C for FT in apatite (Haack 1977; Burchart et al. 1987).

For the analytical procedure of FT dating see Kráľ (1977) or Cambel et al. (1990) and the next chapter of the present work. New FT data are listed in Tab. 1 and 2 of this work, FT data from the CWC realm are depicted in Fig. 1.

Determined model ages, assuming monotonous cooling of granitoid intrusions and model behavior of isotope (K - Ar, Ar - Ar, Rb - Sr) or FT systems, indicate the age of passing of the granitoid massif through the above mentioned blocking temperature. This corresponds, at a given geothermal gradient, to a concrete burial depth of the observed part of the massif at a certain time interval.

For the purpose of our calculations, we have chosen 20 °C/km as an average value of the geothermal gradient, corresponding to recent gradients in the areas of collisional and extensional tectonism in Neoeurope, and more concretely in the present Western Carpathians (Čermák 1984). However, the distinctly higher geothermal gradients (30 - 40 °C/km) can be suggested for uprising metamorphic core complexes, e.g. the Veporic superunit at the end of its paleo-Alpine uplift. We are fully aware the following calculations of paleouplift rates of certain domains are affected by several possible errors and represent only the first approximation which, however, reveals a logical succession of uplift events during the Alpine orogeny and are consistent with the published data on orogenic uplifts (cf. Kukal 1983).

Rocks of the CWC crystalline and Mesozoic cover complexes are subdivided into three principal tectonic superunits: Tatric, Veporic and Gemeric (Fig.1). The Tatric complexes form separate horst elevations - so called core mountains, in contrast to a compact domain of the Veporic and Gemeric units. According to isotope and FT age pattern, the CWC area may be divided into the internal, i.e. southern Veporic-Gemeric and external, i.e. northern Tatric domains.

Analytical procedure of FT measurements

In EDM technique, zircon grains were mounted in FEP teflon and polished to 4π geometry. Grains were etched in eutectic melt of KOH and NaOH for 10 - 30 hours at 200 °C. Spontaneous tracks in zircons were counted in magnification 1200× in oil. Induced tracks were counted in Lexan that was used as external detector for induced tracks registration.

All samples were irradiated in thermal column of nuclear reactor in Swierk (Poland). NBS 962, 963 glass standards were used for neutron fluence determination. For the determination of the total neutron dose, fission track densities in glass were callibrated to Cu wire (Hurford & Green 1982).

The uncertainty of the doses is expressed as confidence interval for the mean (CIM).

The uncertainty of the ages is expressed as square root of the sum of squares of the confident intervals for the mean in spontanneous and induced track densities and standard glasses.

Cretaceous uplift of the Veporic domain

The shortening history of the central zones of the Western Carpathians began by closing of the Meliatic ocean and subsequent collision of its margins. This occured, according to the sedimentary record (Kozur 1991) and isotope datings (Ar - Ar on phengite from glaucophanites of the Meliata unit - Maluski et al. 1993; Dallmeyer et al. 1993a), during the Late Jurassic. The northern - passive margin of the Meliatic ocean, modelled by the Triassic rifting, was shortened and piled up in a thick orogenic wedge of upper-crustal thrust stack of basement/cover nappes, duplexes and imbrications. This nappe pile overrode the Veporic domain probably during the Early Cretaceous (Plašienka 1993). The thermal metamorphic peak in the Veporic basement resulting from thermal equilibration after thrusting is estimated at 350 - 550 °C and 500 - 800 MPa, i.e. in the depths of approximately 20 - 30 km (Vrána 1980; Méres & Hovorka 1991). According to data of Mazzoli et al. (1992), b_0 values of muscovites from the Lower Triassic slates of the south Veporic Foederata Unit reveal an even higher overburden and HP-LT imprint (1.2 GPa, 350 - 400 °C). However, these data are not accepted without limitations by all authors, as the metamorphic imprint of Mesozoic cover rocks points only to low grade P-T conditions, mostly around 300 - 350 °C (Plašienka et al. 1989; Krist et al. 1992). Uplift, cooling and extensional unroofing of the Veporic basement is recorded by the formation of two generations of Alpine-type veins, the older at 420 - 495 °C and 280 - 430 MPa, i.e. 10 - 16 km and the younger at 320 - 420 °C and approx. 250 - 350 MPa in 9 - 13 km (Hurai et al. 1991).

According to the isotopic and FT cooling or closing ages of different mineral phases (Fig. 2), the uplift of the Veporic basement started from relatively deep middle-crustal levels (15 - 20 km) in Lower to Middle Cretaceous times (ca. 120 - 90 Ma). During the Late Cretaceous (90 - 70 Ma ago), the Veporic basement cooled to 300 - 100 °C, which would indicate depths of approximately 3 - 8 km, if a comparatively high thermal gradient of 30 - 40 °C/km, acceptable for uplifting metamorphic domes and indicated by data of Hurai et al. (1991), is taken into account. The corresponding average uplift rate can be estimated at roughly 0.5 mm/year.

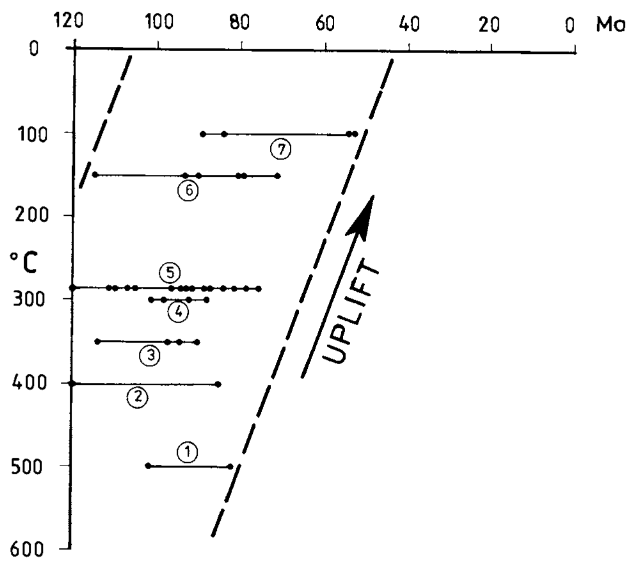

Fig. 2. The Cretaceuos to Paleogene uplift path of the Veporic basement units based on isotope and FT mineral cooling ages. **1** - K - Ar amphibole; **2** - Ar - Ar muscovite; **3** - K - Ar muscovite; **4** - Rb - Sr biotite; **5** - K - Ar biotite; **6** - K - Ar K-feldspar; **7** - FT apatite. References: 1, 3, 5, 6 and 7 Cambel et al. (1990), 2 - Dallmeyer et al. (1993), 3 - Bibikova et al. (1988), 4 - Bibikova et al. (1990), 6 - Hurai et al. (1991), 7 - Kráľ (1977).

The above outlined cooling history and the Alpine structural evolution of the southern Veporicum is consistent with a typical collisional scenario: (1) burial of an upper crustal unit below a thick pile of overthrust units with top-to-north stacking, (2) increasing temperatures in the lower unit due to conductive heating, strain softening, (3) isostatic rebound, extensional collapse with top-to-east unroofing, cooling and strain hardening of detachment shear zones, out-of-sequence thrusting (Plašienka 1993; Hók et al. 1993). At the beginning, a substantial portion of the uplift was probably adjusted by extensional unroofing of the Veporic dome. This is structurally recorded in the Mesozoic, mostly carbonatic lithologies of the Foederata Unit, which forms the Permomesozoic sedimentary cover of the Veporic pre-Alpine crystalline basement. This unit was sandwiched as a subhorizontal ductile horizon within the nappe pile and accomodated, along with basement mylonite zones, most of the extensional strain. After cooling to temperatures below 300 °C, the ductile deformation along subhorizontal shear zones stopped, however. Later on, the continuing uplift had to be compensated mainly by erosion. The erosional products began to fill the Poruba flysch basin of the Fatric and Tatric realms located to the north of the uplifting Veporic domain, starting already from the Early-Middle Albian (approximately 105 Ma). Erosion lasted probably until the Early Senonian. Afterwards, during the Late Turonian in the Tatric realm, the principal overthrust event took place and the great systems of Carpathian cover nappes (Fatric or Krížna, Hronic or Choč and Silicic system) were emplaced. In the Veporic domain, these unmetamorphosed nappes overlie a deeply eroded and peneplained substratum with a marked metamorphic and structural disconformity at their soles (Vrána 1966, Plašienka 1984, 1993). During the Late Senonian, most of this area was flooded by a shallow epicontinental sea (Mišík 1978).

In contrast to the Veporic-Gemeric area, the crystalline basement of the Tatric zones of the CWC was probably never exposed during the Middle and Late Cretaceous. It carried a continuous, mostly deep-marine sedimentary cover depositing until the Lower Turonian, which was overriden by superficial cover nappes and these were again, at least partly, covered by Senonian sediments (Gosau Group). This indicates an increasing burial of the Tatric crystalline basement during the Cretaceous, which may be estimated at 7 - 8 km during the Late Senonian. Nevertheless, the Tatric basement never reached the P-T conditions comparable to that of the Veporic in Alpine times, which is clearly indicated by the preservation of Variscan metamorphic and igneous formation and cooling ages (e.g. Cambel et al. 1990; Janák & Onstott 1993; Dallmeyer et al. 1993b; Maluski et al. 1993). Except the FT datings, the only exception was determined in the Malé Karpaty Mts., where fine-grained muscovite (sericite) of mylonitized granitoids from the Borinka and Modra shear zones provided ages of 77 and 74 Ma, respectively (K - Ar, Kantor 1987 ex Putiš 1991). These locations are confined to the overthrust planes of basement-cover subunits in frontal parts of the Tatric sheet, where the Tatric Mesozoic sedimentary cover also suffered anchimetamorphic imprint due to nappe stacking (Plašienka et al. 1993).

Later on, during the Paleocene, the Tatric basement was probably slowly uprising, as it is indicated by scarce fission tracks accumulated in zircons by passing the 225 °C isotherm (53 ± 12 Ma in the Tribeč Mts. and 69 ± 8 Ma in the Považský Inovec Mts. - see Tab. 1).

Table 1. FT datings from granitoid rocks of CWC crystalline complexes. External detector method. NBS 962, 963 standard glasses were used for the thermal neutron flux determination.

No.	N	N_i	N_s	ps/pi ± SD	dose × 10^{15}	Rxy	age (Ma) ± CIM
Malé Karpaty Mts.							
apatite							
8/63	14	5777	742	0.1280 ± 0.0232	5.620 ± 0.22	0.79	22 ± 3
17/63	23	1235	217	0.1762 ± 0.0233	5.620 ± 0.22	0.84	30 ± 2
28/63	19	17265	1864	0.1176 ± 0.0099	5.620 ± 0.22	0.96	20 ± 1
37/63	9	964	153	0.1288 ± 0.0218	5.620 ± 0.22	0.96	22 ± 3
51/63	17	8405	1496	0.1796 ± 0.0217	5.620 ± 0.22	0.67	31 ± 2
52/63	23	3749	651	0.1624 ± 0.0191	5.620 ± 0.22	0.74	28 ± 2
The Tribeč Mts.							
apatite							
ZK-1	11	1579	507	0.3194 ± 0.0074	2.840 ± 0.11	0.99	28 ± 1
zircon							
ZK-1	8	104	1180	13.7205 ± 3.5700	0.126 ± 0.06	0.83	53 ± 12
The Čierna Hora Mts.							
apatite							
ZK-11	6	1800	475	0.2646 ± 0.0353	2.700 ± 0.11	0.96	22 ± 3
3ZK-12	8	1722	470	0.2755 ± 0.0183	2.840 ± 0.11	0.99	24 ± 2
zircon							
ZK-11	6	86	397	18.8207 ± 8.1050	0.127 ± 0.06	0.79	73 ± 31
ZK-12	12	58	924	17.1640 ± 2.8920	0.127 ± 0.06	0.83	67 ± 7
The Považský Inovec Mts.							
apatite							
ZK-15	7	8691	2248	0.2539 ± 0.0249	2.070 ± 0.08	0.97	16 ± 2
zircon							
ZK-15	11	69	1242	17.8977 ± 3.2170	0.126 ± 0.06	0.85	69 ± 8

N - number of analysed grains, N_i - number of counted induced tracks, N_s - number of counted spontaneous tracs, ps/pi - weighted average of rations calculated from analysed crystales, SD - standard deviation, CIM - confidence interval for determined age, thermal neutron dose, Rxy - correlation coefficient of pi and ps analysed grains.

Tectonic background of the Paleogene burial and uplift in the Tatric area

The Central Alpine - Western Carpathian tectonic evolution was governed by the convergence which gradually passed into a collision of the overriding Alpine plate and the lower - Northern European plate, from the west to the east during the Paleogene (Tollmann 1966, Jiříček 1979).

The advancement of the Alpine part of orogene towards NW and later towards N generated movements along dextral shear zones enabling southeastward motion of the Central Western Carpathians as a part of the Northern Pannonian crustal segment (sensu Csontos et al. 1992, see Fig. 3). This domain was bounded by dextral wrench corridors from both sides: in the south by the Periadriatic-Central Hungarian lineament, and in the north by the zone rimming the Central Alpine and Central Carpathian segment. The latter comprises the Northern Calcareous Alps and the Pieniny Klippen Belt. Right-lateral kinematics of an oblique convergence was probably governed there by the counter-clockwise rotation of the entire, generally rigid Central Alpine-Carpathian domain (Márton 1988a).

The Late Cretaceous and Early Tertiary dextral wrenching along the northern edge of the Austroalpine - Central Carpathian domain is documented by the synsedimentary tectonic evolution of the Gosau basins (Faupl & Wagreich 1993; Wagreich 1993) and transpressional structures in the Northern Cal-

Table 2. FT - datings of apatite from granitoid rocks of Žiar Mts., the POP method. NBS 962 standard glass was used for the thermal neutron flux determination.

No.	Ps ± CIM (× 10^6)	Ns	Pi ± CIM (× 10^6)	Ni	age (Ma)[1]
001	0.41 ± 0.05	2789	2.38 ± 0.09	11441	52 ± 7
003	0.48 ± 0.04	3185	2.96 ± 0.17	13180	49 ± 5
006	0.37 ± 0.03	2307	2.43 ± 0.19	10299	46 ± 5
013	0.37 ± 0.03	2552	2.31 ± 0.09	12337	49 ± 5

1 - FT ages were calculated with a total thermal electron dose of 4.96 ± 0.15 × 10^{15}

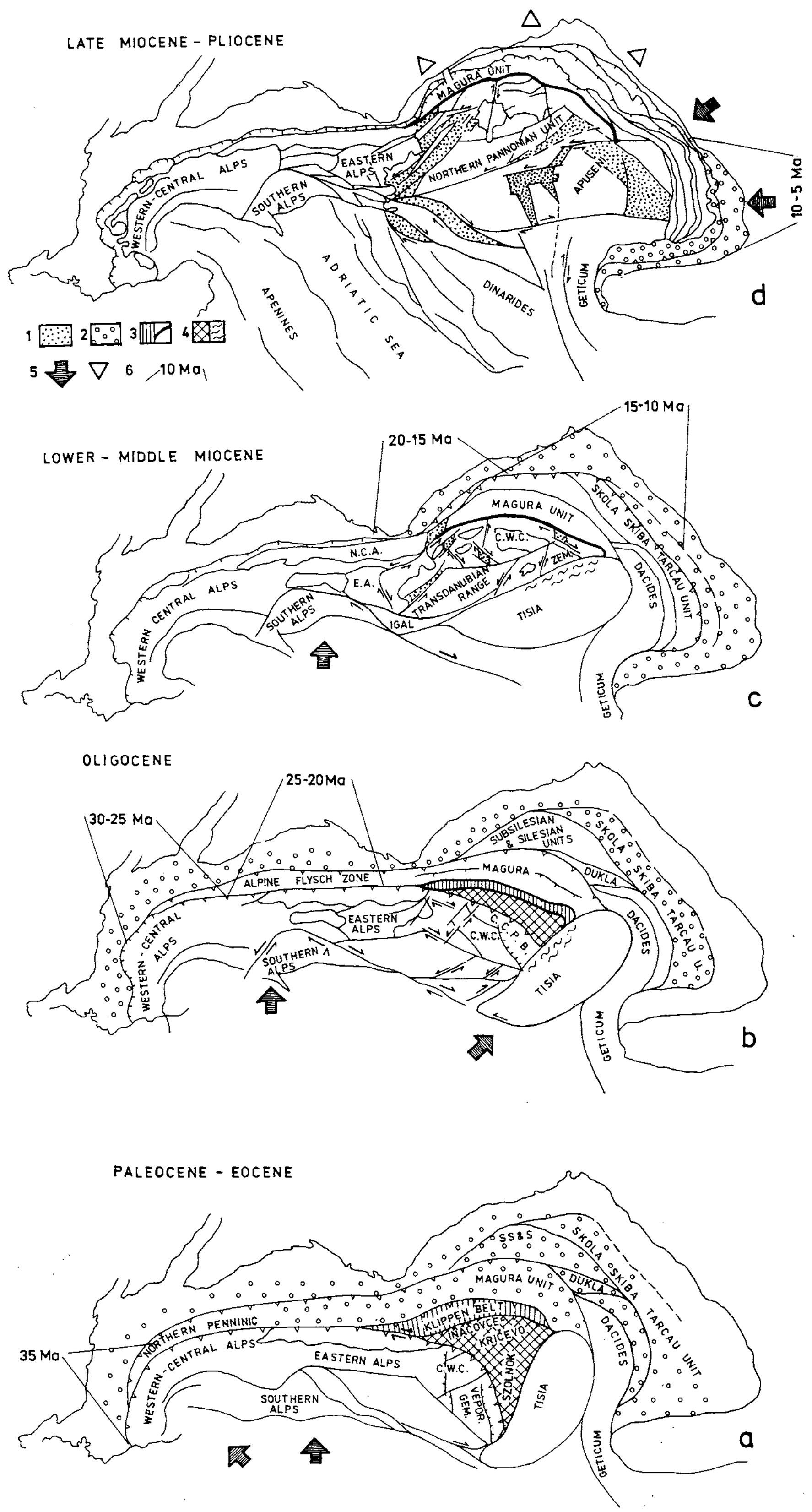

Fig. 3. A sketch of the Tertiary structural development of the Alpine - Carpathian orogen. Adapted from Balla (1984, 1987), Jiříček (1979), Kováč et al. (1989), Royden (1988), Sandulescu (1988), Seifert (1992), etc. Explanations: **1** - Neogene basins; **2** - foreland basins; **3** - Pieniny Klippen Belt; **4** - Szolnok flysch; **5** - orientation of principal compression and extension; **6** - last overthrust movements.

careous Alps (Linzer et al. in press) and in the Malé Karpaty Mts. of the westernmost Carpathians (Plašienka 1990; Marko et al. 1990), as well as in the eastern sector of the Pieniny Klippen Belt (Ratschbacher et al. 1993).

The Northern Calcareous Alps east of the eastern end of the Tauern window suffered clockwise rotation of more than 30° during mid-Cretaceous times (in the Aptian - Cenomanian interval), as it is suggested by paleomagnetic data (Mauritsch & Frisch 1978; Channell et al. 1992). After this, the overall position of the NCA with respect to the stable European margin did not change significantly (Márton 1987, 1993). By contrast, tectonic units of the Carpathian-Pannonian area were considerably displaced in the Tertiary (Fig. 3). There is ample evidence to show that the Outer and Central Western Carpathians together with the Transdanubian Central Range rotated in counter-clockwise sense by angles up to 90° (Márton 1987, 1993).

It is less widely known, however, that paleomagnetic inclinations indicate the southward shift of the Northern Pannonian crustal segment after the Late Cretaceous with respect to the southern margin of stable Europe (Márton 1988a, b). The post-Cretaceous shift southwards was followed at places, e.g. in the Transdanubian Central Range, by a fast counter-clockwise rotation in the Eocene. The late Eocene and Oligocene seems to have been uneventful (Márton 1988b, in press).

The Early Tertiary motion of the Central Western Carpathians was accompanied by further burial of its destructive margin. The Paleogene basins extended mainly above the external zone of the Tatric basement and the Penninic-type Vahic units (sensu Mahel' 1981; Soták et al. 1993; Plašienka in press) situated on the inner side of the Pieniny Klippen Belt. A similar situation is presumed also on the eastern margin of the escaping Northern Pannonian crustal segment (Csontos et al. 1992), where the basins of Buda Paleogene and Szolnok Flysch were located (Fig. 3a).

Subsidence of the Central Carpathian Paleogene Basin, in front of uplifted inner zones of the Central Western Carpathians, reached its peak during the Eocene. The basin evolution was controlled probably by the roll-back effect of the Penninic subduction, and/or collapsed due to a subcrustal erosion of the Tatric sole during the subduction process (cf. Wagreich 1993).

Turbiditic sedimentation predominated in the Central Carpathian Paleogene Basin (CCPB). Besides the input of coarse clastic material from the southern, elevated internal zone of the Central Carpathians - built up mainly of the Mesozoic cover nappes and the Veporic and Gemeric crystalline complexes, some northern sources (cordilleras) were assumed as well (Marschalko 1975, 1978; Gross & Köhler 1980; Nemčok 1989; etc.). The diachronous development of sedimentary facies within the CCPB shows migration of the basin depocentres from the west to the east (Gross et al. 1984). A similar migration of basin depocentres can be observed also in the Buda Paleogene Basin and Szolnok Flysch Basin situated on the southern margin of the Northern Pannonian crustal segment (Báldi 1986; Nagymarosy 1990; Nagymarosy & Báldi-Béke 1993; Tari et al. 1993).

The advance of the Paleogene transgression finaly lead to a marine connection of the Central Western Carpathian and Buda Paleogene Basins (Gross 1978; Nagymarosy 1990). The sea-way was probably opened along the Central Slovakian Fault System which developed as a N-S trending sinistral wrench zone (Kováč & Hók 1993) bounding the western margin of the rigid Veporic-Gemeric domain, individualized and stabilized during the Cretaceous. The transtensive character of this strike-slip zone indicates its function as a boundary between the influence of the Alpine collision in the west and roll-back effect of the Penninic oceanic subduction in the east during the Paleogene.

In the Alpine-Carpathian-Pannonian junction area, the transtensional regime enabled basin formation not only on the Central Carpathian margin, but also in more internal parts (Fig. 4). In addition to the N-S sinistral strike-slips, also the dextral shears of ENE-WSW direction and NW-SE trending normal faults played a significant role during the basin formation in the western part of the Carpathians. This fault activity created the Paleogene structural pattern which is presently characterized by NW-SE compression or NE-SW trending extension in the western part of the Central Western Carpathians and Transdanubian Central Range (Marko et al. 1990, 1991; Fodor 1992; Fodor et al. 1992; Kováč & Hók 1993; Vass et al. 1993).

In contrast with that, the estimated paleostress field in the eastern part of the Central Western Carpathians was characterized by NE-SW compression (Nemčok 1993), which is in a good agreement with the NE-SW and ENE-WSW orientation of the normal and sinistral strike-slip faults, respectively, controlling the tectonic evolution of this region during the Paleogene (Gross & Köhler 1980; Nemčok 1989).

The Early Tertiary uplift of the inner CWC zones is documented by the presence of rock fragments derived from the Veporic-Gemeric domain in the basal conglomerates of the CCPB in north-eastern Slovakia (Marschalko 1966, 1970). The Eocene uplift of the Žiar and a part of the Nízke Tatry Mts., which on the basis of the apatite FT ages crossed the 100 °C isotherm 46 - 52 Ma ago (Tab. 2), and their subsequent denudation can be related to a compressive event accompanied by the Eocene counter-clockwise rotation estimated by Márton (1988a, b, in press).

The uplift of the innermost zones of the Tatric basement to the surface and their subsequent erosion is confirmed by fragments and pebbles derived from the crystalline complexes found in the Eocene and Oligocene flysch conglomerates of the Liptov, Poprad and Bánovce Basins (Mahel' et al. 1968; Gross & Köhler 1980; Mahel' 1985). Considering the predominance of Mesozoic rocks in the conglomerates from the Bánovce Basin, we assume the crystalline core of the Žiar Mts. was exposed only minimally.

During the Oligocene, the transtensional regime was gradually replaced by the transpressional one. It led to the desintegration of the Paleogene basins in the western part of the CWC (Fig. 3b). Scarce relics of Oligocene deposits are preserved in Malé Karpaty Mts. (Marko et al. 1990), Bánovce Basin, and central Slovakia (Bystrická 1979, 1990). Oligocene sediments deposited on the Cental Carpathian destructive margin are known in the whole Central Carpathian Paleogene Basin, but they reach significant thicknesses only in eastern Slovakia - in the Levočské vrchy and Šarišská vrchovina Mts. (Marschalko 1966; Marschalko & Gross 1970; Gross & Köhler 1980; Molnár et al. 1992, etc.). The Iňačovce-Krichevo zone, assumed as a Penninic analogue by Soták et al. (1993) was closed and overriden by the CWC units in the Transcarpathian Basin pre-Neogene basement in post-Eocene times. Similarly, the origination of the Szolnok unit flysch nappes in front of the Northern Pannonian crustal segment is supposed during the Late Paleogene - Early Miocene (Csontos et al. 1992; Nagymarosy & Báldi-Béke 1993).

Late Tertiary and Quaternary burial and uplift of the Central Western Carpathians

The Early Miocene paleogeographical and structural pattern changes were induced by the beginning of north- to northeastward motion of the Western Carpathian domain (Fig. 3, 4), into an unconstrained realm of the Outer Carpathian Flysch Basin

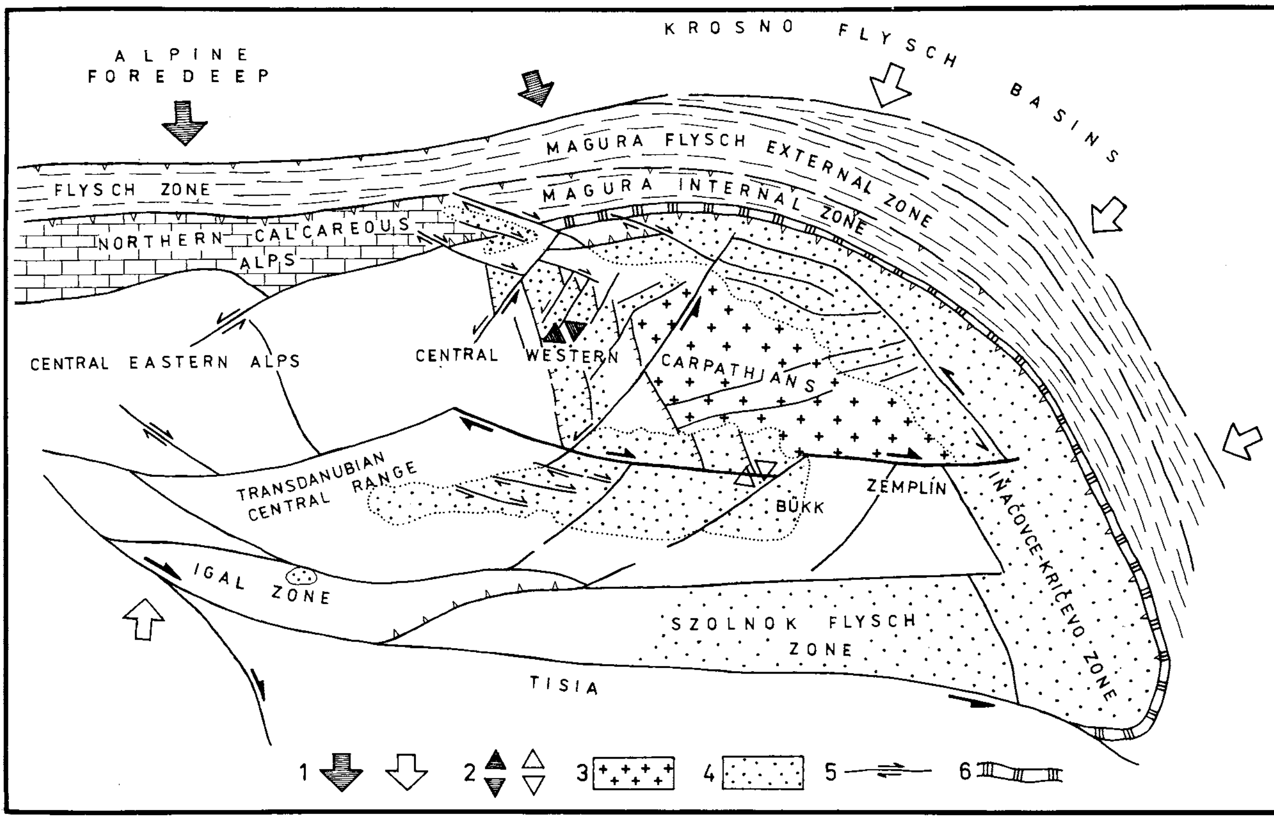

Fig. 4. A scheme of the Central Western Carpathians and Northern Pannonian Unit structural pattern during the Tertiary. **1** - orientation of principal compression axis during the Paleogene and Oligocene - Early Miocene; **2** - orientation of transtension during the Paleogene and Oligocene - Early Miocene; **3** - uplifted areas; **4** - Paleogene and Oligocene - Early Miocene sediments; **5** - faults; **6** - Pieniny Klippen Belt.

(Csontos et al. 1992). Sedimentation continued in front of the northern margin of the CWC, still deeply buried and covered by Paleogene deposits, mainly in eastern Slovakia and in the piggyback basin situated on the Magura flysch accretionary wedge (Cieszkowski 1992).

The NE oriented compression (Nemčok 1993) led to a gradual desintegration of the Central Carpathian Paleogene Basin in the frontal part of the uplifting Tatro-Veporic and Gemeric domains during the Egerian. Closing of the Egerian basin, similarly as the closing of the Eggenburgian basin in the northern part of the Transcarpathian Depression, was followed by further upheaval during the Ottnangian (Rudinec 1989, 1990).

The Lower Miocene structural pattern of the western part of the Central Carpathians documents also a transpressional regime, but with a NW-SE oriented principal compression axis. Basin opening in front of the upheaved Tatro-Veporic domain (at present represented by the pre-Neogene basement of the Vienna and Danube Basins) was controlled by the ENE-WSW dextral strike-slips, accompanied by NW-SE normal and NE-SW to ENE-WSW reverse faulting (Kováč et al. 1989, 1993a; Marko et al. 1990, 1991; Tomek et al. 1987). Besides these faults, the N-S sinistral strike-slip faults were active as well (Fig. 5A), passing eastwards gradually into the Central Slovakian Fault System with transtensional regime (Kováč & Hók 1993).

Displacement along N-S sinistral strike-slip faults (active also in the Paleogene) could be one of the reasons of counter-clockwise block rotations, inducing the present arrangement of the crystalline cores of the Suchý-Malá Magura and Žiar Mts. (Fig. 1). These horsts are bounded by NW-SE normal faults on their western slopes (Nemčok 1989).

In contrast to transpression in frontal parts of the upheaved ancient Central Western Carpathians, in their hinterland (southern Slovakia) a transtensional regime continued (Fig. 4), with sedimentation controlled by NE-SW oriented extension (Vass et al. 1993).

The Oligocene - Lower Miocene transpressional regime accelerated the uplift of the CWC crystalline complexes, associated with diminishing of the overburden of the Mesozoic and Central Carpathian Paleogene complexes. According to FT data, most of the Tatric granitoid rocks were gradually uplifted to 5 km depth and some of them appeared at the erosional surface. During this period (35 - 20 Ma), the individualization of the Malé Karpaty, Tribeč, Suchý - Malá Magura, Veľká and Malá Fatra, Tatry as well as Čiena hora "core mountains" commenced. The average uplift rate of the crystalline complexes varied between 0.1 and 0.2 mm/year.

Both direct and indirect evidences indicate a Lower Miocene rotation, which caused counter-clockwise declination deviations on the Paleogene and Lower Miocene complexes in the Outer Carpathian Subsilesian, Silesian and Dukla Units (Krs et al. 1977, 1982), in the western part of the CWC (Túnyi & Kováč 1991; Márton 1993), in the Transdanubian Central Range (Márton 1986) and northern Hungary (Márton 1988b; Márton et al. 1988a, 1991). The timing of the counter-clockwise rotations of the Western Carpathians, as well as the whole Northern Pannonian crustal segment is remarkably coeval with the clockwise rotation of the Southern Pannonian crustal segment as inferred by Márton (1993) and later directly proved by paleomagnetic data.

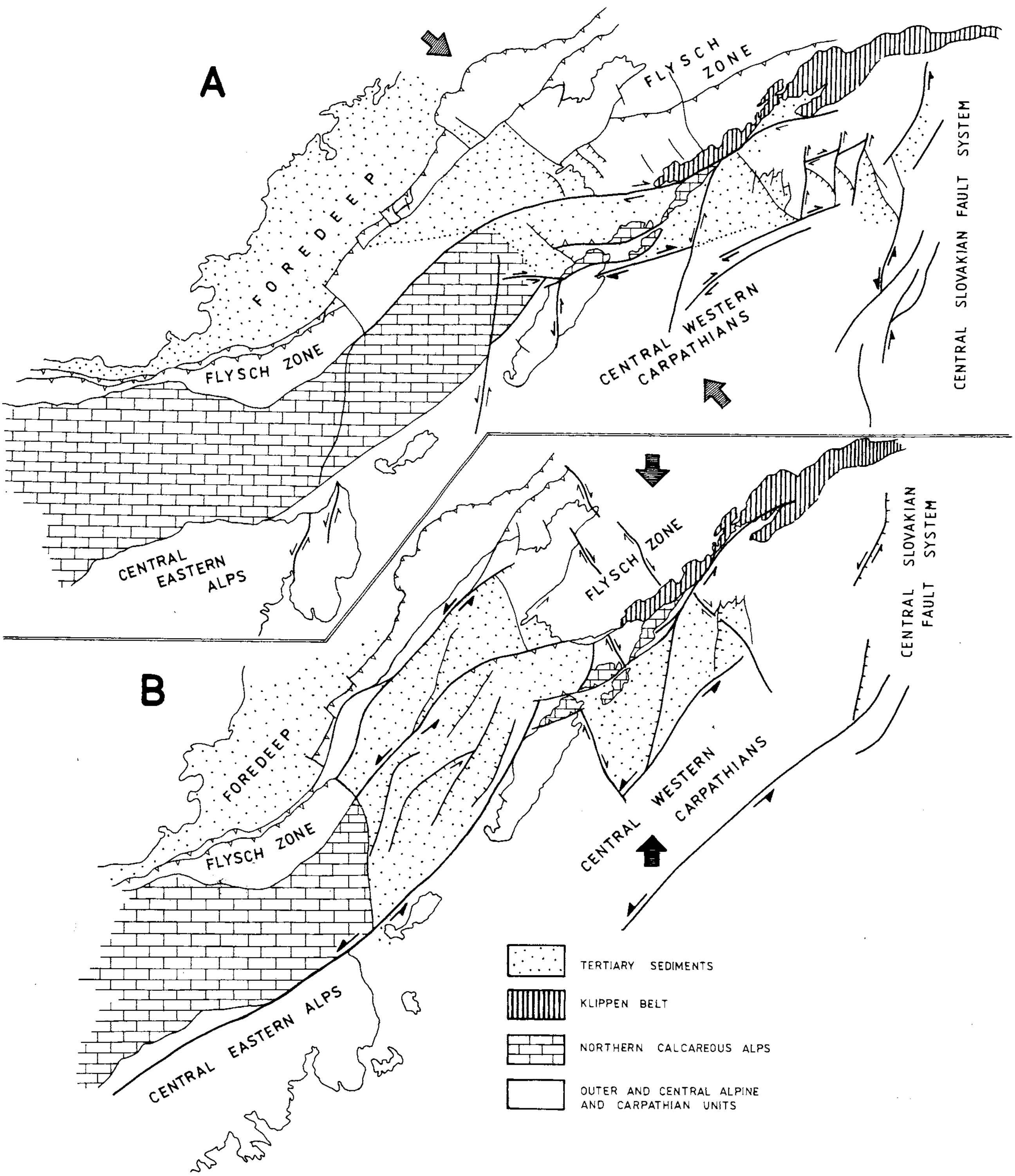

Fig. 5. A scheme of the Lower Miocene structural development of the Alpine - Carpathian junction area: **A** - Early Lower Miocene; **B** - Late Lower Miocene (Karpatian).

Transpressional regime and uplift of the Tatric and Veporic domains, associated with counter-clockwise rotation of the Northern Pannonian crustal segment, can be regarded as a consequence of the tectonic escape induced by the collision of the Alps with the Northern European Platform.

The Tertiary movement trajectory of the Western Carpathians (Fig. 3) is evidenced by the paleomagnetic inclinations and declinations showing 30°- 90° counter-clockwise rotation (Márton 1993). Consequently, the Paleogene - Lower Miocene paleostress fields recorded in the western part of the Central Carpathians and in the

Transdanubian Central Range should have been rotated as well. Though, the present observations show NW-SE compression (Nemčok et al. 1989; Fodor 1992; Kováč et al. 1993a; Kováč & Hók 1993), originally the paleostress field was characterized by a N-S to NE-SW main compression, e.g. similar to the paleostresses known from the westward situated Alpine region (Neubauer & Genser 1990; Decker et al. 1993). A more southern position of the CWC during the Paleogene and Early Miocene, compared to their present position (Fig. 3), is indicated also by paleogeographic considerations and palinspastic restorations of the Carpathian foredeep and the flysch accretion wedge considerations (Balla 1984, 1987; Kováč et al. 1989, 1993b, c; Oszczypko & Slaczka 1985; Royden 1988; Sandulescu 1988; Csontos et al. 1992; Seifert 1992; etc.).

In the Late Lower Miocene (Karpatian), further movement of the Western Carpathians northwards accelerated. Transpressional regime governed the uplift and formation of an arcate shape of the orogen. On the other hand, the transtesional regime allowed the opening of new depocentres with rapid subsidence on the western and eastern CWC margin.

In the west, the evolution of the Vienna Basin was controlled mainly by NE-SW sinistral strike-slips (Royden 1988; Kováč et al. 1993a), as a consequence of a sinistral displacement of the Western Carpathians northeastward (Fig. 5B). In the east, the opening of the northern part of the Transcarpathian Basin was initiated by NW-SE trending dextral strike-slips (Vass et al. 1989; Kováč et al. in press.).

During the Middle Miocene, the transtensional regime prevailed in the Central Western Carpathian area. Collisional processes in frontal parts of the orogen induced further tectonic escape of the CWC northeastwards (Csontos et al. 1992). The roll-back effect of the Outer Carpathian Flysch Basin floor subduction (Fig. 3) and the mantle upheaval in the orogenic hinterland caused crustal extension. The orogenic collapse was followed by formation of new basins, where subsidence accompanied the uplift of neighbouring mountain chains.

The Middle Miocene structural pattern development was controlled by paleostress fields with NE-SW oriented principal compression axis in the west and the N to NW-SE oriented axis in the eastern and southern Slovakia (Kováč et al. 1993b, c; Vass et al. 1993; Kováč et al. in press).

The northern part of the Vienna Basin, Blatné and Bánovce depressions (northern embayments of the Danube Basin, see Fig. 6), suffered only a thin-skinned extension during the Miocene (Lankreijer et al. in press). The last documented counter-clockwise rotations of the Lower Miocene sediments in this region can be regarded as a result of block rotation inside the ENE-WSW trending sinistral shear zone controlling the Middle Miocene sedimentation together with NE-SW oriented normal faults (Túnyi & Kováč 1991; Marko et al. 1991; Márton et al. 1992; Kováč et al. 1993a, c).

In the southern and central parts of the Vienna and Danube Basins, the crustal extension was controlled mainly by NE-SW trending normal listric faults, activity of which created the graben and horst structure (Horváth 1993). The listric faults documented by seismic profiles from the Little Hungarian Plain (i.e. the Danube Basin) tectonically unroofed the Penninic units and opened the basin during the Middle-Late Miocene (Tari et al. 1992).

A similar function of faults can be assumed also along the reactivated Tatric and Veporic overthrust planes controlling the subsidence in the central and northeastern parts of the Danube Basin (Plašienka et al. 1991; Lankreijer et al. in press.). The similarities of the Paleozoic crystalline units of the northern part of Považský Inovec Mts. (Selec block) and the northeastern part of the Tribeč Mts. (Rázdiel block), separated by the partial Rišňovce Depression of the Danube Basin (Fig. 6), support the above mentioned opinion.

Moreover, the marked reflex lines in the basement of the western part of the Danube Basin on the seismic profile 3T, interpreted as listric décollements with a westward shift (Tomek et al. 1987), have lead us to consider a tectonic separation of some Tatric crystalline complexes. The opening of the southern part of the Blatné Depression can be regarded as a result of tectonic sliding of the southern part of the Malé Karpaty from the southern prolongation of the Považský Inovec Mts. This is supported by similarities between the granitic as well as metamorphic complexes in both mountains (the Bratislava and Bojná massifs).

Structural unroofing of the southern part of the Danube Basin basement during the Middle and Late Miocene is evidenced by the absence of nappe or sedimentary cover units older than Middle Miocene (Fusán et al. 1987) and by the fact that heavy mineral assemblages of the Lower Miocene sequences in the northern part of the Malé Karpaty Mts. indicate a so far unknown source. This source is different from hitherto known Variscan granitoids of the CWC area and it could have been situated rather in plutonic rocks of the Alpine and/or Pannonian provenance (Uher & Kováč 1993).

Gradual Middle Miocene uplift of the Tatric "core mountains" to the erosional level in the western part of the CWC was compensated by basin subsidence (Royden 1988; Kováč et al. 1989; Nemčok et al.1989; Vass et al. 1993). This process is well documented e.g. by the Badenian uplift of the Tatric granitoid massif of the Malé Karpaty Mts. as a source of the conglomerates and breccias of the Devínska Nová Ves Beds transported to the Vienna Basin (Vass et al.1988) and later the Doľany conglomerates deposited on the western margin of the Danube Basin (Kováč et al. 1991).

The end of the collision of the Western Carpathians and the Northern European Platform is recorded by the last overthrusts of the Outer Carpathian flysch accretionary wedge front onto the foredeep during the Sarmatian (Jiříček 1979). The still active transtensional regime in the Central Carpathians, with the NE trending compression axis, was probably induced by a trench-pull effect of the subduction and subsequent slab detachment in the Eastern Carpathians (Kováč et al. in press.).

During the Late Miocene and Pliocene, the transtensional regime was replaced by extension in hinterland of the orogen, due to cooling of the upheaved mantle followed by thermal subsidence in the Pannonian area (Horváth 1984; Horváth & Rumpler 1984; Nemčok & Lexa 1990). The extension-inducing subsidence in the hinterland was probably later compensated by a transpressional regime in the orogen, manifestated by further uplift of the CWC. The compression axis had a NW-SE to WNW-ESE orientation in the west, and NE-SW to ENE-WSW orientation in the eastern part of the Western Carpathians (Nemčok et al. 1989; Nemčok & Lexa 1990; Vass et al. 1993; Kováč et al. 1993b, in press).

The last still buried granitoid massifs of the external Tatric zone - the Považský Inovec and Tatry Mts. reached temperature 100 °C 10 - 20 Ma ago, as revealed by FT apatite ages (Tab. 1). Their upheaval to the errosional level represents the youngest uplift process in the CWC area. The Selec crystalline complex in the northern part of the Považský Inovec Mts. has been exposed during the Pliocene and became a source of clastics deposited in the Bánovce Basin (Brestenská 1980; Kováč et al. 1993d). The Tatry Mts. were uplifted to the erosional level during the

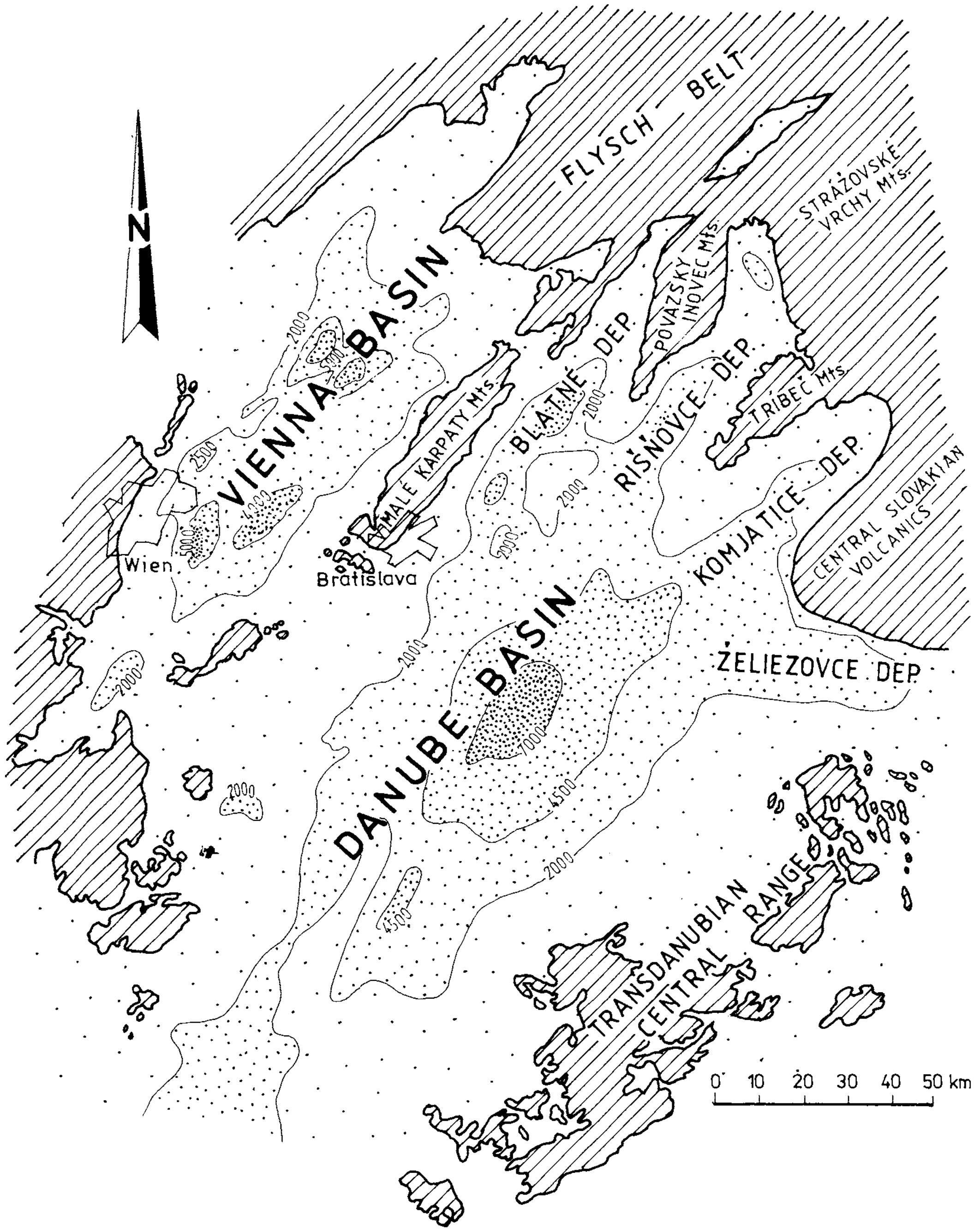

Fig. 6. Schematic sketch of tectonic control of the Vienna Basin subsidence and opening of the extensional Danube Basin (Little Hungarian Plain) during the Middle/Late Miocene.

Quaternary, and became a source of glacio-fluvial sediments of neighbouring basins (Gross & Köhler 1980).

The uplift of the above mentioned core mountains was accompanied by further subsidence in the Vienna, Danube and Transcarpathian Basins. Nevertheless, it is worth noting that the extensional regime was in places substituted by NW-SE to N-S compression, above all in the western and central parts of the Western Carpathians and Transdanubian Central Range (Gerner 1992), and by NE oriented compression in eastern Slovakia (Kováč et al. in press) during the Pliocene and/or Quaternary. The compressional regime accelerated the uplift of "core mountains" of the Považský Inovec and Tatry Mts., with comparatively high recent uplift rates of 1 - 2 mm/year (Kvitkovič 1975). However, the FT zircon - apatite age pairs indicate generally slow average uplift rate of the Tatric and Veporic granitoid massifs from the Late Cretaceous to Neogene, generally ranging 0.1 - 0.2 mm/year (Fig. 7).

Conclusions

The Central Western Carpathians, from the point of view of the Alpine uplift history, consist of two principal domains: the internal Veporic-Gemeric, and the external Tatric domain.

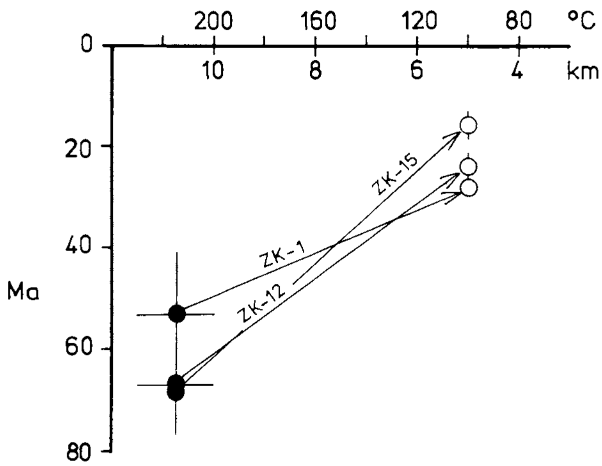

Fig. 7. Average uplift of the Tribeč (ZK-1), Považský Inovec (ZK-15) and Čierna hora Mts. (ZK-12) granitoid massifs during the Upper Cretaceous to Neogene according to FT zircon (225 °C) and FT apatite (100 °C) cooling ages. FT data see Tab. 1.

The story, depicted in Fig. 8, started by the uplift of the Veporic-Gemeric domain during the Cretaceous. The Early Alpine burial, heating and low-grade metamorphism of the Veporic crystalline complexes were caused by crustal thickening due to a basement nappes emplacement driven by the subduction/collision processes along the southern CWC margin. The Veporic basement, as indicaded by the isotope cooling data, was buried to middle-crustal depths of 15 - 20 km (350 - 450 °C) during the Early Cretaceous. From the Middle - Late Cretaceous to the Early Paleogene (90 - 55 Ma), the gradual rise, tectonic and erosional denudation uplifted the Veporic basement to the depth of about 5 km. The suggested average uplift rate was about 0.5 - 1 mm/year (Figs. 1, 2 and 8).

To the contrary, the Tatric pre-Alpine complexes were buried to depths not exceeding 12 km (ca. 250 °C) after the Permian. Their uplift, as documented by the zircon and apatite FT data, started from depths of 10 - 11 km (225 °C) about 70 - 50 Ma ago and reached 5 km (100 °C) depth level 30 - 15 Ma ago. Accordingly, the average uplift rate was 0.1 - 0.2 mm/year.

The Paleogene collision in the Alps led to the southeastward displacement of the Central Western Carpathians as a part of the Tertiary Northern Pannonian crustal segment in the sense of Csontos et al. (1992). This process was accompanied by further uplift of the internal, Veporic-Gemeric and innermost Tatric region and burial of the outer Tatric zone in frontal parts of the escaping terrain. The extent of the buried Tatric domain is indicated by the sedimentary fill of the Central Carpathian Paleogene Basin. The Alpine-Carpathian-Pannonian junction area also exhibited subsidence in this time. This was triggered by the transtensional regime between the Alps and ancient Carpathians.

The Central Slovakian Fault System functioned as a transtensional boundary separating influences of the Adriatic-European collision in the western Alpine sector and shortening of the Carpathian front by subduction of the Penninic-type Iňačovce-Krichevo zone in the east during the Paleogene.

The Paleogene uplift of the Veporic-Gemeric domain was accompanied by the upheaval of the adjacent internal Tatric complexes. On the basis of the apatite FT ages, the Žiar and a part of the Nízke Tatry Mts. crossed the 100 °C isotherm 55 - 35 Ma ago. Their uplift and subsequent erosion can be

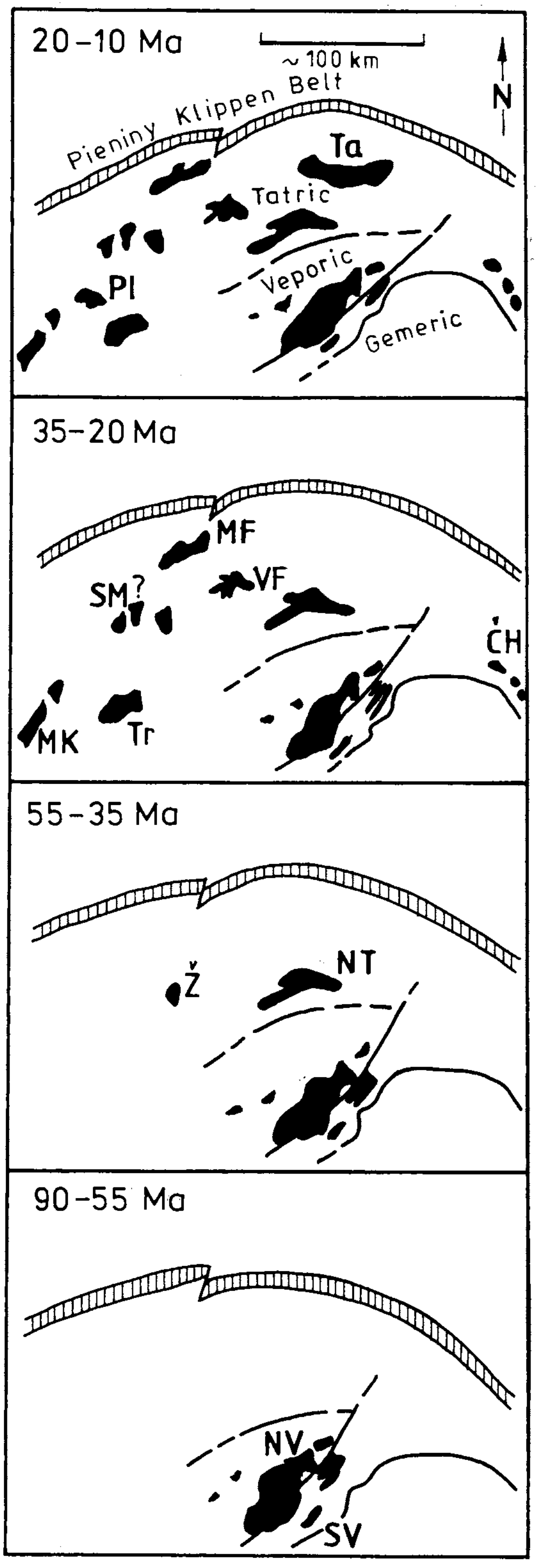

Fig. 8. A general sketch of the Central Western Carpathian Alpine uplift history from the Late Cretaceous to the Late Neogene (9 - 10 Ma), according to FT apatite data from the Variscan granitoid massifs (black areas). **Abbreviations:** SV - South Veporic unit; NV - North Veporic unit; NT - Nízke Tatry; Ž - Žiar; MK - Malé Karpaty; SM - Suchý and Malá Magura; MF - Malá Fatra; VF - Veľká Fatra; ČH - Čierna hora; PI - Považský Inovec; Ta - Tatry.

related to the compressive event accompanying the Eocene counter-clockwise rotation.

The Oligocene - Lower Miocene transpressional regime in front of the orogen accelerated the uplift of the Central Western Carpathian crystalline complexes and was associated with lowering of the overburden of the Mesozoic and Central Carpathian Paleogene sequences. According to FT data, most of the Tatric granitoid rocks were gradually uplifted to the 5 km depth and some of them appeared at the erosional surface. During this period (35 - 20 Ma), the development of most of the "core mountains" horsts started. The average uplift rate varied between 0.1 and 0.2 mm/year.

The disintegration of the Alpine-Carpathian chain accelerated in the Late Lower Miocene (Karpatian) due to further movement of the Western Carpathians northwards. New depocentres with rapid subsidence controlled by transtension opened the Vienna Basin evolved along NE-SW sinistral strike-slips and the Transcarpathian Depression along NW-SE oriented dextral strike-slips.

The Middle Miocene crustal thinning in a transtensional regime was driven by the subduction roll-back in the Outer Carpathians and the mantle upwelling in the orogen hinterland. Some new basins were formed and the altitude differences between the Neogene basin floors and neighbouring "core mountains" increased (Fig. 8).

The Late Miocene - Pliocene extension and compression controlled further uplift of the CWC mountain ranges and subsidence in the Neogene basins. Crustal extension in the Danube Basin basement was accompanied by structural unroofing of the crystalline complexes. The most external zone of the Tatric domain, uplifted to the 5 km depth during the Miocene (20 - 10 Ma), reached the erosional level during the Pliocene and Quaternary. The average uplift rate of granitoid cores of the Považský Inovec and Tatry Mts. attained ca. 0.1 mm/year. However, their Quaternary uplift has reached even 1 - 2 mm/year.

The Late Alpine evolutionary model of the Western Carpathians is consistent with Beckers (1993) definition of the neotectonic period in central and northern Europe.

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