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CRETACEOUS TECTONOCHRONOLOGY OF THE CENTRAL WESTERN CARPATHIANS, SLOVAKIA

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Abstract: During the Cretaceous, the Central Western Carpathians (CWC) evolved as an intracontinental thrust belt by progradational shortening from the inner (Meliatic) towards the outer (Penninic-Vahic) bounding oceanic domain. The Early Cretaceous basement nappe stacking in the internal CWC zones was coeval with distension in the external zones, followed by a collapse of the overthickened crust, unroofing of the Veporic metamorphic core complex and gravity gliding of the cover nappe systems towards the unconstrained Tatric foreland in mid-Cretaceous times. In the Late Cretaceous, shortening affected the external CWC zones and the Vahic ocean was consumed. The available data on the geochronological, magmatic, metamorphic, structural, lithostratigraphic and sedimentological record of these processes are reviewed and their broad-scale tentative interpretation is presented.

Key words: Central Western Carpathians, Cretaceous, orogenic processes, rock record data, paleotectonic scenario.

Introduction

All fundamental features of the imposing nappe structure in the Central Western Carpathians (CWC, Fig. 1) originated during the Cretaceous. The CWC are considered here as an early Alpidic orogenic belt located between two principal, more or less latitudinally trending oceanic sutures: the Penninic-Vahic in the north and the Meliata-Hallstatt in the south (all directional statements in the paper refer to the present structures and coordinates). In this sense, the CWC encompass all the units which were paleogeographically located between the axes (although poorly defined) of these two oceanic domains. The units which were clearly derived from the zones beyond the oceanic axes, i.e. the Oravic units of the Pieniny Klippen Belt in the north and the Turnaic nappes of the southern Meliatic margin will not be treated here, though especially the latter shared a common history with the southern CWC zones after being emplaced probably in the Early Cretaceous.

The sutures are diachronous — the Meliata-Hallstatt ocean was rifted in the Middle Triassic (or even earlier) and closed in the Late Jurassic (e.g. Kozur 1991), while the Penninic-Vahic opened in the Middle Jurassic and was locked during the latest Cretaceous to Early Tertiary (Plašienka 1995a, b). However, the surface exposures of both sutures are rather poor and discontinuous. Their exact position in the Carpathian edifice is a matter of discussion and several branches of both oceanic domains may be present (Kozur & Mock 1996).

Another problem arises with the affilation of the Gemeric basement sheet which is usually considered to be an Inner West Carpathian element (e.g. Mock 1978; Mišík et al. 1985; Kozur & Mock 1996), on the basis of its compositional affinities to the Upper Austroalpine - South Alpine units. In spite of this, the Gemeric sheet is one of the three main crustal-scale imbrications of the CWC, as seen in the deep Transcarpathian seismic lines 2T (Tomek 1993) and G (Vozár et al. 1995). The Gemeric units exhibit close structural relationships to the underlying Veporic superunit and there are no indications of an oceanic suture in between, at least along the Lubeník or Hrádok lines in the western part. In the eastern Margecany sector of the Gemeric/Veporic interface, the presence of the Folkmár suture zone as a Meliatic branch has been inferred by Kozur & Mock (1995). However, this may be an apparent suture - tectonic outlier of the Meliatic Bôrka Nappe (ascertained nearby by Németh 1996), later incorporated into a steep transpressional structure along the Košice-Margecany shear zone, either dextral (Gazdačko 1994), or sinistral (Jacko et al. 1996). In this respect, the relation of the Gemeric Unit to the Veporic Unit is comparable to, for example, that of the Paleozoic of the Graz thrust complex to the Middle Austroalpine superunit (e.g. Fritz et al. 1991).

Accordingly, the CWC, as a lateral analogue of the Austroalpine system, would be composed of the Tatric, Veporic and Gemeric thick-skinned basement sheets, adjacent parts of bounding oceanic realms (Vahic and Meliatic), and the Fatric, Hronic and Silicic cover nappe systems (Fig. 1). Paleogeographically, only the Fatric (Krížna) nappes were clearly positioned within the CWC basement area — between the Tatric and Veporic domains. The homeland of the Hronic (Choč) nappes remains disputable (as that of the Bajuvaric–Tirolic system of the Northern Calcareous Alps does), though most probably still northerly of the Meliata-Hallstatt oceanic channel. The upper Juvavic and Silicic units with obvious “southern” affinities, which are often underlain by Meliatic slices, may have been derived from the southern margin of this ocean (Hók et al. 1995), though most authors place the Silicic depositional area north of the Meliatic oceanic basin (e.g. Andrusov 1975; Kovács 1982, 1992; Kozur 1991; Dercourt et al. 1992; Michalík 1994a; Haas et al. 1995; Kozur & Mock 1996). Nevertheless, after being emplaced during the Late Cretaceous, the Silicic nappes became integral constituents of the CWC, far to the north of the Meliatic suture.

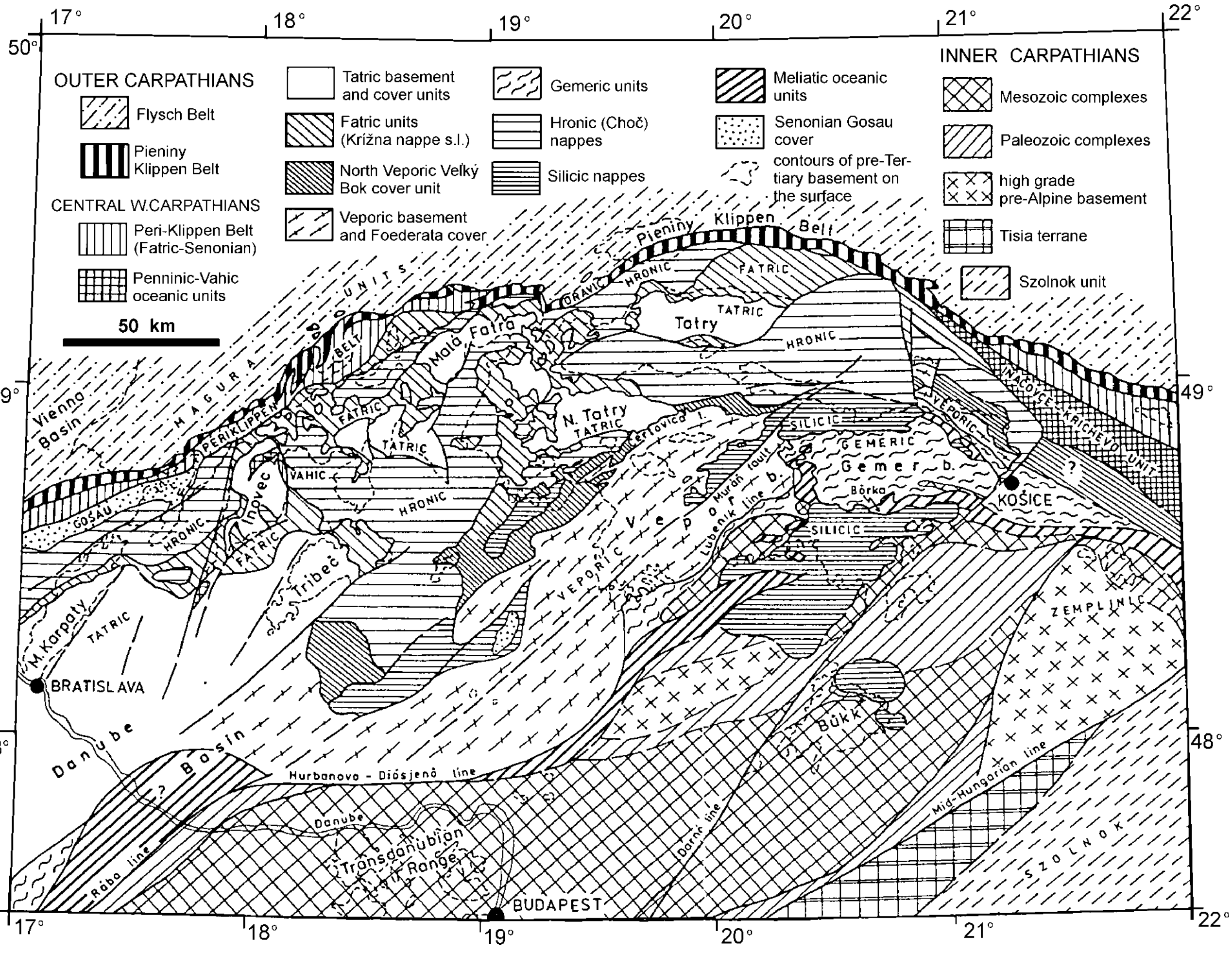

Fig. 1. Distribution of pre-Tertiary tectonostratigraphic units in the West-Carpathian area.

The present contribution aims at an integration of the available rock record data, a lot of them collected during recent years, into a tentative temporal/spatial scenario for the Cretaceous tectonic processes in the CWC area. The whole story is described in seven, more or less independent, evolutionary stages. The data are listed following the most frequently accepted S-N arrangement of the principal isopic zones, though not necessarily representing their original palinspastic positions: Meliatic–Gemeric–Veporic (Silicic and Hronic as possible lateral paleogeographical analogues of the latter two, respectively)–Fatric–Tatric–Vahic Zone. First of all the most important general articles, where extensive data sources can be found, and the newest results, are quoted. Concerning the geochronological datings, preferably reliable $^{40}Ar/^{39}Ar$ ages and reconsidered isochron datings are taken into account. The interpretations consider all fundamental information on the stratigraphic, sedimentary, magmatic, metamorphic, structural and thermochronological records of the respective stage which are relevant to the paleotectonic assumptions and the geodynamic background of the reconstructed processes. The most topical problems and enigmatic points in the evolution which need further detailed studies are also mentioned.

Principal evolutionary stages

(1) Late Jurassic – Early Cretaceous (150–125 Ma, Early Tithonian to Early Barremian according to the timescale by Gradstein et al. 1994)

Data:

— end of flysch and olistostromatic sedimentation in the Meliatic and Silicic zones before the Kimmeridgian (Kozur 1991; Sýkora & Ožvoldová 1996);
— Tithonian shallow-water limestones in the Silicic (only known from pebbles in the Senonian and Tertiary conglomerates, cf. Mišík & Sýkora 1980);
— 160–150 Ma $^{40}Ar/^{39}Ar$ phengite ages of HP/LT metamorphism in the Meliatic Bôrka Nappe (Maluski et al. 1993; Dallmeyer et al. 1994, 1996; Faryad & Henjes-Kunst 1995);
— blueschist pebbles of the same glaucophane $^{40}Ar/^{39}Ar$ plateau age (155 Ma — Dal Piaz et al. 1995) occur in mid-Cretaceous conglomerates of the Periklippen Klape Unit;
— two Rb-Sr isochrons of whole rock — biotite couples from the Gemeric granites (138 and 142 Ma, Kovách et al. 1986; Cambel et al. 1990);

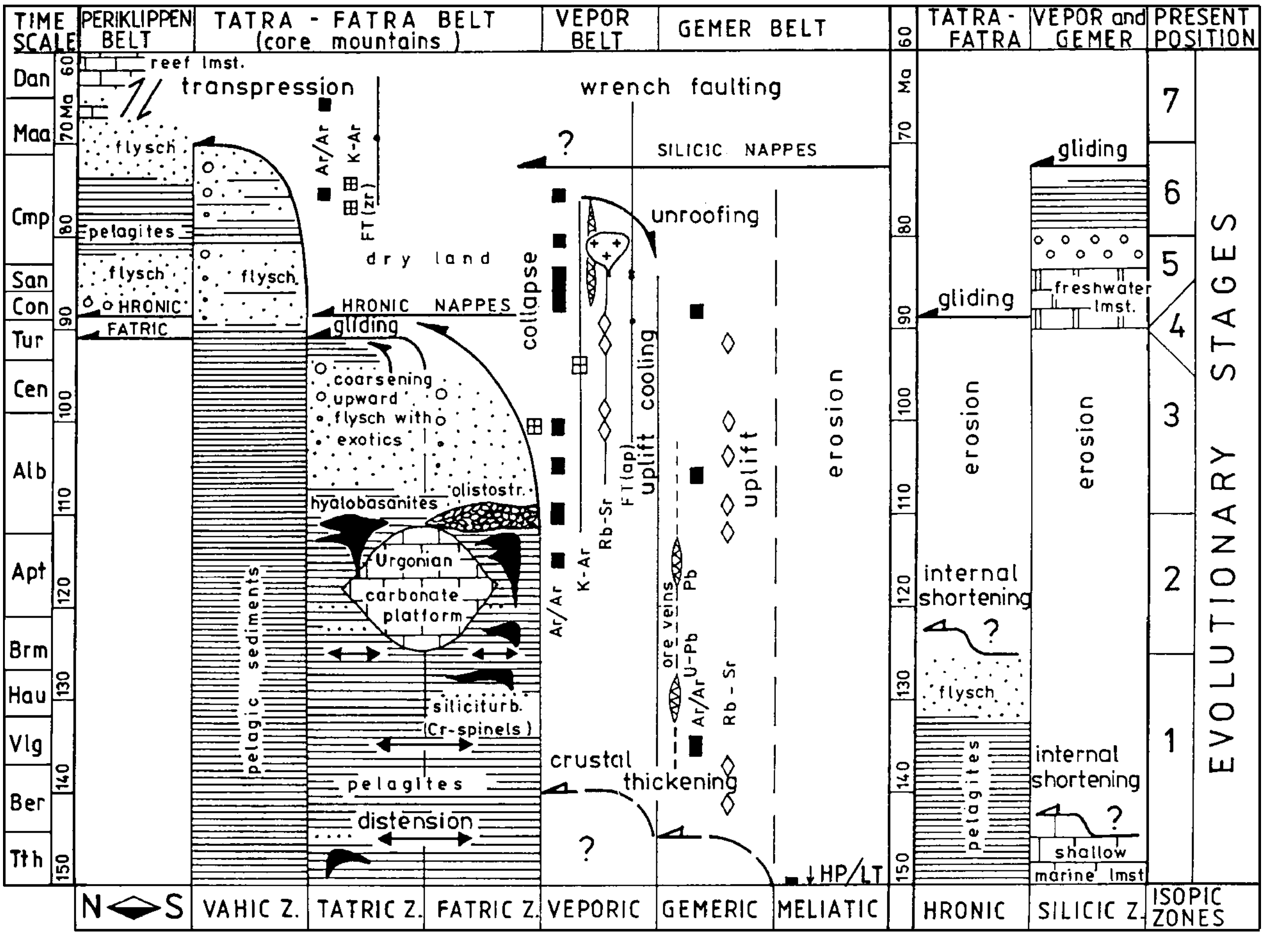

Fig. 2. Synoptic chart of Cretaceous tectonic events within the Central Western Carpathians.

— low-temperature step in the $^{40}Ar/^{39}Ar$ spectrum of muscovites from the Košice-Margecany fault mylonites at the Veporic/Gemeric contact (135 Ma, Maluski et al. 1993);
— $^{40}Ar/^{39}Ar$ plateau ages of recrystallized pre-Alpine amphiboles may represent mixed ages of not fully reequilibrated isotopic systems (143 Ma, Maluski et al. 1993; 150 and 137.3 Ma, Kováčik et al. 1996);
— no sedimentary data from the Gemeric and Veporic (except the Veľký Bok Unit paleogeographically assigned to the Fatric);
— pelagic sedimentation followed by the Hauterivian turbiditic sequence (Jablonský 1992) terminated deposition in the Hronic area;
— continuing, mostly deep-water pelagic sedimentation in the Fatric and Tatric;
— Neocomian allodapic turbidites in the Tatric and Fatric pelagites, mostly derived from local intrabasinal sources, but Rossfeld-like siliciturbidites with abundant chrome-spinel grains are rarely present in some Fatric units, being derived from distant southern sources (Jablonský 1992; Michalík & Reháková 1995);
— Tithonian (?) submarine hyalobasanitic lavas ("limburgites") in the Tatric Osobitá succession;
— pelagic sedimentation below CCD in the Vahic Basin (Plašienka et al. 1994).

All the fundamental data are synoptically depicted in Fig. 2. "Exotic" pebbles (i.e. of disputable provenance), representing this and younger stages, which occur in the mid- to Late Cretaceous conglomerates of the CWC (Poruba Fm.) and Peri-Klippen Belt units (Klape and related) will not be considered in particular here, since they cannot be unambiguously regarded as being derived (at least partly) from CWC units following the above definition (see Plašienka 1995a and references therein).

Interpretation

The paleotectonic scenario comprises closing of the Meliata ocean during the latest Jurassic and/or earliest Cretaceous (designated as the "Eohelenic" phase in the Inner Carpathian Bükkic Unit by Árkai et al. 1995) and loading of the southern (Gemeric) passive CWC margin by the Meliatic accretionary complexes, including the rapidly exhumed HP/LT units and ophiolitic mélanges probably during the earliest Cretaceous. Then shortening proceeded by footwall propagation of collisional thrust faulting within the lower CWC plate transporting the Gemeric and Meliatic units atop the southern Veporic domain (some tens of Ma before the metamorphic peak, as required by thermal modelling) — see Fig. 3. Structuralization (décollement and internal shortening) of the Silicic and later Hronic units occured in their unknown (but probably laterally adjacent) original homelands, related to the homelands of the Tirolic and Juvavic units of the Northern Calcareous Alps, the Lower Cretaceous thrusting of which is indicated by radiometric datings as well (Kralik et al. 1987). The first input of the ophiolite-derived detritus (Hronic, Fatric) was probably derived from the colliding and gradually uplifting southern zones. Post-rift thermal subsidence continued in the northernmost Veporic (Veľký Bok), Fatric and Tatric areas, interrupted by weak extensional faulting events.

Inferred suturing of the Meliata oceanic domain, collisional thickening and footwall propagation of thrusting in the lower CWC plate were probably driven by the southwards subcrustal slab-pull of the Meliatic lithosphere (Plašienka 1995b), like the continuing distension in the distal foreland Fatric-Tatric areas, still unconstrained by the orogenic front prograding from the southern hinterland (Fig. 3).

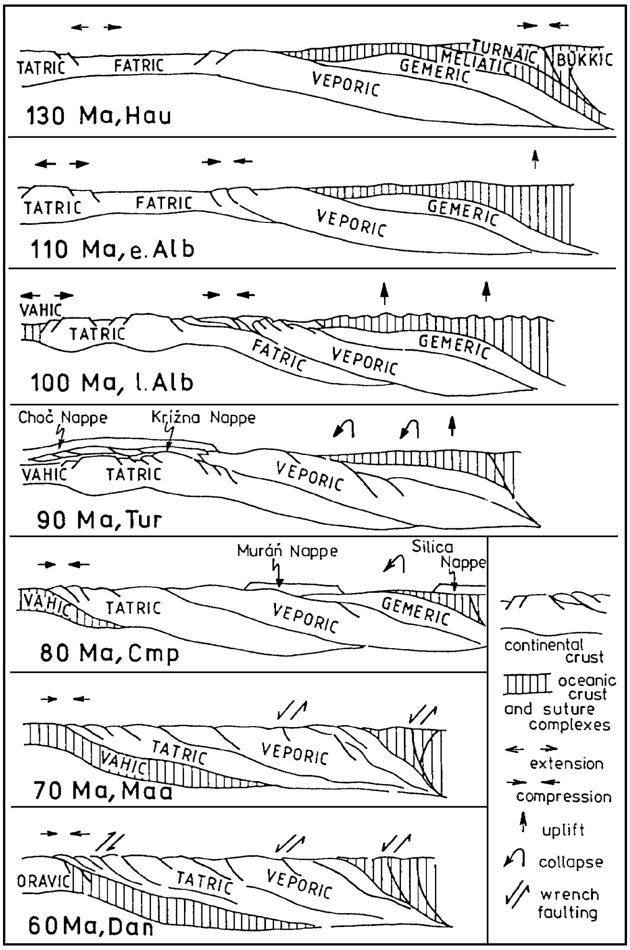

Fig. 3. Cretaceous crustal tectonic evolution of the Central Western Carpathians shown in seven stages outlined in the text. The position of the Hronic and Silicic units is not specified, since profiles follow the meridian of the Gemeric Unit, where these cover nappes were probably emplaced laterally. Not to scale.

(2) Late Early Cretaceous (125–110 Ma, Late Barremian to Early Albian)

Data:

— very scarce direct data from the Meliatic, Silicic, Hronic, Gemeric and south Veporic units;
— Alpidic remobilization of hydrothermal vein mineralization in the northern Gemeric domain (130±20 Ma, U-Pb isotopic dating of higher-grade U- and Mo-bearing veins, and 115±10 Ma Pb/Pb model age of low-grade Cu veins — Rojkovič et al. 1993);
— Veporic basement: $^{40}Ar/^{39}Ar$ ages of newly-formed Alpine tschermakite-type amphiboles (115.3 Ma, Kováčik & Maluski 1994; 111.2 and 109.9 Ma, Kováčik et al. 1996);
— termination of pelagic sedimentation at the north Veporic/south Fatric interface (Veľký Bok Unit);
— huge olistostromatic bodies in the Fatric Zliechov Basin derived from the south (Jablonský & Marschalko 1992);
— short-living "Urgonian" carbonate platforms in the north Fatric–south Tatric domains, rimmed by allodapic clastic fans (Mišík 1990; Michalík & Soták 1990; Michalík 1994b);
— generally pelagic deposition continued in the Fatric-Tatric-Vahic area, but some siliciclastic turbidites of local sources occur in the northern Tatric Unit (Solírov Fm., Jablonský et al. 1993);
— areally extensive, but volumetrically negligible submarine hyalobasanitic volcanism in the Fatric and Tatric region (Hovorka & Spišiak 1988, 1994), dated by features of submarine extrusion within unconsolidated Barremian–lower Albian sediments (Hovorka & Sýkora 1979; Kullmanová & Vozár 1980) and by isotopic dating: two amphibole concentrates yielded ages 116 and 106 Ma (K-Ar, Bujnovský et al. 1981) — Fig. 2.

Interpretation

Gradual thermal equilibration and slow uplift of the southern "Ultraveporic" collisional zones were associated with the northward progradation of contraction to the Veporic/Fatric margin and its internal imbrication (Fig. 3), producing the topographic gradient controlling mass slope resedimentation in the Fatric trough. Coeval extensional impulse occurred in the Fatric-Tatric foreland, where rejuvenization of normal faulting and block tilting was accompanied by small portions of mantle-derived alkaline basaltic lavas piercing the strongly thinned crust. Carbonate buildups grew on elevated edges of tilted blocks, probably supported by bulge upbending and sea-level drop.

The driving forces are inferred as in the previous stage. The extensional event in the foreland Tatric-northern Fatric areas appears to be related to the crustal rupture and initiation of a convergent zone along the Veporic-Fatric margin, where the attenuated Fatric crust came to be underthrust beneath the developing north Veporic orogenic wedge with stacking of the Veľký Bok basement/cover subunits at its tip.

(3) Mid-Cretaceous (110–90 Ma, Middle Albian to Late Turonian)

Data:

— only scarce well age-constrained data in the Meliatic, Gemeric, Veporic, Silicic and Hronic areas, except thermochronological;
— low-grade metamorphic imprint in the Gemeric Unit is documented by the 105.8 Ma plateau age from the Permian metasediments (Dallmeyer et al. 1994);
— Veporic basement: newly formed amphibole 105 Ma (Kováčik et al. 1996), K-Ar biotite isochron 94±18 Ma (Burchart et al. 1987), Rb-Sr model ages of recrystallized biotites from the Veporic metagranitoids (98±7 and 88±4 Ma, Bibikova et al. 1990, Putiš 1992), Rb-Sr biotite-whole rock couples isochrons of the Gemeric granites and the Veporic Rochovce granitic body (between 92 and 112 Ma, Kovách et al. 1986; Cambel et al. 1990 — 8 samples), 101.3 muscovite plateau age from the Veporic Permian cover metasediments at the contact with the overlying Gemeric basement (Dallmeyer et al. 1996), see also summary by Kováč et al. (1994);
— the Alpidic metamorphic peak in the Veporic Unit has been recently estimated to the maximum of 550–600 ˚C and about 8–10 kbar in the deepest basement unit (Janák & Plašienka 1996) and to at least 400 ˚C and 6–8 kbar in the Permian cover (Janák & Plašienka 1996; Putiš et al. 1995);
— thrusting-related structural record in the rear parts of the Fatric Krížna cover nappe and in the Veľký Bok units (their décollement and stacking) is generally well known (Plašienka 1983, 1995c and references therein), accompanied by anchizonal metamorphism (Plašienka et al. 1989), and partly radiometrically dated (101 Ma, K-Ar on newly formed white micas — Nemčok & Kantor 1989);
— after the rapid submersion of the Urgonian carbonate platforms, only pelagic and synorogenic coarsening-upward flysch sedimentation (Poruba Fm.) is present in the Fatric (up to the Early Cenomanian) and Tatric (up to the Early Turonian) zones (Fig. 2);
— similar, but much thicker Albian-Cenomanian, shallowing-upward wildflysch prisms deposited in the Peri-Klippen Belt Klape Unit (Marschalko 1986);
— these flysch conglomerates contain, apart from common CWC lithofacies, also a lot of “exotic” pebbles of disputable provenance (see reviews by Mišík et al. 1981; Mišík & Marschalko 1988) and abundant Cr-spinels in the heavy mineral fraction (Jablonský 1978, Mišík et al. 1980);
— only pelagites are present in the Vahic Belice Unit (Plašienka et al. 1994);
— shortening within the Tatric basement already began to the end of this stage, since some contractional macrostructures at the South Tatric ridge — Šiprúň Basin interface (Nízke and Vysoké Tatry Mts.) are partly sealed by the superimposed Krížna Nappe (Bujnovský 1979; Dumont et al. 1996).

Interpretation

The thermal equilibration and the peak of Barrowian-type metamorphism was probably reached in the deeply buried Veporic basement and cover complexes around 110 Ma b.p., indicated by amphibole ages close to their crystallization. Thermal softening of the Ultraveporic thrust stack enabled its later unroofing. During the mid-Cretaceous stage, a rapid underplating of the Fatric basement below the Veporic one forced compressional upheaval of the Veporic–Gemeric–Meliatic (“exotic”) pile (Fig. 3), the top of which came to be exposed to intense erosion and fed the neighbouring Poruba Flysch Basin with coarse clastics, mostly “exotic”. The position of the Klape Basin, which received the same types of clastic material, is a matter of controversy (see discussion in paper by Plašienka 1995a, who considers the Klape Unit to be a Fatric element). However, most authors place the Klape Basin north of the Tatric Unit. The Tatric Urgonian platforms were submerged due to flexural downbending of the lower orogenic plate, which also contributed to the development of the fore-arc or trench-type flysch basins. Contemporaneously, the sedimentary succession of the Fatric Basin was gradually detached from its underthrust substratum along the horizon of Upper Scythian shales and evaporites and formed up an imbricated fold-and-thrust wedge accreted to the upper Veporic plate (Plašienka & Prokešová in press). Positive inversion started in the inner Tatric zones.

The above scenario requires physical modelling to assess the interplay among foreland extension, bulge upbending and flexural downbending, and interland contractional uplift. These processes might be driven by the southward pull of the lower plate triggering the foreland propagation of thrust faulting of units accreted step-by-step to the toe of the upper plate orogenic wedge (Plašienka 1995b).

(4) Late Turonian (around 90 Ma)

Data:

— extensive surface overthrusting event in the CWC: emplacement of the Fatric (Krížna) and Hronic (Choč) décollement cover nappe systems, closely time-constrained by the youngest Tatric cover sediments below the Krížna overthrust plane (lower Turonian — Cúlová & Andrusov 1964; Bujnovský & Polák 1985) and the oldest basinal post-nappe Gosau deposits atop the Hronic nappes (Upper Coniacian in the western part of the CWC — e.g. Salaj & Began 1983) — Fig. 2;
— structural features at the soles of superficial nappes include overpressured tectonic carbonate breccias (Plašienka & Soták in press), sometimes entirely dissolved (“macrostylolite” of Jaroszewski 1982), without a considerable deformation effect on the footwall rocks;
— emplacement of the Krížna Nappe is recorded by extensional structures superimposed on the older contractional ones in its rear and dorsal parts (Prokešová 1994; Plašienka & Prokešová in press).

Interpretation

Structural associations and relationships in the cover nappes point to the final gravity gliding emplacement mechanism, though push from the rear and gravity spreading might have contributed as well, especially in the first phases of thrusting. The necessary topographic gradient was produced by overstepping the frontal Tatric ramp in the case of the Krížna Nappe (cf. Plašienka & Prokešová in press). The detachment and driving mechanisms of the Hronic nappes, especially of those floored by thick Upper Paleozoic sedimentary and volcanic sole (Ipoltica group), is more difficult to interpret. Probably the Hronic nappes were derived from southern, rapidly uplifting zones juxtaposed to the ultra-Veporic thrust stack to the SW (?), which avoided considerable Early Cretaceous basement stacking. The Silicic units might be originally related to the Hronic ones, their final emplacement seems to be younger, however.

There is a limited time interval available for the final emplacement of the Fatric and Hronic nappes over the Tatric Unit, not exceeding ca. 2–3 Ma. On the basis of the clear structural disconformity at the sole of Hronic units with respect to the rear parts of the Krížna and Veľký Bok units, the Choč and related nappes had to be emplaced with some delay, but still within this interval. There are even indications of overthrusting of the Hronic nappes onto an actively shortened substratum. Nevertheless, both systems might have moved more or less simultaneously in the frontal CWC zones (Fig. 3). Summing up, the emplacement of the Fatric and Hronic nappe systems appears to be a comparatively very short surface event, being driven by gravity gliding towards the unconstrained basinal foreland, not directly related to the main shortening phases in their respective homeland paleogeographical domains.

(5) Early Senonian (90–80 Ma, Late Turonian to Early Campanian)

Data:

— 87.7 Ma plateau age of muscovites from the Gemeric basement (Dallmeyer et al. 1996);
— most of the isotopic cooling ages from the Veporic metamorphic core complex fall within this time interval (Fig. 2), as revealed by $^{40}Ar/^{39}Ar$ thermochronology (Maluski et al. 1993; Dallmeyer et al. 1993; 1994, 1996; Kováčik et al. 1996; additional data see in review by Kováč et al. 1994): amphibole 87.4, white micas and whole-rock phyllites 88.1, 87.2, 86.9, 86.4, 86.1, 86, 85.2 and 83.9 Ma, biotites 86.7, 86.6 and 80 Ma;
— 89–71 Ma K-Ar model ages of adularia from Alpine-type mineralized fissures in the Veporic basement (Hurai et al. 1991);
— first FT apatite ages from the Veporic basement (Kráľ 1977);
— cooling was accompanied by ductile extensional unroofing of the Veporic core with top-to-the east kinematics in its eastern part (Hók et al. 1993; Plašienka 1993);
— orogen-parallel extension occurred under a general N-S contractional regime with sinistral transpression and transtension along SW-NE trending wrench zones (e.g. the Pohorelá fault zone — Hók & Hraško 1990; Putiš 1991, 1994; Madarás et al. 1994);
— extension culminated by intrusion of the Rochovce Granite in the southern Veporic Unit (81 Ma zircon age — Hraško et al. 1995), which is an alkaline granitic intrusion generated by anatexis of crustal rocks and emplaced in an extensional regime into the upper crustal levels (Radvanec 1995) with a contact metamorphic aureole superimposed on regional mineral assemblages (Korikovsky et al. 1987; Vozárová 1990; Bezák 1991; Krist et al. 1992);
— unmetamorphosed Silicic nappes in the Veporic and Gemeric area overrode a deeply denuded substratum, therefore a pronounced metamorphic and structural gap exists at their bases, representing some 15–20 km of the missing rock column in between;
— sporadically preserved Lower Senonian sediments in the CWC (except their northern rim — Peri- Klippen Belt) consist of probably Santonian continental conglomerates and fresh-water limestones, as well as Campanian open-marine variegated marls;
— the Vahic Belice succession exhibits the turnover from eupelagic to coarsening-upward flysch sedimentation at the Turonian/Coniacian boundary (Plašienka et al. 1994);
— Lower Senonian sediments along the outer Tatric edge in the Periklippen zone show variable compositions and sedimentary enviroments, from transgressive and then deepening Senonian succession of the Gosau Group up to continuous (?) Upper Cretaceous pelagic and flysch sequences (e.g. Marschalko 1986; Salaj 1994a,b, 1995).

Interpretation

Extensive gravitational collapse of the overthickened southern CWC zones was triggered by contractional uplift of the Veporic core probably due to underplating of buoyant Fatric crust (Fig. 3) and/or subcrustal slab detachment and was enhanced by strain softening after thermal relaxation of the Lower Cretaceous thrust stack. The cooling ages of minerals with different blocking temperatures cluster between 88 and 84 Ma (Coniacian – Santonian) which indicates an accelerating uplift in this time. The rapidly exhumed Veporic cover and basement units were in turn overthrust by unmetamorphosed cover nappes of the Silicic system, probably as subaerial relief thrusts (Plašienka & Soták in press). The Veporic cover and upper parts of the basement were highly mobile during the low-angle extension which superposed sheet-like units with an upward discontinuously decreasing metamorphic overprint and telescoped isograds (Fig. 4). The sedimentary area above the Silicic nappes (probably still in their original homelands) was flooded by an epicontinental sea in the Campanian (partly also as a consequence of the sea level highstand). No record of this stage has been recognized in the northern (Tatric) area of the CWC, which was most probably a dry land exposed to karstification especially of Triassic carbonate complexes of the uppermost Hronic nappes (Michalík & Činčura 1992; Činčura & Köhler 1995). On the other hand, zones along the northern CWC margin underwent the main compressional phase after the conversion of the Tatric/Vahic passive margin into an active one (Plašienka 1995a,b). The frontal Fatric-Hronic nappe ele-

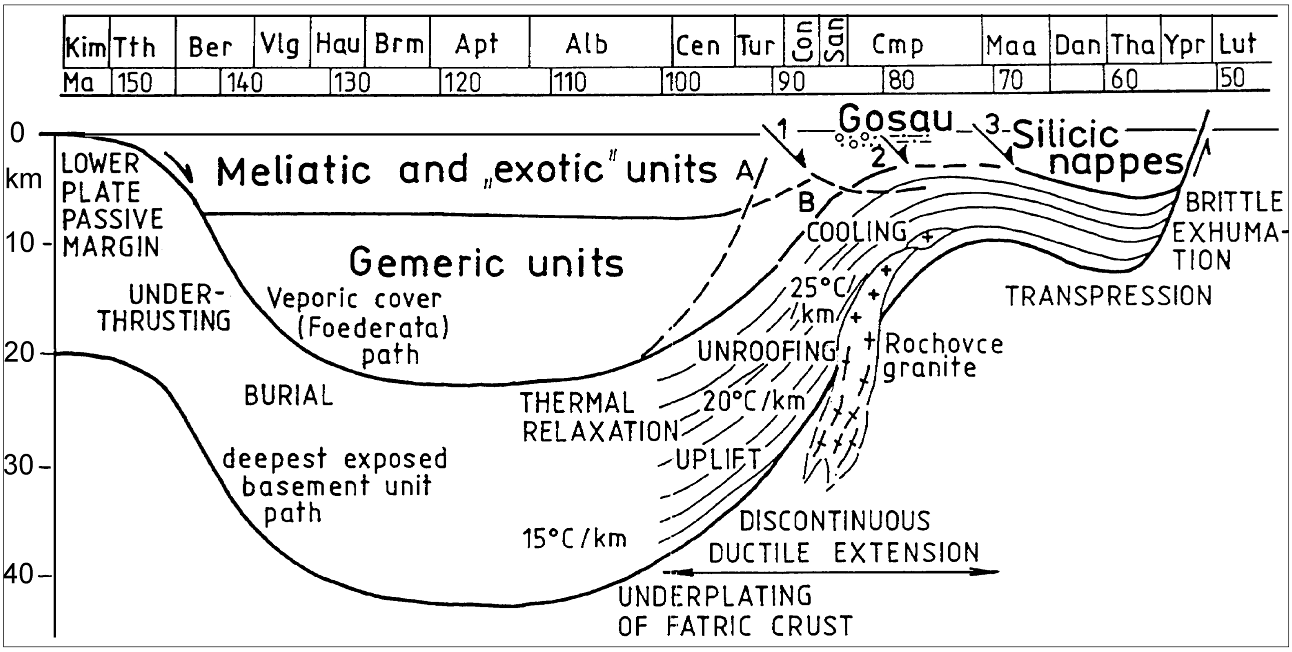

Fig. 4. Tentative diagram of Cretaceous burial and uplift history of the Veporic metamorphic core complex. Three variants of the time of final emplacement of the Silicic nappes are considered: (1) the late Turonian (pre-Gosauian) overthrust, coeval with the Fatric and Hronic nappes, is not in line with the thermochronological data from the Veporic basement and cover and would mean inprobably high uplift rates in excess of 2 mm/a already before 90 Ma (path A); (2) the Campanian (intra-Gosauian) between deposition of continental conglomerates and marine marls; (3) the latest Senonian (post-Gosauian). Variants (2) and (3) fit the reliable uplift rates around 0.7 mm/a for the Veporic cover and 1 mm/a for the deepest Veporic basement unit (path B), but these are not sufficiently justified by regional data. Variant (3) is favoured.

ments partly glided into a position above the subducted Vahic oceanic crust in front of the Tatric edge (Fig. 3), where they became incorporated into a fold-and-thrust wedge accreted to the toe of the upper (Tatric) plate. The sedimentary cover of the oceanic Vahic basement was partly detached to form a subcretionary complex underneath the Tatric toe (Plašienka 1995d). It follows that the converging zone was composed of distinct sectors where the Tatric/Vahic contact was buried below the Central Carpathian nappe units topped by compressional piggyback forearc-type basins, and other sectors where this contact was exposed at the surface and trench-type wildflysch sedimentation occurred atop the lower Vahic plate (Belice Unit — Plašienka 1995a, his Fig. 8).

The available cooling data and uplift rate estimates of the Veporic metamorphic dome shift the possible emplacement event of the Silicic Muráň and Stratená nappes up to at least the Early Campanian, most probably even to the late Campanian (Fig. 4). This is clearly documented by the unmetamorphosed Muráň Nappe rocks directly overlying the Veporic Foederata cover, which passed only the 300 °C isotherm during the earliest Senonian. This poses a question of the time relationships between the sedimentation of the Gosau deposits and the overthrusting event in this area (Fig. 4). From the above facts, the intra-Senonian or even post-Senonian emplacement of the Silicic Stratená Nappe (suggested by Hovorka et al. 1990), or of the Drienok Nappe (Slavkay & Rohálová 1993) cannot be excluded. However, the homelands, translation directions and time schedule of the Silicic nappes remain enigmatic, though a number of solutions has been proposed by different authors (recently e.g. Hók et al. 1995; Kozur & Mock 1995). The possibility exists that the Silicic nappes were displaced from the rear of the Hronic-Silicic stack by gliding induced by eastward lowering topographic gradient produced by westward migrated uplift and eastward unroofing of the Veporic core. In that case, the Silicic nappes could translate across and/or along the principal structural trends of exhumed domains, i.e. towards the N to NNE (Drienok Nappe), NE (orogen-parallel, Muráň and Stratená nappes), or E to SE (Silica-Aggtelek Nappe, possibly also the Kisfennsík Nappe in the Bükk Mts. — cf. Csontos 1988). Accordingly, the Silicic "homeland" might be situated in the southern CWC zones (north of the Hurbanovo–Diósjenö line, Fig. 1), in the area which had avoided the overriding by the Meliatic units and now is hidden below the Tertiary sedimentary and volcanic cover. This mechanism could reasonably account for the presence of Meliatic slices at the soles of the Silicic nappes. These would not be torn out substratum slivers during their S-N translation across the Meliatic suture, but rather decoupled fragments (or even ophiolite-bearing conglomerates) from the top of the collapsed ultra-Veporic thrust stack later incorporated into tectonic breccias at the soles of the Silicic nappes (Plašienka & Soták in press).

(6) Middle Senonian (80–70 Ma, middle Campanian to early Maastrichtian)

Data:

— scarce well age-constrained data in the internal CWC zones, except that of biotite $^{40}Ar/^{39}Ar$ (75.1 Ma, Kováčik et al. 1996) from the Veporic basement;

— $^{40}Ar/^{39}Ar$ low temperature step of 75.3 Ma from muscovites of mylonitized Tatric granitoids of the High Tatra Mts. (Maluski et al. 1993);
— K-Ar datings of the basement mylonites within the semiductile shear zones accompanying overthrust planes between the infra-Tatric and Tatric units in the Malé Karpaty Mts. (77 and 74 Ma — Kantor ex Putiš 1991);
— sediments of this age, mostly couches-rouges type pelagites, are present only in the Periklippen area (Gosau Group);
— the unique "red flysch" Hranty beds of the Vahic Belice Unit, cropping out from below the infra-Tatric basement-cover units in the Považský Inovec Mts. are an exception consisting of pelagic marls, calciclastic turbidites and bodies of chaotic megabreccias (Plašienka et al. 1994) which terminate sedimentation in the exposed sections of the Vahic Belice Unit (Fig. 2).

Interpretation

The uplift and collapse in the internal CWC zones slowly ceased, though they were continuously supported by a contractional tectonic regime. The gliding emplacement event of the Silicic cover nappes probably occurred. In the most external CWC zone, the final basement nappe edifice of the outer Tatric edge was formed (Fig. 3), where the infra-Tatric (e.g. the Borinka Unit) and Tatric s.s. (e.g. the Bratislava Nappe) complexes underwent very low- to low-grade metamorphism due to the basement nappe stacking (Plašienka et al. 1991, 1993). The subcreted Vahic (Belice) rocks were anchimetamorphosed as well (Plašienka 1995d). On the surface, the sea-level highstand caused flooding of local terrigenous sources, hence mostly marly sediments were deposited, except the extremely proximal Belice trench-type trough fed by the overriding fronts of infra-Tatric and higher units.

The structuralization of basement units in the CWC was completed by stacking along the outer Tatric edge. The overall Cretaceous shortening polarity within the CWC realm indicates that the passive to active margin inversion of the Tatric/Vahic contact was not a cause, but a consequence of the CWC contraction (Plašienka 1995b). Rather than "active" B-type oceanic subduction, an underthrusting of (sub) oceanic Vahic crust beneath the delaminated upper-crustal Tatric sheet probably occurred (Fig. 3). To drive the underthrusting, a southward subcrustal pull and/or northward upper-crustal push had to operate.

(7) Late Senonian–Early Paleogene (70–60 Ma, middle Maastrichtian to Danian/Thanetian boundary)

Data:

— low-temperature step at 66 Ma in the $^{40}Ar/^{39}Ar$ age spectrum from white micas of mylonitic Tatric granites in the High Tatra Mts. (Maluski et al. 1993);
— the cooling zircon FT age of 69±8 Ma (Kováč et al. 1994) from the Tatric basement granitoids of the Považský Inovec Mts.;
— a biostratigraphically determined sedimentary record of this stage is missing in the CWC;
— the structural record in the CWC is only roughly age-constrained by the youngest sediments involved (Middle Senonian - Campanian) and the oldest postdating deformation (Eocene);
— in the Peri-Klippen and Pieniny Klippen belts sedimentation exhibits coarsening and/or shallowing-upwards in an actively shortened accretionary wedge under the dextral transpressional regime (Nemčok & Nemčok 1994);
— a new transgressive sedimentary cycle after the main shortening phase of the Klippen belt units is inferred in its Polish sector (Maastrichtian Jarmuta Fm. — Birkenmajer 1986);
— ephemeral upper Danian reefs (e.g. Köhler et al. 1993) were later destroyed to form olistolites in Paleogene flysch deposits.

Interpretation

In the central and inner West Carpathian zones, a continental regime with subaerial weathering and karstification is indicated by the development of karst relief and redeposition of bauxites into karst depressions at the beginning of the Early Tertiary, southwards younging transgression (e.g. Činčura 1990). The sedimentary and structural record in the Vahic Belice Unit indicates the closing of the Penninic-Vahic oceanic trough and a collisional event during the latest Senonian (Plašienka 1995d). The northern CWC margin and the Oravic (Pieniny Klippen Belt s.s.) Czorsztyn continental ribbon came into collision (Fig. 3), later shortening prograded northwards into the Outer Carpathian Magura flysch basin (e.g. Soták 1992; Oszczypko 1992; Winkler & Slaczka 1994). However, suturing of the Penninic-Vahic ocean shows an eastward migration, since the youngest pre-thrusting sediments of the subsurface Iňačovce-Krichevo Unit in the basement of the Transcarpathian Basin in eastern Slovakia and western Ukraine (parallelized with the Alpine Penninic units by Soták et al. 1992, 1994) are Eocene in age. A collisional event between the CWC and Oravic units cannot be justified in the East Slovak sector as well. In the CWC hinterland areas, the Oravic/Tatric collision is manifested by restricted backthrusting and development of "synclinoria" involving higher nappe units and scarce remnants of Senonian sediments (e.g. Maheľ 1995). These were formed under the overall N-S contractional regime along the NW–SE trending dextral and SW–NE trending sinistral wrench corridors (Plašienka 1995c), subsequently truncated by discrete brittle strike-slip faults (e.g. the Muráň fault — cf. Marko 1993) — Fig. 3.

There is a considerable difference between the structures of the western (SW–NE trending) and eastern (WNW–ESE) sectors of the Pieniny Klippen belt, Periklippen zone and marginal CWC zones. In western Slovakia, the latest Cretaceous collision was followed by Paleogene - Early Miocene dextral transpression and Middle Miocene sinistral transtension (cf. Marko et al. 1996 and references therein). On the contrary, in eastern Slovakia the CWC front is buried below the thick Tertiary cover, however, the outer CWC edge gradually bifurcates from the Klippen Belt (except for the Humenské vrchy sliver) and the subsurface Iňačovce-Krichevo unit appears (Fig. 1). This may be tentatively explained by a lateral non-persistence of the Czorsztyn ribbon continent. The Iňačovce-Krichevo Unit should therefore represent a fragment of the Early Tertiary remnant flysch basin, eliminated later together with the Magura trough. The position of the Klippen Belt in between (with scarce Czorsztyn-type klippes) may be explained by a large-scale dextral wrenching along the southern (and possibly also the northern) boundary fault of the Pieniny Klippen Belt (Plašienka 1995e).

Concluding remarks

The presented database and its interpretation represent the "state-of-the-art" review of knowledge (though may be subjective in some aspects) about the Cretaceous paleotectonic evolution of the Central Western Carpathians, an important piece of the marvellous European Alpidic orogenic belt. Unlike many other Alpine segments, the CWC record their Cretaceous history mostly in an original state, almost untouched (in the meso- to macroscopic scales) by superimposed Tertiary movements. The main aspect of this history is the "ocean to ocean", progradational shortening of a mobile belt floored by a stretched and attenuated continental crust, a former constituent of the North European Epivariscan platform. Its "3-S" (stretching–stacking–splitting) evolution certainly had periods of relative quiescence and slow movements, interrupted by paroxysmal events, but all display compatible kinematic and dynamic characteristics and causal relationships.

The above outlined paleotectonic scenario for the CWC is consistent with the recently proposed double-ocean history of the Eastern Alps (Thöni & Jagoutz 1993; Froitzheim et al. 1996; Dallmeyer et al. 1996; von Blanckenburg & Davies 1996). This model has been originally envisaged by sedimentological studies (Decker et al. 1987; Pober & Faupl 1988; Tollmann 1989; Faupl & Wagreich 1992; Wagreich et al. 1995; Winkler 1996) and recently confirmed by the twofold ages of Alpine eclogites (Thöni & Jagoutz 1993; Bowtell et al. 1994; Froitzheim et al. 1996 and references therein) and by the footwall propagation of post-collisional thrust stacking within the Austroalpine system (Dallmeyer et al. 1996). In the Carpathians, the northward shortening polarity is evident from most of the available lithostratigraphic, structural and geochronological data.

The main feature, which apparently contradicts this scenario, is the presence of huge mid-Cretaceous flysch complexes with "exotic" material along the outer CWC edge, mainly in the Klape Unit (Marschalko 1986). On the basis of this, the concept of the "Pieniny exotic cordillera" or "Andrusov Ridge" (cf. Mišík & Sýkora 1981; Mišík & Marschalko 1988; Birkenmajer 1988, and references therein) as a mid-Cretaceous compressional structure has been widely accepted, obviously in line with the concept of the "northern" ophiolites- and HP/LT metamorphic rocks-bearing sources for clastic prisms along the northern Austroalpine margin (e.g. Gaupp 1983; Winkler 1988, 1996; Pober & Faupl 1988). Recently, however, the Variscan age of at least the HP minerals has been proved by von Eynatten et al. (1996) for this northern source.

In the Carpathians, the presence of lowermost Middle Triassic pelagic limestones (Birkenmajer et al. 1990) and Upper Jurassic blueschists (Dal Piaz et al. 1995) among the pebble material in the Klape Unit would consequently predict rifting of the Penninic-Vahic oceanic domain already in the Early Triassic (proposed by Kozur & Mock 1996) and its closing (at least incipient) during the Late Jurassic — a conclusion which is in a severe contradiction with the geological record in the CWC, and in the Austroalpine as well. For this reason, Plašienka (1995a) proposed a different model: the Klape and related units (their pre-Upper Turonian formations) are constituents of the Fatric (Krížna) nappe system rooted in the inner CWC zones, originally juxtaposing collisional Meliata-Hallstatt suture zones, from which the exotic clastic material was derived. Although this hypothesis needs further confirmation (or rejection) by thorough analyses and a number of objections can be put against it (Mišík 1996; Kozur & Mock 1996), it could reasonably account for geodynamic inconsistencies between the supposed contraction along the outer (Tatric) CWC margin and the prolonged distensional regime within the CWC throughout the Late Jurassic and Early Cretaceous (Plašienka 1995a, b). Recently, an alternative solution has been presented by Kozur & Mock (1996). They assume the "Pieniny ocean" as a northern branch of the (South) Penninic ocean, opened already in the Early Triassic. The South Penninic proper (corresponding to the Vahic, opened in the Middle Jurassic) should therefore have prolonged between the Tatric and Veporic (i.e. somewhere along the Fatric Basin) to reach the Iňačovce-Krichevo Unit in the east. However, this opinion seems not to be supported by any relevant geological datum either in the Carpathians (as concerns the oceanic character of Fatric or adjacent zones), or in the Alps (as concerns the possibility of pre-Jurassic rifting of any Penninic oceanic branch).

In addition to these uncertainties, there are still basic gaps in our knowledge about the Cretaceous paleotectonic evolution of the CWC proper. Following the seven stages discerned, these may be listed as follows:

(1) Late Jurassic – Early Cretaceous: the sedimentary records in the Meliatic (if ever present), Silicic, Hronic and Fatric units should be thoroughly studied to obtain new information about the temporal and spatial characteristics of sedimentation and provenances of clastic material. The structural record of thrust stacking and crustal thickening in southern CWC zones needs to be investigated more detaily, together with definition of their temporal constraints.

(2) Late Early Cretaceous — more precise age limiting of the stacking period in the Veľký Bok Unit (inferred Aptian – early Albian) is desired. The age of the widespread vein mineralization and material remobilization in southern CWC zones (Gemeric, Veporic) should be better defined (this applies for the whole Cretaceous).

(3) Mid-Cretaceous — geochronological evaluation of the thermal metamorphic peak in the Veporic Unit; provenance, age and the temporal and spatial dispersal of the "exotic" clastic material in Albian-Cenomanian flysches.

(4) Late Turonian — emplacement mechanisms of the cover nappe systems, their translation paths and precise age constraints of the main thrusting events. The possibility of the

Fatric provenance of the Peri-Klippen Belt units (especially the Manín and Klape) should be evaluated by profound structural, sedimentological and litho-biostratigraphical studies of key sections.
(5) Early Senonian — physical modelling is required to interpret the observed P-T-t characteristics of metamorphism and to evaluate the possible contribution of delamination of the lithospheric root to the Veporic thermal budget and uplift. The position of the Gosau sediments with respect to the Silicic nappes needs to be reconsidered.
(6) Middle Senonian — tectonic events in the infra-Tatric and Tatric basement, as well as cover units should be dated by means of $^{40}Ar/^{39}Ar$ isotopic method. Sedimentary record along the outer CWC margin should be reassessed through integrated sedimentological, biostratigraphic and structural studies, together with isotopic datings of clastic material.
(7) Late Senonian to Early Paleogene — new geochronological data, especially zircon FT cooling ages from the Tatric basement and sediments of this age would much help in paleotectonic reconstructions. Structural analysis has to be more widely applied in the Klippen and Periklippen belts.

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