Geol Rundsch (1995) 84:748–760

ORIGINAL PAPER

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Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia)

Received: 13 February 1995 / Accepted: 9 June 1995

Abstract The Tatricum, an upper crustal thrust sheet of the Central Western Carpathians, comprises pre-Alpine crystalline basement and a Late Paleozoic–Mesozoic sedimentary cover. The sedimentary record indicates gradual subsidence during the Triassic, Early Jurassic initial rifting, a Jurassic–Early Cretaceous extensional tectonic regime with episodic rifting events and thermal subsidence periods, and Middle Cretaceous overall flexural subsidence in front of the orogenic wedge prograding from the hinterland. Passive rifting led to the separation of the Central Carpathian realm from the North European Platform. A passive margin, rimmed by peripheral half-graben, was formed along the northern Tatric edge, facing the Vahic (South Penninic) oceanic domain. The passive versus active margin inversion occurred during the Senonian, when the Vahic ocean began to be consumed southwards below the Tatricum. It is argued that passive to active margin conversion is an integral part of the general shortening polarity of the Western Carpathians during the Mesozoic that lacks features of an independent Wilson cycle. An attempt is presented to explain all the crustal deformation by one principal driving force – the south-eastward slab pull generated by the subduction of the Meliatic (Triassic–Jurassic Tethys) oceanic lithosphere followed by the subcrustal subduction of the continental mantle lithosphere.

Key words Western Carpathians · Mesozoic · Paleotectonic history · Continental margins · Driving forces

Introduction

In most of the Mesozoic (Jurassic–Early Cretaceous) palinspastic reconstructions, the West Carpathian segment occupies the position of a 'northern transform zone' (Trümpy 1988). This is viewed as a broad sinistral wrench corridor along the northern Apulian (Adriatic) margin joining the progressively widening, SW–NE trending Penninic oceanic domain in the west and the gradually closing, roughly N–S trending Transylvanian-Vardar *sensu lato* (Tethys) oceanic realm in the east (Biju-Duval et al. 1977; Weissert and Bernoulli 1985; Debelmas and Sandulescu 1987; Lemoine and Trümpy 1987; Trümpy 1988; Rakús et al. 1990). The eastward drift of Apulia with respect to Europe was therefore more or less space-preserving, leaving little place along the northern Apulian margin for the creation of broad oceanic domains. These would have been prolongations of the Piemont–Ligurian ocean, opened by a transtensive pull-apart mechanism rather than by orthogonal rifting processes (Bourbon et al. 1977; Kelts 1981; Boccaletti et al. 1984; Weissert and Bernoulli 1985; Trümpy 1988). However, there are many uncertainties in these reconstructions due to a nearly complete lack of undoubtedly Penninic-derived units in the surface structure of the Central Western Carpathians. Upper Cretaceous to Palaeogene flysch complexes exposed along the northern Tatric edge in the Periklippen Belt may represent the Carpathian Penninic; however, their original basement is not known. Several tectonic models for the Western Carpathians assume a Penninic-type oceanic character of this disappeared substratum (including possible continental fragments), which was underthrust along the northern Tatric continental edge and is inferred to form middle and lower crustal portions of the present Central Carpathian edifice (e.g. Leško and Varga 1980; Rozložník 1990; Jacko and Sasvári 1990; Tomek 1993). This hypothetical ocean-derived superunit was given the name Vahicum (Mahel' 1981).

The main reason of the scarcity of Penninic units at the present surface of the Central Western Carpathians lies in their Tertiary evolution. The Central Carpathians, in contrast with the Central Alps, underwent only moderate Tertiary collision. Their development

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was controlled by the subduction of the basement of the Flysch belt along their northern and eastern margin and by the lateral extrusion resulting from the Alpine collision (e.g. Ratschbacher et al. 1991; Nemčok 1993). Consequently, the Carpathians escaped Tertiary crustal thickening and uplift of young Alpine metamorphic core complexes. A slight Late Tertiary rise of the West Carpathian 'core mountains', which are asymmetrical horst structures, was caused by block tilting and rotations in a transpressional–transtensional tectonic regime (e.g. Kováč et al. 1994) and enabled the local removal of only a few upper kilometers of pre-Tertiary rock complexes, which was not sufficient to exhume Penninic units.

In spite of this, there are some rather small areas in the Central Western Carpathians where the presence of Penninic-related rock complexes has been suggested. These are the Borinka unit in the Malé Karpaty Mts (Mahel' 1981, 1987; Plašienka 1987) and the Belice unit in the Považský Inovec Mts (Soták et al. 1993a; Plašienka et al. 1994; see also Leško et al. 1988); both in western Slovakia (Fig. 2) in a position comparable with that of the Rechnitz Penninic window group of the easternmost Alps. The large Iňačovce-Krichevo unit in the subsurface basement of the Neogene Transcarpathian Basin in eastern Slovakia and western Ukraine has been interpreted as a Penninic element by Soták et al. (1993b, 1994). The unit is known only from boreholes; it comprises Permoscythian phyllites, Triassic carbonates, a thick Bündnerschiefer-like complex of Jurassic to Cretaceous age, Upper Cretaceous to Paleogene flysch sediments and tectonic thrust sheets of peridotites and serpentinites, all affected by low-grade metamorphism and post-Eocene thrusting (Soták et al. 1993b, 1994).

The objective of this paper is (1) to outline the Mesozoic paleotectonic history of the Tatric superunit and especially of its outer, northern part which probably faced the Penninic oceanic realm, and (2) to discuss the timing and mechanisms of the formation of a passive margin in this position and its conversion into an active margin at a later time. The reconstruction is based mainly on new lithostratigraphical and structural data in two key areas in western Slovakia: in the Malé Karpaty and Považský Inovec Mts (cf. Plašienka 1995).

General framework

The Western Carpathians form the northernmost segment of the Alpine–Carpathian orogenic arc. Part of their pre-Neogene basement appears in an E–W trending, moderately high mountainous region between the lowlands of the Pannonian Basin in the south and the Bohemian Massif and Polish Platform of the North European Plate in the north. They are linked to the Eastern Alps in the west and to the Eastern Carpathians in the east (Fig. 1). The present structural pattern of the Western Carpathians was formed by the Cretaceous–Tertiary subduction–collision processes in a mobile belt between the stable North European plate and Africa-related, drifting Apulian continental fragments. One of the most characteristic features of the West Carpathian evolution is a marked northward migration of orogenic processes, including rifting and extension of the Variscan continental crust, compression and nappe stacking of attenuated continental crust and subduction of longitudinal oceanic basins (e.g. Mahel' 1981, 1989; Birkenmajer 1988; Rakús et al. 1990; Plašienka 1991), as well as transpression and transtension postdating the main shortening phase. The West Carpathian orogeny ended during the Late Tertiary by slab detachment terminating the southward subduction of the ocean crust substratum of the Outer Carpathian Flysch Belt (Tomek 1988; Tomek and Hall 1993).

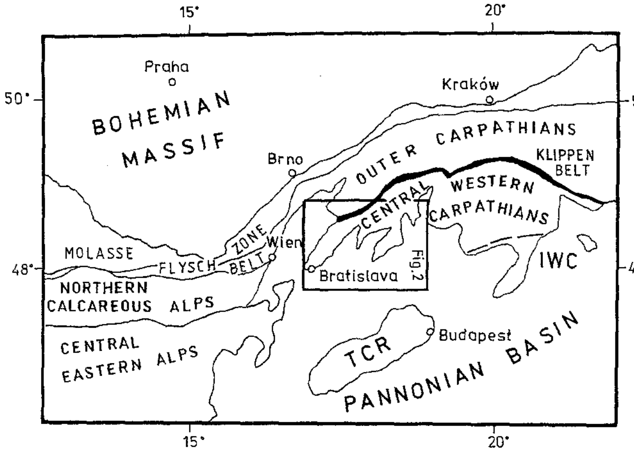

Fig. 1 Position of the studied area in Central Europe. IWC, Inner Western Carpathians; TCR, Transdanubian Central Range

The boundary between the Outer West Carpathian (OWC) Flysch Belt and the Central West Carpathian (CWC) basement-cover units is formed by a narrow zone with an intricate structure, the Pieniny Klippen Belt (PKB; Fig. 2). The PKB has been considered as a surficial expression of the suture, along which some oceanic domains disappeared during the Cretaceous and Early Tertiary (e.g. Mišík 1979; Mahel' 1981; Birkenmajer 1988). At present, the PKB is usually subdivided into two belts: the outer Pieninic units *sensu stricto* (renamed as Oravic by Mahel' 1986) with the typical Czorsztyn and Kysuca units and the inner Periklippen Belt, built up mainly of Central Carpathian cover units (Drietoma, Bošáca, Haligovce, Klape and Manín units).

The CWC domain is composed of three principal superunits: the Tatric, Veporic and Gemeric basement-cover crustal imbricates, which are overridden by décollement cover nappes of the Fatric, Hronic and Silicic systems built up by Late Paleozoic–Mesozoic, mostly sedimentary complexes. These are in places hidden below a very thick Tertiary sedimentary and volcanic cover (Fig. 2). The external Tatric superunit comprises pre-Alpine crystalline basement including mainly Lower

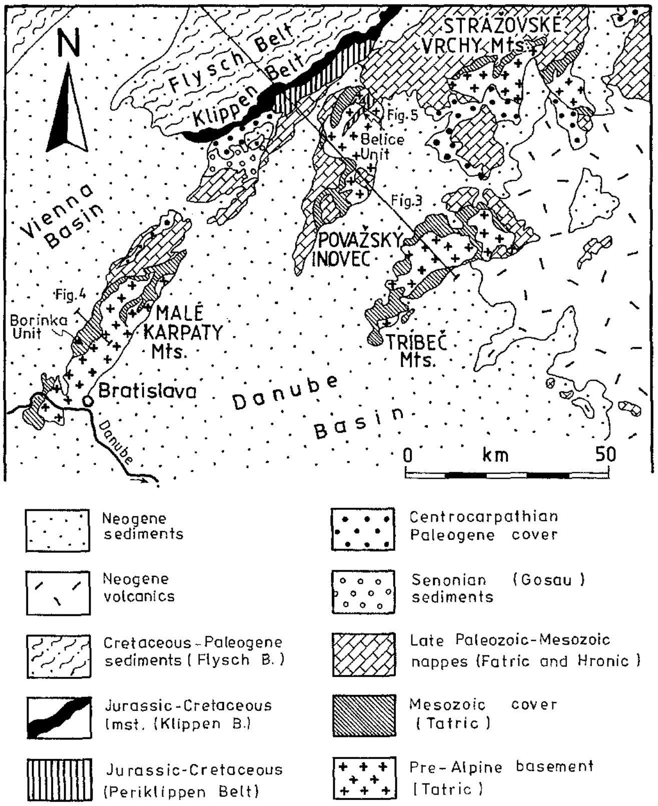

Fig. 2 Simplified geological map of the south-western part of the Western Carpathians. Profile lines are depicted in the respective figures

Paleozoic medium to high-grade metamorphic rocks and Variscan granitoid plutons and its Late Paleozoic–Mesozoic (up to the Lower Turonian), generally well-preserved sedimentary cover. The Tatric units, especially the lowermost units, are usually correlated with the Lower Austroalpine nappes of the Eastern Alps (see discussion in Häusler et al. 1993).

The oceanic character of the zones north of the Tatric is inferred only from circumstantial reasoning. The unusually wide range of rock types found in the pebbles of the PKB Cretaceous flysch conglomerates includes, among others, glaucophane-bearing basalts, calc-alkaline volcanic rocks, chrome spinel and glaucophane grains in Urgonian limestones and several types of deep-water sediments, considered as indications of former oceanic and active margin provenances (see review by Mišík and Marschalko 1988). As these clasts have no equivalents in the presently outcropping units, their original sources and the conglomerates themselves, are traditionally called 'exotic'. Many Carpathian evolutionary models consider the existence of an active continental margin along the northern Tatric edge already starting during the Late Jurassic or Early Cretaceous (e.g. Birkenmajer 1988; Mišík 1979; Marschalko 1986; Winkler and Slaczka 1994), the uplift of a hypothetical exotic ridge in mid-Cretaceous times and its destruction during the Late Cretaceous. Nevertheless, there is no certainty that the pebble material was derived from zones immediately north of the Tatric and thus is really a witness of active margin processes in this area.

Structure of the northern Tatric and adjacent zones

The northern Tatric zone frames the outer edge of the CWC block formed dominantly by rigid pre-Alpine crystalline basement complexes. The zones immediately north of it, up to the huge Magura unit of the Flysch belt, are composed of mostly soft, detached sedimentary complexes of the PKB, with a complex, steeply dipping fan-like structure (Fig. 3). The direct contact between the Tatric and more external units is not exposed, but is hidden below the Central Carpathian cover nappes in the western part of the CWC and by Tertiary sediments in the northern and eastern parts. The closest neighbourhood at the surface of the Tatric basement with the PKB may be seen in the northern part of the Považský Inovec Mts (Fig. 2). The general structural position of this area is shown in the schematic profile in Fig. 3. The boundary between the Tatric and the more external units is interpreted as an original overthrust steepened by oblique-slip fault system developed during Late Cretaceous–Early Tertiary dextral transpression (Plašienka 1990) and Late Tertiary sinistral transtension (e.g. Fodor et al. 1990; Marko et al. 1991; Kováč et al. 1993). Cretaceous structures, which are the object of this paper, can be studied only in the uplifted horst mountains, where the Tatric and possible infra-Tatric units come to the surface.

The Tatricum is generally interpreted as a wedge-shaped upper crustal thrust sheet (Fig. 3). Its frontal parts are complicated by the presence of nappe subuni-

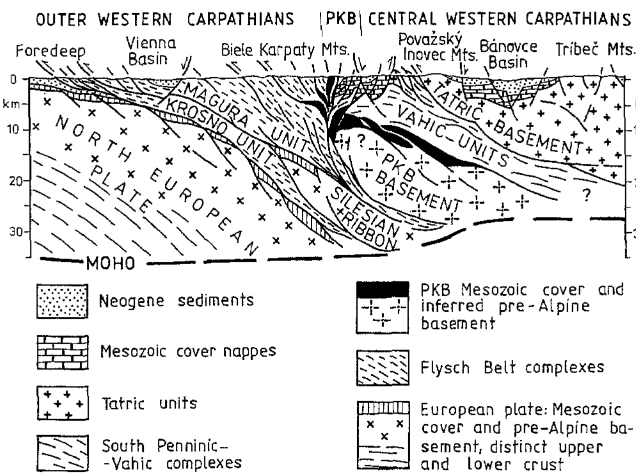

Fig. 3 Conceptional section across the Outer Carpathians and northern part of the Central Western Carpathians, partly based on reflection seismic profiling. The PKB basement (Pieniny Klippen belt, or Oravic) is an extensional continental ribbon created by Jurassic rifting which collided with the Tatric margin during the latest Cretaceous–earliest Tertiary. The inferred Vahic units are accretionary complexes of the Penninic–Vahic ocean underthrust below the Tatricum

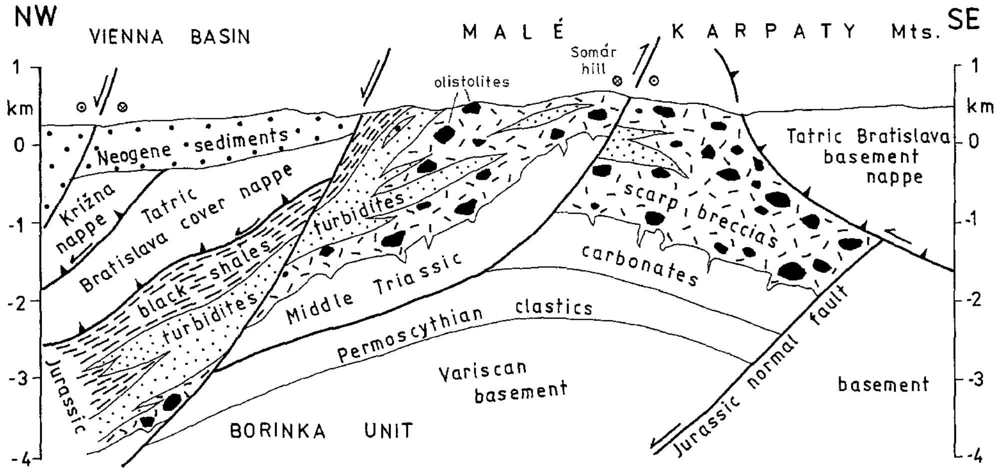

Fig. 4 Schematic cross-section showing Jurassic resediments of the Borinka unit overriden by the Tatric Bratislava basement-cover nappe. For location of section, see Fig. 2

ts and recumbent folds. In the Malé Karpaty Mts, the extensive Tatric Bratislava basement nappe overthrusts the infra-Tatric Borinka unit, the latter with some analogies to the Penninic and/or Austroalpine marginal successions (Fig. 4; cf. Plašienka et al. 1991; Häusler et al. 1993). In the Považský Inovec Mts, the Tatric Inovec nappe, dismembered into several subunits, overrode the Belice unit (Fig. 5). The lithostratigraphy of the Belice unit is entirely different from any other Carpathian unit and may represent the only Carpathian surface exposure of an oceanic, (south) Penninic Mesozoic complex (Fig. 5; cf. Soták et al. 1993a; Plašienka et al. 1994).

Mesozoic paleotectonic evolution

The reconstruction of the Mesozoic paleogeographical and paleotectonic evolution of the north Tatric and adjacent zones is based on an almost continuous sedimentary record (Scythian–Maastrichtian) and on the structural signatures of large-scale tectonic processes. Several stages of short-lived tectonic activity separated by longer periods of relative quiescence can be distinguished.

Triassic pre-rift platform stage

During the whole Triassic period, the Tatric domain was part of the northern European, slowly subsiding shelf with only restricted fault activity and stable paleogeographical conditions (Michalík 1994a). Upper Permian to Lower Triassic ('Permoscythian') quartzose clastics, Middle Triassic carbonate platform sediments and Upper Triassic terrestrial–lagoonal, partly hypersaline deposits (Carpathian Keuper Formation) are the principal lithologies. Rhaetian biodetrital limestones have been rarely preserved.

Surprisingly, the Middle Cretaceous flysch conglomerates of some PKB units and of the Tatric and Fatric units themselves contain pebbles of deep-water, conodont-bearing pelagic Middle and Upper Triassic limestones (Mišík et al. 1977 1981; Birkenmajer et al. 1990). Similar pelagic Triassic rocks are also known from Tertiary exotic conglomerates of the OWC Flysch Belt (Soták 1990). These findings have led to the assumption of the existence, from the Anisian onward, of a Tethyan oceanic branch propagating westward from the Transylvanian ocean (Birkenmajer et al. 1990). Another explanation would be a post-Early Cretaceous left-lateral transport of the CWC domain along the northern Tatric edge towards the Triassic–Jurassic Tethys (Marschalko 1986; Soták 1992; Michalík 1992). Structural evidence for such a long-distant translation is missing and exotic Triassic pebbles may also be derived from remote southern Inner West Carpathian sources (Meliatic and related units) – a solution, however, rejected by Mišík and Marschalko (1988).

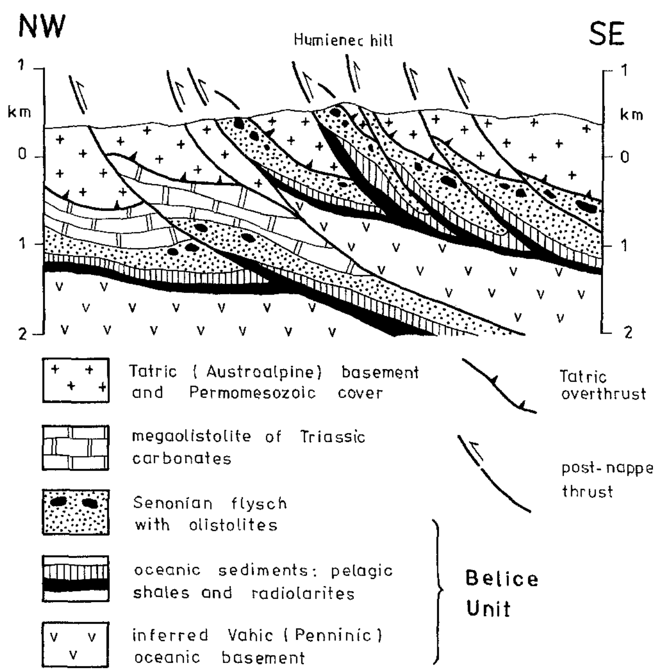

Fig. 5 Interpretative profile of the position of the Belice unit in the northern part of the Považský Inovec Mts (see Fig. 2)

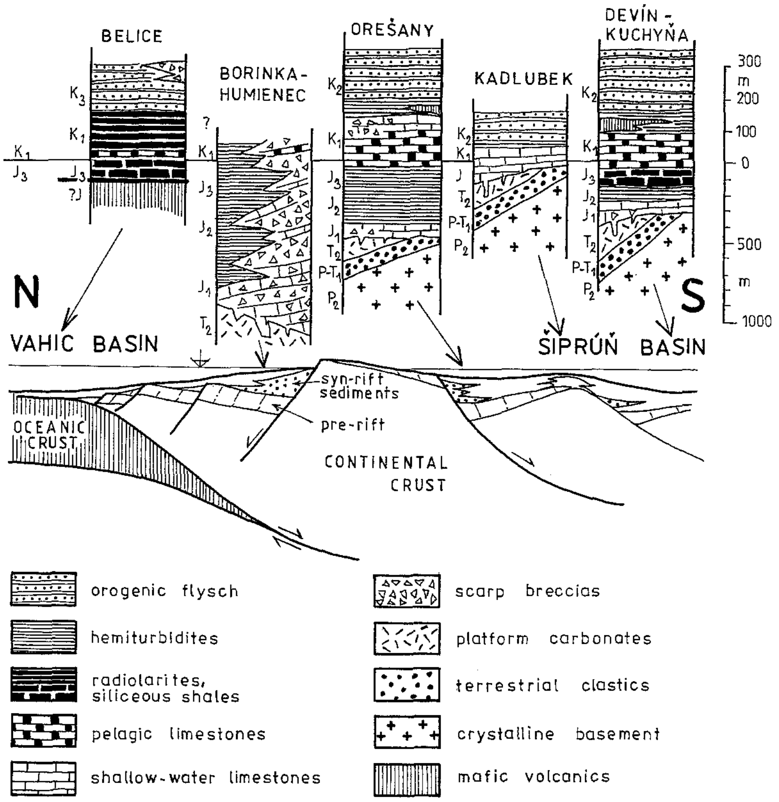

Fig. 6 Paleotectonic reconstruction of the northern Tatric passive margin at approximately Jurassic–Cretaceous boundary. Principal lithofacies of several successions defining the North Tatric ridge are shown

Early Jurassic rifting

A pronounced rifting event in the Early Liassic, which led to the disintegration of the Triassic carbonate shelf, was accompanied by moderate uplift and deep erosion of Triassic sediments at the rift shoulders in the outermost Tatric zones. The whole CWC area split into several orogen-parallel elevated swells and subsiding basins. During the Jurassic and Early Cretaceous, the basins expanded at the expense of the swells. Three principal basins came into existence: the Vahic (South Penninic, later oceanic) basin in the north, the intra-Tatric Šiprúň trough and the broad Fatric (Krížna, or Zliechov) basin in the south, separating the later Tatric and Veporic crustal units (Figs. 9 and 10).

Elevated domains are characterized by syn-rift neptunian dykes, extraclastic carbonate breccias, sandy biodetritic limestones and sandstones, whereas in the basins the calci-turbiditic formations were deposited from the Sinemurian onward. Simultaneously, the northern margin of the Tatric area was formed. It was defined by steep north-dipping normal fault escarpments delivering clastic material for resediments of peripheral half-grabens (Figs 4 and 6 – the Borinka half-graben; cf. Plašienka 1987).

Middle Jurassic–Early Cretaceous extensional regime

During the Toarcian stage, extensional faulting was renewed, along with sinking, partly eustatic, of former ridges. The majority of the former source areas of terrigenous material was flooded and only the northern edge of the North Tatric ridge supplied olistolite-bearing scarp breccias to the Borinka half-graben, probably until the Early Cretaceous (Fig. 4). The general rearrangement of basin architecture at the Lias/Dogger boundary may reflect the final break-away event of the Penninic–Vahic rift. From this time on, the stretched CWC continental fragment was separated from the European continental shelf by a basin floored by oceanic crust. The CWC domain became a part of the 'Carnic plate' (Dewey et al. 1973), or 'Kreios continent' (Tollmann 1978; Michalík and Kováč 1982) – the northern prong of Apulia, slowly drifting to the east.

The reconstruction of the northern Tatric zone in western Slovakia reveals the existence of an elevated, partly subaerial continental ridge separating the Vahic oceanic area and the intra-Tatric Šiprúň trough with thinned continental crust (Fig. 6). The North Tatric ridge was rimmed by a system of half-graben from the side of the Vahic ocean – a feature typical of Atlantic-type continental margins.

Deep-water basins of the CWC area (Šiprúň, Fatric) developed on a thinned continental crust and reached bathyal to abyssal depths during the Callovian–Oxfordian (radiolarites) and maintained these depths up to the end of Neocomian (Maiolica-type pelagic limestones). Deep-sea eupelagic sediments probably represent the thermal subsidence stage of the basin evolution.

During the Tithonian and Neocomian, several synsedimentary faulting events have been recognized in ridge and slope domains (Michalík 1992). The most conspicuous is the evidence for Barremian differential uplift and the installation of 'Urgonian' build-ups (Michalík and Soták 1990; Michalík 1994b). These late events may have been caused by the onset of intraplate compressional stresses and/or by upheaval of a foreland bulge caused by lithospheric surface loading of southern CWC zones by the orogenic wedge prograding from the hinterland. Nevertheless, during the Aptian and Early Albian, the CWC lithospheric stretching culminated with the extrusions of some submarine hyalobasanitic lavas of upper mantle origin (Hovorka and Spišiak 1988; cf. Trommsdorff et al. 1990) piercing the strongly thinned CWC crust (Fig. 10).

Mid-Cretaceous flexural subsidence

Processes of Cretaceous shortening, crustal stacking and nappe emplacement in the CWC area show a marked northward polarity (e.g. Biely and Fusán 1967; Andrusov 1968; Mahel' 1974; Plašienka 1991). Already during the Late Jurassic and Early Cretaceous, compression affected the Inner Carpathian and southern CWC zones (i.e. the southern Veporic and Gemeric) in connection with the closure of the Meliatic ocean (Fig. 10). These early Alpine (or late Cimmerian) compressional events are revealed by both the sedimentary and geochronological record (e.g. Kozur 1991; Maluski et al. 1993; Kováč et al. 1994). During the Aptian, the compressional orogenic front reached the southern margin of the Fatric (Krížna) basin at its border zone to the Veporic domain. In this basin, sedimentation ceased (Vel'ký Bok unit, Fig. 10) and underthrusting of the attenuated Krížna basement below the northern Veporic edge occurred (Plašienka 1983). The foreland of the thrust wedge – the Fatric (Krížna) and Tatric domains – became an area of early orogenic flysch sedimentation in the Albian–Cenomanian Poruba flysch basin. The Poruba Formation contains exotic conglomerates with similar pebble material as in those of the PKB Klape unit (Mišík et al. 1981).

In this period, an important paleogeographical change occurred. At the position of a rugged submarine topography with numerous highs, slopes and depressions, typically rimmed by carbonate resediments derived from local intrabasinal sources, a wide flysch trough fed by extrabasinal, partly exotic sources developed. These phenomena may be attributed to both flexural downbending of the CWC lithosphere due to a topographic load produced by the orogenic crustal wedge prograding from the hinterland, and the burial of earlier local sources below thick flysch sediments. During the Turonian, shortening also affected the Tatric domain and its crust was accreted to the overridding plate. This brought about the termination of the previously continuous sedimentation, uplift and erosion.

Late Cretaceous shortening and thrusting

During shortening, extensional normal fault systems of the thinned Tatric crust were reactivated as frontal ramps, over which basement-cover recumbent folds and imbricated thrust nappe sheets developed (Plašienka 1991). Examples are known mainly from the Malé Karpaty Mts (Plašienka et al. 1991) and the Vysoké Tatry Mts (Veizer 1970; Bac-Moszaszwili et al. 1982). Later on, a substantial part of the Tatric complexes was covered by the Fatric–Hronic–Silicic décollement gliding nappe system (Krížna, Choč and higher nappes) and by post-orogenic Late Cretaceous and Tertiary deposits.

As a consequence, the relationship between the outermost Tatric units and the more external zones is highly uncertain, with the exception of the northern part of the Považský Inovec Mts (Fig. 2). There, Jurassic and Cretaceous rocks of the Belice unit, of supposed Vahic origin, crop out from below the Tatric basement and its Late Paleozoic–Mesozoic cover (Plašienka et al. 1994). The Belice unit consists of Upper Jurassic cherts, Lower to Middle Cretaceous siliceous shales and Senonian flysch with conglomerates and olistolites associated

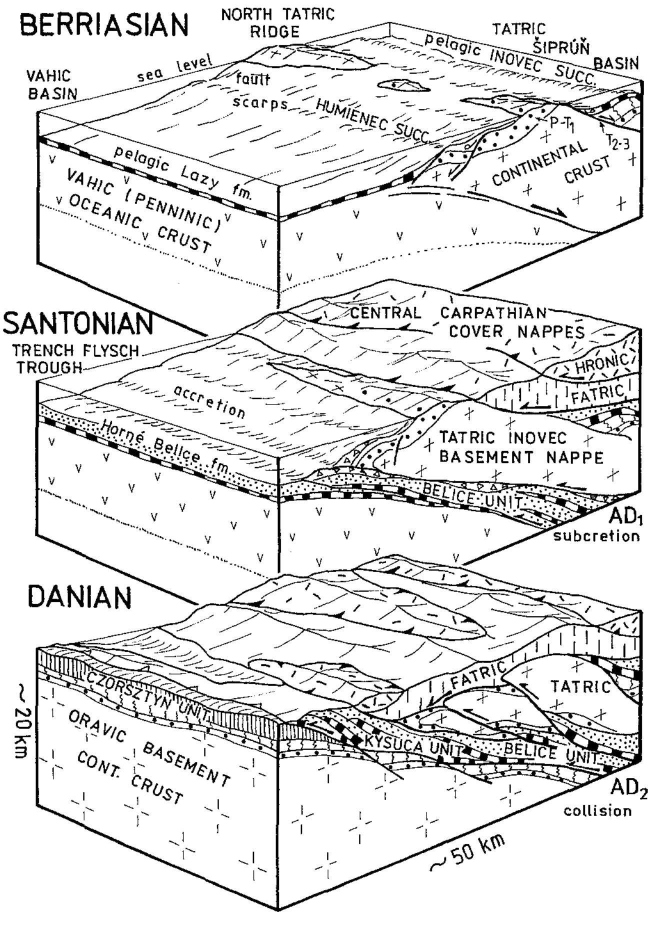

Fig. 7 Block diagrams illustrating a passive to active margin conversion, as recorded in the Považský Inovec Mts. The Senonian flysch conglomerates of the Belice unit contain mostly Tatric material

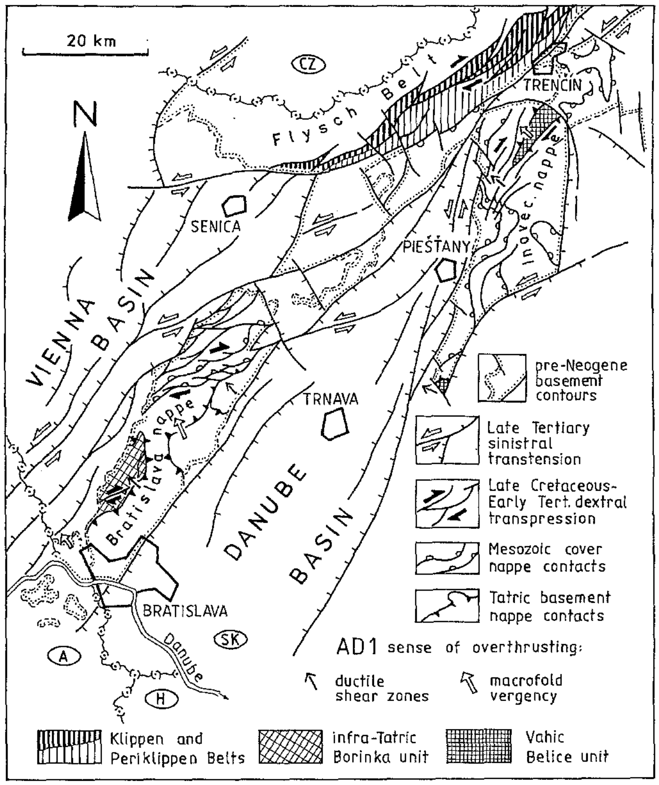

Fig. 8 Structural sketch of the Malé Karpaty and Považský Inovec Mts (compare with Fig. 2). Note three main structural stages: (1) mid-Cretaceous top to NW nappe overthrusting (deformation stage AD1); (2) Late Cretaceous–Early Tertiary dextral transpression; and (3) Late Tertiary sinistral transtension and Neogene pull-apart basin development

with breccias composed mainly of Tatric material (Figs 5 and 7). The unit is dismembered into numerous slices and resembles a mélange, similar to the Matrei zone at the contact of the Pennine and Austroalpine nappes in the southern part of the Tauern window (Frisch et al. 1987). The Upper Cretaceous coarsening and thickening upwards terrigenous flysch succession of the Belice unit most probably records a gradual convergence of the Tatric continental and Vahic oceanic domains, subduction of the latter below the former and the inversion of the Middle Jurassic–Middle Cretaceous passive margin into a Late Cretaceous active margin. All the principal units of the northern part of the CWC became the source terrains of the Upper Cretaceous terrigenous clastic sequences, marking the closing period of the Vahic ocean (Fig. 7).

Structurally, the Late Cretaceous to earliest Tertiary shortening period of the northern Tatricum is recorded by the associations of two principal deformation stages. The stage AD1 represents nappe stacking and crustal thickening, expressed by subhorizontal ductile–brittle overthrust shear zones with stretching lineation perpendicular to the nappe fronts and top to NW kinematic indicators (Fig. 8). Large recumbent folds and basement-cover nappes were emplaced under very low to low grade metamorphic conditions (Putiš 1991; Plašienka et al. 1993). The stage AD2, represented by linear macrofolds with subvertical axial plane cleavage, reverse faulting and local backthrusting, reflects the transition to the transpressional regime (Plašienka 1990).

Discussion of the general processes

Stretching period

The Cretaceous crustal shortening and nappe stacking in the CWC area obliterated the original paleogeographical configuration to a considerable extent. Extensional normal faults were often reactivated as large-scale thrust faults, leading to the superposition and/or juxtaposition of cover units which originated in different isopic zones. Therefore a palinspastic reconstruction has to consider both the analysis of the tectonic edifice and the interpretation of the lithostratigraphy of the individual units to locate the isofacial zones.

The general tectonic restoration of the CWC is difficult because the higher Mesozoic cover units of the Hronic–Silicic system are typical gravity-gliding, ‘rootless’ nappes, and the precise position of their homelands is still a matter of controversy. There are lesser doubts about the original setting of the Fatric (Krížna) nappe group, which was detached from the thinned continental basement originally located between the present Tatric and Veporic superunits and subsequently underthrust beneath the Veporic. The Tatric cover is more or less para-autochthonous with respect to its pre-Alpine basement, which makes restoration possible.

A schematic reconstruction of the northern part of the CWC area depicting the Late Jurassic situation is presented in Fig. 9. The arrangement of ridge and basinal domains was certainly more irregular than presented here, but the general pattern fits most of the up to date paleogeographical reconstructions (e.g. Rakús et al. 1990; Michalík 1992, 1994a). Lateral non-persistence of individual domains indicates the partly transtensional character of stretching. This is supported by the probable presence of a transversal strike-slip fault system, documented in the Alps as oceanic transform faults (Weissert and Bernoulli 1985; Koller and Höck 1992) and as continental transfer faults influencing the facies distribution during the latest Triassic (Michalík 1978). This late pre-rift stage (‘borderland phase’ of Kelts 1981, or ‘transtensional stage’ of Stampfli et al. 1991) reflects non-orthogonal rifting processes. Later extension produced a more regular paleogeographical pattern and a passive continental margin developed along the northern Tatric edge during the Late Jurassic–Early Cretaceous drifting phase.

Rifting and extension are expressions of lithospheric stretching and crustal thinning. The extensional fault pattern interpreted from the facies distribution and thrust sheet geometry indicates an asymmetrical simple shear model of the CWC crust attenuation (Plašienka 1991). Several longitudinal zones of crustal thinning

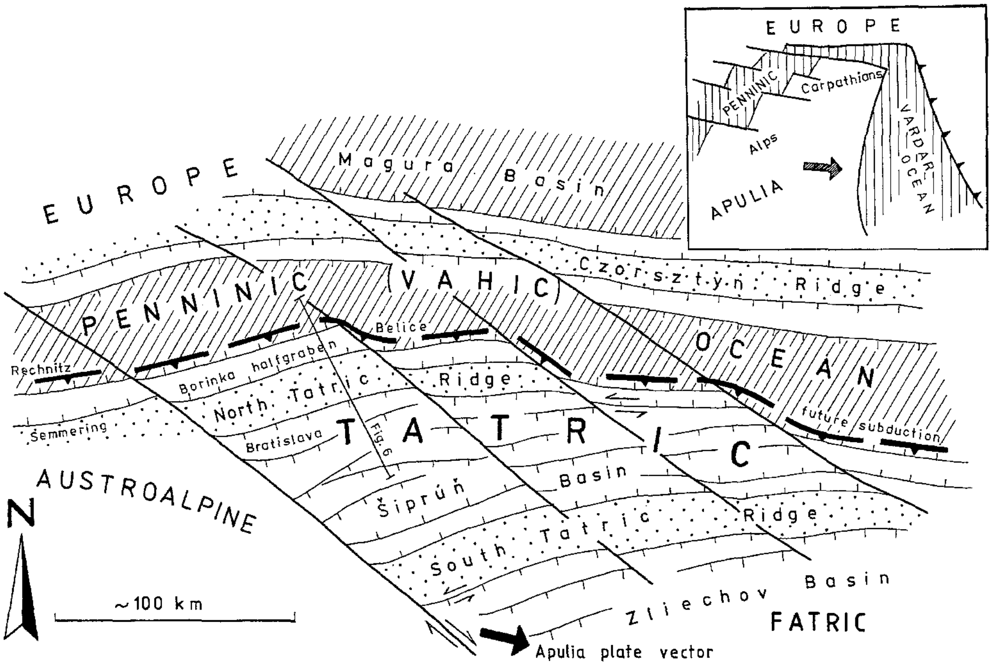

Fig. 9 Paleogeographical scheme of the Tatric area during the Late Jurassic period. The Carpathian sector lay at the northern prong of eastward moving Apulian block governed by subduction of the Vardar sensu lato and spreading of the Penninic ocean. The Czorsztyn ridge (the PKB, or Oravic continental ribbon) separated the Vahic (South Penninic) and the Magura (North Penninic) oceanic domains

with south-dipping low-angle master faults evolved during the Early Jurassic (Fig. 10). The location of thinned zones was determined by rheological properties and weaknesses in the crust, depending on the composition and structure of the pre-Alpine basement. However, only the Penninic–Vahic rift zone has finally broken away to produce a new oceanic crust, probably by mantle denudation (Oxburgh 1982; Lemoine et al. 1987; Drury et al. 1990; Stampfli et al. 1991; Vissers et al. 1991; Trommsdorff et al. 1993). The general paleotectonic arrangement seems to approach closely the Penninic rifting model of Stampfli and Marthaler (1990). Accordingly, the extensional basins of the CWC area would have developed in the position of a rim basin on the upper plate of an asymmetrical rift zone. This mechanism points to a 'passive' rifting process, triggered by horizontal tensile forces acting within the lithosphere (e.g. Cloetingh and Wortel 1988; Hoogerduijn Strating 1991). As a supporting fact, the absence of pre-rift doming and syn-rift volcanism typical of 'active' rifts initiated by mantle plumes may be mentioned.

Shortening period

As evidenced by the Cretaceous paleotectonic evolution of the CWC, the shortening and crustal stacking prograded northward and at the Turonian–Senonian boundary reached the northern Tatric edge (Fig. 10). According to Plašienka et al. (1991), the overthrust fault of the Tatric Bratislava basement-cover nappe of the Malé Karpaty Mts (Fig. 5) originated from an inversion of south-facing listric normal faults along the northern flanks of the intra-Tatric Šiprúň trough. The Bratislava sheet then overrode the North Tatric ridge and the northern peripheral half-grabens. However, the relationships of these subautochthonous units with their substratum and to the foreland are not exposed. As is indicated by some deep-reflection seismic profiles, they should overlie some unknown, probably Vahic–Penninic units (Plašienka et al. 1991).

The situation in the Považský Inovec Mts is different: remnants of the assumed North Tatric ridge as well as peripheral half-grabens are incorporated into the frontal tip of the huge Tatric overthrust sheet and split up into several large recumbent folds and imbricates. These together overrode the only sparsely exposed, Vahic-related oceanic complexes, leading to important upper-crustal shortening and stacking along the northern Tatric edge. Any oceanic zone present must have disappeared by southward underthrusting below the Tatric during the Late Cretaceous (Fig. 7).

Passive to active margin conversion

The initiation of subduction of oceanic lithosphere and conversion of a passive margin to an active one is a poorly understood process. This is caused by the unsatisfactory knowledge of actual examples and by difficulties in the interpretation of fossil examples. Tectonic modelling of initiation of subduction presumed rupture and downsinking of old oceanic lithosphere due to negative buoyancy forces, conversion of a transform fault into a subduction zone as a consequence of the plate movement reorganization (Dewey 1975), or downflexing and failure of a young lithosphere due to an extreme sediment load at a passive margin (Cloetingh et al. 1982), possibly enhanced by the build-up of regional compressive stresses (Cloetingh and Wortel 1988; Ziegler 1992). These concepts are rather theoretical

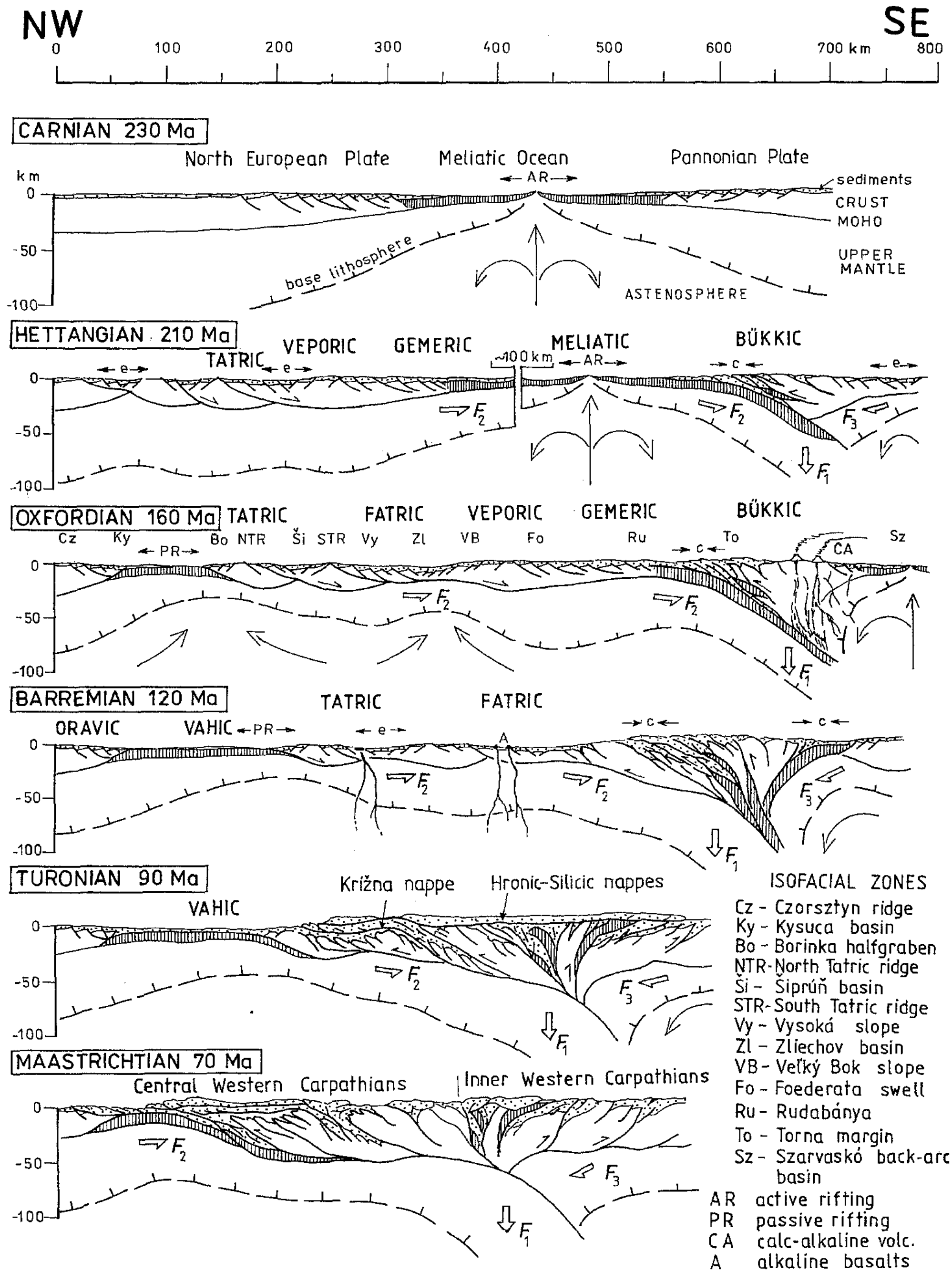

Fig. 10 Two-dimensional geodynamic interpretation of the West Carpathian evolution during the Mesozoic. Driving forces: F1, subduction pull; F2, slab pull (lower plate); F3, trench suction (upper plate). e, Extension; c, compression

and consider 'normal' oceanic lithosphere created along a mid-oceanic spreading centre. In this instance, the oceanic crust would be oldest at the passive margin and progressively younger towards the mid-oceanic rift zone. However, it is doubtful whether a regular mid-oceanic ridge system developed during oblique passive rifting in the northern transform zone, i.e. in the Vahic domain discussed here. In this setting a rather irregular pattern of spreading centers neighbouring the upper plate passive margins would be expected. The complete lack of the sheeted-dyke complex in Ligurian–Piemont ophiolites is interpreted as an indication of 'diffuse' spreading by Hoogerduijn Strating (1991). Consequently, narrow lozenge-shaped oceanic domains could have hardly been subducted due to self-generating body forces, in spite of being split by numerous tensional oblique-slip faults capable of inverting into underthrusting fault planes.

As has been previously pointed out, narrowing and closure of the Vahic oceanic zone is an integral part of the overall shortening polarity of the CWC. Based on the sedimentary record in the Belice unit, the convergence along the northern Tatric margin started as late as at the Turonian–Senonian boundary and the last Vahic domains were probably eliminated during the earliest Paleocene (Periklippen Belt). However, most of the Periklippen units, especially the Klape unit, comprise thick Albian–Cenomanian flysch complexes containing exotic conglomerates. The reconstruction of the source area of these conglomerates points to the existence of an active margin area with a volcanic arc and a high-pressure metamorphic belt, called 'Ultrapienidic cordillera' which was in existence at least in the Middle Cretaceous (see Mišík et al. 1977; Marschalko 1986; Mišík and Marschalko 1988; syn. 'Andrusov exotic ridge' of Birkenmajer 1988; Birkenmajer et al. 1990). This ridge should have been located between the Klape basin and the Tatric domain and would imply subduction processes in this area, starting possibly already in the Late Jurassic. This is indicated by some radiometric ages of high-pressure metamorphic and calc-alkaline volcanic rocks. Nevertheless, although the pebble material indicates active margin provenance, this does not have to be located north of the Tatric. The Klape and related units are décollement sedimentary cover nappes strongly affected by younger transpression in the Periklippen Belt and may originally have represented early diverticulations of the Fatric (Krížna) gliding nappe system (Plašienka 1995). If this were so, the exotic conglomerates would have been supplied by sources located south of the present Tatric–Veporic boundary, most probably from units of the Inner Western Carpathians (Meliatic and higher units), which in mid-Cretaceous times still covered the southern CWC zones (Veporic and Gemeric units, Fig. 10).

Based on the previously reported data and interpretations, we propose that reactivation of south dipping low-angle detachment faults and their conversion to crustal-scale thrust faults has been the dominating mechanism of the passive to active margin transformation. Hence the same fault plane may have accommodated Jurassic to Early Cretaceous extension and Vahic oceanic crust production by subcontinental mantle unroofing and its later underthrusting below the Tatric plate as well (Fig. 10). This process followed the energetically most convenient way of overcoming great resistive forces in the upper mantle during the initial subduction. The Moho discontinuity might be the principal detachment plane and the south-eastward slab pull the principal driving force (Fig. 10).

Driving forces

Since the advent of plate tectonics and the rediscovery of Argand's ingenious treatment 'La tectonique de l'Asie' (Argand 1924), the Alpine orogeny is considered to have been a consequence of the collision of the Apulian promontory of Africa with the stable European margin. Although the roughly N–S Late Cretaceous–Tertiary convergence path of Africa towards Europe is fairly well constrained by the Atlantic spreading history and paleomagnetic data (Dewey et al. 1973 1989), it is disputable whether Africa–Europe convergence alone can explain all the complicated movements inside the Alpine–Mediterranean mobile belt. Numerous small continental blocks in the Carpathian realm, such as the Apulian prong (the Austroalpine-CWC domain), Oravic continental ribbon, Tisia terrane, Dacides, Moesia, Serbo-Macedonian Massif etc. (e.g. Balla 1986; Dercourt et al. 1990; Csontos and Vörös 1992), were separated by oceanic domains, subduction zones and sutures during most of the Meso-Cenozoic times and cannot be ultimatively considered to have been part of the rigid African plate. Consequently, the complex movements of crustal blocks of the Alpine–Mediterranean collage seem also to have been controlled, in addition to the global lithospheric plate movements, by local interactions of driving forces. In particular, forces arising from the subduction of several, often meridionally trending, ephemeral oceanic zones (i.e. the distensive slab pull exerted on a local lower plate and compressive collisional or tensile trench suction forces operating within an upper plate) may have considerably influenced the regional stress fields and movement pattern of individual domains. The resulting structural record is therefore often in contradiction to a simple orthogonal collisional scenario of a typical 'Wilson cycle'.

In the Carpathians, several features are inconsistent with the simple Africa–Europe translation–collision scenario, as proposed for the Alps (e.g. Dewey et al. 1973; Coward and Dietrich 1989). In the first place, there is the conspicuous orogenic polarity displaying generally northward migration not only of contraction, but also of the preceding distension of crustal fragments rifted off the European margin. We attribute this to the activity of a local slab pull force (Fig. 10). Southeastward pull started to affect the south European margin at the Triassic–Jurassic boundary and was probably generated by the onset of subduction of the Meliatic oceanic lithosphere. Transmitted distensive stresses brought about the Penninic–Vahic asymmetrical passive rifting, with the Austroalpine–Centrocarpathian domain as an upper plate (Plašienka 1991; Trommsdorf et al. 1993), and an extensional tectonic regime in the CWC terrane separated from the European shelf. Late Jurassic to Early Cretaceous collision of the Inner West Carpathian Bükk and related upper plate terranes with the southern CWC margin did not terminate by a slab detachment, but subduction continued by consumption of the mantle lithosphere detached from below the CWC crust that was apparently driving the ongoing stretching of the lower plate foreland crust. Upper crustal CWC blocks separated by rifting and extension were accreted step by step to the leading edge of the orogenic wedge prograding from the hinterland during the entire Cretaceous (Fig. 10). The Late Cretaceous elimination of the Penninic Vahic oceanic realm is an integral part of this process, lacking the features of an independent lithospheric subduction cycle, and was coeval with the spreading period of the adjacent North Penninic–Outer Carpathian Magura oceanic furrow. At the Cretaceous–Tertiary boundary, subduction jumped to the Magura zone and later to the still more external Krosno (Silesian–Moldavian) sea. The final slab detachment occurred as late as during the Neogene below the frontal parts of the Carpathian flysch nappes (Tomek and Hall 1993), in the time when slab pull was not able any longer to induce stretching of the foreland cratonic areas.

The simultaneous compression of the hinterland and stretching in the foreland, though in proximal zones, need only one, unilaterally operating driving force. Subcrustal subduction pull can explain the Carpathian polarity by a mechanism which has been proposed also by Mattauer (1986). This model also makes allowance for the appearance of several subparallel, moderately wide, sequentially opening and closing oceanic zones within an areally limited, or even diminishing, space.

Conclusions

The Tatricum, a prominent superunit of the external part of the CWC was individualized during Jurassic rifting of the future margins of the evolving South Penninic (Vahic) oceanic domain in the north. To the south (or south-east) it was bordered by the Fatric (Krížna) basin, underlain by a strongly thinned continental crust. During rifting and subsequent, approximately 100 Ma long period of episodical crustal extension, the Tatric terrain split into two parallel ridge domains (the North and South Tatric), which became partly subaerial highs, partly shallow marine or pelagic swells during the Jurassic and Early Cretaceous. The ridges were separated by the Šiprúň trough – a basinal domain with a thinned continental crust, partly open to the Vahic oceanic realm (Fig. 9). The northern Tatric edge represented a passive continental margin marked by a system of north-dipping, domino-type normal faults and tilted half-grabens (e.g. Borinka basin). This rugged topography was buried by widespread flysch sediments supplied from distant, partly exotic sources during the final pre-compressional downflexing in mid-Cretaceous times.

The shortening history exhibits northward migration of contraction and individual deformation stages. The basement was shortened by the inversion of earlier extensional normal faults to thrust faults generating basement-cover nappes of different orders with thrust polarity towards the external parts of the orogen. In zones of previously strong crustal attenuation, the basement was almost completely underthrust and its sedimentary cover was detached to form décollement cover nappes. At approximately the Turonian–Coniacian boundary, the compressional front reached the northern Tatric edge and initiated a change from passive to active margin, where the Vahic oceanic crust was consumed during the Senonian. In the latest Cretaceous and earliest Paleogene, the northern Tatric margin and the accretionary complexes piled up along its front, collided with the Oravic ribbon continent (Fig. 10; PKB basement in Fig. 3, Czorsztyn ridge in Fig. 9), causing additional shortening of the Vahic suture and also of the Central and Inner Carpathians. All processes of Mesozoic crustal distension and convergence partly had a oblique-slip character, resulting in lateral wedging out of sedimentary domains (sinistral transtension) as well as later tectonic units (dextral transpression).

The outlined tectonic scenario is not fully consistent with the generally accepted Mesozoic palinspastic pattern of the zones between the Tatric and Oravic domains. These usually consider the presence of an active margin developing from the Late Jurassic onward and uplift of a mid-Cretaceous exotic ridge along the northern Tatric edge, based on the presumed position of the Klape unit with its exotic conglomerates (e.g. Birkenmajer 1988; Mišík and Marschalko 1988). However, the sedimentary and structural record along the northern Tatric margin reveals that the change from a passive to an active margin occurred considerably later, during the Late Cretaceous. This is in line with the overall shortening polarity of the Mesozoic Western Carpathians at that time.

I infer that the consumption of the Penninic–Vahic ocean was not the cause, but the consequence, of orogenic shortening prograding from another, more southerly located Meliatic oceanic suture. It is imaginable that all Mesozoic extension and compression tectonic processes in the CWC area were produced by only one driving force – the inward (roughly south-eastward) slab pull. This generated both tensile stresses within the lower plate and compressive stresses in the frontal parts of the upper plate. Lithospheric stretching, crustal thinning and passive rifting in the CWC were changed into contraction, overthrusting, crustal thickening and subduction of the Vahic oceanic crust, when lower plate continental fragments were accreted to the leading edge of the upper plate orogenic wedge prograding generally from the south towards the north (Fig. 10). During this process, the primary subduction zone may not have changed its position considerably with respect to the mantle. Consequently, the Penninic–Vahic oceanic lithosphere was not directly subducted into the mantle, but was underthrust below the Central Carpathian crust, together with the Oravic (Klippen belt) continental basement (Plašienka et al. 1991) – a structural homologue of the Briançonnais ridge (Tomek 1993). They replaced the continental lithospheric mantle consumed in the primary subduction zone (Fig. 10). This might explain the complete lack of subduction-related late Mesozoic volcanism in the Central Carpathians, as well as in the whole Austroalpine domain.

Acknowledgements Fruitful discussions with R. Marschalko, J. Soták, F. Marko and other colleagues participating on the research projects No 125 and 1081 are thanked. Financial support from the Grant Agency for Science, Slovakia, is gratefully acknowledged.

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