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Dynamics of Mesozoic pre-orogenic rifting in the Western Carpathians

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7 Figures

Content

Abstract

The West Carpathian Mesozoic sedimentary successions provide evidence about important pre-orogenic rifting events that generated subsiding basinal domains separated by submarine and/or subaerial highs. Since the geometry of rift-related fault structures can seldom be studied directly, the rifting process is reconstructed by interpretation of relative bathymetry/subsidence curves of individual sedimentary successions. Five rifting phases, which represent climaxes of a long-termed extensional tectonic regime, can be distinguished: (1) the latest Permian – Early Triassic phase which was completed by the Anisian break-up of the Meliata Ocean; (2) the Early Liassic phase which was characterized by overall lithospheric stretching and wide rifting; (3) the restricted Late Liassic phase which manifested itself by extensional block tilting; (4) the Middle Jurassic asymmetric rifting which was terminated by the break-up of the South Penninic-Vahic ocean in the late Bajocian – early Bathonian and (5) the Early Cretaceous asymmetric rifting that led to the break-up of the North Penninic-Magura Ocean. The passive, asymmetric rifting mode is inferred in this study from distinctly different subsidence and/or uplift patterns of opposite margins of extended basinal domains. Further it is assumed that solely asymmetric rifting resulted in the break-up of the European continental lithosphere to generate the Penninic oceanic domains. Since rifting in the foreland of the lower plate occurred contemporaneously with advancement and shortening of the compressional orogenic wedge prograding from the hinterland Meliata suture, a common geodynamic scenario for simultaneous foreland extension and hinterland compression during one orogenic cycle is proposed in this study.

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1. Introduction

It is generally assumed that Mesozoic units assembled in the Western Carpathians were derived from various neighbouring sections of the Mesozoic Tethyan shelves (e. g. Michalík and Kováč, 1982; Rakús et al., 1990; Haas et al. 1995). Units presently located in the Central Western Carpathians between the Pieniny Klippen Belt and the Meliata suture represent parts of the northern, passive European margin of the Meliata Ocean in the Triassic. During the Jurassic, this so called Slovakocarpathian (eastern prolongation of the Austroalpine) area was separated from the North European Platform by the Ligurian-Piemont-Vahic branch of Tethys (South Penninic Ocean), hence becoming an autonomous continental domain between two oceanic realms. The subsequent Late Jurassic to Early Cretaceous closure of the Meliata Ocean amalgamated the Slovakocarpathian realm with continental fragments derived from the north-eastern Adriatic margin (Transdanubian Range, or Pelso mega-unit). In addition, during the Early Cretaceous, the Oravic ribbon continent was detached from the European shelf by opening of the North Penninic-Magura oceanic branch. Subsequently, the Penninic oceanic domains were gradually diminished and closed during the Late Cretaceous and Early Tertiary.

This Mesozoic geodynamic scenario is recorded in numerous, often continuous, sedimentary successions in the Western Carpathians. The investigation of this preserved evidence of rifting and eventual oceanic break-up events that preceded the Late Cretaceous contraction and nappe stacking is the main goal of this paper. In general, two independent, large-scale rifting events can be reconstructed from the sedimentary record of the Western Carpathians. The first event involves the Late Permian – Early Mesozoic extension of the young post-Variscan continental lithosphere along the southern active European margin. This event took place within the reach of back-arc extensional processes generated by the northward subducting Paleotethys (Stampfli, 1996). It was associated with widespread magmatism and high-temperature/low-pressure metamorphism (e. g. Bonin, 1990; von Raumer and Neubauer, 1993; Ring and Richter, 1994). This indicates that stretching affected a thermally weakened lithosphere. Although numerous Permian rift arms were aborted, those located in the proximity of the active margin developed then into the Meliata Ocean which opened during the Anisian (Kozur, 1991).

The second rifting event occurred within the consolidated epi-Variscan lithosphere and led to the break-up of the Triassic carbonate platform. This event took place in the Jurassic and ultimately led to the opening of the Alpine Tethys basins as rift arms propagated from the Central Atlantic Ocean to the East (Dewey et al., 1973; Frisch, 1979; Stampfli, 1994). The oblique drift of Africa and Adria relative to Europe during the Jurassic requires rifting to be oblique as well and therefore the Penninic oceanic basins were probably formed as transtensional pull-apart basins which later widened due to oceanic spreading (Kelts, 1981; Weissert and Bernoulli, 1985; Lemoine and Trümpy, 1986; Lemoine et al., 1986, 1987). The reconstructed paleogeographic configuration of continental and oceanic domains in the western Tethyan – Atlantic realms requires the connection between the oceanic branches of the Atlantic Alpine Tethys and the north-east Tethys-Vardar Ocean through a transform corridor in the Eastern Alpine-Carpathian area (Debelmas and Săndulescu, 1987, Trümpy, 1988). However, this model is hampered by the absence of Jurassic ophiolites in those Western Carpathian zones, which are laterally linked with the Alpine oceanic domains. This fact can be explained by the fundamentally different Tertiary evolution of the Alps in comparison with the Western Carpathians. Continental collision, crustal thickening and exhumation of deeply buried Penninic complexes occurred in the Alps, while the Western Carpathians were governed by subduction and back-arc lithospheric stretching, hence keeping the Penninic ophiolite-bearing complexes mostly hidden. Nevertheless, there is some reflection seismic evidence for the existence of the South Penninic oceanic suture in the deep structure of the Western Carpathians (Tomek, 1993). Other evidence comes from secondary occurrences of pebbles of ophiolite material (e. g. Mišík and Marschalko, 1988) and heavy mineral spectra (Winkler and Ślączka, 1994) from Cretaceous flysch complexes. However, since it was also suggested that most of this ophiolite material may well have been derived from the Meliatic suture (Plašienka, 1995a), these secondary ophiolite occurrences do not provide unambiguous evidence about the paleogeographic positions of oceanic zones in this area.

Another problem of the reconstruction of Mesozoic rifting processes in the Western Carpathians is the deficiency of high mountains and good outcrops, in which the geometry and kinematics of extensional faults can be studied. In addition, many of original rift-related normal faults were reactivated as thrust faults during the Eo-Alpine evolution thus making the reconstruction of extensional structures difficult. In spite of these difficulties, it was possible to present fairly well constrained models of the geometry and kinematics of extensional structures from the Tatric area (Plašienka et al. (1991), Dumont et al. (1996), Plašienka (2003)) and the Czorsztyn Ridge (Aubrecht and Túnyi, 2001). Nevertheless, the reconstruction of the Mesozoic oceanic domains in the Western Carpathians presented in this paper is still mainly based on circumstantial reasoning and indirect criteria from the sedimentary rock record similar to previous studies by Michalík and Kováč (1982), Birkenmajer (1986), Plašienka (1995b) and Wieczorek (2000). Therefore relying on the rich sedimentary record, this present paper aims at the discrimination and paleotectonic interpretation of the principal Early Alpine pre-orogenic rifting events.

2. Outline of the structure and Mesozoic evolution of the Western Carpathians

The Western Carpathians are bordered by the Tertiary foredeep against the North European Platform and by the subsurface Mid-Hungarian lineament against the South Pannonian Tisia terrane. The lateral boundaries to the Eastern Alps are conventionally placed between the Malé Karpaty and Leitha Mts. and the Uh river valley forms the boundary to the Eastern Carpathians. Within this frame, the Western Carpathians are generally divided into the Internal, Central and External Western Carpathians (IWC, CWC and EWC, respectively – Plašienka, 1999). The units of the IWC (Pelso terrane – see e. g. Kovács et al., 2000) occur in pre-Tertiary horsts in the Neogene Pannonian Basin in northern

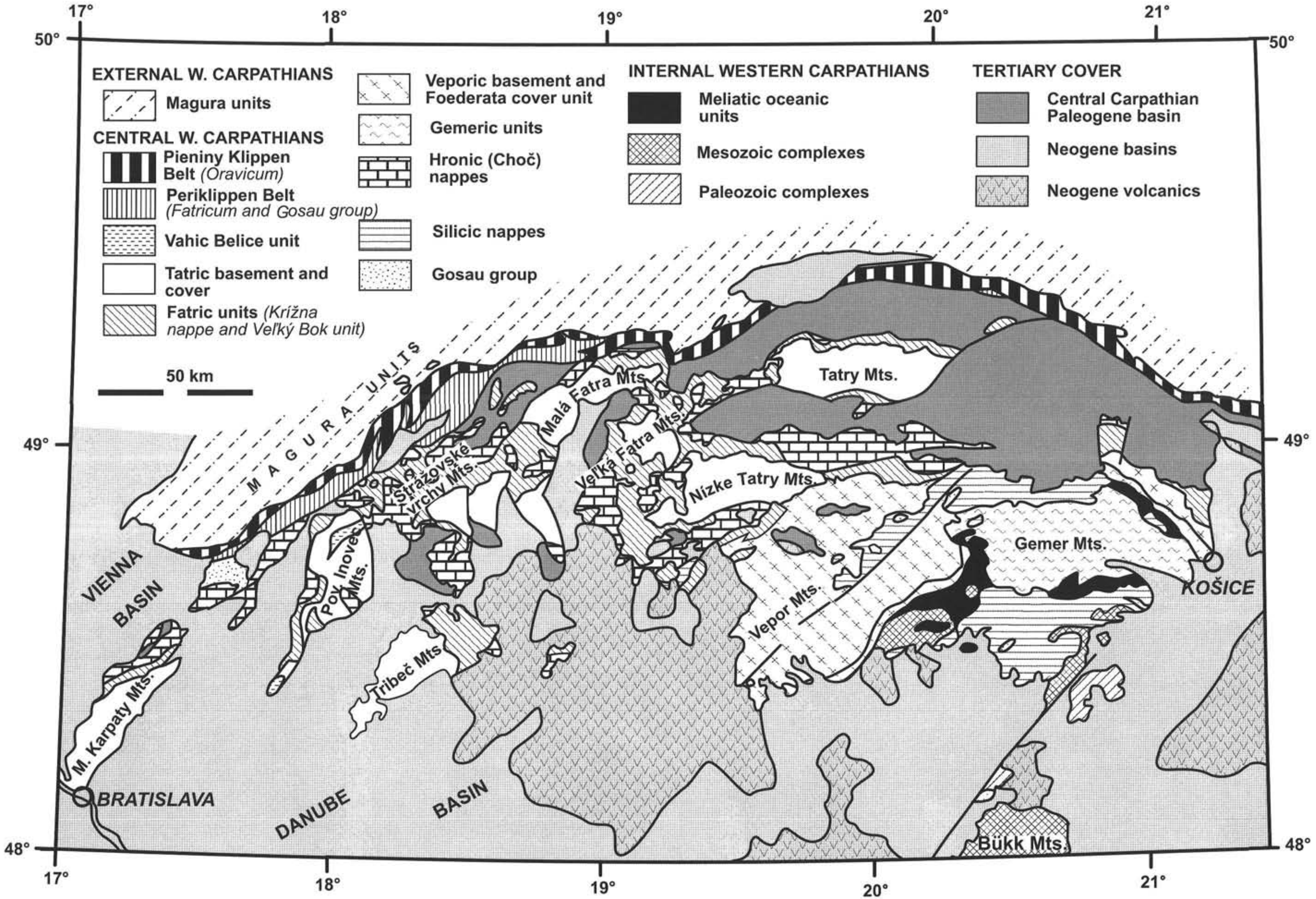

Fig. 1
Simplified geological map of the Central and Internal Western Carpathians. All boundaries of pre-Tertiary units are tectonic by origin.

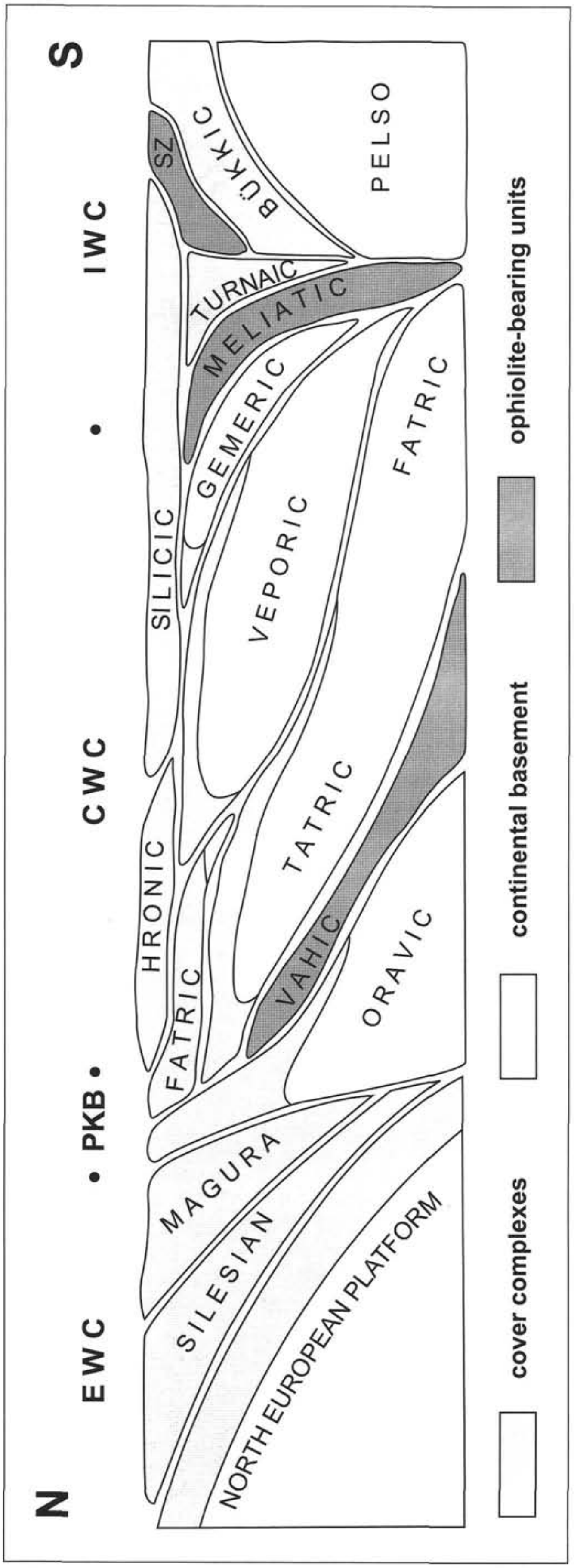

Fig. 2
Schematic cross-section of the Western Carpathians showing relationships of their principal tectonic units. EWC – External Western Carpathians, PKB – Pieniny Klippen Belt, CWC – Central Western Carpathians, IWC – Internal Western Carpathians, SZ – Szarvaskő Unit. Not to scale. Note that the Hronic and Silicic superunits are out-of-sequence cover nappe systems that do not respect the polarity of the basement units.

Hungary such as the Transdanubian Range and the Bükk and adjacent mountains, which show evolutionary affinities to the South Alpine-Dinaridic realms. The Meliata suture forms the divide from the CWC, although its position is mostly hidden and ambiguous. The CWC are built up by a system of north-verging basement and/or cover nappes of the Slovakocarpathian tectonic system which formed during the Cretaceous. The contact between the CWC and EWC follows a narrow zone with intricate structure – the Pieniny Klippen Belt (PKB). The EWC (so-called Flysch Belt) are composed of two large nappe systems which form the Tertiary frontal accretionary wedge of the Western Carpathian orogen (Fig. 1, 2), the Rhenodanubian-Magura and the Silesian-Krosno-Moldavian.

The evolution of the IWC can be described as follows: Early Mesozoic Tethyan rifting which culminated in the opening of the Meliata Ocean occurred in the Middle Triassic, was followed by closure of this ocean during the Late Jurassic (e. g. KOZUR, 1991; KOVÁCS, 1992; HAAS et al., 1995; KOVÁCS et al., 2000). These events were followed by additional shortening phases, commonly displaying a southern polarity during the Early Cretaceous (the so-called "retro-wedge" in Fig. 7, which is formed by the IWC units of the Bükk Mts. – cf. CSONTOS, 1999). The position of the Meliata suture can be traced based on occurrences of tectonically dismembered formations containing oceanic Triassic and Jurassic sediments, ophiolites and blueschists.

The CWC are composed of three northward directed thick-skinned basement/cover sheets (the Tatric, Veporic and Gemeric from bottom to top) and three systems of detached cover nappes (the Fatric, Hronic and Silicic – see Figs. 1, 2). Altogether these superunits comprise the Slovakocarpathian tectonic system, which is the eastern analogue to the Austroalpine system of the Alps. Compared to the Austroalpine system, the basement sheets correlate with the Lower and Middle Austroalpine units (Infratatric and Veporic units), whereas the Tatricum has no equivalent in the Alps. The cover nappe system can partially be compared to the Northern Calcareous Alps (NCA). The Triassic formations of the Tatric, Fatric and northern Veporic superunits show close European affinities with Germanic-type epicontinental succession, while the broad Tethyan shelf represented by the southern Veporic, Gemeric, Hronic and Silicic domains is charac-

Fig. 3
Tectonographic chart summarizing the Mesozoic tectonic evolution of the Western Carpathians. Abbreviations to geochemical typology of magmatism: A – alkaline to subalkaline (acid), CA – calc-alkaline (acid to intermediate), TH – tholeiitic (intermediate to basic), WP – within-plate (basic).

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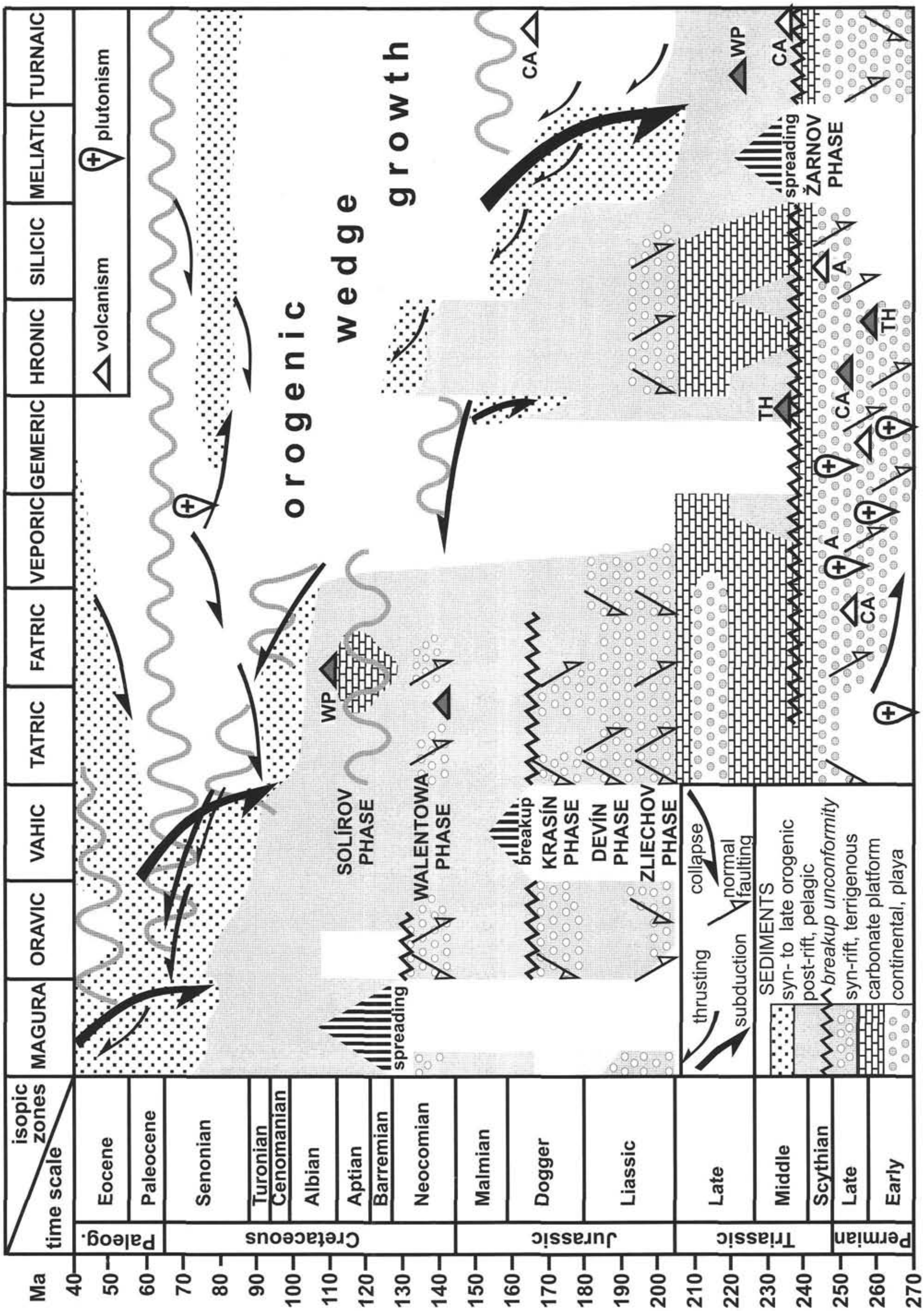
Ma
time scale
isopic zones
MAGURA
ORAVIC
VAHIC
TATRIC
FATRIC
VEPORIC
GEMERIC
HRONIC
SILICIC
MELIATIC
TURNAIC
40
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220
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240
250
260
270
Paleog.
Cretaceous
Jurassic
Triassic
Permian
Eocene
Paleocene
Senonian
Turonian
Cenomanian
Albian
Aptian
Barremian
Neocomian
Malmian
Dogger
Liassic
Late
Middle
Scythian
Late
Early
volcanism
plutonism
thrusting
subduction
collapse
normal faulting
SEDIMENTS
syn- to late orogenic
post-rift, pelagic
breakup unconformity
syn-rift, terrigenous
carbonate platform
continental, playa
orogenic wedge growth
spreading
SOLÍROV PHASE
WALENTOWA PHASE
breakup
KRASÍN PHASE
DEVÍN PHASE
ZLIECHOV PHASE
spreading
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WP
WP
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CA
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terized by increased Triassic subsidence of carbonate-dominated ramps, platforms, lagoons, intra-shelf basins and shelf edge and slope. During the Early Jurassic, the Triassic carbonate platform was broken apart and drowned, leading to the formation of a system of quickly subsiding rift basins separated by narrow ridges. During the Late Jurassic, the Silicic and Gemeric zones adjacent to the Meliata Ocean underwent first contractional deformation after the closure of this ocean. During the Early Cretaceous, shortening and nappe stacking then affected the Hronic and southern Veporic zones and in mid-Cretaceous times it prograded into the northern Veporic, Fatric and southern Tatric domains (Fig. 3). The northernmost Tatric (Infratatric) zone was deformed during the Senonian. The syn-orogenic flysch sedimentation also migrated northwards during the Cretaceous (e. g. PLAŠIENKA, 1998, 1999).

The PKB is often characterized as a tectonic megabreccia, mélange, or it was even considered to represent an olistostrome. However, the peculiar "block-in-matrix" structural appearance of the PKB is the result of later stages of deformation, due to along-strike transpressional and transtensional movements in the Tertiary (e. g. KOVÁČ and HÓK, 1997). Therefore, the PKB appears to be a tectonic mixture of cover units which differ in their provenances and tectonic histories. The Oravic units are considered to be PKB units sensu stricto, and are represented by the swell-type Czorsztyn, the basinal Kysuca-Pieniny and several transitional units. All of these units only contain Jurassic and Cretaceous strata (Fig. 3). The Oravic units were derived from an intra-oceanic continental ribbon or a marginal plateau in a Middle Penninic position, bordered to the Slovakocarpathian domains by the South Penninic-Vahic Ocean and by the North Penninic-Magura Ocean to the North European Platform and/or the Silesian-Krosno ridges and basins. Most of the units that originated from the Vahic oceanic realm are hardly accessible in the Western Carpathians, only the Belice Unit of the Považský Inovec Mts. (Fig. 1) and the Iňačovce-Krichevo Unit which was drilled bellow the East Slovakian Neogene Basin, thus being the exceptions (PLAŠIENKA et al., 1994; SOTÁK et al., 1994; PLAŠIENKA, 1995a, b). After at least partial closure of the Vahic Ocean during the latest Cretaceous – earliest Tertiary, the Oravic units were then detached from their underthrust substratum and amalgamated with frontal elements of the Slovakocarpathian nappes, mainly belonging to the Fatric (Krížna) system (Drietoma, Manín, Klape and related units – see PLAŠIENKA, 1995a and discussion therein). Along with the syntectonic Senonian – Paleogene sediments (Gosau Group), the units of the Oravic and Fatric systems were strongly deformed between the basement-involved Slovakocarpathian orogenic wedge and the developing Carpathian frontal accretionary wedge (EWC) to form the present PKB.

The EWC contains rootless nappes of the Magura and Silesian-Krosno systems that include Jurassic to Lower Miocene sediments which are dominated by flysch lithologies. The Magura nappes rarely involve Jurassic and lowermost Cretaceous strata, whereas sediments from the Barremian and younger are more widespread. The more external EWC units, the Silesian Unit in particular, comprise continuous successions starting from the uppermost Jurassic (Tithonian).

3. Subsidence history

3.1 Methodical approach

Subsidence is defined as a downward displacement of the Earth's surface relative to an arbitrary reference plane, e. g. a local erosional base level, the geoid, or most commonly the mean sea level for marine basins. In a sedimentary basin, which is part of the Earth's surface exhibiting an excess subsidence (or, less commonly, reduced uplift) in relation to its surroundings, subsidence creates an accumulation space filled with sediments to a various degree. There are several ways of how to generate subsidence and hence sedimentary basins and most of them consider at least some tectonic mechanism as a triggering factor which mostly occurs in contractional, or extensional tectonic settings. Since extensional tectonic regimes are more effective in creating accumulation space; the majority of sedimentary basins on the Earth are extensional basins, especially those occurring at divergent plate boundaries and in plate interiors.

Formation of a sedimentary basin in an extensional tectonic setting requires a reduction in thickness of the underlying crust, which can be most easily accomplished by stretching and thus thinning continental lithosphere. The depth vs. time curve of tectonic subsidence of sedimentary basins formed by stretching of the continental lithosphere therefore follows a characteristic path. Initially, during the first 10-20 Ma of syn-rift subsidence, the curve is steep and subsidence is rapid (modelled as instantaneous), recording the isostatic compensation of crustal thinning. Later on, the subsidence curve acquires a smooth shape and reflects exponential heat decay due to lithospheric cooling during the thermal subsidence phase (MCKENZIE, 1978). The characteristics of the subsidence curves, necessary for an evaluation of the mechanisms of a basin origin, can be obtained by backstripping analyses of the sedimentary record in that particular basin. The backstripping techniques have been developed to analyse stratigraphic logs of drillcores from uninverted, or only slightly inverted basins. Application of this technique on inverted and tectonically disturbed basins is hampered by many significant problems, nevertheless, it was successful in some instances (e. g. POPRAWA et al., 2002).

Although the stratigraphic record is often seemingly continuous, the Western Carpathian units seldom provide sections suitable for backstripping analyses. This is mainly due to an inadequately refined stratigraphic record of pre-Tithonian strata, significant uncertainties in exact bathymetry, frequent tectonic omissions and/or duplications and local erosion. An attempt of backstripping analyses of some Western Carpathian sections by WOOLER et al. (1992), who used the stratigraphic logs of RAKÚS et al. (1989), was not very successful since these authors recognized only one, Triassic principal rifting phase and failed to explain frequent post-Triassic turns in subsidence rates, or even conversions of subsidence into uplift. They also did not consider the abyssal depth of sedimentation of radiolarites associated with deep-water pelagic successions, therefore both their values defining the maximum subsidence and the lithospheric stretching factors controlling the subsidence appear to be underestimated.

The approach applied in the present paper does not aim at the determination of exact subsidence curves of individual Western Carpathian sedimentary successions; it rather emphasizes their relative subsidence and/or uplift tendencies inferred from bathymetric estimates (Fig. 4). Since the Jurassic – Lower Cretaceous sedimentary successions represent fillings of sediment-starved basins and they seldom exceed 1 km of cumulative thickness, the subsidence during this time was generally uncompensated by sediments and the inferred bathymetry curves can be approximated with tectonic subsidence history. It is generally assumed in this study that all vertical movements reconstructed are tectonically driven. Although the coincidence of some tectonic events with important sea-level changes may have amplified the expressions of the former at certain time intervals, it is inferred that the tectonically driven surface subsidence and uplift intervals described below considerably exceed the eustatic effects in magnitude.

Almost all information used in this paper comes from the sedimentary record, information about the sedimentary environments, and from the thickness and age of sedimentary formations. An emphasis is given to the "turning points" in the tectonic evolution, especially to the presence of break-up unconformities which are considered to be indications of commencement of the oceanic crust production, and to the uplift events which are interpreted either (1) as the thermal expansion and/or isostatic response due to heterogeneous lithospheric stretching, or (2) as a consequence of the build-up of intraplate compressive stresses. This approach will then be applied to several Western Carpathian lithotectonic units, especially the Mesozoic (particularly pre-Senonian) sedimentary successions which are briefly characterized below and interpreted in terms of subsidence vs. uplift evolution. The following description below is based upon the likely south-north (in the present coordinates) palinspastic arrangement of the units considered (Fig. 3).

3.2 Units derived from the proximity of the Meliata Ocean

The Turnaic Superunit consists of several cover nappe units occurring in the southernmost Western Carpathian zones, where they override the Meliatic units and underlie the nappes of the Silicicum. They comprise slightly metamorphosed and in some places strongly deformed sedimentary formations of Middle Carboniferous to Jurassic (VOZÁROVÁ and VOZÁR, 1992), or only Triassic age (LESS, 2000). The Triassic succession involves Scythian shales

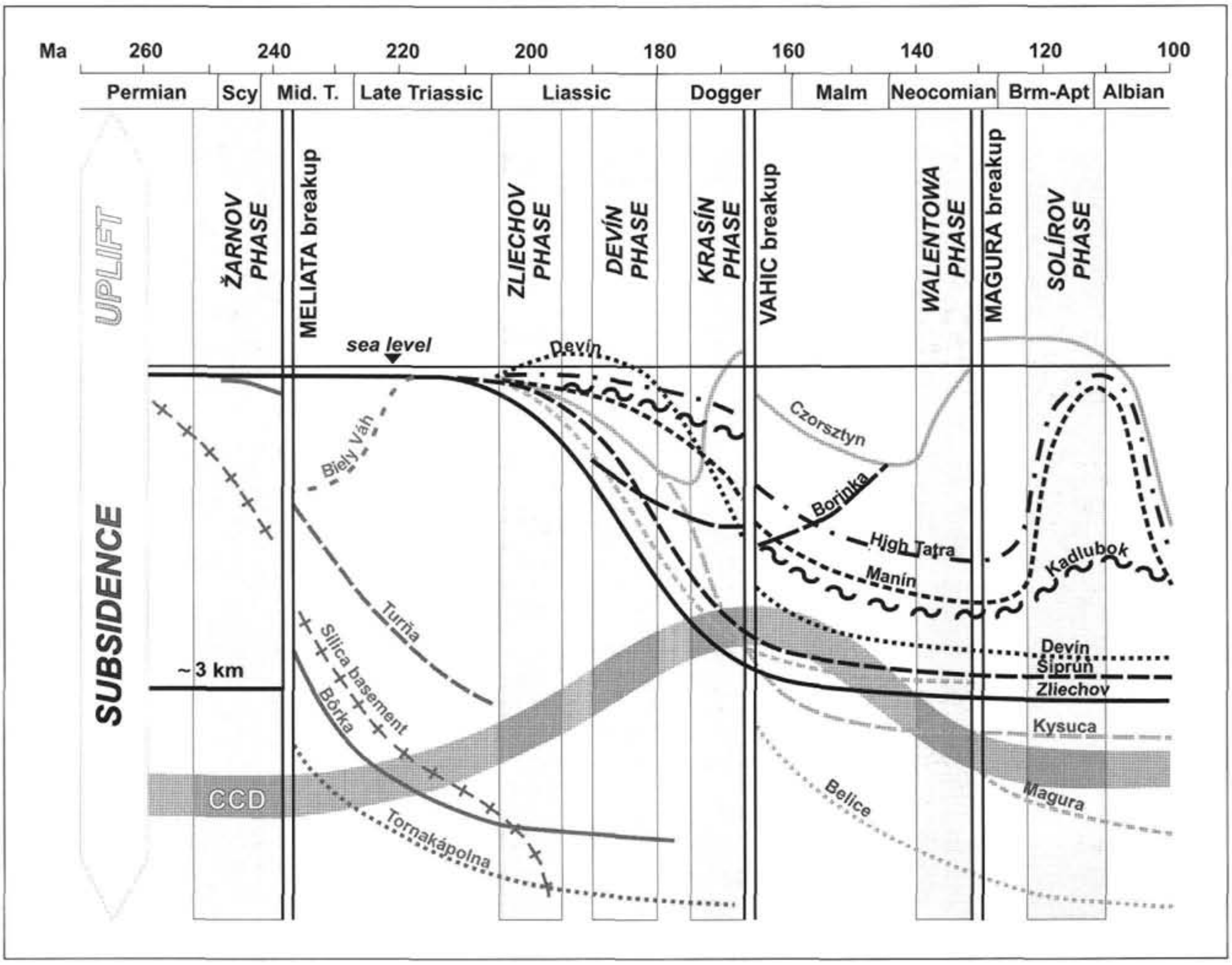


Fig. 4
Relative subsidence/uplift curves inferred from bathymetry of various Western Carpathian sedimentary successions. The turning periods are interpreted as distinct extensional tectonic phases (except the probably contractional Solírov Phase), some of them grading into ocean break-up (double vertical lines).

and marlstones, Lower Anisian Gutenstein and Steinalm Formations followed by Pelsonian red pelagic limestones, which often fill neptunian dykes and cavities in underlying platform limestones. The Ladinian – Late Triassic sequence is pelagic, mainly with nodular limestones (e. g. Pötschen Fm.) and Carnian Raibl shales. Paleogeographically, the Turnaic successions are usually placed at the southern margin of the Meliata Ocean (e. g. Kovács et al., 2000). They reflect Pelsonian break-up of the carbonate platform and subsequent gradual uncompensated post-rift thermal subsidence (*Turňa Succession* in Fig. 4). Equivalents of the Turnaic (= Süd-Rudabányaic) units from the Eastern Alps were described by Kozur and Mostler (1992).

The highly dismembered subduction complexes of the Meliatic Superunit include Jurassic dark shales, sandstones, radiolarites, ophiolite- and blueschist-bearing mélanges and olistostromes (e. g. Kozur, 1991; Kozur and Mock, 1997; Mock et al., 1998). Sedimentary olistolites are composed of Lower Anisian platform carbonates with neptunian dykes of Pelsonian red pelagic limestones, Ladinian and Upper Triassic radiolarites and various pelagic limestones. Some parts of the Meliatic ophiolitic complexes were incorporated as blocks and slabs into evaporitic breccias at the soles of the overriding nappes of the Silicicum (Triassic pillow lavas and radiolarites – Réti, 1985; *Tornakápolna Succession* in Fig. 4). The lower part of the Meliatic accretionary complex is formed by a partly independent tectonic unit, called the Bôrka Nappe (e. g. Mello et al., 1998), which overthrusts the Paleozoic complexes of the Gemeric Superunit. The Bôrka Nappe is composed of Gemeric-type Upper Paleozoic and Scythian strata followed by platform carbonates probably Anisian of age, Middle Triassic basic volcanics and Upper Triassic – Jurassic siliceous shales. All these strata were affected by high pressure/low temperature metamorphism (Faryad, 1995) during the Upper Jurassic (Maluski et al., 1993; Dallmeyer et al., 1996; Faryad and Henjes-Kunst, 1997). Paleogeographically, the *Bôrka Succession* (Fig. 4) represents an original distal southern passive margin of the Slovakocarpathian Triassic shelf domain, in which the Middle Triassic break-up is recorded by extrusions of basaltic lavas followed by thermal subsidence (right panel of the Gemeric column in Fig. 3). The Alpine equivalents of the Meliatic units were identified by Mandl and Ondrejičková (1991) and Kozur and Mostler (1992) in the Florianikogel area of the NCA.

The Silicic Superunit (Silica Nappe s.l.) is a system of rootless cover nappes occupying the highermost structural position in the Western Carpathian Mesozoic nappe stack. Its palinspastic position with respect to the Meliata Ocean is still a matter of controversies (see Kozur, 1991; Kovács, 1992; Kozur and Mock, 1997; Less, 2000 and Péró et al., 2002 arguing for the "northern" position vs. Hók et al., 1995 and Rakús, 1996 holding an opposite opinion). Overall, the paleogeographic arguments in favour of its setting on the northern (outer) shelf seem to be more convincing. The debate about this problem is analogous to the current debate about the paleogeographic position of the Upper Juvavic nappes (which are largely comparable to the Silicic units by their lithostratigraphic content) with respect to the lower Upper Austroalpine units of the NCA. The structurally-based view of Schweigl and Neubauer (1997) and Neubauer et al. (2000) about the position of the Upper Juvavic unit at the southern margin of the Meliata-Hallstatt Ocean was rejected based on stratigraphic arguments (Gawlick et al., 1999; Mandl, 2000) which favour its location on the northern Tethyan shelf. The present knowledge of the Western Carpathians does not allow solving this problem either, since the Silicic nappes represent late, out-of-sequence thrust and/or extensional allochthonous outliers that apparently do not agree with the generally northward polarity of the underlying basement thrust sheets (Fig. 2). Consequently, the palinspastic positions of both, the Upper Juvavic and Silicic units, still remain ambiguous. The oldest member of the Silicic nappes are Upper Permian evaporites after their deposition subsidence was considerable, but compensated by sedimentation of shelf clastics (Scythian) and platform carbonates (Middle – Upper Triassic), building altogether a 3-4 km thick sequence. The Pelsonian event led to the drowning of the platform and is locally recognizable in intra-shelf basin successions, but reef-cored carbonate platforms kept pace with subsidence (Wetterstein Fm. – e. g. Michalík et al, 1993a; Polák et al., 1996; Wieczorek, 2000). The southernmost Silicic units (Bódva Nappe) exhibit a distinct post-Pelsonian pelagic sedimentation (Hallstatt, Zlambach Fm.) and provide transition to the Meliata Ocean environments. Lower Jurassic strata not only record drowning of the platform and pelagic swell formation (Hierlatz, Adnet Fm.), but also basinal sedimentation (Allgäu Fm.). Middle Jurassic to Oxfordian deposits show additional (compressional?) deepening with radiolarites and olistostromes. To indicate the Triassic subsidence history, the basement subsidence path is outlined in Fig. 4 (*Silica basement*) instead of the surface subsidence shown in other curves.

The Silicic successions show close relations to the more northerly emplaced superficial nappes of the Hronic Superunit (Choč Nappe s.l.), which resemble the Alpine Tirolic and Upper Bajuvaric units as far as their Triassic lithostratigraphies (Hauptdolomit and Dachstein facies) are considered. The Hronic nappes are superimposed on the Fatric and North Veporic units (Fig. 1, 2) where the Hronic lower structural complex is composed of Upper Carboniferous – Scythian succession of continental and shallow marine clastics (Ipoltica Group – Vozárová and Vozár, 1988), dominated by thick, riftogenous Permian red-beds and basic volcanics, and the tectonically partly independent upper structural complex is mainly built up of Middle – Upper Triassic shelf carbonates. Latter show the formation of a Lower Anisian ramp and a platform followed by facies differentiation after the Pelsonian. This manifests itself as carbonate buildups (Ramsau, Wetterstein Fm.) intervened by basinal successions (*Biely Váh Succession* in Fig. 3) which include pelagic limestones (Reifling Fm.) and Carnian clastics (Lunz Fm.) – e. g. Maheľ (1979), Masaryk et al. (1993), Michalík et al. (1993a), Polák et al. (1996). The high production of Upper Triassic platform carbonates compensated the decaying subsidence. The Triassic carbonate platform was broken apart and subsequently drowned during the Early Jurassic, whereby sedimentary successions show a change from a gradual, uncompensated subsidence from condensed pelagic swell facies (Adnet Fm.) to bathyal basins (Barmstein, Oberalm Fm.). Hauterivian synorogenic siliciclastic turbidites then terminate the Hronic successions in some places.

3.3 Slovakocarpathian units

The Triassic carbonate platform facies arrangement of the Hronic area exhibits close relationships to the more southerly located Silicic area, but the exact provenance of both is not exactly known, because when taking their present position on the northern Meliatic shelf into consideration, problems arise since the Silicic nappes occupy the structural position above, not below the Meliatic stack (Fig. 2). Instead, the Meliatic units (the transitional Bôrka Nappe in particular) directly override the Gemeric Superunit, which is almost devoid of Mesozoic cover sequences. The more external Veporic Superunit is a huge thick-skinned thrust sheet carrying two distinct sedimentary cover units. The South Veporic Foederata Unit only contains Triassic sediments recording a transition from continental to shallow marine environments during the Scythian and early Middle Triassic. During the Ladinian – Carnian the platform drowned, but re-established during the Norian. The North Veporic Vel'ký Bok Unit contains already tripartite Germanic-type Triassic succession, followed by Jurassic and Cretaceous strata similar to those of the main Fatric realm (*Zliechov Succession* in Fig. 4).

Triassic sediments of most parts of the Fatric and Tatric realms are formed by epicontinental successions which overlap a peneplained substratum with triple division similar to that of the Germanic Basin. Scythian alluvial plain clastics of rather uniform thickness overlie either restricted Permian continental rift basins, or directly Variscan high-grade basement rocks. Evaporites and marine carbonates appeared at the end of the Scythian. The Middle to Late Triassic subsidence was very slow and fully compensated by sediments, not exceeding 1500 m in thickness. Carbonate ramp deposits (Gutenstein, Ramsau Fm.) are characteristic for the Middle Triassic and the Carnian and continental playa lake and sabkha deposits prevailed during the Norian (Carpathian Keuper Fm.). The Rhaetian shallow marine strata are preserved in the Fatric area only.

Differentiation of sedimentary environments during the Early Jurassic led to the deposition of variously composed Jurassic – Cretaceous sedimentary successions, the most important are characterized below. The Fatric Superunit was established as a wide basinal area between the Tatric and Veporic domains, and was diminished by crustal shortening processes during the Late Cretaceous. The Fatricum is a cumulative term (introduced along with Hronicum by ANDRUSOV et al., 1973) for a system of cover nappes (Krížna Nappe s.l.) which occur in the northern part of the CWC and to a lesser extent also in the PKB. Its principal constituent is the Krížna décollement cover nappe, which overrides the Tatric basement and its cover. The Krížna nappe system can partially be correlated with the lower Bajuvaric units, e. g. the Frankenfels and Allgäu Nappes except for the Upper Triassic strata.

The Krížna Nappe is dominated by the Jurassic – Cretaceous *Zliechov Succession*, characterized by a sequence of syn-rift, post-rift and synorogenic formations (Fig. 4). The syn-rift strata record increasing, uncompensated subsidence ranging from littoral clastics to hemipelagic spotted marls ("Fleckenmergel", Allgäu Fm.) during the Lias. The Middle Jurassic to Early Cretaceous thermal subsidence gave rise to eupelagic sediments, partially deposited below the CCD during the Late Dogger and the Oxfordian (e. g. BORZA et al., 1980; POLÁK et al., 1998). In mid-Cretaceous times, the Zliechov Basin changed into a compressional basin in front of the advancing orogenic wedge. It then received an increasing amount of clastic material derived from the wedge, which fed the coarsening-upward synorogenic flysch deposits (Poruba Fm.), thus terminating the Zliechov Succession. This Albian – Cenomanian exotics-bearing flysch sequence was often paralleled with the Alpine "Cenoman Randschuppe" and the Losenstein Fm. (see e. g. WAGREICH, 2001).

The northern margin of the Zliechov Basin was characterised by a distinct shallowing of the sedimentary successions and by the presence of various Jurassic slope and/or swell facies, which constitute the lowermost Vysoká-type Fatric units. The external Manín Unit (presently located at the southern margin of the PKB, i. e. in the "Periklippen Belt" – Fig. 1), forms the transition to the southernmost part of the Tatric Superunit. Both units, the *Manín* and the *High-Tatra Successions* (Fig. 4) are dominated by comparatively shallow marine pre-Bathonian strata with numerous gaps and erosion surfaces. The late Bajocian – early Bathonian break-up resulted in a subsidence to bathyal depths, but still with distinct signs of a relative elevated position compared to the surrounding Šiprúň and Zliechov Basins (KOŠA, 1998; RAKÚS and OŽVOLDOVÁ, 1999). The most conspicuous feature of both of these successions is a remarkable shallowing during the Barremian – Lower Albian, indicated by the presence of Urgonian-type platform limestones amidst pelagic sequences. By the middle Albian, the platform was rapidly drowned, succeeded by a condensed horizon and then by pelagic marls (LEFELD, 1988; RAKÚS, 1977; MICHALÍK and VAŠÍEK, 1984, 1987; BORZA and MICHALÍK, 1987; MICHALÍK and SOTÁK, 1990; WIECZOREK, 2000, 2001). The intra-Tatric *Šiprúň Succession* (Fig. 4) represents a basinal area with a subsidence history similar to the Zliechov Basin, but in contrast it shows partial uplift and erosion during the earliest Jurassic (BUJNOVSKÝ et al., 1979) and the main syn-rift subsidence period during the Late Lias, and it reached slightly lesser depths during the post-rift thermal subsidence period. The Tatric successions are terminated by the Albian – lower Turonian siliciclastic flysch sequence (Poruba Fm.). The northern flanks of the Šiprúň Basin are represented by the Kuchyňa and *Devín Succession* (Fig. 4) which show signs of remarkable Liassic uplift and erosion of pre-rift strata and a subsequently rapid subsidence during the Dogger (PLAŠIENKA et al., 1991; MICHALÍK et al., 1993b). The neighbouring *Kadlubok Succession* corresponds to a pelagic high with thin, mostly condensed strata, numerous gaps, neptunian dykes and hardgrounds (MICHALÍK et al., 1994). The Infratatric (i. e. the structurally lowermost and paleogeographically outermost part of the Tatricum) *Borinka Succession* substantially differs from any other succession previously described. It is composed of exceptionally thick Lower – Middle Jurassic syn-rift sequences of scarp breccias, debris flows, turbidites and anoxic shales. Large amounts of terrigenous clastic material indicates its deposition in the vicinity of a subaerial high, named the North-Tatric Ridge. The Borinka Succession is interpreted to represent a filling of a marginal halfgraben at the northern edge of the Tatricum (PLAŠIENKA, 1987; PLAŠIENKA et al., 1991) and its positions is supposed to be analogous to the Lower Austroalpine margin of the Eastern Alps (HÄUSLER, 1988; HÄUSLER et al., 1993). Although the Tatric Superunit probably has no direct prolongation into the Alps, the analogues of the

Infratatric elements can be identified in the Lower Austroalpine basement/cover units.

3.4 Penninic units

During the Late Jurassic and Cretaceous, the northern Tatric (Infratatric) margin faced the South Penninic oceanic realm named the Vahic Ocean (MAHEĽ, 1981). In the present surface structure of the WC, it is represented by only one well-defined element, the Belice Unit of the Považský Inovec Mts. (Fig. 1). The *Belice Succession* includes slices of amygdaloidal basalts (discriminated as within-plate basalts based on trace element analysis by SOTÁK et al., 1993). The highly dismembered and imbricated sedimentary rocks are composed of Upper Jurassic ribbon radiolarites, Lower Cretaceous dark siliceous slates with thin intercalations of Calpionella limestones in the lower part, and Senonian coarsening-upward flysch sequence (KULLMANOVÁ and GAŠPARIKOVÁ, 1982; PLAŠIENKA et al., 1994). This succession is similar to the South Penninic oceanic lithologies of the Alps (e. g. DIETRICH, 1970; WEISSERT and BERNOULLI, 1985; DECKER, 1990; STAMPFLI et al., 1998).

The Vahic Ocean separated the Slovakocarpathian realm from the Oravic continental ribbon or marginal plateau. The Oravic Superunit involves several successions occurring exclusively in the Pieniny Klippen Belt. The basinal *Kysuca Succession*, representing a former slope environment neighbouring the Vahic Ocean, exhibits the Jurassic – Early Cretaceous subsidence pattern almost identical with that of the Zliechov Basin (Fig. 4). The lower Liassic Arietites-bearing sandstones (Gresten Fm.) occur in places, but younger Liassic – Aalenian strata also record deepening with spotted hemipelagic marls and black shales, partly with intercalations of turbiditic sandstones. Deep-water siliceous, cherty and nodular limestones, radiolarites and Calpionella limestones constitute the Middle Jurassic – Neocomian Kysuca formations, followed by mid-Cretaceous marlstones and Senonian synorogenic flysch deposits. The contrasting *Czorsztyn Succession* represents a ridge or swell environment recording very complex subsidence history. The comparatively deep-water Liassic – Aalenian sequence was replaced by extremely shallow-water encrinitic and sandy limestones during the Bajocian. By the end of Bajocian, these sandbanks collapsed and experienced Late Jurassic subsidence to bathyal depths indicated by the ammonitico rosso facies (e. g. WIERZBOWSKI et al., 1999). However, parts of the Czorsztyn Ridge remained in a very shallow position, indicated by the presence of Upper Jurassic platform limestones (MIŠÍK, 1979). During the Neocomian, the ridge was elevated again, as indicated by shallow-water sediments and signs of emersion. The post-rift thermal subsidence in the Mid-Cretaceous definitely drowned the Czorsztyn Ridge, which then turned into a submerged pelagic swell (MIŠÍK, 1994) characterized by sedimentation of variegated marls of the "couches-rouges" type during the Late Cretaceous. The dissimilar Kysuca and Czorsztyn Successions are linked by several "transitional" successions showing characteristic features of both (Czertezik, Niedzica, Pruské, Branisko Successions – e. g. BIRKENMAJER, 1977).

The northern margin of the Oravic ribbon faced the Magura Ocean. The *Magura successions* rarely include sediments older than the Senonian (except the Grajcarek unit), therefore reconstruction of their Jurassic – Early Cretaceous evolution is rather difficult. The Jurassic rocks are known only from small tectonic and/or sedimentary blocks and pebbles in younger formations (SOTÁK, 1990). These would indicate a basinal environment with similar facies succession as in the Zliechov or Kysuca Basin. The lowermost Cretaceous strata are known from several small tectonic slices in front of the Magura Superunit in Moravia, where they are composed of marly pelagic limestones with slump breccia bodies. The oldest strata that build up the continuous Magura successions are Barremian – Aptian in age, and are composed of deep marine, calcite-free, sometimes also calcareous shales and turbiditic sandstones (Gault "Flysch" and Hluk Fm.). They change into mid-Cretaceous distal passive-margin turbidites (Kaumberg Fm.) and then into the synorogenic Senonian – Paleogene flysch (OSZCZYPKO, 1992; ŠVÁBENICKÁ et al., 1997; MALATA, 2000). The Magura Superunit is traditionally correlated with the East Alpine Rhenodanubian Flysch Belt (e. g. SCHNABEL, 1992).

The Grajcarek Unit was described on the Polish territory only (BIRKENMAJER, 1977), where it represents the innermost Magura subunit adjacent to the Klippen Belt, partly overridden by the Czorsztyn Unit (JUREWICZ, 1998). The Grajcarek Unit embraces a complete basinal succession starting with the Toarcian spotted marls and ending with the Maastrichtian wildflysch (Jarmuta Fm.). The Cretaceous strata of the Magura successions represent "dirty", terrigenous sediments of Bündnerschiefer-type deposited in proximity of the European passive margin. These sediments are a typical feature of the North Penninic basins (Rhenodanubian and Valais – e. g. WILDI, 1988; SCHNABEL, 1992; FLORINETH and FROITZHEIM, 1994).

4. Timing of the principal Mesozoic rifting events

4.1 Permian – Triassic events

The Early Mesozoic rifting was preceded by significant distensional tectonic events during the Permian (VOZÁROVÁ and VOZÁR, 1988). A notably thick, rift-related, continental sequence forms the sole of the Hronic cover nappe system. In this sequence, the Permian red-beds are associated with voluminous calc-alkaline to continental tholeiitic, andesitic and basaltic volcanism, which erupted in two distinct phases during the Early and Late Permian (VOZÁROVÁ and VOZÁR, 1988; VOZÁR, 1997), but the original paleogeographic position of this mature rift sequence is not known. Other deep, but comparatively narrow Permian rift basins originated in the North Tatric, Veporic and Gemeric zones, accompanied by calc-alkaline and/or subalkaline volcanism and A-type (UHER and BROSKA, 1996), as well as S-type (POLLER et al., 2002) granitic plutonism. The duration of this rift-related silicic magmatism has been estimated to last as long as the Middle Triassic (KOTOV et al., 1996; PUTIŠ et al., 2000; UHER and BROSKA, 2000). The site of the future Meliata oceanic rift was characterized by strong Scythian subsidence and shallow marine terrigenous sedimentation accompanied by alkaline rhyolitic volcanism (UHER et al., 2002). These features indicate that the terminal Variscan events – orogenic collapse and lithospheric attenuation, could have genetically been related to the early Alpine rifting in the southern CWC zones, which ultimately led to the opening of the Meliata Ocean (Fig. 3).

The Upper Anisian (Pelsonian) initial opening of the Meliata Ocean is designated as the Žarnov Phase here (named after the Žarnov Fm., which is composed of red pelagic limestones of this age described by MELLO and MOCK, 1977). In units derived from areas adjacent to the Meliata rift, this event is indicated by the unconformity between the Lower Anisian ramp and platform carbonates and Pelsonian red pelagic limestones. The younger Triassic pelagic facies include deep-water-, partially condensed nodular limestones and Ladinian – Norian radiolarites.

4.2 Jurassic events

Based on the timing of turning points in the bathymetric evolution (Fig. 4) and on the character and distribution of syn- and post-rift sedimentary sequences, four principal Jurassic – Cretaceous rifting phases can be discerned within the Western Carpathian area: (1) two Early Jurassic rifting phases due to lithospheric stretching and breakdown of the epi-Variscan Triassic platform; (2) one rifting phase as a result of the break-up of the South Penninic-Vahic Ocean in the late Dogger and (3) one rifting phase as a result of the break-up of the North Penninic-Magura Ocean in the Early Cretaceous (Fig. 4, 5).

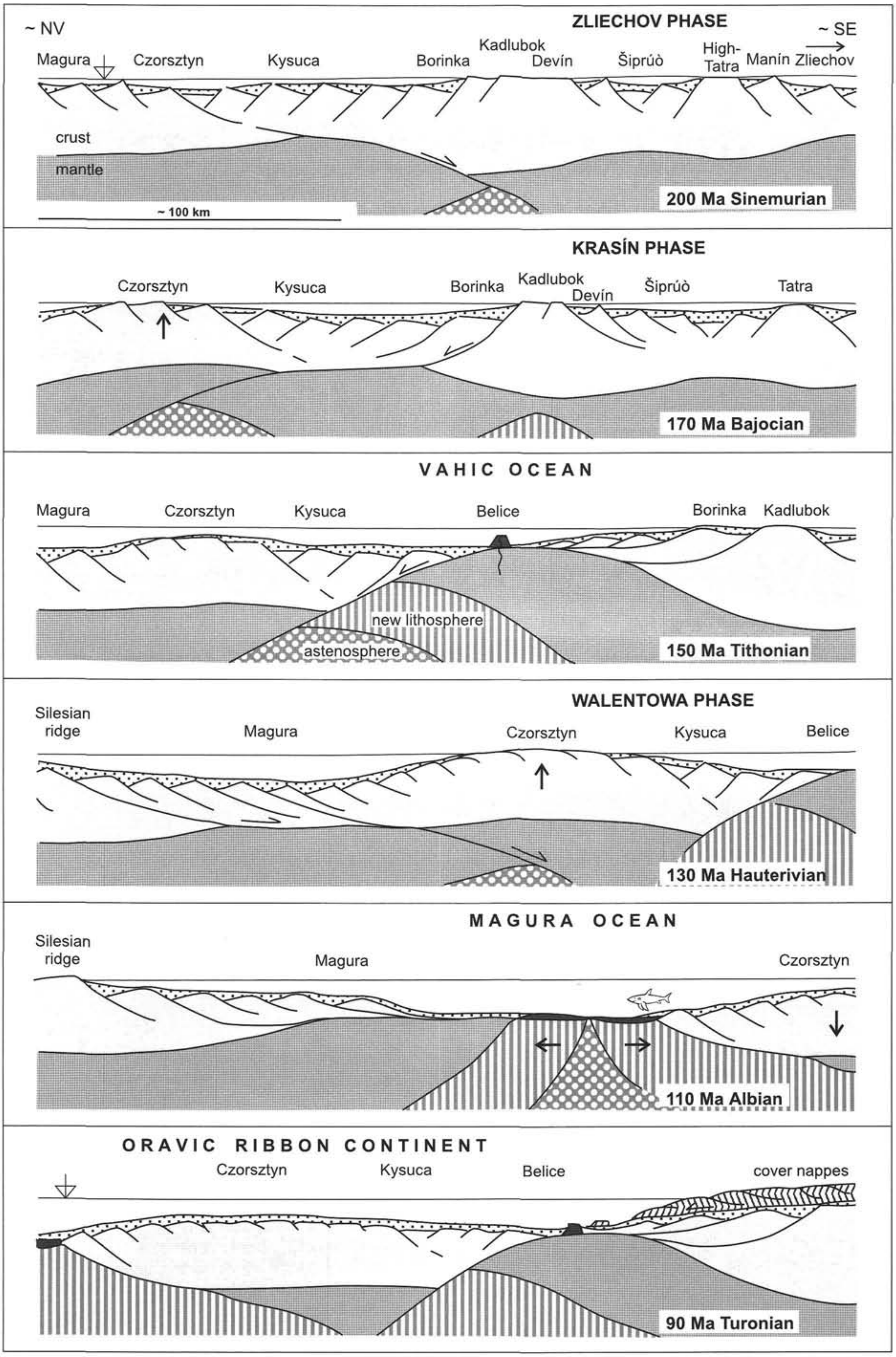
The Hettangian-Sinemurian "wide-rift" type Zliechov Phase is well recorded in the Tatric and Fatric domains. It led to a more-or-less uniform stretching of the epi-Variscan continental lithosphere and created broad subsiding intracontinental basins (Zliechov, Šiprúň, Kysuca-Czorsztyn-Magura – Fig. 5) separated by narrower subaerial highs, which later submerged (South-, or High-Tatric and North-Tatric Ridges). Lithospheric stretching and crustal heating during this rifting event is documented by a radiometrically dated thermal event in the Tatric and North Veporic basement around 200 Ma (MALUSKI et al., 1993; KRÁĽ et al., 1997), but no volcanism occurred at that time. For the next 100 Ma after the Zliechov Phase, sediment-starved basins within the Tatric area (Šiprúň Basin) and the Fatric zone (Zliechov Basin) of the Slovakocarpathian realm were subjected to slow thermal subsidence and pelagic sedimentation.

The less distinct Toarcian Devín Phase only occurs on a very local scale. The area of the North-Tatric Ridge (partly analogous to the Lungau Swell of TOLLMANN, 1977) experienced Lower Jurassic uplift and erosion of pre-rift Triassic successions, whereby Upper Liassic – Lower Dogger extraclastic limestones overlap deeply eroded Triassic strata, or directly overlie pre-Alpine basement complexes in some places (MICHALÍK et al., 1993b; PLAŠIENKA, 1999). The Devín Phase was probably also the main stage of extensional block tilting indicated by an increasing contrast between the hemipelagic, partly anoxic sedimentation in halfgrabens (Allgäu Fm.) and the deposition of well aerated "ammonitico rosso" limestones (Adnet Fm.) on the edges of domino blocks (SOTÁK and PLAŠIENKA, 1996; WIECZOREK, 2000, 2001). These phenomena are tentatively interpreted as having been caused by a transfer of the rifting mode into a locally slightly asymmetric, "simple shear" extension during the Devín Phase.

The Bajocian Krasín Phase strongly affected areas north of the North-Tatric Ridge. The "simple shear" asymmetric extension (adopting the model by WERNICKE, 1985) along the foreland-ward dipping lithospheric detachment fault resulted in additional crustal extension in the Kysuca Basin and the probably late Bajocian to early Bathonian break-up and opening of the Vahic (South Penninic) Ocean. The break-away zone of the detachment fault was obviously situated along the bounding fault of the Infratatric Borinka halfgraben, which received exceptionally thick Middle Jurassic terrigenous scarp breccias (Somár Fm. – PLAŠIENKA, 1987) from the North-Tatric Ridge, forming the lower plate margin at that time. On the other hand, the Czorsztyn Ridge originated at the distal upper plate margin by thermal uplift above the subcrustal part of the detachment fault (Fig. 5). The uplift is indicated by remarkable shallowing and scarp breccias with signs of freshwater cementation (Krasín Breccia – MIŠÍK et al., 1994a; AUBRECHT et al., 1997). Coeval, allodapic crinoidal limestones (Samášky Fm. – AUBRECHT and OŽVOLDOVÁ, 1994), were deposited in slope environments (Pruské Succession). The late Bajocian to early Bathonian thermal collapse and break-up unconformity between the syn- and post-rift strata has also been identified in ridge areas south of the Vahic Ocean (DUMONT et al., 1996; WIECZOREK, 2000, 2001). Simultaneously, the basinal areas (Magura, Vahic, Šiprúň, Zliechov) submerged to abyssal depths below the CCD, as indicated by widespread deposition of radiolarites during the Callovian up to the Kimmeridgian (Fig. 4).

4.3 Cretaceous events

The Berriasian – Hauterivian Walentowa Phase marks the further foreland-ward migration of rifting and is interpreted to record the break-up of the Magura Ocean. The break-up was, similar to the Krasín Phase, preceded by asymmetric rifting. In this case the direction of the detachment fault can be reconstructed as hinterland-ward dipping. Lithospheric extension and mantle upwelling triggered the second thermal uplift event of the upper plate, the Czorsztyn Ridge, which is manifested through shallowing of sedimentary successions, syn-rift debris flow deposits and carbonate scarp breccias (Walentowa Breccia – BIRKENMAJER, 1977). This is followed by a widespread surface uplift, karstification, erosion and non-deposition until the Albian. Coeval, the allodapic Horná Lysá Limestone and the Hauterivian turbidites occur in the basinal Kysuca Succession (MIŠÍK et al., 1994b; AUBRECHT, 1994). The same rifting event was also detected on the other side of the Magura Ocean, in proximity to the Silesian Ridge which is in the lower plate position (ELIÁŠ and ELIÁŠOVÁ, 1984; REHÁKOVÁ et al., 1995; ELIÁŠ et al., 1996), as well as in the Silesian Basin behind this ridge (KROBICKI and SŁOMKA, 1999). The Tatric-Fatric realm (including the swell areas) is characterized by a rather uniform pelagic sedimentation during the Neocomian. However, carbonate scarp breccias and associated basic volcanics indicate reactivation of normal faults between the basin and ridge areas (Nozdrovice Breccia – MICHALÍK et al., 1996; STANISZEWSKA and CIBOROWSKI, 2000). In the Zliechov Basin, pelagic sedimentation was interrupted by incursions of turbidites, which may be also related to the Walentowa Phase. Valanginian terrigenous, siliciclastic, chrome spinel-bearing turbidites (related to nappe stacking in the inner Carpathian zones) were followed by Hauterivian allodapic limestones derived from the northerly located South Tatric Ridge (MICHALÍK et al., 1996; WIECZOREK, 2000).


~ NV
ZLIECHOV PHASE
~ SE
Magura
Czorsztyn
Kysuca
Borinka
Kadlubok
Devín
Šiprúò
High-Tatra
Manín
Zliechov
crust
mantle
~ 100 km
200 Ma Sinemurian
KRASÍN PHASE
Czorsztyn
Kysuca
Borinka
Kadlubok
Devín
Šiprúò
Tatra
170 Ma Bajocian
VAHIC OCEAN
Magura
Czorsztyn
Kysuca
Belice
Borinka
Kadlubok
new lithosphere
astenosphere
150 Ma Tithonian
WALENTOWA PHASE
Silesian ridge
Magura
Czorsztyn
Kysuca
Belice
130 Ma Hauterivian
MAGURA OCEAN
Silesian ridge
Magura
Czorsztyn
110 Ma Albian
ORAVIC RIBBON CONTINENT
Czorsztyn
Kysuca
Belice
cover nappes
90 Ma Turonian

Remarkable subsidence of the Magura Basin down to abyssal depths after the Walentowa Phase and Magura Ocean break-up is revealed by hemipelagic and turbiditic sedimentation commonly below the CCD starting from the Barremian throughout the Cretaceous – see Fig. 4. The Walentowa Phase was also accompanied and followed by submarine extrusions of primitive, mantle-derived alkaline basalts starting in the Berriasian up to Lower Albian which occur in the Fatric, Tatric and Silesian domains (e. g. SPIŠIAK and HOVORKA, 1997; LUCIŃSKA-ANCZKIEWICZ et al., 2002).

The above characterized distensional tectonic phases were post-dated by an additional distinct tectonic event, designated as the Solírov Phase here (partly corresponding to the Manín Phase defined by ANDRUSOV, 1968). This event occurred during the Barremian – Early Albian in zones south of the Vahic Ocean only. It is indicated by the growth of the Urgonian carbonate platform on the former South-Tatric Ridge and by tectonically driven re-sedimentation events around the North-Tatric Ridge (calciturbiditic Solírov Fm. – JABLONSKÝ et al., 1993). Both Tatric ridges were once more elevated from bathyal depths to the sea level, but were rapidly drowned again afterwards. Shortly after this phase, in the Middle Albian, the synorogenic, coarsening-upward flysch sedimentation commenced in the Fatric and Tatric domains (Poruba Fm.).

5. Discussion

5.1 Kinematics of pre-orogenic rifting in the Western Carpathians

The opening of the Meliata, or Meliata-Hallstatt Ocean is commonly interpreted as the result of back-arc rifting generated by a northward subduction of the Paleotethys below the Eurasian plate (e. g. STAMPFLI, 1996). This interpretation is corroborated by widespread Middle Triassic calc-alkaline arc volcanism in the South Alpine-Dinaridic-Pelso realm (Pietra Verde, Buchenstein, Szentistvánhegy Fm. – see e. g. SZOLDÁN, 1990), which was, at least in its eastern part, separated by the Meliata rift from the North European Platform at that time. The Meliata ophiolites are strongly dismembered and do not provide an unambiguous geodynamic information, since the geochemical signals of the arc, MORB and within-plate basalts were encountered at different localities (FARYAD, 1995; IVAN and KRONOME, 1996). Nevertheless, IVAN (2002) interpreted the Meliata Ocean as an initial back-arc basin gradually acquiring the typical ocean-floor characteristics during advanced stages of spreading.

Based on the interpretation of the sedimentary record, the Jurassic – Lower Cretaceous rifting process occurred in several distinct stages affecting different domains differently. The oldest, earliest Liassic Zliechov Phase seized extensive areas and developed a basin-and-swell realm with rugged topography. Rifting created wide basinal areas and narrow intra-basinal swells, showing moderate uplift of the rift flanks. The basinal successions retained complete and mostly undisturbed pre-rift sequences, but deep erosion occurred in the North-Tatric Ridge area where rifting was probably slightly asymmetric. These features indicate the initial rifting was of the "pure shear" type, symmetric to slightly asymmetric, generated through nearly homogeneous lithospheric stretching and crustal thinning. The initial rifting phase was followed by the weaker upper Liassic Devín Phase, during which additional crustal attenuation and extensional block tilting occurred. It is noteworthy that the prominent Czorsztyn Ridge did not exist at that time yet, and the Czorsztyn domain was part of a wide basinal area including the neighbouring Kysuca and Magura Basins.

The Middle Jurassic Krasín Phase rifting took place in a more restricted area around the future break-up zone of the Penninic-Vahic Ocean. Asymmetric rifting mode is indicated by contrasting subsidence histories of the margins of the rift zone. The lower, Slovakocarpathian plate margin acquired a narrow rift shoulder and the break-away system of half-grabens was filled with thick aprons of scarp breccias, while the distal, broad upper-plate margin (Czorsztyn Ridge) was uplifted. The late Bajocian – early Bathonian break-up is widely recorded by a partly subaerial unconformity followed by a pronounced thermal subsidence stage during the Late Jurassic.

Interestingly enough, the Czorsztyn Succession records a second, distinct uplift event during the Early Cretaceous, the Walentowa Phase. It is interpreted here as a consequence of another phase of asymmetric lithospheric rifting, which ultimately led to opening of the Magura Ocean on the other side of the Czorsztyn Ridge (Fig. 5). The ridge retained its upper plate position, therefore it experienced the syn-rift thermal uplift again. The reconstruction of the overall rift geometry closely resembles the model of a passive margin affected by several extensional detachment systems, developed by LISTER et al. (1986). Following their terminology, the Czorsztyn Ridge may be considered as a marginal plateau or ribbon continent (see Fig. 4 in LISTER et al., 1986).

5.2 Correlation with the Alps

A succession of rifting events comparable to that described above was reconstructed for large areas on the European, Austroalpine and South Alpine shelves of the Alpine Tethys (e. g. LEMOINE et al., 1986; BERNOULLI et al., 1993; FROITZHEIM and MANATSCHAL, 1996; CLAUDEL and DUMONT, 1999). The Liassic symmetrical rifting was succeeded by the Middle Jurassic simple shear extension and break-up of the Ligurian-Piemont Ocean, which produced also a thermal uplift of the broad, upper plate Briançonnais rift shoulder. Finally, the separation of the Briançonnais ribbon continent from the European margin and the break-up of the Valais Ocean occurred probably in the Early Cretaceous (FRISCH, 1979; FLORINETH and FROITZHEIM, 1994; STAMPFLI, 1994). Opening of both, the South and North Penninic oceanic branches was ascribed to the eastward propagation of the Central Atlantic and the North Atlantic – Bay of Biscay rift systems, respectively (FRISCH, 1981; LEMOINE et al., 1987; STAMPFLI, 1994, 1996).

It is now well established in the Alps that opening of the South Penninic oceanic zone was initiated by asymmetric

← Fig. 5
Paleotectonic interpretation of Jurassic – Early Cretaceous rifting processes that separated the Slovakocarpathian realm from the North European Platform by opening of the South Penninic (Vahic) and North Penninic (Magura) oceans with the Oravic continental ribbon in an intermediate position.

passive rifting and subcontinental mantle exhumation, followed by diffuse slow spreading. This model is based upon evidence from the composition of the oceanic bottom ophiolites (LEMOINE et al., 1987; TROMMSDORFF et al., 1993; MARRONI et al., 1998) and the geometry and kinematics of the rift-related extensional fault structures (FROITZHEIM and EBERLI, 1990; BERNOULLI et al., 1993; FROITZHEIM and MANATSCHAL, 1996). Though not directly supported by proofs, an analogous model is adopted for the Western Carpathians, since certain features in the sedimentation and subsidence/uplift patterns of the proximal (Lower Austroalpine-Infratatric) and distal (Middle Penninic-Oravic) margins of the asymmetric South Penninic-Vahic oceanic rift seem to correlate well.

5.3 Geodynamic background of rifting

As indicated by the synoptic evolutionary scheme (Fig. 3), the above discerned Jurassic – Cretaceous rifting events occurred within the lower plate of the Western Carpathian convergence orogenic system. The absence of rift-related volcanism and the persistence of an extensional tectonic regime for many tens of Ma indicate a passive rifting mode generated by tensile deviatoric stresses within the European lithosphere. Adopting the Alpine model to the Western Carpathians, an eastward lateral propagation of the Alpine Tethys rift, i. e. sequential opening of the South Penninic Ligurian, Piemont and Vahic oceanic basins, would be expected. However, as it has already been pointed out by DUMONT et al. (1996), that no such rift propagation can be reconstructed and rifting, punctuated by the late Bajocian – early Bathonian break-up, was more-or-less coeval in all these basins. Therefore, an alternative model is suggested below.

The continental fragments in the Alpine-Carpathian realm (including Getic-Bucovinian, Tisia, Slovakocarpathian, Austroalpine and Pelso consisting of Transdanubian and Bükk terranes) are usually considered as a NE-trending spur of the Adriatic microplate during the Jurassic (e. g. STAMPFLI et al., 1998 – their reconstruction is partially adopted in Fig. 6 of this work). From the SE, this spur faced the Neotethys-related Meliata-Vardar oceanic realm bordered by active

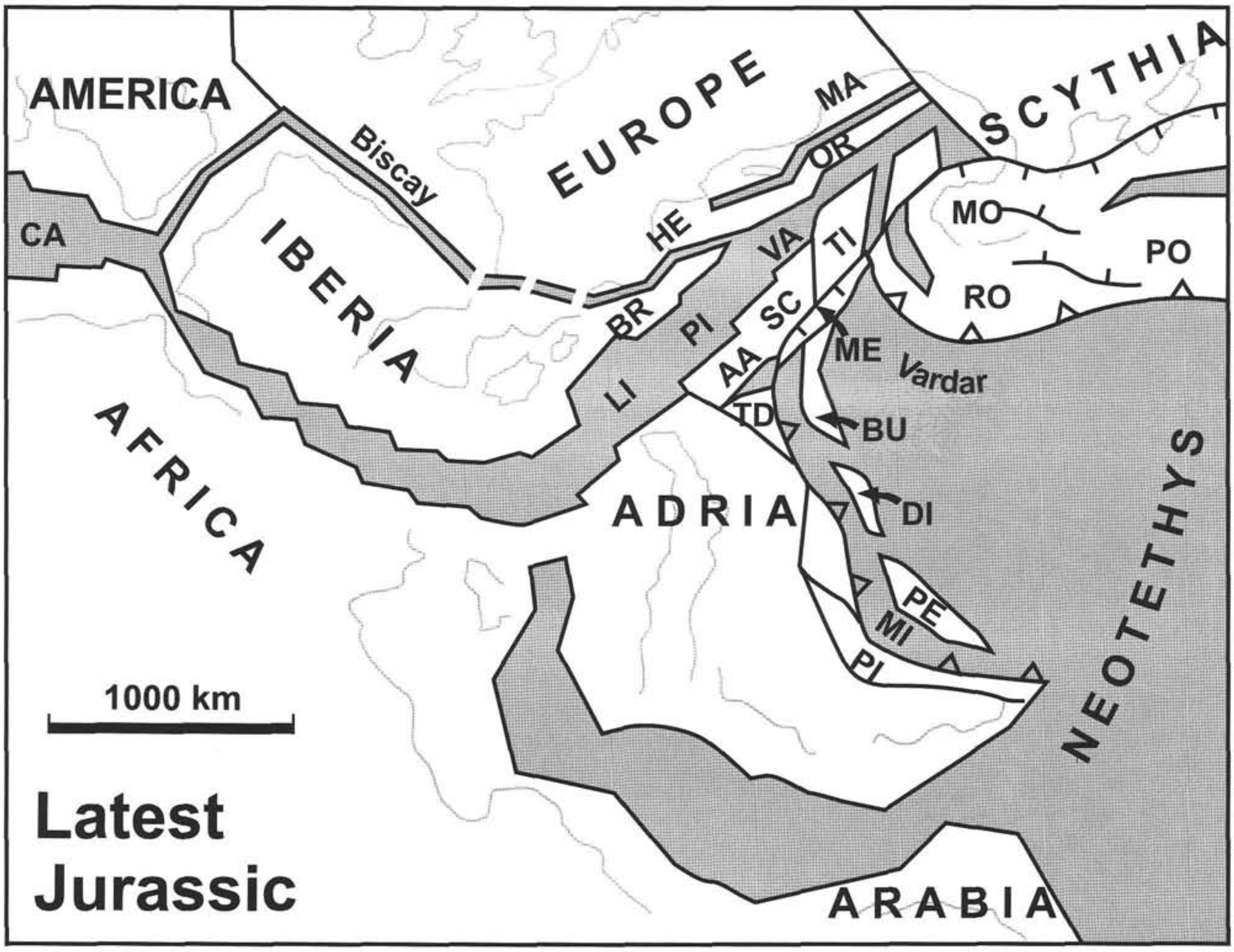


Fig. 6
A possible arrangement of oceanic (grey) and continental (white) domains in the western Tethyan realm during the latest Jurassic. Plate configuration, present shorelines and orogenic fronts (grey lines) are drawn after STAMPFLI et al. (1998). Strongly modified in the Carpathian area to outline the relationship between the extensional and compressional areas. Solid lines with teeth denote subduction zones, those with ticks indicate suture zones. CA – Central Atlantic, BR – Briançonnais, HE – Helvetic, MA – Magura, OR – Oravic, LI – Ligurian, PI – Piemont, VA –Vahic, AA – Austroalpine, SC –Slovakocarpathian, TI – Tisia, TD – Transdanubian, ME – Meliatic suture, BU – Bükk, DI – Drina-Ivanjica, PE – Pelagonian, MI – Mirdita, PI – Pindos-Budva, MO – Moesia, RO – Rhodope, PO – Pontides.

margins. After closure of the Meliata Ocean, collision between the Europe-related passive margin and the Adria-related drifting fragments occurred in the Alpine-Carpathian sector. This suggests that in its eastern sector, Penninic rifting took place in the foreland of the advancing collision front (see also Fig. 3) and that the Austroalpine-Slovakocarpathian continental blocks had a weak, if any, connection with Adria (Fig. 6). Consequently, it appears to be questionable whether the Penninic rifting might have solely been triggered by the eastward drift of Adria and Africa relative to Europe.

In the new model it is assumed that rifting-related horizontal tensile stresses, operating within the lower plate of the convergence system, were generated by the subduction slab pull force of the Meliata oceanic lithosphere (Fig. 7). Although the present geodynamic models assume that slab pull forces to be largely subtracted by resistive forces within the mantle and the collision zone, at certain circumstances it possibly could have been effectively transmitted towards the lower plate of the convergence system to produce significant horizontal deviatoric tension. After commencement of the continental collision, the subcrustal mantle subduction might continue (see e. g. model by BEAUMONT et al., 1996) and the driving slab pull force might prolong to generate lower plate extension in the foreland of the collision zone. This idea is outlined in Fig. 7 for the earliest Cretaceous time, when the Meliata Ocean was already closed in the Carpathian area and the southern zones were already undergoing collisional shortening, but rifting and lithospheric stretching still operated in the foreland of the convergence system.

6. Conclusions

In the Western Carpathians, the Late Jurassic – Tertiary orogenic contraction influenced areas that were affected by earlier lithospheric stretching, crustal rifting

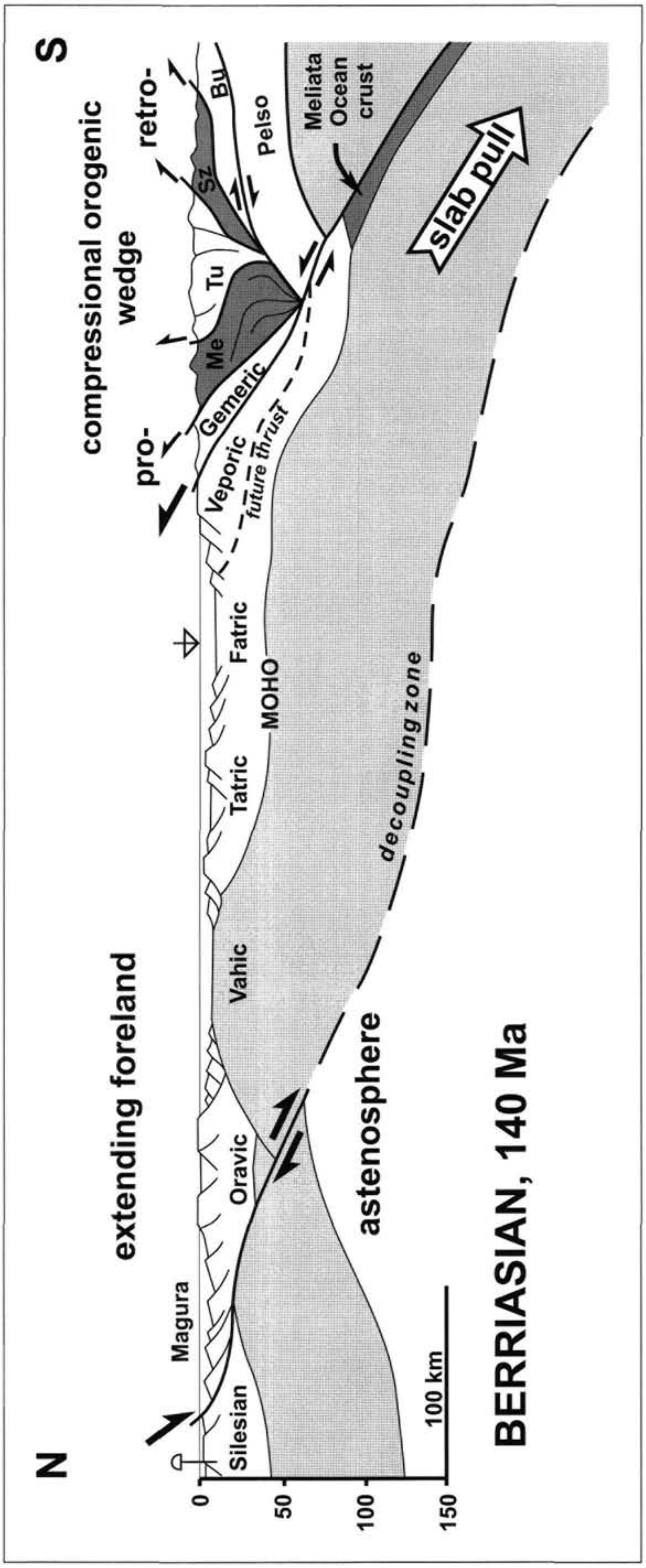


Fig. 7
Geodynamic interpretation of the Western Carpathian area at the beginning of the Cretaceous. The negative buoyancy of the subducting Meliata ocean lithosphere is considered to be the main driving force for both the upper plate shortening and orogenic wedge growth, as well as for the extension and oceanic rifting of the lower plate attached to the sinking slab. Arrangement of the collision zone was inspired by the model of BEAUMONT et al. (1996). Me – Meliatic accretionary complex, Tu – Turnaic units, Sz – obducted ophiolites of the Szarvaskő unit, Bu – Bükk "paraautochthon".

and eventually by oceanic break-up and subsequent spreading in some zones. Poor outcrop conditions and widespread tectonic inversion do not allow to directly study the rift-related structures and therefore the pre-contraction rifting processes have been reconstructed through analysis and interpretation of the sedimentary record. This analysis reveals a long-term extensional regime escalating into several distinct rift phases during the Mesozoic. The first phase led to opening of the Meliata Ocean during the Middle Triassic, most probably by an active rifting process in a back-arc tectonic setting. The Jurassic – Lower Cretaceous rifting phases were contemporaneous with compressional deformation within the orogenic wedge prograding from the hinterland to the foreland lower plate. It has been suggested that both, foreland extension and hinterland contraction, occurred in a linked geodynamic system driven by the subduction pull force exerted by the sinking oceanic Meliata slab. Two subsequent non-volcanic rifting modes have also been recognized – the initial symmetric "pure shear" extension was followed by two localized asymmetric "simple shear" rifting phases that ultimately resulted in the break-up of continental lithosphere and the spreading of the Penninic oceanic domains.

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