Mesozoic paleogeography and facies distribution in the Northern Mediterranean Tethys from Western Carpathians view

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Abstract

West Carpathian Mesozoic paleogeographic development indicates the effect of a left lateral shift of the Alpine-Carpathian microcontinent along the European shelf since the Early Jurassic. The evolution during Late Triassic/Early Jurassic was controlled by convergence along the border of the Meliata Ocean and by contemporaneous divergence along the Middle Atlantic/Penninic rift. During Mid-Cretaceous, the convergence between Africa and Paleoeurope started, which finally resulted in collision of Alpine-West Carpathian microcontinent with the Paleoeuropean margin and in the formation of the Alpine Orogen.

Keywords: *Mesozoic, Mediterranean Tethys, lithofacies, paleogeography, Western Carpathians.*

1. Introduction

The North Alpine- and West Carpathian Mesozoic sequences were deposited on fragmented remnants of the Variscan consolidated North European shelf crust after its collision with the Gondwana supercontinent [1]. Since the Permian time, the Outer Carpathian domain belonging to the eastern European continental border between the Bohemian Massif and the Ukrainian Shield was peneplenized.

At that time, it formed a segment of southern Palaeoeuropean shelf of the Paleotethys Ocean. The Triassic sedimentary record in this area is mostly unknown. This block was mostly emerged, local deposits were eroded, covered, or tectonically fragmented during Late Alpine Orogeny [2]. In contrary, the central West Carpathian block together with the Eastern Alpine basement (Austroalpine unit) formed a part of an independent microcontinent located far to the west. This terrain was attached to another part of the Palaeoeuropean margin between the Bohemian and the Armorican Massifs and its southern side bordered the Meliata Ocean. The Triassic sequence of this area consists of two sedimentary megacycles of neritic carbonates, separated by clastic terrigeneous deposits (produced by Scythian, Carnian, Rhaetian more humid episodes). These sequences indicate deposition under changing climatic, eustatic and palaeoceanographic conditions in the Western (Mediterranean) Tethys.

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Since latest Triassic, the area was involved into the Mediterranean Tethys Ocean. Hemipelagic and eupelagic sediments prevailed here until Mid-Cretaceous. In the Turonian, convergence of African and European continents resulted in the Alpine collision, which produced nappe structure. Formation of the Alpine - Carpathian orogenetic mountain chain peaked during Oligocene and Early Miocene.

2. Triassic development
2.1 Scythian sedimentary megacycle

The N-S convergence trend of Laurasia and Gondwana changed into W-E one after Variscan consolidation of the Paleoeurope. Rifts were re-activated by tensional stress and subsidence of basins started. Both the lack of volcanism and relatively low subsidence were remarkable features of these rifts [3]. The European craton was rimmed by wide belt of subsiding depressions (Fig.1). The first Triassic sedimentary megacycle started with transgression of a shallow epicontinental sea across these extensive nearshore flats modelled by post-Variscan erosion and subsidence. Scythian clastics (mostly quartzitic pebble sand, silt and argillites) of the Alpine-Carpathian region accumulated in a huge playa-and deltaic fan system (its volume was calculated as having more than 100 000 km^3) in a such a belt of several hundred kilometers width [4]. The sedimentary record was rather punctuated, affected by changing seasonal

climate and by fluctuating rise of sea level. This material was transported by periodical river systems from a large area (estimated by Michalík, [1] as 750 000 km^2) between the Bohemian- and the Armorican massifs. The location of sources of these considerable laterally dispersed terrigeneous clastic sediments was assumed in the „Vindelician Land", situated to the north [1,2, 4 and 34]. If the source rocks were of granite composition, and the erosion rate was not greater than 200 mm/ka, quartzose sand must be derived of 400 000 km^3 volume of mother rocks [5]. The zonality pattern with sediments fining southwards is neither in the Eastern Alps, nor in the Outer and Central Western Carpathians, nor in the Eastern Carpathians and in subsurface Pannonian units the same. This fact indicates location of proximal zones with coarse terrigeneous sedimentation in the north, and distal ones with more pronounced marine influence in southern parts of the area [6]. Quartz sandstones, lithic sandstones, arcoses, and greywackes with conglomeratic layers fining southwards accumulated in a complex system of low sinuous braided rivers passing into piedmont plains with local lacustrine or palustrine environments (the Lúžna Formation; [7] Fig.1). Heavy mineral content (zircon, tourmaline, apatite, barite,) proves for variability of sources and could serve as a paleogeographic indicator.
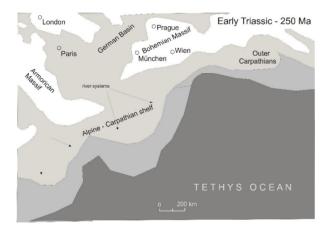

Fig.1. Paleogeographic sketch of Early Triassic situation of northern Mediterranean Tethys (white = dry land; light gray = lowlands; gray = sea).

In more distal parts of the fan, the thickness increased up to thousand metres and the material consisted of siltstones, clays and argillitic limestones. The sequence contains marine bivalves (Claraia clarai and C. aurita), gastropods and ammonites. Diversity of the fauna increases even more basinwards (the Szín Formation contains rich ammonite fauna, gastropods, foraminifers, and conodonts of Smithian and Spathian age). If we realize that all Scythian sequences were deposited on a very flat bottom, the subsidence of basement must have been very differentiated: it was calculated as 5-20 mm/ka in proximal zones, but the zones close to the southern edge of the shelf sinked ten times more rapidly, reaching as much as 200 mm/ka [5].

2.2 Middle Triassic carbonate ramp stage

At the end of Scythian, the decrease of temperature gradients between low and high latitudes resulted in blocking of sea currents and in stabilization of extremely dry climate. The major breaks happened during the „Badian transgression" and the „Reichenhaller Wende" [35 and 34], when extensive evaporite sedimentation started and the clastics were substituted by aleurilitic and argillaceous carbonates. Monotonous sedimentation on extensive shallow areas, small and insignificant lateral and vertical lithofacies changes, and homogeneous ecotopes under strong physical stress were characteristic features of this early developmental stage. Restriction of connection with open sea, limited environmental dynamics, salinity and oxygen regime caused that (at least) skelet forming organisms occured only sporadically. During Early Anisian, a carbonate ramp developed in arid climate on wide (300 x 1000 km) submerged alluvial plains with accomodation space controlled by gradual sea level rise (20-30 mm/ka) and by compaction of underlying pelitic complexes (another 60-70 mm/ka). Diversification of this ramp was gradual: lagoonal- or ramp- like Reichenhall-, Gutenstein-, Annaberg- formations passing into channelized Vysoká Formation. Typical feature of these monotonous sequences are irregular dolomitization, evaporite-rich layers, sporadic organodetrital layers, flat pebble breccias, vermicular textures, or tempestite horizons. Laminated texture indicates influence of short orbital cyclicity (precession cycles). Beginning tectonic and seismic activity during the Late Anisian is documented by slump breccias and tsunamite layers [8 and 9].

Despite of a general facies uniformity typical of carbonate ramps, sedimentary rate and subsidence in individual Anisian shelf zones were substantionally different: less than 20 mm/ka in northern Tatric Domain, 39 mm/ka in the Fatric Domain, 40 to 2100 mm/ka in southern Hronic and Silicic domains. These differences were evoked both by increased carbonate precipitation in the area with free seawater exchange, and by higher subsidence of the shelf margin. If the rise in accomodation space of the northern area will be interpreted as an effect of eustatic sealevel rise, active differential subsidence (at least 40 mm/ka) must be supposed along distal shelf margin.

The biostromatic Steinalm Formation differentiated along the seaward edge of the ramp. Although true reefs occur in this formation only rarely, they initiated formation of a shelf reefal rim. The carbonate platform of the Wetterstein Limestone, which evolved during Ladinian, was differentiated into fore-reefal, core-

reefal, back-reefal or lagoonal facies. The formation is almost 400 to 1200 m thick. The presence of Tubiphytes obscurus, sphinctozoans, calcareous algae, hydrozoans, stromatoporoids, bryozoans, corals, sessile foraminifers, codiaceans, and algal problematics is characteristic in the reefal facies, while dasycladaleans, bivalves, gastropods and brachiopods occur in the lagoonal limestones. Reef slope facies represented by the Raming and Podhradie formations is composed of thick organodetrital biomicrital wackestones and mudstones with abundant fragments of bryozoans, sphinctozoans, solenoporids, tubiphytes, corals and algae.

Middle Triassic Mediterranean carbonate platform evolution was affected by tensional stress evoked by rifting processes in the Tethys [36]. This evolution in the Alpine-Carpathian shelf resulted in opening of intrashelf rift structures. Huge carbonate megabreccia (the Farkašovo Formation) accumulated on their bottom, followed by bituminous limestones of open marine lagoons (the Zámostie Formation; [37]). Broadening of rifts produced small pull-apart basins. The morphology of subsiding basins was accentuated by differential sedimentary rates: the sedimentation on their bottom (the Reifling Limestone, the Partnach Beds, 4-15 mm/ka; [1 and 5]) was rather slow if compared with rapidly growing reefal margins keeping up the page with the subsidence rate (up to 400 mm/ka). Until the end of Ladinian, when the sea level began to fall, the basins attained depths of 1200-1500 m [38].

The Reifling Limestone Formation consists of well bedded cherty limestones: the Alpine authors use to distinguish marginal thick bedded facies (Bankkalk member), distal nodular limestone facies (Knollenkalk member) and deep basinal siliceous facies (Göstling Member). Basinal marls (Partnach beds) deposited in the centre of the basins [39].

2.3. Upper Triassic megacycle

The Julian humid event was a time of mass transport of clastics (about 10 000 km^3; [40] , [41]) that have completely filled former tensional basins in the Slovakian-Carpathian – Austro-Alpine shelf. This rapidly (500 – 700 mm/ka) accommodated material has been carried under occasional monsoonal climate from the adjacent Palaeoeuropean continent. It is interesting that the proximal facies of these clastics have been preserved only exceptionally. Sandstone dominating facies uses to be called as the Lunz beds, prevailingly black shale development [42] is designated as the Reingraben beds. The rocks do not contain carbonate clasts, granitoid pebbles are rare. Lunz sandstones contain clasts of relics minerals derived from shallow cut peraluminous anatectic granites of crustal origin, greisenised granitoids, high temperature tholeiitic mantle granites and from ultramafic intrusions. Rests

of metamorphic rocks are rare [8]. Low maturity of mineral composition and high morphological maturity of grains is typical. Visscher and Van der Zwan [43] proposed the model of „Nile delta in Carnian Sahara". The sequence attains thickness from some tens to 600 meters. It is equal to sedimentary rate of 50 to 500 mm/ka. Shells of marine bivalves and occasional ammonites occur in the basal part of the sequence. Higher up, only phytodetrite and spores occur. Transport of Lunz detritics covered only norther part of the Alpine - Carpathian shelf. The depressions in its southern zones were filled by debris of their desintegrated reef rims.
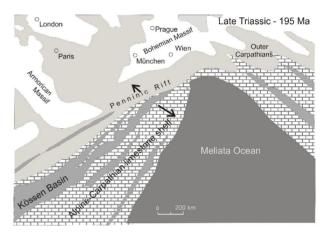

Fig. 2. Paleogeographic sketch of Late Triassic situation of northern Mediterranean Tethys (white = dry land; light gray = epicontinental sea; gray = marine basins; bricks = carbonate platforms; dark gray – oceanic bottom).

The arid climate, continuing regression and tectonic rise of the Alpine – Carpathian shelf during Late Triassic led to the re-establishment of a carbonate platform system with a continuous reef margin. Extensive back-reef flats (of the Dachstein Limestone and Hauptdolomit formations) separated the Mediterranean Tethys Ocean from Dead Sea-type dry basins with Carpathian Keuper sedimentation. Sedimentation rate of the Carpathian Keuper was seven times slower than the sedimentation rate of the German Keuper, as the clastic supply had to cross the incipient rift valley. The thickness of the Carpathian Keuper sequence and its composition is extremely variable. It contains deposits of evaporite, fluvial and eolic environment, intercalated by occasional short-time marine transgressions. The Hauptdolomit (Main Dolomite) is one of the most typical Upper Triassic formations. Toward the sea, it passed into the Dachstein Limestone Formation. Both formations are typical of shallow marine shallowing upwards cycles with megalodons, gastropods and corals and terminated by algal laminite. The thickness of both formations sometimes oversteps thousand meters. On the other hand, reef belt rimming the shelf on its distal edge grew and attained thickness of many hundreds of

meters. The slope and basinal facies limiting it from the southern side and sometimes filling channel like depressions in it, are known from the southermost units, forming today the highest parts of the Western Carpathian nappe file.

At the end of the Triassic, propagating Penninic rift formed a branch of the major Middle Atlantic Oceanic rift system. Spreading of the Penninic detached northern Mediterranean microcontinents from its Palaeoeuropean foreland (Fig.2). The breakage of the Tethyan shelves resulted in the „mega-shear" model of numerous megablocks separated by strike-slip faults [1 and 5]. Lakes and swamps with rich flora and occasional dinosaur fauna [16] created in more distal depressions in seasonally humid climate on the Carpathian foreland. The prograding sea filled tensional depressions in subsiding Alpine-Carpathian block. All depression of the Kössen basinal system were flooded by sea transgression.

Typical representative of these semi-isolated sea basins, the Zliechov Basin opening in the former shelf, gave rise to typical shallow marginal marine sediments of the Fatra Formation with abundant neritic fauna [10 and 44]. Rhaetian transgression inundated an arid Carpathian Keuper basin with seasonal rivers, temporal lakes and local swamps overgrown with vegetation. Later, in nearshore swamps and lagoons laminated clays accumulated with restricted fauna of the Rhaetavicula association. Continuing transgression formed a zone of storm - dominated shallows with semi-infaunal bivalve Corbula association alternating with temporal Placunopsis association. Drowning of the bottom below the wave base resulted in black shales deposition, interrupted by occasional input of eolian dust during storm events. New shallowing enabled short-timed biostrome growth, but later the "barren interval" member started, characterized by redeposition of older sediments. Rhaetian sequences are typical with preserved orbital cyclicity in shallowing upwards cycles and by storm sediments. In the reefal margin of the shelf, biostromal sediments have accumulated during latest Triassic time. Depressions are typical with stratified water column [11], argillitic limestones and shales of the Zlambach Formation. However, this area has been mostly elevated and deformed during Early Cimmerian tectonic movements and the youngest Triassic sediments have been partly removed by later erosion [12].

The Triassic – Jurassic boundary beds are marked by several major events: by the termination of carbonate sedimentation, by the occurrence of spherulite containing beds, by C and O isotope excursions, and by the onset of clastic input due to changing climate at the beginning of the Hettangian transgression [13 and 14]. On the other hand, subduction of the Meliata Ocean during Cimmerian movements led to convergence of both the Alpine-Carpathian and the Adriatic microcontinents.

3. Jurassic evolution

The onset of Jurassic sedimentation was affected by emersion and non-sedimentation in the majority of paleogeographical zones [15]. Breakage of the Pangea started together with Jurassic rifting in Middle Atlantic. Blocks of Kimmeria converged with the Eurasia margin and large part of the Paleotethys oceanic crust have been subducted [16]. During the Meliata Oceanic crust subduction, the southern margin of the Austroalpine-Centrocarpathian microcontinent collided with small blocks in its foreland. Carbonate platforms on it have been emerged and karstified. Also the Tatric and the Veporic domains much more distant of it have been uplifted. On the other hand, the subsidence continued in the Fatric Domain lying between them.

3.1. Lower Jurassic clastic – carbonate megacycle

At the beginning of the Jurassic, climate changed to more humid. River systems transported material eroded from continent through rift valleys in the Paleoeurope foreland to the sea. Marine claystones with occasional sandstone and sandy organodetrital limestones (the Gresten and the Kopieniec formations) have been deposited on Alpine and Carpathian shelves, which became detached from the Europe by the opening Penninic rift. Similar sediments (the Mecsek Formation, with thickness up to 1500 m) is known from the Mecsek Mts in Hungary. High amount of large poorly rounded quartz grains indicates rapid transport of material derived from rejuvenated relief of a land, dissected by normal faults [17 and 18].

The base of Jurassic sequence rests in many units transgressively on eroded basement. This phenomenon is most significant in norther marginal units („supra-Penninic" Borinka Unit of the Malé Karpaty Mts, Tatric units in the Tatra Mts, etc), where the underlying Triassic sequence is considerably reduced by erosion. The sediments are represented by huge megabreccias and breccias, passing into calciturbidites [19]. This fact proves for block desintegration of the substrate, connected with tension associated with Penninic rift spreading [20]. This rift gave origin to the Penninic Oceanic Branch, which gradually separated the Alpine – Carpathian continental block from Paleoeurope (Fig.3). Subsidence of this block and sedimentary rate on it was evoked by tectonic instability and to differentiation of individual subbasins. The sedimentary rate in the European shelf basins was equal to 10 to 300 mm, the rates of sediment deposition on the Alpine - Carpathian block were much smaller (almost 2 to 60 mm/ka).
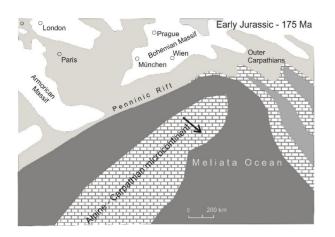
Fig. 3. Paleogeographic sketch of Early Jurassic situation of northern Mediterranean Tethys (white = dry land; light gray = epicontinental sea; gray = marine basins; bricks = carbonate platforms and basins; dark gray – oceanic bottom).

During Sinemurian and Lotharingian, quartzose sandstone (the Baboš Quartzite) passing distally into sandy limestones (the Trlenská Formation) indicates the last riverine influx from the continent. Later on, transport routes of this material were cut by the Penninic rift. More ubiquitous crinoidal limestones (Hierlatz Limestone, Vývrat Fm) have been deposited on submarine highs and thresholds and on their slopes, while deeper hemipelagic settings were characterized by bioturbated marlstones (the Janovky Fm). Condensed red nodular limestones and marls of the Adnet Fm indicated slowered sedimentary rate at the end of Early Jurassic. Also in the Hronic Basin the Lower Jurassic sedimentary cycle started by crinoidal limestones (the Mietusia Fm), and terminated by red nodular limestone.

During Toarcian, Carpathian basins were affected by tensional stress. The most convincing record comes from the marginal Tatric units of the Malé Karpaty Mts and the Tatra Mts, where slumps and breccia complexes (the Pleš Breccia) originated. Black shale sedimentation covered the bottom of pelagic basins, while red „Ammonitico Rosso" limestones, often with manganese-ferruginous crusts [21] were deposited on submarine highs.

3.2. Middle Jurassic siliceous – limestone megacycle

Continuing spreading of middle Atlantic oceanic bottom and its eastern continuation (in the Penninic Oceanic Branch) resulted in origin of the „Atlantic Tethys Ocean" not less than many hundreds (but probably first thousands) of kilometers wide. Rapid oceanic spreading was followed with a phase of relative stagnation, which caused thermal subsidence of adjacent basins. Several authors called the Middle Jurassic developmental stage of the Mediterranean Tethys as the „Jurassic collapse", characteristic of wide

distribution of hemi- and eupelagic facies [15 and 22]. Lefeld [23] supposed gradual deepening from red nodular limestone facies through red siliceous limestone and red silicites to greenish gray silicite environment with lack of oxygen. In contrary, other sequences recorded sudden change of sedimentary regime from hemipelagic sediments to eupelagic accumulates. In the centre of the Zliechov Basin, the top hemipelagic member if formed by red marls and greenish fine detrital (distal turbidite?) limestones. These beds are affected by submarine slumping and are covered by siliceous radiolarian limestone containing blocks of rocks of underlying beds. Bottom instability indicates a rapid subsidence event. The bottom subsidence generally reached 300 mm/ka and it was hardly compensated by slow sedimentation. Deep basin development in the Alpine-Carpathian shelf fragment was neither connected with eustatic sea level rise, nor with basement compaction, but rather with regional tension [1] associated with thermal subsidence.

Qualitatively new stage of evolution started in Outer Carpathians. The bottom of uniform basin, covered by simple delta cones of material transported from the European foreland, have changed in a complex system of mobile tilted blocks, which created a set of broadening pelagic basins and elevated ridges. The most prominent of them, the Czorsztyn Ridge, became the most typical element of Jurassic and Cretaceous paleogeography of this area. Its Jurassic sequence is typical of huge clinoforms of crinoidal limestones, coquinal limestones, reefal bodies and mudmounds [24], with frequent condensations, gaps and neptunian dykes [25].

The Middle Jurassic sedimentary cycle in Central Carpathians started with organodetrital and crinoidal limestone of lateral slope calciturbidite facies passing basinwards into siliceous limestones, radiolarites and dark marls (the Ždiar Formation). The last formation was formed in a tensional basin with thinned crust and with manifestation of submarine hydrothermal activity. Widely distributed siliceous deposition was enabled by shallowing of the CCD in oceanic basins. On the other hand, the subsidence of basinal bottom was higher that the sedimentary rate reaching only several tenths- to several milimeters for thousand years. Elevated thresholds were covered by condensed red marls and limestones, by stromatolitic limestones, or by crinoidal limestones (the Vils Formation).

3.3. Upper Jurassic limestone megacycle
During Late Jurassic, individualisation of European epicontinental basins increased. Extensive areas were differentiated into shallow depressions with deposition of clayey sediments, into sponge bioherms and lagoons and into evaporite basins. Callovian-Oxfordian transgression peaked. Boreal faunal domain was rimmed by Subboreal and Submediterranean provinces. The climate was warm, monsoons were localized in

eastern Gondwana by paleoclimatic models [45]. Warm hypersaline water sinked from shallow areas towards the bottom of oceanic basins. In the Tethys, radiolarites and dark marlstones and clays accumulated on deep basinal bottom, while the Ammonitico Rosso facies dominated on shallow ridges of tilted blocks. Oceanic water stratification proves for absence of vertical currents. On the other hand, horizontal surface currents supported growth of reefs. Clasts of neritic limestones formed important part of breccias in submarine delta fans, turbidites and olistoliths. These allodapic bodies occur in pelagic facies (Barmstein Limestone) of southern units. Late Cimmerian collision, connected with final subduction of the Meliata oceanic crust, caused deformation and emersion in southern zones of the Alpine-Carpathian crustal block.

4. Cretaceous evolution
4.1 Early Cretaceous pelagic stage

During Early Cretaceous, tension in Alpine – Carpathian area continued. In outer zones, carbonate platforms and reefs were destructed and shallow areas were emerged. Submarine ridges were covered by white crinoidal limestones and coquinal breccias. In the basins, mass evolution of calcareous plankton formed first true pelagic planktogeneous limestones which covered both elevations and basinal bottom and produced the typical "Maiolica" facies. Black shale facies sedimentation continued only in the proximal Outer Carpathian basins (the Těšín Formation). Compared to coeval successions from the Carpathians, the continuous Jurassic - Cretaceous pelagic limestone succession of the Brodno section offers the best possibility to document the J/K passage in a wide area [13]. This section comprises a complete calpionellid, and nannofossil stratigraphic record, that supports older paleomagnetic data.

Moreover, the sequence stratigraphy and stable isotope ($\delta^{18}O$, $\delta^{13}C$) data gave additional important results, too, enabling comparison with known key sections from the Mediterranean Tethys area. In the Central Carpathians, scarcely preserved platform limestones (the Raptawicka Turnia,or the Staré Hlavy formations) composed of peletal wackestones with oncoids represent the most proximal facies.

On the other hand, the majority of Lower Cretaceous sequences is represented by hemipelagic basinal ("Neocomian") calpionellid limestones (the Schrambach-, Lučivná-, Osnica-, Padlá Voda-Mráznica-, Hlboč- and Kościeliska formations). The Nozdrovice Breccia Member indicates important tensional event in Late Berriasian, when the basinal bottom was disrupted by series of normal faults [44].

Pelagic limestone sequence contains siliciturbiditic Kryta Member [46] produced during the Oravice Event – a Late Valanginian tectonic pulse connected with

Late Cimmerian compression of southernmore tectonic block producing the input of quartz debris with abundant chromium spinel grains into the basin [47 and 28]. The Hauterivian turbidites (the Strážovce Member on the west, the Muráň Formation in the eastern part of the Zliechov basin) were triggered by a significant sea-level lowstand (Ha-5). They contain mostly biogenic material derived from destructed biogenic rim of the basin [44].
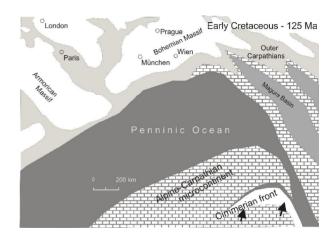

Fig. 4. Paleogeographic sketch of Early Cretaceous situation of northern Mediterranean Tethys (white = dry land; light gray = epicontinental sea; gray = marine basins; bricks = carbonate platforms and basins; dark gray – oceanic bottom).

4.2 Early stage of convergence

The Barremian was the time of break in Tethyan sedimentation. After the "Neocomian" stabilization of the pelagic phase, bathymetric contrasts became accentuated, current systems reorganized. Upwelling regime ceased and horizontal currents supported carbonate platform growth. The "Urgonian" (Upper Hauterivian-Lower Albian) sequences start with deposition of slope- and submarine delta fans derived from carbonate platforms prograding basinwards (Muráň Fm [48], Bohatá Fm, Podhorie Fm, etc.). Carbonate platform cores proper were mostly destroyed by erosion (Wysoka Turnia-, Manín formations). These changes heralded convergence of blocks in the Mediterranean Tethys between Africa and Paleoeurope. Small hyaloclastite and paleobasalt bodies in basinal sediments indicate late tensional zones and formation of a new tectonic pattern.

The Outer Carpathians were situated on destroyed Paleoeuropean shelf, changed into dynamic system of tilted blocks (basin-and-ridge pattern). Sedimentation on elevated ridges was accentuated, interrupted by frequent gaps. In poorly aerated basins, early flysch deposits started. During the late Early Aptian humid event, Lower Cretaceous pelagic carbonate (Maiolica)

sedimentation was interrupted by terrigenous input as a consequence of the first major mid-Cretaceous climate perturbations. Warming during Aptian caused decrease of oxygenation and increase in carbon content of the basinal sediments (the Párnica-, Muránska Lúka-, Osobitá formations).

The fluctuation of radiolarian abundance indicated an expansion of the oxygen-minimum zone due to upwelling conditions and salinity changes. Foraminifera, radiolarians, non-calcareous dinocysts and calcareous nannofossils encountered in the West Carpathian Rochovica section enable a comparison of the black shales of the upper Lower Aptian Koňhora Formation with the well-known Selli Event [2]. Subsequent anoxia patterns (depositional, productive and stagnant) have taken part in the depositional regime. Early Aptian climate perturbations both in the Outer Western Carpathians, Swiss Prealps (situated in a similar position on the distal southern edge of the former Paleoeuropean shelf) and/or in other parts of the world are traceable with sedimentological, biological and chemical proxies [26].

In the contact zone of the Outer and Central Western Carpathians, the first signs of space shortening appeared. Accretion prisms of coarse conglomerates containg pebbles from now vanished zones started to form. [27] stressed that Urgonian limestones in Central Carpathian sequences never contain ophiolite detritus and glaucophane from eroded oceanic crust and their faunal spectrum is much poorer.

4.3 Mid-Cretaceous synorogenic formations

During Middle Albian, opening of the Mid-Atlantic sea passage caused decrease of endemism of Tethyan faunas.. At this time, the convergence between Gonwana- and Laurasian margins started, resulting in subduction of the Penninic oceanic bottom, and in destruction of former basinal systems [28]. Tensional development in Outer Carpathian basins continued. On the other hand, in central Carpathians, carbonate platforms were covered by dark marls (Zabijak- and Butkov formations, [29]).

Sudden deepening was probably evoked by thermal collapse of Penninic oceanic bottom. Removal of shallow water barrier opened passage for oceanic currents which interrupted carbonate deposition in the Mediterranean Tethys. The basins here were mostly filled by thick (300-600 m) black (the Zabijak Marl), brownish, often bioturbated gray marls with siltstone intercalations (the Butkov Formation), or even with olistoliths (the Poruba Fm), passing into Cenomanian rhytmic sandstone-claystone sequence (the Belušské Slatiny Formation). A complex stacked pile of superposed units comprising the pre-Alpine basement, its Mesozoic cover, and superficial nappes originated during Turonian in Central Carpathians.
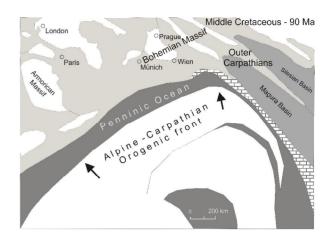

Fig. 5. Paleogeographic sketch of Middle Cretaceous situation of northern Mediterranean Tethys (white = dry land including emerged orogenic belt; light gray = epicontinental sea; gray = marine flysch basins; bricks = carbonate platforms and basins; dark gray – oceanic bottom).

4.4 Late Cretaceous "Gosau" stage

After the major compression and deformation finished, folded structures collapsed again. New tensional basins evolved in the middle of the incipient orogenic system [26, 30 and 31]. Variegated breccias of local material, cemented by yellowish and red argillaceous matrix filled cavities, fissures and depressions in surface of carbonate complexes [32]. On the other hand, basinal sequence starts with fresh-water Upper Turonian / Lower Coniacian limestones with fresh-water algae (the Pustá Ves Formation). Braided river- and subaerial delta clastics (the Ostrież Fm) start the Senonian marine sequence composed of thick flysch of alternating graded calcareous sandstones, variegated (mostly red) marls, sandy marls and sandy limestones (Gosau stage, e.g. [33]).
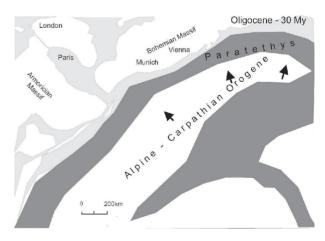

Fig. 6. Paleogeographic sketch of Oligocene situation of northern Mediterranean Tethys (white = dry land including emerged orogenic belt; light gray = epicontinental sea; gray = marine flysch basins).

5. Mesozoic eustatic fluctuations, sedimentary rates, and basinal subsidence in Western Carpathians
5.1 Conclusions to the Triassic changes

-During Triassic, sudden eustatic changes of sea level have not been recorded: there were two important transgressions (Early to Middle Triassic and latest Triassic) and one (Late Triassic) regression.

-With the exception of Early Triassic, the subsidence in central Western Carpathians never reached values of the sedimentary rate (despite of some „undersaturated" sections could exist in individual basins).

-Sedimentary rate was more-or–less proportional to subsidence changes. At the beginning (Scythian to Anisian), sedimentary rate gradually decreased. Anisian subsidence was equal to 50 to 500 meters, but the Ladinian one 1000 to 1500 meters. Acceleration of reefal growth followed with some delay after origin of Ladinian tensional depressions. Reingraben Event was accompanied by mass transport of terrigeneous deposits, which filled the depressions in proximal zones at all. Until the end of Triassic, the sedimentary rate gradually decreased (evidently being influenced by aridization of the climate).

-Gradual compaction of lithifying deposits played an important role during Anisian, Norian and Rhaetian in areas built of clayey complexes.

-Relative subsidence of the sea bottom was accentuated during Early Triassic, Ladian and Rhaetian – in time sections when the accelerated subsidence was not followed by an accelerated sedimentary rate.

5.2. Conclusions to the Jurassic changes

-Global sea level was affected by two transgressions (Hettangian to Bathonian and Callovian to Kimmeridgian), separated by two regressions (Bathonian and Tithonian). Sea level was relatively high at all, being influenced by active oceanic rifting and sea bottom spreading.

-There were four maxima of Jurassic subsidence in Western Carpathians (Hettangian, Aalenian to Bathonian, Callovian and Kimmeridgian). The first and the last of them were compensated by sedimentation, other two represented periods of „starved" basins, designed as the „Jurassic collapse". Rapid fall (300 mm/ka) of Tethyan bottom started 175 Ma ago.

-Sedimentary rate reached highest value at the beginning (Hettangian) and at the end of Jurassic. Smaller maxima (Aalenian flysch) were at the beggining of the Middle Jurassic. Low values of sedimentary rate were caused by arid climate on continents, but also by origin of deep rift valleys in the Tethyan shelf, cutting transport routes of terrigeneous input.

-Only small part of Early Jurassic subsidence could be ascribed to the compaction of substrate. Middle

Jurassic subsidence was not influenced by any compaction of basement and its causes must be sought in the thermal subsidence of oceanic bottom [19].
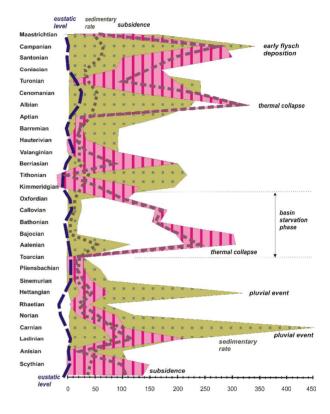

Fig. 7. A scheme of Mesozoic sea level changes (blue broken line), subsidence (minimum and maximum "values of vertically hatched red area, average values by red broken line) and sedimentary rate (minimum and maximum" of brown dotted area: average values by dotted line) in Western Carpathians. The numbers on horizontal axis are milimeters /ka.

5.3 Conclusions to the Cretaceous changes

-Eustatic sea level changed many times during the Cretaceous period. The most important maxima were reached during Hauterivian, Albian to Cenomanian and Campanian.

-Subsidence maxima were reached during Berriasian, Albian, and Santonian. On the other hand, the lowest subsidence was during Barremian, Coniacian and Maastrichtian. Basement subsidence did not play any important role during Cretaceous. In some respect, it could affect flysch basins of Outer Carpathians. The subsidence was connected with tectonic mobility of crustal substrate. The Berriasian subsidence was mostly compensated with the sediment input. The most expressive relative subsidence was during Albian (the „Albian collapse"), Santonian flysch basin deepened less expresively.

-The highest sedimentary rate was during Berriasian, Cenomanian - to Turonian, and during Campanian. In contrary, sedimentation minima

characterized Valanginian − to Barremian. Coniacian and Maastrichtian.

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