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Review

Nearshore Pelagic Influence at the SW Margin of the Paratethys Sea—Examples from the Miocene of Croatia

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Abstract: (1) The ancient Paratethys Sea was a spacious inland salt-water basin, extending from the Alps, over Central Europe, to Central Asia. The southwestern part of its central area, the Croatian part of the Pannonian Basin System (CPBS), is generally known for shallow-water deposition and biota. The main purpose of this paper is to emphasize the significance of its less widespread deeper-water deposits in environmental and applied geology. (2) The authors consulted the previously published data, combined with their own results, obtained from the paleontological and sedimentological research, seismic stratigraphy and well-log analyses. (3) During our research in the CPBS, we noticed the connection between the tectonic structures and deep marine canyons and depressions within the Paratethyan shallows. Such structures can be recognized on well-logs and seismic or surface outcrops. They are situated along the faults, and deposits are characterized by the domination of pelagic over the benthic biota, sometimes with visible selective dissolution of aragonite/calcite tests. (4) Studied sedimentary sequences from these structures proved to be a precious source of data on the transgressive-regressive cycles, ancient migrations, modes of deposition and hydrocarbon formation during the Miocene Epoch in the CPBS.

Keywords: pelagic influence; near-shore environment; biota; Miocene; Central Paratethys; Croatia

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1. Introduction

Deep marine sedimentary sequences are highly valued among geologists, as they often comprise complete information on depositional models and paleoenvironments not present in shallow-water successions. In ecological crises, such biotopes act as sanctuaries or migration routes for endangered biota (e.g., [1–7]) and have also been studied by biologists in recent times (e.g., [8,9] and references therein). Petroleum geologists investigate basinal deposits for hydrocarbon potential (e.g., [10–16]). Such environments may represent vast pelagic marine basins but can also be restricted to narrow elongate structures (canyons, trenches and troughs) on steep slopes and sea shallows, often formed along the faults (e.g., as seen in [13,17–20]).

The epicontinental Paratethys Sea covered spacious areas of Europe and Asia during the Miocene. This epicontinental marine basin initially (from the Oligocene till the Early Miocene) comprised three units: the Western, the Central and the Eastern Paratethys (e.g., [21–25]). The Western Paratethys was soon isolated and dried out, and only the Central and the Eastern marine basins were flooded during the Middle Miocene. They were temporarily connected, and also had periodical communication with other marine areas (Figure 1) (e.g., [2,3,21–26] and references therein). Due to the intense tectonic activity in the wider region (Figure 2) (e.g., [27–31]) and sea-level fluctuations, the Central and Eastern Paratethys had a complex geological history, leading to a variety of problems in the stratigraphic correlation of these two sub-basins, and particularly, their correlation with the Proto-Mediterranean Sea, Northeastern Atlantic Ocean and the Indopacific (e.g., [4,21,22,25,26,32–34] and references in the papers). Here, we focus on the Miocene stratigraphy of the southwestern margin of the Central Paratethys, i.e., the North Croatian Pannonian Basin (NCPB).

An additional problem is the application of different stratigraphic divisions, from the biostratigraphic, over the lithostratigraphic and magnetostratigraphic, to the chronostratigraphic point of view.

After a series of papers dominantly focused on stratigraphy and sedimentology, a paleogeographic approach to the Paratethys Sea was introduced in the second half of the 20th century [21,22,35–42]. According to the newly available data, paleogeographic studies improve from time to time (e.g., [3,4,33,34,43,44]).

Figure 1. Simplified paleogeography of the Paratethys Sea during the Early to Middle Miocene (modified after [45]; original after [26,46]). Northern Croatia was a part of the Central Paratethys (underlined).

The Pannonian Basin System (PBS) was a part of the Central Paratethys, extending over the area of about 400 × 800 km. It is often interpreted as the Mediterranean back-arc extensional basin of the Middle Miocene age (e.g., [19,21,22,47–52]).

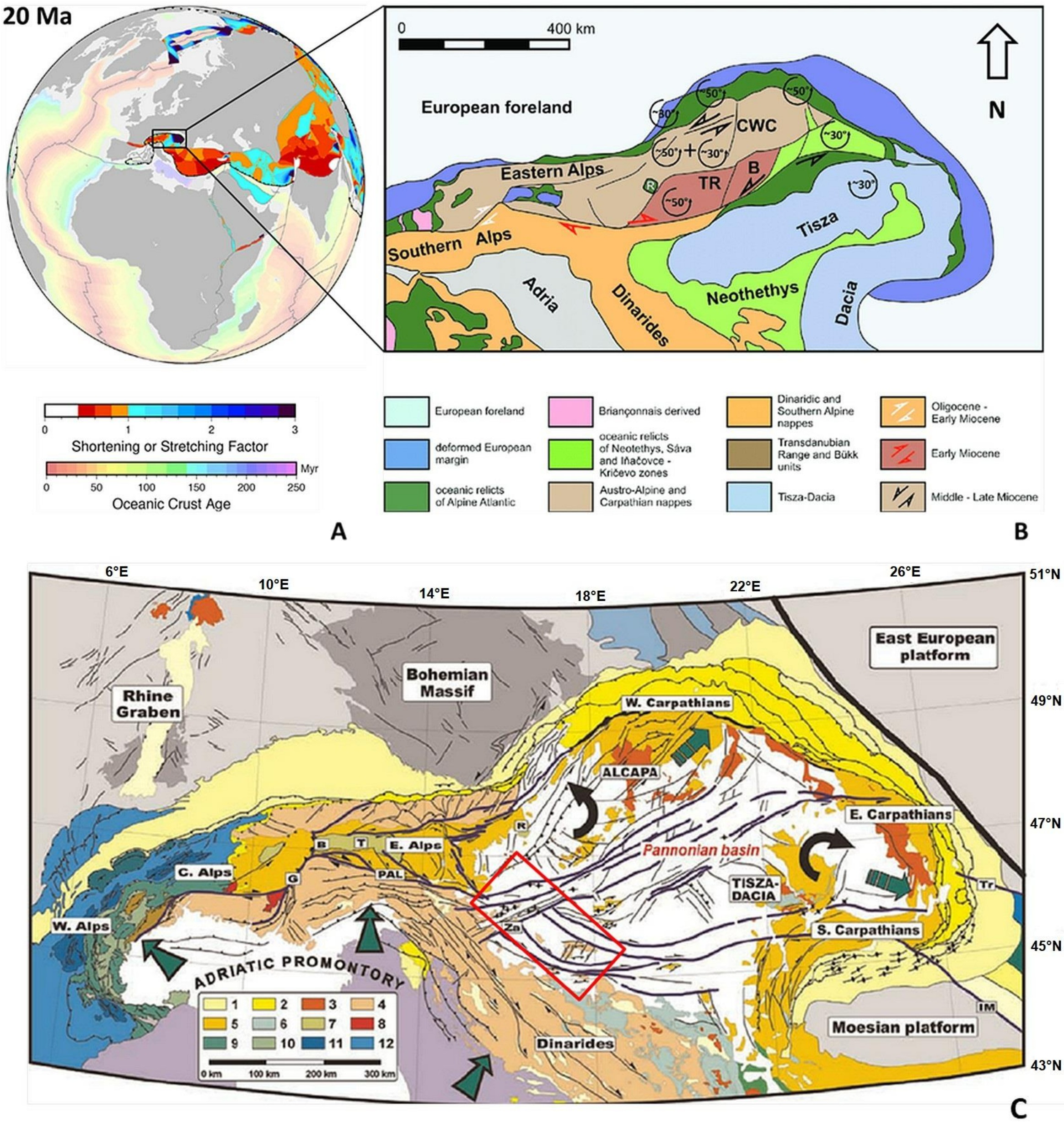

Figure 2. (**A**) Orthographic projection of the Earth before 20 Ma. presenting plate deformations, dominantly present in the Peri-Mediterranean region. Continents—medium grey; submerged continental regions—light grey. Oceanic crust age shown in colors. Regions in extension (stretching factor >1)—blue; compressed regions (stretching factor <1)—orange/red colors [29]; (**B**) Tectonic mega-units of the Alpine-Carpathian-Pannonian system with rotation of their individual segments (CWC-Central Western Carpathians; TR-Transdanubian Range; B-Bükk Mountains) [52] (**C**) Simplified Late Cenozoic tectonic map of the Alpine-Carpathian-Pannonian-Dinaric Systems, with formation/deformation data after [53], from [48]. Legend (from [48]): 1, Foreland (molasse) basins; 2, flysch nappes; 3, Neogene volcanic rocks; 4, Southern Alps, Dinarides and Northern Calcareous Alps; 5, pre-Tertiary units of the East Alpine-Carpathian domain and the Jura Mts; 6, Variscan basement of the European Plate, and Dinaric, Vardar and Mures ophiolites; 7, Pieniny Klippen Belt; 8, Oligocene tonalites; 9, Penninic basement; 10, Penninic cover; 11, Helvetic basement; 12, Helvetic cover. T, Tauern Window; R, Rechnitz Window; PAL, Periadriatic Lineament (PAL); G, Giudicarie Fault; Za, Zagreb Fault; B, Brenner Fault; Tr, Trotu Fault; IM, Intramoesian Fault. Croatian Pannonian Basin System (CPBS) is situated within the red rectangular frame.

Miocene marine sedimentary rocks in northern Croatia (Figure 3) were deposited at the SW edge of the Central Paratethys, named the Croatian part of the Pannonian Basin System (CPBS) (e.g., [54] and references therein).

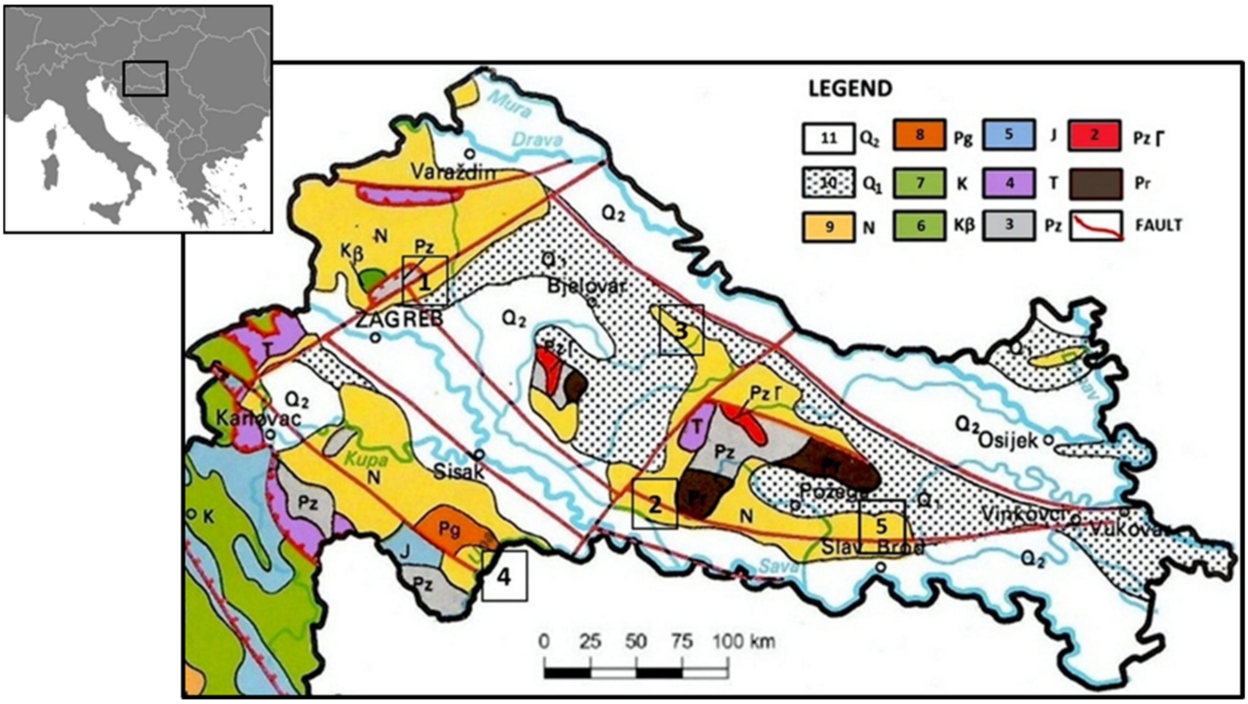

Figure 3. Geological map of northern and north-eastern Croatia (modified after [55]) which was, during the Miocene, flooded by the Paratethys Sea. Paratethyan deposits are marked with yellow, and faults with red color. Legend: 1. Precambrian metamorphic rocks; 2. Paleozoic granites; 3. Paleozoic sedimentary rocks; 4. Triassic carbonates, sporadically clastites; 5. Jurassic carbonates with scarce volcanoclastites; 6. Cretaceous dominantly carbonate rocks; 7. Cretaceous basalts; 8. Paleogene limestones; 9. Neogene clastic and carbonate rocks; 10. Pleistocene, dominantly unconsolidated clastites; 11. Holocene unconsolidated clastites. Localities mentioned in this study: Medvednica Mt. (1); Sava Depression (2); Drava Depression (3); Kostajnica (4); Dilj (5).

Shelf-type deposition prevailed in this part of the Central Paratethys, while pelagic deposits occur only sporadically, in most cases related to the high-stand periods (peaks of the Middle Miocene transgressions ([54] and references therein) (Figure 4). The detailed biozonation of the investigated Miocene deposits in the CPBS was dominantly based upon the benthic foraminifers. Within the lower part of the Middle Miocene, known as the Badenian Stage in the Paratethys stratigraphy, the Lower and Upper Lagenidae zone was recognized (Langhian; corresponds to Early–Middle Badenian); followed by the *Spirorutilus* zone (Early Serravallian or Middle–Early Late Badenian) and *Ammonia beccarii* zone (in the shallow), or *Bulimina–Bolivina* zone (in the deeper marine environment) of the Serravallian, i.e., Late Badenian. The upper part of the Middle Miocene, known as the Sarmatian Stage, can be divided into the eco/bio-zones: *Anomalinoides dividens*, *Elphidium reginum*, *Elphidium hauerinum* and *Porosononion granosum* zones. Foraminiferal zones were correlated with the pelagic biozones, primarily based upon the planktonic foraminifera, coccolithophores and, sometimes, dinoflagellates (e.g., [56–60] and references therein) (Figure S1).

Several transgressive-regressive cycles (Figure 4) affected the Middle Miocene deposition in the Central Paratethys, through the mode of deposition and opening/closing the marine corridors with the neighboring seas and oceans (e.g., [3,4,21,22,25,34,61,62] and references therein). Most of the published papers from the CPBS present the evidence of transgressive-regressive cycles 2.4 and 2.5 (Badenian) and 2.6 (in the Sarmatian) (Figure 3) (e.g., [54,56–60,63–65]).

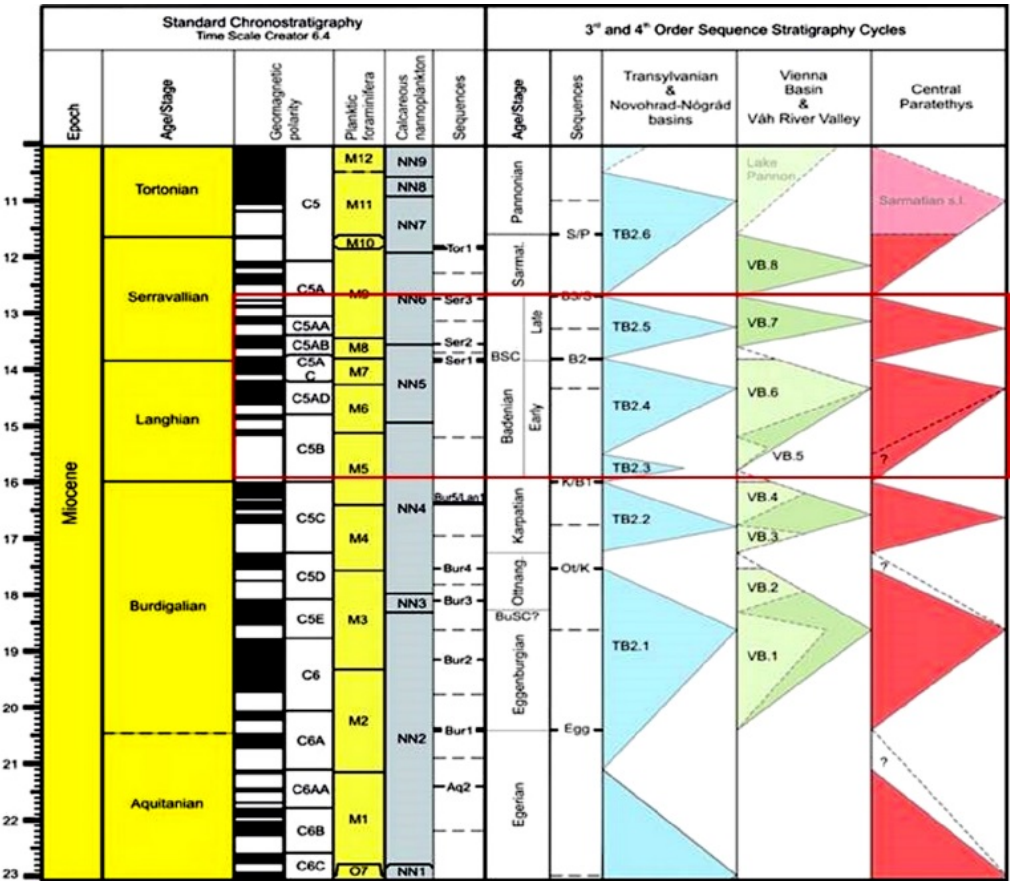

Figure 4. Central Paratethys sequence stratigraphy (after [2,66–68] from [4]). Badenian Stage, the most relevant for this paper, is within the red rectangle.

Hydrocarbon potential in the CPBS was studied by various authors (e.g., [10,12–14,16,69–80]), although most of the hydrocarbons accumulate within the Upper Miocene clastic reservoirs of the lacustrine origin (e.g., [73,81,82]).

The main goals of this study are: (1) to compile the known data on the deeper-marine environments in the CPBS, considered from different approaches (paleoenvironmental or applied-geology point of view); (2) point to the dilemmas and inconsistencies in the research of such successions; (3) supplement the known data with the new authors' results; and (4) propose the new possibilities in the research of outer-shelf/bathyal environments in the marginal areas of epeiric seas.

2. Methodology

During the research, we applied data obtained from numerous research methods. Field work was performed in order to reconstruct the detailed stratigraphic columns, recognize the sedimentological or tectonic structures and collect the samples for further investigations.

A wet-sieving technique was applied to marls and clays, in order to extract the whole microfossils with mineral tests for research under a light microscope. The finest fraction from the suspension was further used for the preparation of palynomorph and nannoplankton samples. Thin sections were prepared from solid samples (limestones, biocalcarenites). These laboratory methods were done at the Faculty of Science and the Croatian Geological Survey in Zagreb.

Subsurface exploration methods, seismic stratigraphy and well-log analyses and interpretations were mostly obtained from the data archive of INA Plc. The later interpretations had been done in the same company or the University of Zagreb and published in numerous papers and theses. The special value of this compilation has been attributed to regional characteristics of well-logs (such as spontaneous potential and gamma ray), seismic sections and selected cores of the Lower and Middle Miocene.

We compared the obtained results with the published data from the neighboring areas in order to establish the correlation between the different approaches to the deep-marine Miocene environment.

3. Miocene History of the CPBS and Its Descendants

Prior to the Paratethys Sea transgression in the CPBS, a long-lasting terrestrial phase took place in this area. Due to the tectonic processes and erosion, prominent relief forms developed, highly influencing the depositional processes. Alluvial and lacustrine environments occur in the base of the earliest Middle Miocene deposits (Figure 5). Unconformity is always present between the basement and the oldest marine deposits (Figure 5) (e.g., [10,54] and references therein).

Faulted and weathered Mesozoic and Paleozoic rocks from the basement were a primary source of building material for the medium and coarse-grained clastics, deposited along the shores, and often transported a few kilometers into the deeper sublittoral parts.

During the lower part of the Middle Miocene (Badenian) a maximum transtensional phase took place in the CPBS (e.g., [13,83]). A syn-rift phase [13,83,84] reactivated some of the inherited pre-Neogene deep fault zones, similar to the Caucasus and some other Paratethyan areas (e.g., [85–87] and references therein). During this phase, sea-level rose, and the deepest parts of the sea-bottom, even in this marginal part of the Paratethys, could temporarily become hostile for the benthic biota. Pelitic sediments with remnants of pelagic organisms were deposited in such an environment.

The Badenian−Sarmatian boundary (within the Serravallian) is marked by a pronounced regression in the CPBS. On subsurface well-logs, it is usually recognized as EL−marker Rs7 (Figure 6). After the following Sarmatian high-stand period (T.B 2.6/VB 8 from Figures 4 and 5) regression took place, some parts of the Central Paratethys emerged, and eventually a lake environment had been created during the Sarmatian–Pannonian transition (e.g., Vienna Basin [88]) and marine basins of northern Croatia were geographically reduced (e.g., [80]). A fully marine environment, particularly the deep marine basins/troughs in CPBS, were no more observed after the Sarmatian, i.e., in sediments younger than EL-marker Rs7. Nevertheless, the Paratethyan descendant, the Pannon Lake, passed through another transgressive phase during the Pannonian age (see Figure 4) (e.g., [54,88,89] and references therein). Turbidite lacustrine flows temporarily took place in the Pannonian Lake and its later successors, with sporadic influences of local sources ([46,89,90] and references therein).

A lacustrine (brackish to fresh water) environment in the CPBS lasted till the Late Pliocene (Piacenzian) when a terrestrial environment finally prevailed in the whole of northern Croatia.

4. Depressions, Depositional Megacycles and Lithologies in the CPBS

A common terrace-shaped configuration of the continental shelf, observed in the spacious water-basins, is well known by sedimentologists. The features such as clinoforms and clinothems occur as the dominant architectural strata forms (e.g., [91] and references therein). In epicontinental seas, including the Paratethys, such an idealized model is not always applicable, although clinoform elements can be recognized from some subsurface data [92]. The geological history of the Paratethys was extremely dynamic, with frequent fluctuations in sea-level and emersion periods, not providing enough time and space for the typical shelf configuration to fully develop. Additionally, that area was never developed as an oceanic realm. According to the available data from the Central Paratethys, deeper marine environments occur in the central, more sunken parts, with the largest volumes of deposited sediments [12,93,94] and elongate trenches and troughs related to the tectonic structures (e.g., [17]) (Figure 5).

During the Middle Miocene transtensional (syn-rift) phase, elongate depressions were developed along the main strike-slip faults (Figures 2B, 5, 6 and 7). Besides the faults of the typical Dinaric orientation (NW-SE), a highly tectonized SW-NE orientated zone occurs between the Pelso Unit (African origin) and Tizsa or Tisia Unit (Eurasian origin), and marginally, the Moessian Platform (Figure 2B,C), additionally enabling the formation of deeply incised geomorphological structures in the Pannonian Basin System (e.g., [95–97]). This zone (or some of its parts) is cited in papers under different names, e.g., Zagreb-Zemplin Zone/Line/Fault System, Mid-Hungarian lineament, etc. (e.g., [96,98,99] and references cited in these papers).

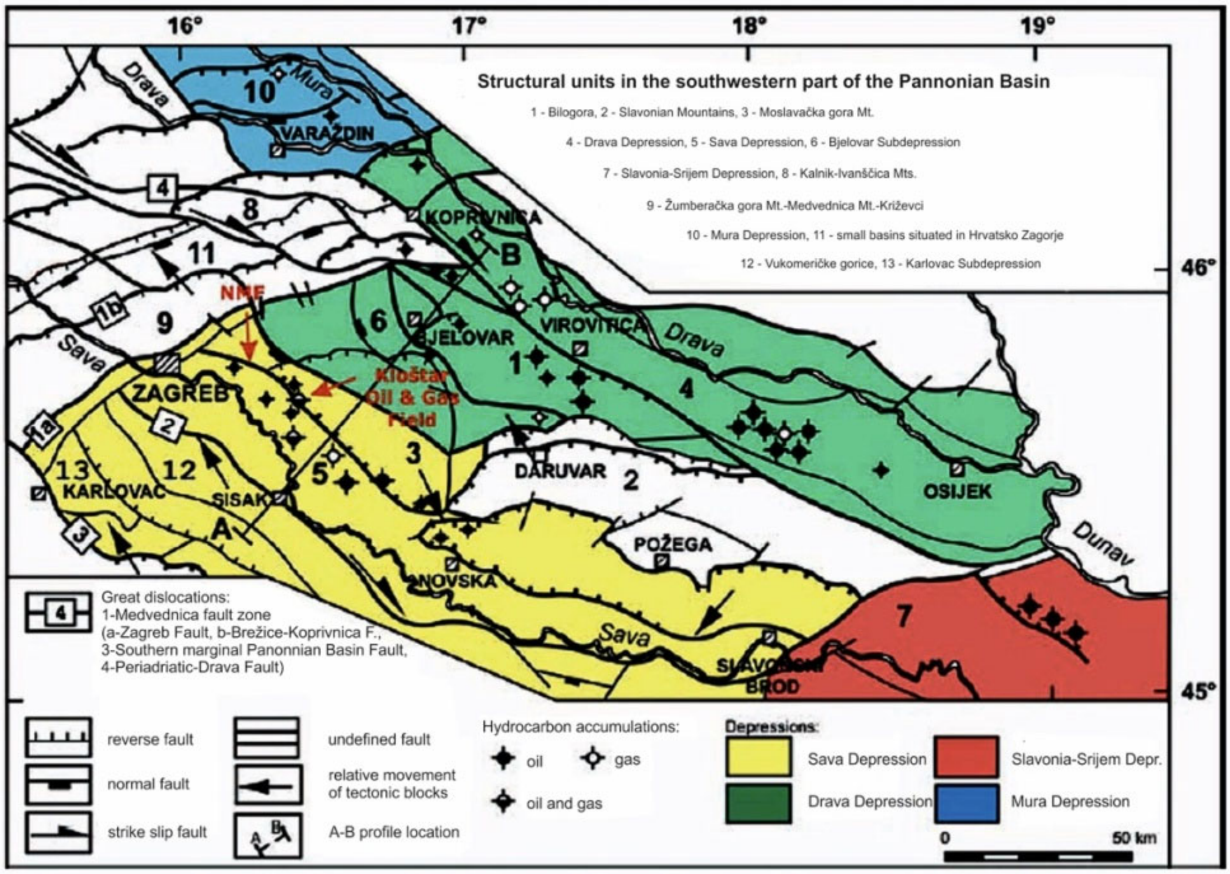

Figure 5. Main structures and fault systems in the CPBS, with position of hydrocarbon accumulations (modified after [100]).

The most important depressions for hydrocarbon accumulations were formed along the Dinaric-striking normal faults (Figure 5), orderly from NW to SE: The Mura (blue color), Drava (green color), Sava (yellow) and Slavonia–Srijem Depression (brownish red) ([100] and references therein). In the CPBS area, covering c.a. 30,000 km, almost 1000 exploration wells were drilled [101].

In order to easily compare the subsurface data from different localities, a lithostratigraphic nomenclature for the CPBS was established (for the first time by [102]), with regionally defined units (Figure 6). Boundaries, recognized through EL (electrolog) markers, can be traced in the entire CPBS. Here, we pointed out EL-marker Rs7 (first proposed by [102]) defined in almost all Sava and Drava Depressions, as a chronostratigraphic border between the Sarmatian and the lower Pannonian, i.e., between the Mosti and Križevci Members in the Drava Depression and the Prečec and Prkos Formations in the Sava Depression (see Figure 6). The Rs7 marker in the PBS is particularly well recognizable, as it points to the time of the inversion phase at the Middle/Late Miocene boundary, followed by the truncation and erosion (e.g., [48,103]).

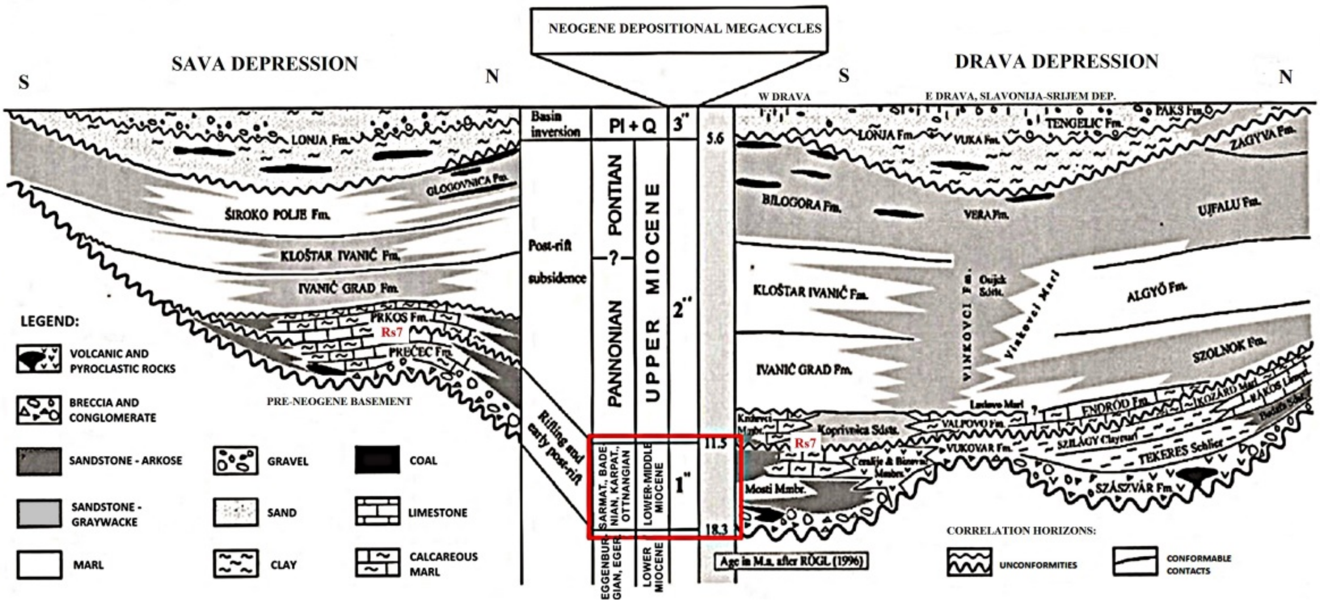

Figure 6. Subsurface lithostratigraphic units in the Sava and the Drava Depressions, grouped in the three Neogene megacycles. Middle Miocene deposits belong to upper part of the 1st megacycle, marked by a red rectangle (modified after [10]). A boundary between the Paratethyan marine and the Pannonian Lake lacustrine deposits can be well recognized from well-logs and is known as the Rs7 marker. Position of depressions shown in Figure 5.

The sediments of the Neogene Period in the CPBS can be grouped into three depositional megacycles of the 3rd order, composed of sequences of well-defined lithological units (formations and members) (Figure 6; [104]).

The oldest, the 1st megacycle of the Early and Middle Miocene, is linked with the marine transgressive-regressive phases in the CPBS. It points to the early to middle syn-rift phase and, possibly, the beginning of the post-rift deposition (e.g., [54]). Some other authors suggest that a post-rift phase began after the Middle Miocene (e.g., [86,105]). Sandstones, subordinate coal seams, talus breccias and conglomerates are overlain by shallow to deep marine marls and shales of varying carbonate content, while biogenic and bioclastic limestones were deposited in the nearshore zone. There are also tuffs and effusive rocks within these sediments (Figure 6). On the thickness map of the deposits from the 1st megacycle (Figure 7) the areas with thickness >1 km are the loci of the main depocenters. The deepest troughs are found in the northern part of the Drava depression (Figures 5 and 7) [10].

Source rocks—dark grey to black marls, calcareous marls, argillaceous limestones, siltstones and shales—were deposited during the 1st and at the beginning of the 2nd megacycle, mostly between the Neogene basement and the Pannonian Lake turbiditic successions. In these sediments, the organic matter is usually uniformly dispersed in the matrix. The source rocks contain kerogens type II and III.

The main hydrocarbon reservoirs occur above the present-day structural traps in sedimentary successions, or in the top of the fractured Neogene basement associated with basal conglomerates and sandstones, or breccias composed mostly of the Mesozoic dolomite fragments. The end of the megacycle is characterized mostly by the fine-grained deposition in the starved brackish basin.

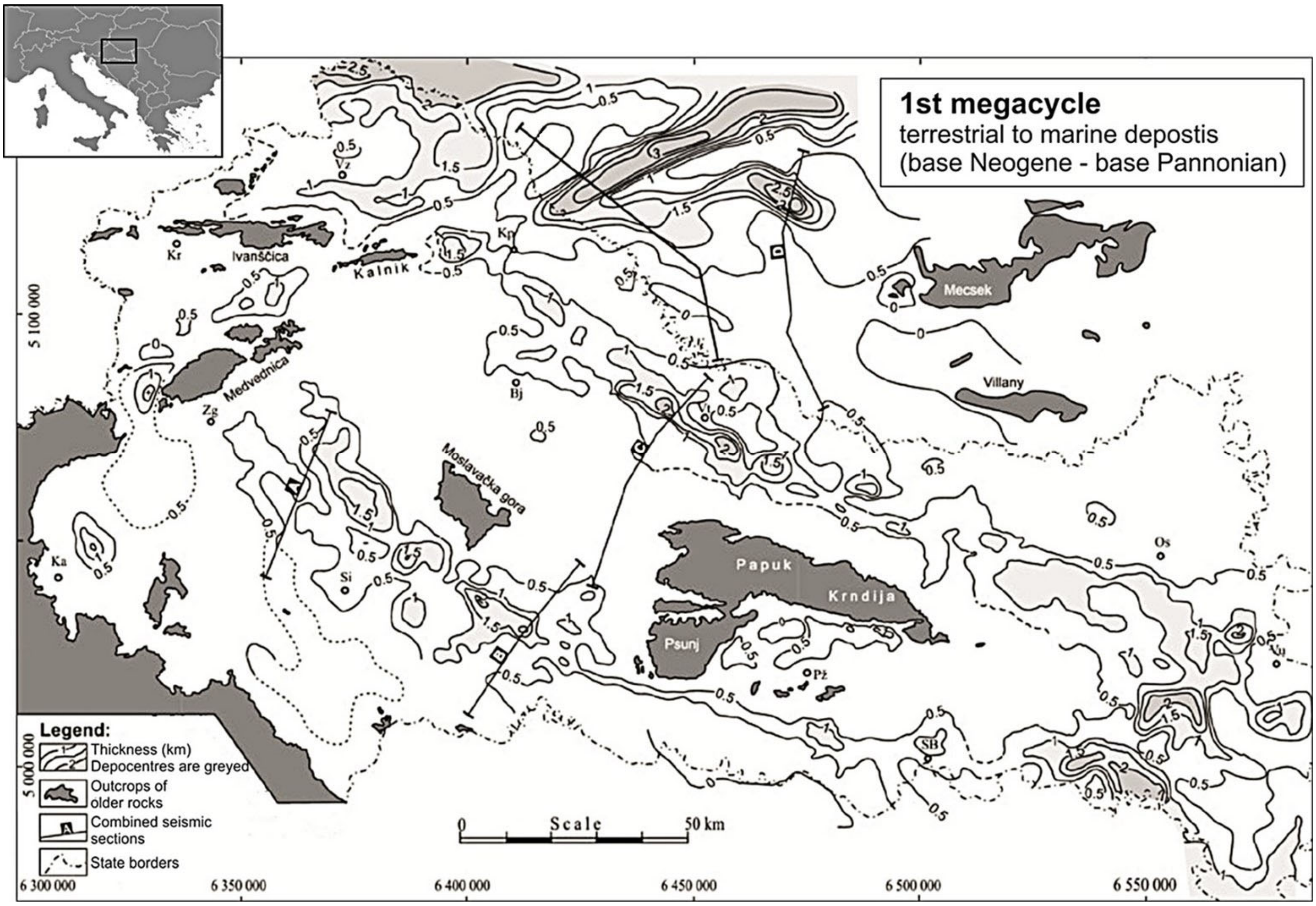

Figure 7. Isopach (thickness) map of the 1st megacycle (Lower−Middle Miocene) in the Pannonian Basin. Depocenters, situated in the deepest depressions, are marked by light grey color. A, B, C and D lines show the position of seismic sections [10].

5. The Development of the Deeper (Outer Shelf−Bathyal) Environment in the CPBS

During the syn-rift, transtensional phases [13], some parts of the north Croatian territory were subsided enough to enable the development of outer shelf-bathyal depositional environments. The 1st transtensional phase lasted during the Middle Miocene (Langhian-early Serravallian, Badenian; Figure 4), resulting in the marine environment increased depths, and the 2nd during the lower part of the Upper Miocene (Tortonian; Pannonian and Early Pontian; Figure 4), with deep lacustrine realms. Locally developed deep structures can be assumed in two ways. The first approach includes the palinspastic analysis, e.g., as it was done for the Sava Depression [106] or Bjelovar Subdepression [107] (Figure 8; depressions shown at Figure 5). Although, due to the two distinct transpression phases in the CPBS, many structures were partially or completely inverted. However, present-day thickness and hereditary structures visible on palinspastic sections show that thick sequences could be deposited and accommodated preferably in the bathyal environment (Figure 8).

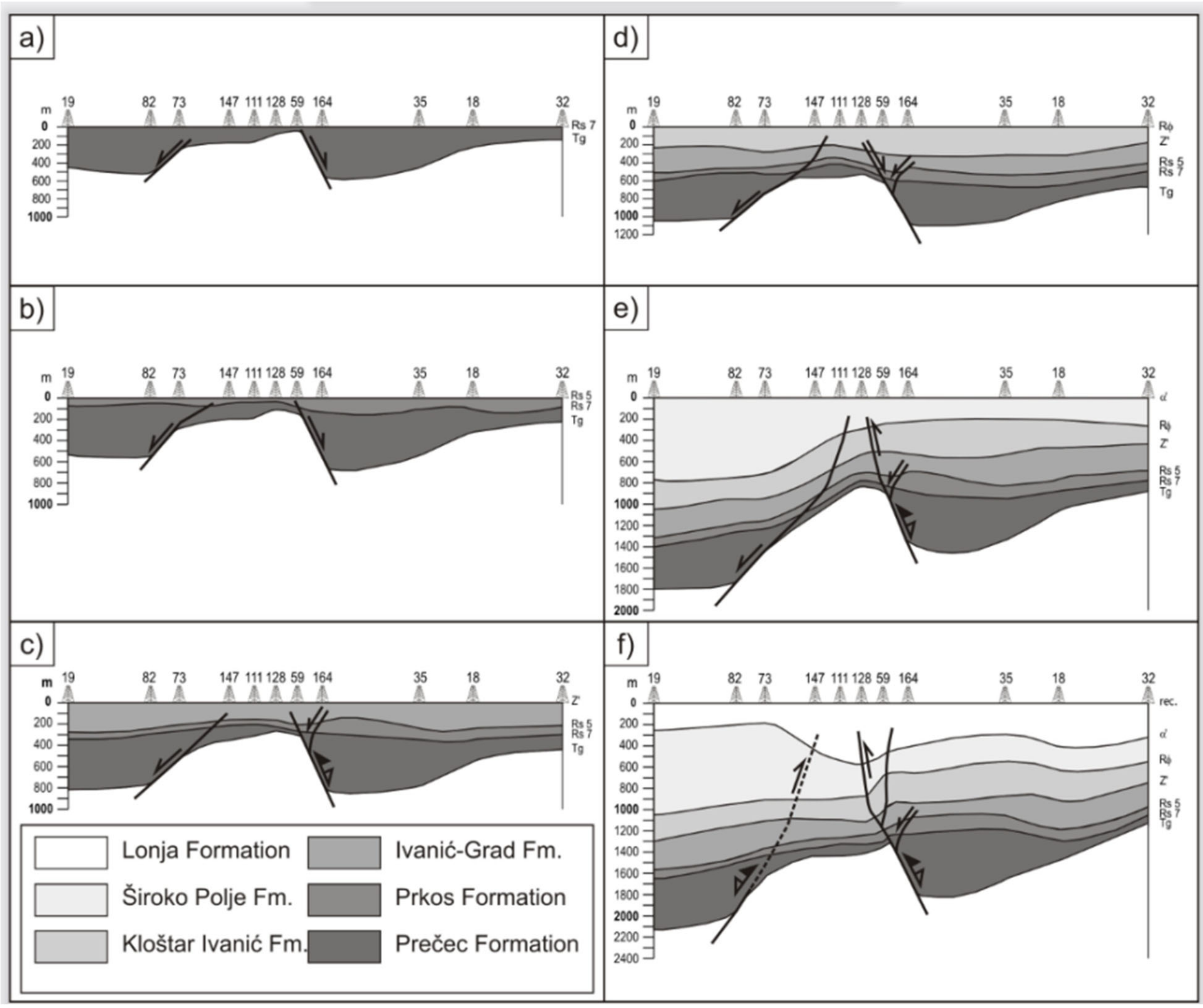

Figure 8. Palinspastic analysis of the Kloštar structure in the Sava Depression. The thickness and shape of the oldest, Prečec Formation (upper part of the Early Miocene and Middle Miocene), was dominantly influenced by a paleorelief (**a**). Relief still influenced the deposition and thicknesses of the overlying Prkos and Ivanić-Grad Fms. (lower part of the Late Miocene) (**b**,**c**). The overlying Kloštar Ivanić Fm. was deposited with less tectonic influence (**d**). The two youngest formations (Široko Polje and Lonja Fm.) (upper part of the Late Miocene) are much thicker (**e**), and the main depositional area had shifted to the SW. Normal faulting is no more dominant, and the main fault (on the NE side of the large uplifted central structure) is reactivated as a reverse fault [106].

Outer shelf-bathyal environments were characterized by deposition of pelitic sediments, forming thin layers lacking the inner textures, prevalence of planktonic over the benthic biota and, sometimes, the selective dissolution of aragonitic tests, while the calcitic tests remain preserved. In some parts of the basin, accumulated material from the hinterland and/or the marginal marine environment was transported into the deeper parts of the basin by means of the gravitational flows/turbidites (Figure 9). Such deposits were described from several areas in the CPBS: Medvednica Mt. near Zagreb (see Figure 3—area 1), Sava Depression (Figure 3—areas 2 and 5), Drava Depression (Figure 3—area 3) and Kostajnica (Figure 3—area 4) (e.g., [59,60,64,80,93,108–110]). The pelagic biota will be described in more detail later in the text.

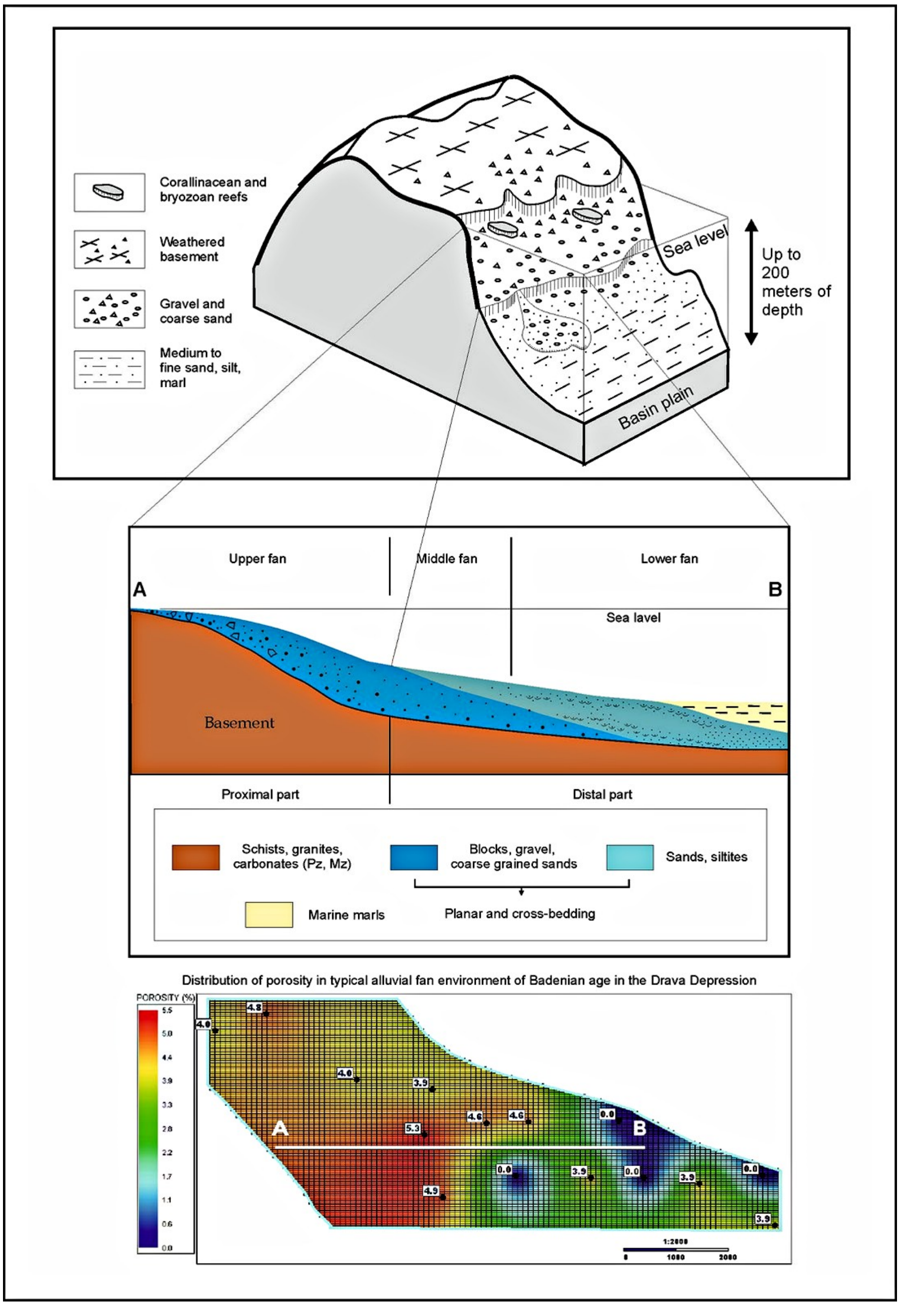

Figure 9. A typical Early Badenian depositional environment, with clinoform structures, reconstructed by [80], based upon the data from the Drava Depression (Stari Gradac Structure).

6. Deep Marine Successions on the Margins of the CPBS—Medvednica Mt. Example

During the Middle Miocene sub-epoch, Medvednica Mt. (Figure 3, area 1) represented an island situated not far from the SW coast of the Central Paratethys (see Figure 10). Coarse-grained beach conglomerates, sometimes with remnants of land flora, sporadically occur in the base of transgressive sequences (e.g., [56,63,65,111,112]). Bioclastic limestones with coralline algae, bryozoans, benthic foraminifers and many other fossils were deposited on the inner shelf (Figure 11). Deeper parts (outer shelf-bathyal) are usually characterized with argillaceous limestones, marls or argillaceous marls. The amount of pelagic organisms in fossil assemblages increases with water-depth, while, at the same time, the sea bottom becomes hostile and supports only the survival of specialized biota. Fossils of pelagic organisms can be found all around Medvednica Mt., but they are present in significant amounts at a small number of studied sections (Figure 10).

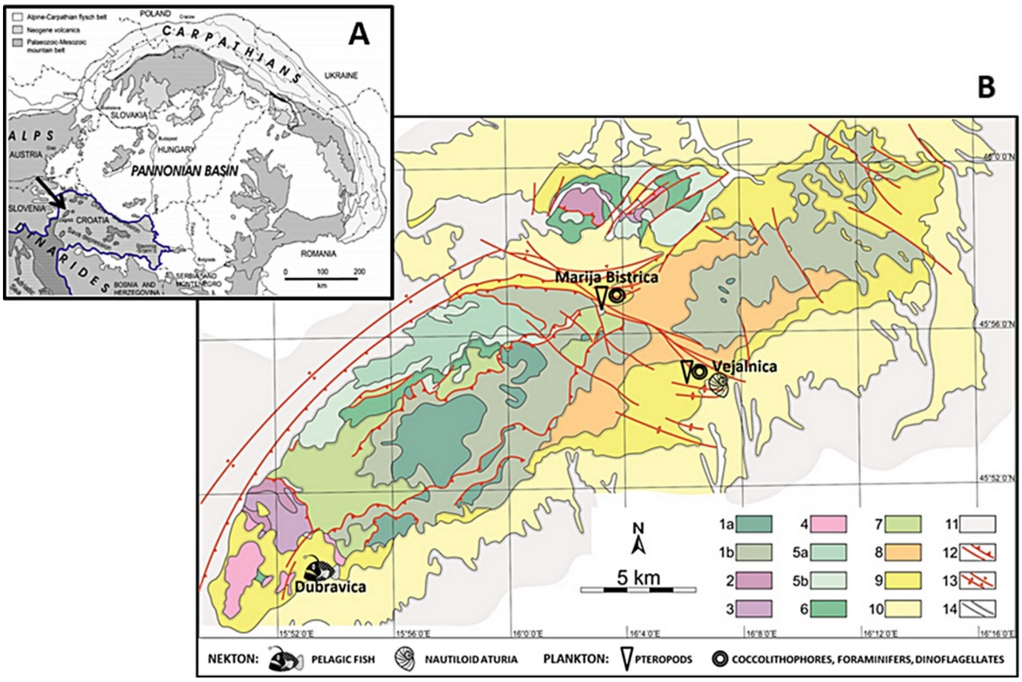

Figure 10. (**A**) Position of Mt. Medvednica near the SW shoreline of the Central Paratethys, marked by the black arrow (after [2]; from [65]). (**B**) Geological map of the Medvednica Mt. according to [113]; modified. Legend: 1a,b. Silurian to Middle Triassic metamorphic rocks; 2–4. Triassic clastic and carbonate sedimentary rocks; 5 a,b. Mesozoic ophiolites; 6. Aptian to Cenomanian marine sedimentary rocks; 7. Uppermost Cretaceous to Paleocene transgressive succession; 8. Early Miocene fluvial and lacustrine deposits; 9. Middle Miocene marine to brackish sedimentary rocks; 10. Late Miocene brackish and marsh deposits; 11. Pliocene clastic deposits; 12. Faults; 13. Fold axes; 14. Normal and transgressive boundaries.

Croatian paleontologists in several papers have discussed the three Middle Miocene sedimentary realms (in original: developments), as suggested by [114] in the area of Medvednica Mt. (NW Croatia): Dolje, Čučerje and Zelina Realm (Figure 12).

The Dolje Realm (SW part) during the Middle Miocene represented a dominantly shallow sedimentary basin, which was situated closest to the Dinarides mainland (see locality Dubravica in Figure 10). During the regressive phases, this area emerged. Deposits from the first Badenian (Langhian) transgressive phases TB 2.3 and TB 2.4 are not present, or they were eroded during the later emersions. Only younger Badenian (Serravallian) deposits, of the TB 2.5 cycle, outcrop in this realm (see Figures 4 and 12). The transgression begins with basal conglomerates, deposited over the Triassic dolomites. Biocalcarenites are common, with preserved magnesium calcite rhodoliths and echinoid tests, along with calcitic oyster and pectinid shells, while aragonitic skeletons in the vadose zone are dissolved. Less distributed marls, developed in sheltered bays or lagoons, comprise well-preserved tests of all mineralogy types. Pelagic organisms from this realm are generally scarce, while benthic organisms are common and diverse [56,58,64,110,115]. Nevertheless, at the Dubravica locality, a rich collection of otoliths was collected, pointing to the pelagic influence (see Figures 10 and 11) [116].

The Čučerje Realm is situated in the central part of the Medvednica Mt., in an area of active tectonic faults (see locality Vejalnica in Figures 10 and 12). It comprises the deposits from at least two, and possibly three, Middle Miocene (Badenian / Langhian-Serravallian) transgressive-regressive cycles (TB 2.3?; TB 2.4 and TB 2.5, e.g., [2,54,57,66–68]). Argillaceous limestones and calcareous marls are dominant in this area, but biocalcarenites also occur, marking the shallowing-upward episodes and initial transgression phases. Planktonic foraminifers, calcareous nannoplankton, dinoflagellate cysts and pteropods are common, along with small benthic foraminifers, brachiopods, mollusks and scarce other fossils. Calcifying plankton (e.g., coccolithophores, foraminifers) is well preserved, while pteropods and benthic clams occur only as casts and molds. Additionally, pelagic nautiloids (*Aturia* sp.) occur only in this realm ([56–59,108,117] and references therein). It is interesting that some of the determined bivalves (lucinoids, solemyoids) can live today up to the depths of 6000 m, due to their chemosynthetic symbionts. Offshore lucinids are usually found at sites of organic enrichment, including sunken vegetation, oxygen minimum zones, hydrocarbon seeps and hydrothermal vents [118]. Basinal deposits in this area occur in a rather narrow belt, probably representing the infill of a deep trench/trough.

The Zelina Realm (NE part of the Medvednica Mt.) (see locality Marija Bistrica at Figures 10 and 12) comprises both, shallow marine deposits with benthic biota in basic parts of the transgressive successions [56,63,111,112] and pelagic deposits with calcareous nannoplankton, benthic foraminifers and pteropods in younger parts of the succession, indicating the high-stand phases of TB 2.4/TB2.5 cycles (Figure 11) [59]. Aragonitic shells in shelf biocalcarenites are dissolved, pointing to the vadose zone. In contrast, pteropod casts from pelagic marls are pyritized and deformed by compression [59].

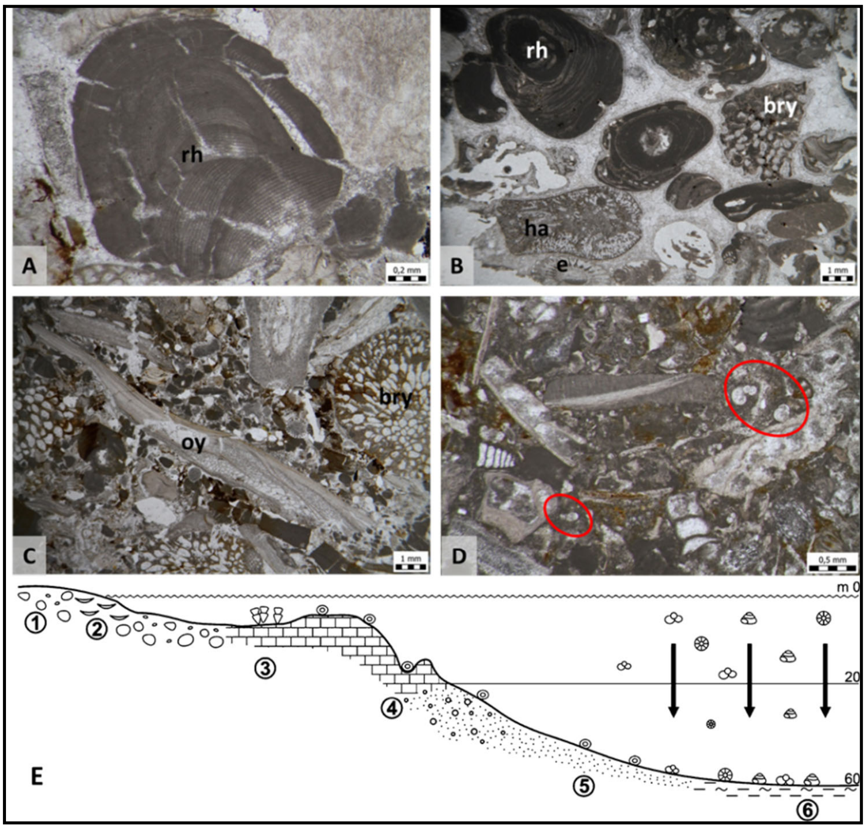

Figure 11. Photomicrographs of slides from the Marija Bistrica site (NE Medvednica Mt., Figure 10), representing a succession from a rapidly drowned Miocene ramp (from the research in [65]; unpublished). (**A**) Rhodolith (rh) with desiccation cracks in outer layers, from the basal parts of the transgressive sequence (see 11 (E)/environment 1). (**B**) Algal bryozoan rudstone from a shallow lagoon (11 (E)/environment 3). Rhodolith (rh), Bryozoan (bry) and halimeda (ha) marked on the photo. (**C**) Bryozoan floatstone with oyster (oy) fragments deposited on inner shelf (11 (E)/environment 4). (**D**) Floatstone with fragments of shelf biota, transported downslope and mixed with planktonic foraminifera (see red ellipses) (11 (E)/environments 4 and 5). (**E**) Reconstruction of the paleoenvironment during the Middle Miocene at the research locality, from [65] (assemblages reconstructed after [119]; sedimentary features after [120]). Numbers indicate the following environments: 1. Beach and proximal shelf; 2. Oyster banks; 3. Lagoons and embayments; 4. Patch reefs and surrounding bioclastic deposits; 5. Maërl; 6. Distal slope. Dimensions not to scale.

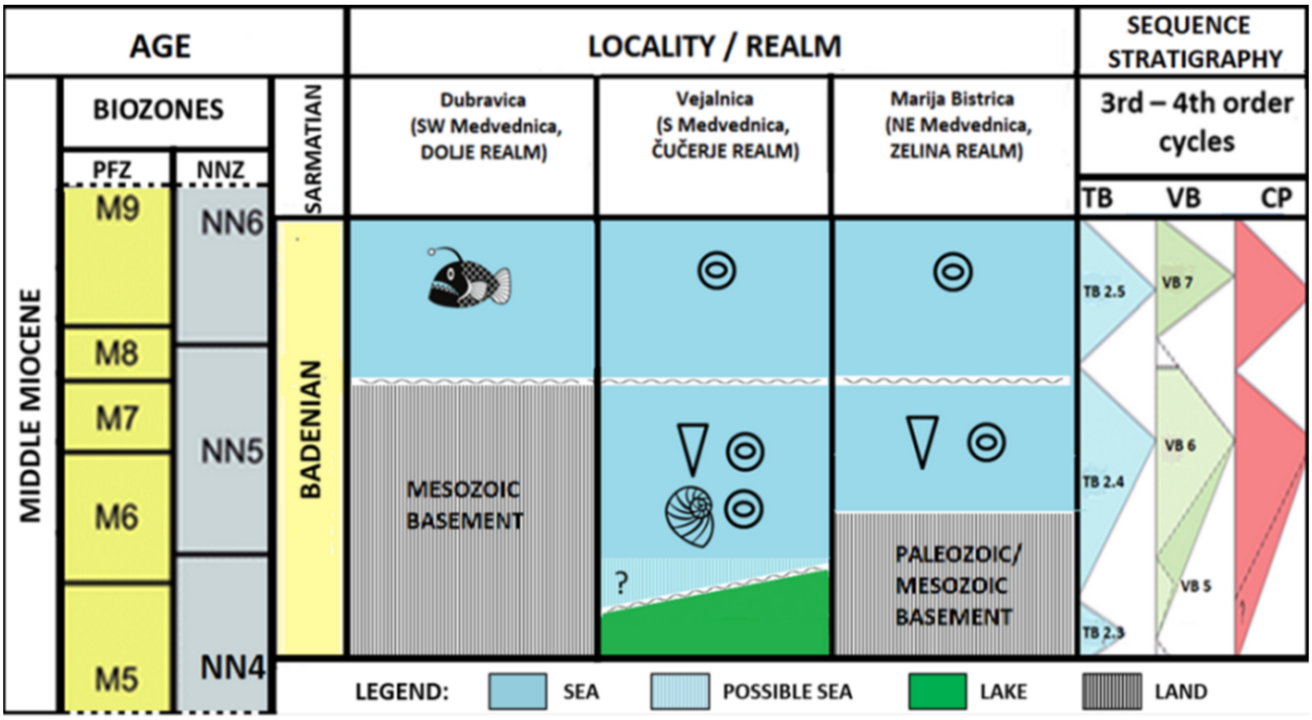

Figure 12. Evidence of three Badenian (Langhian−Serravallian) transgressive-regressive cycles (TB 2.3, TB 2.4 and TB 2.5) at three Miocene localities, representing sedimentary realms in the area of Medvednica Mt. (sensu [114]): Marine transgressions are highlighted with blue color. Lacustrine deposits in the base of the Čučerje Realm succession are green (after [115] modified). For the biozones and TB cycles see absolute age at Figure 4, after [4]. For the fossil legend see Figure 10.

Differences among the Miocene depositional realms around the Medvednica Mt., besides the paleontological features, can be additionally confirmed by the thickness of Miocene successions. A detailed study by [121] estimated the thickness of a succession from the Dolje Realm to be ca. 180 m, while in the deepest, Čučerje Realm thickness ranges from 590–660 m. Total thickness of Neogene (marine and lacustrine) deposits ranges from 785 m in the Dolje Realm, to 1860 in Čučerje Realm according to [121]. Thickness of the Middle Miocene marine deposits shown on the Basic Geological Map, sheets Zagreb and Ivanić Grad, ranges from 330 m in the western part (Dolje Realm) to 910 m in the eastern part (Zelina Realm) [122–125].

7. Deep Marine Biota as Paleoecological and Stratigraphic Markers

The most commonly used stratigraphic markers in the Mesozoic and Cenozoic Eras are the calcareous nannoplankton and planktonic foraminifers. These groups flourished in the warm Miocene seas (e.g., [4,25,43,57,58,126–131]) and occur in the Middle Miocene deposits of northern Croatia.

Coccolithophores, common single-celled planktonic algae in Cenozoic seas and oceans, are highly valued among geologists. Their calcite particles (coccoliths) are easy to recognize (Figure 13), and remain resistant at depths up to 5000 m. In paleontological papers dealing with the age of the Middle Miocene deposits, nannozones (first established by [132]) are commonly discussed (e.g., [56,57,59,60,64,65,68]). Coccoliths were extracted from marls found at several localities from Medvednica Mt., most commonly near the pronounced fault zones, e.g., near Marija Bistrica and Vejalnica ([65]; see Figure 10).

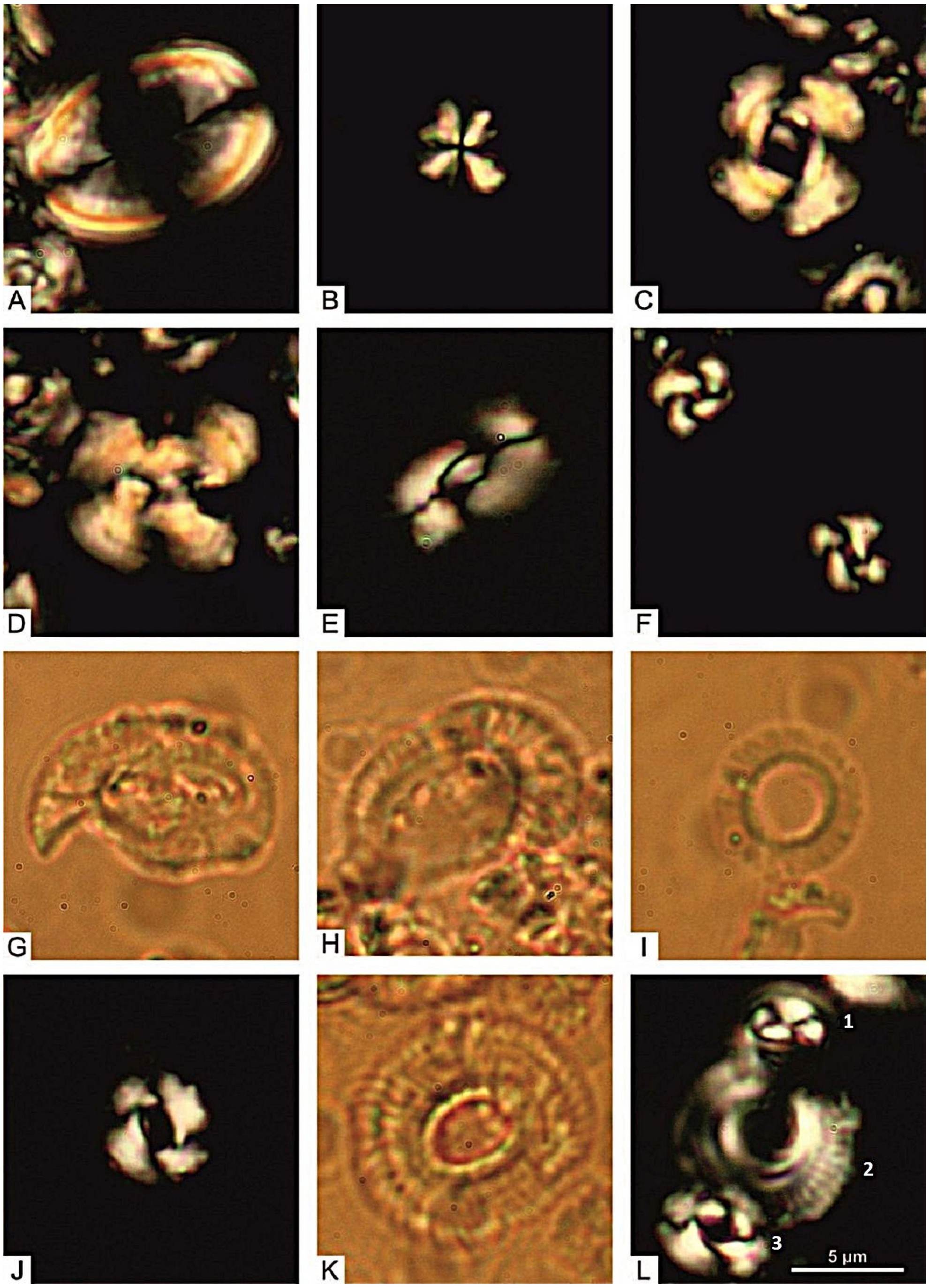

Figure 13. Coccolithophores from the Marija Bistrica site (see Figure 10). (**A**) *Pontosphaera discopora* Schiller, 1925; (**B**) *Sphenolithus moriformis* (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967; (**C**) *Reticulofenestra dictyoda* (Deflandre in Deflandre and Fert, 1954) Stradner in Stradner and Edwards, 1968; (**D**) *Reticulofenestra bisecta* (Hay, Mohler and Wade, 1966) Roth, 1970; (**E**) *Helicosphaera intermedia* Martini, 1965; (**F**) *Reticulofenestra perplexa* (Burns, 1975) Wise, 1983; (**G**) *Helicosphaera perch-nielseniae* (Haq, 1971) Jafar and Martini, 1975; (**H**) *Helicosphaera carteri* (Wallich 1877) Kamptner, 1954; (**I**) *Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982; (**J**) *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969; (**K**) *Calcidiscus premacintyrei* Theodoridis, 1984; (**L**) 1. *Coccolithus pelagicus* (Wallich, 1977); 2. *Calcidiscus tropicus* (Kamptner, 1956) Varol 1989 sensu Gartner, 1992; 3. *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969. Figures. G, H, I and K PPL, others XPL. Scale bar 5 µm for all figures [59].

Planktonic foraminifers are the second most applied fossil group in proving the existence of basinal environments and enabling the stratigraphic zonation. A basic zonation calibrated to the Geomagnetic Polarity and Astronomical Time Scale, proposed by [133], is commonly used.

Malvić [93] listed numerous planktonic taxa in the Middle Miocene deposits from the Drava Depression. They comprise the taxa: *Globigerina bulloides* d'Orbigny, 1826, *Globigerina concina* Reuss, 1850, *Globigerina* sp., *Globigerinella obesa* (Bolli, 1957), *Globoturborotalita nepenthes* (Todd 1957), *Globigerinoides sacculiferus* var. *irregularis* LeRoy, 1944, *Trilobatus trilobus* (Reuss, 1850), *Trilobatus bisphericus* (Todd, 1954), *Orbulina universa* d'Orbigny, 1839, *Praeorbulina curva* (Blow, 1956) and *Praeorbulina glomerosa* (Blow, 1956).

Planktonic foraminifers (*Orbulina suturalis* Brönnimann, 1951, *Orbulina universa* d'Orbigny, 1839, *Globigerina bulloides* d'Orbigny, 1826, *Globigerinoides* sp. div.) dominate in grey marls cropping out near Marija Bistrica, at NE slopes of Medvednica Mt., similar to the Drava Depression, also associated with benthic taxa [65]. They are also common in limestones from the Vejalnica locality in the Čučerje Realm (position of localities at Figure 10) [59].

At the locality Sv. Barbara, near the Vejalnica locality at the southern slopes of Medvednica Mt., planktonic foraminifers, together with the small benthic taxa, point to the inner shelf, outer shelf and upper bathyal environment [134]. The dominant species are *Globigerina bulloides* d'Orbigny, 1826, *Globigerinella obesa* (Bolli, 1957) and *Orbulina universa* d'Orbigny, 1839.

Some specialized palynomorph studies contributed significantly to the knowledge of Miocene stratigraphy, mostly based on dinoflagellate cysts [58]. In the SW part of the CPBS [109,135] relatively open-marine conditions existed according to oceanic to outer neritic dinoflagellate cysts *Impagidinium patulum* (Wall, 1967) Stover and Evitt, 1978, *Nematosphaeropsis labyrinthus* (Ostenfeld, 1903) Reid, 1974, and *Batiacasphaera sphaerica* Stover, 1977 [135] (Figure 14). In the Čučerje Realm, in the central part of Medvednica Mt. (Figure 3, area 1), index fossil *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988, points to the open-marine conditions and connections. A similar situation is in Dilj and Požeška gora Mts. (Figure 3, area 2) and the Drava Depression (Figure 3, area 3) [136].

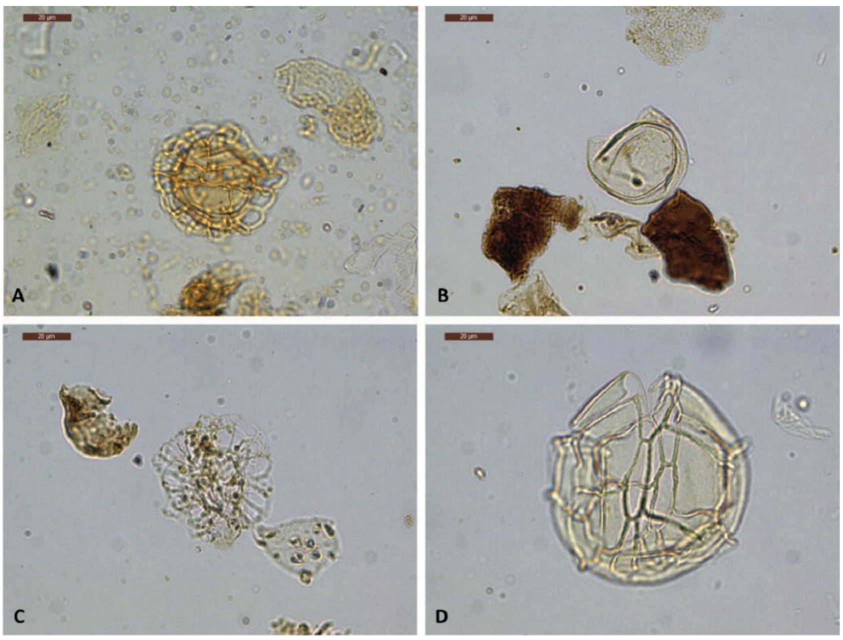

Figure 14. Middle Miocene dinoflagellates typical for the open marine conditions: (**A**) *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988, locality Laz Stubički (position 1 at Figure 3); (**B**) *Batiacasphaera sphaerica* Stover, 1977; (**C**) *Nematosphaeropsis labyrinthus* (Ostenfeld, 1903) Reid, 1974; (**D**) *Impagidinium patulum* (Wall, 1967) Stover and Evitt, locality Kostajnica (position 4 at Figure 3). Scale bars: 20 µm.

Some other, more specialized studies, take into consideration less common planktonic biota, such as peculiar floating snails, Pteropoda. These cute sea-angels and sea-butterflies still live in modern oceans. They can be nude or develop delicate aragonitic shells in the form of cones, fans or spirals, and their shell dissolution points to the ocean acidification (e.g., [137]). In the Paratethys Sea, pteropods were most widely distributed during the Middle Miocene—Badenian (Langhian-Serravallian) (e.g., [138–146]), and among them, genera *Limacina* Bosc, 1817, *Vaginella* Daudin, 1800, and *Clio* Linnaeus, 1767, are also recorded in the Badenian sediments of the Croatian part of the Pannonian Basin System (e.g., [59,114,147]) (Figure 15).

Some of the studied Miocene taxa still live in modern oceans (e.g., *Limacina valvatina* (Reuss, 1867)), while some extinct taxa can make good index fossils, such as the most common Miocene species *Vaginella austriaca* Kittl, 1886.

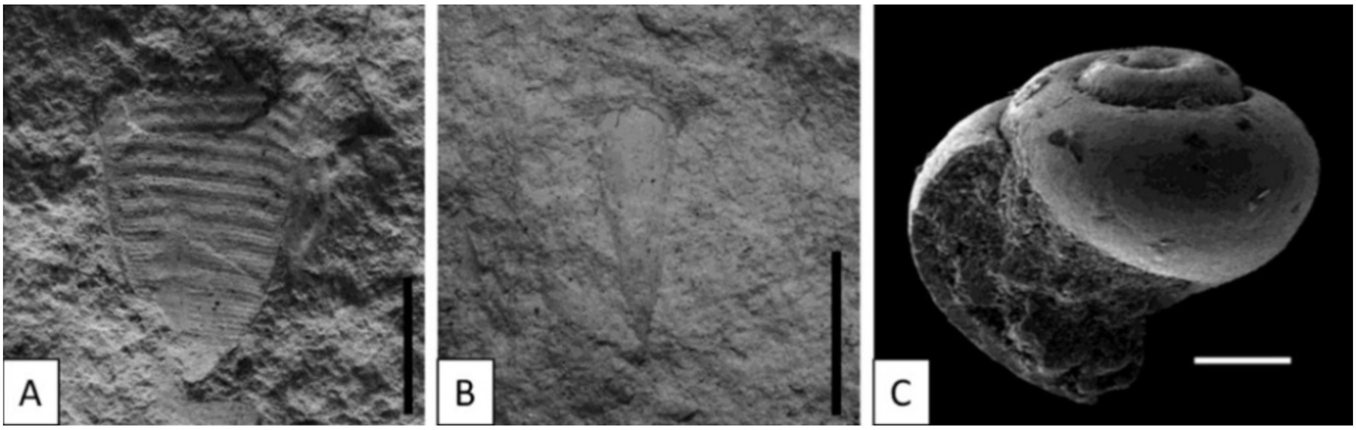

Figure 15. Pteropods from the Middle Miocene deposits in Medvednica Mt. (position 1 at Figure 3); (**A**) *Clio fallauxi* (Kittl, 1886); (**B**) *Vaginella austriaca* Kittl, 1886; (**C**) *Limacina valvatina* (Reuss, 1867). *Clio* and *Vaginella* occur in Early–Middle Badenian (Langhian) deposits at the Vejalnica locality, while *Limacina* is more common in the Late Badenian (Serravallian) deposits of the Marija Bistrica locality (localities shown in Figure 10). Scale bars: A, B: 5 mm; C: 100 µm ([59], modified).

Fine-grained marls from the Dubravica locality (Figures 10 and 12) comprise otoliths of pelagic genera of cods, lanternfishes and silvery lightfishes (*Gadiculus* Guichenot, 1850; *Physiculus* Kaup, 1858; *Diaphus* C. H. Eigenmann and R. S. Eigenmann, 1890; *Valenciennellus* Jordan and Evermann, 1896; and *Maurolicus* Cocco, 1838) (Figure 16), opening the possibility that even in this, generally shallow, shelf area, some parts were deeper, or temporarily connected with the open sea ([116] and references therein).

Based on the stratigraphic span of the planktonic and benthic biota, Middle Miocene biostratigraphy can be correlated with other relevant data (Figures 4 and 17).

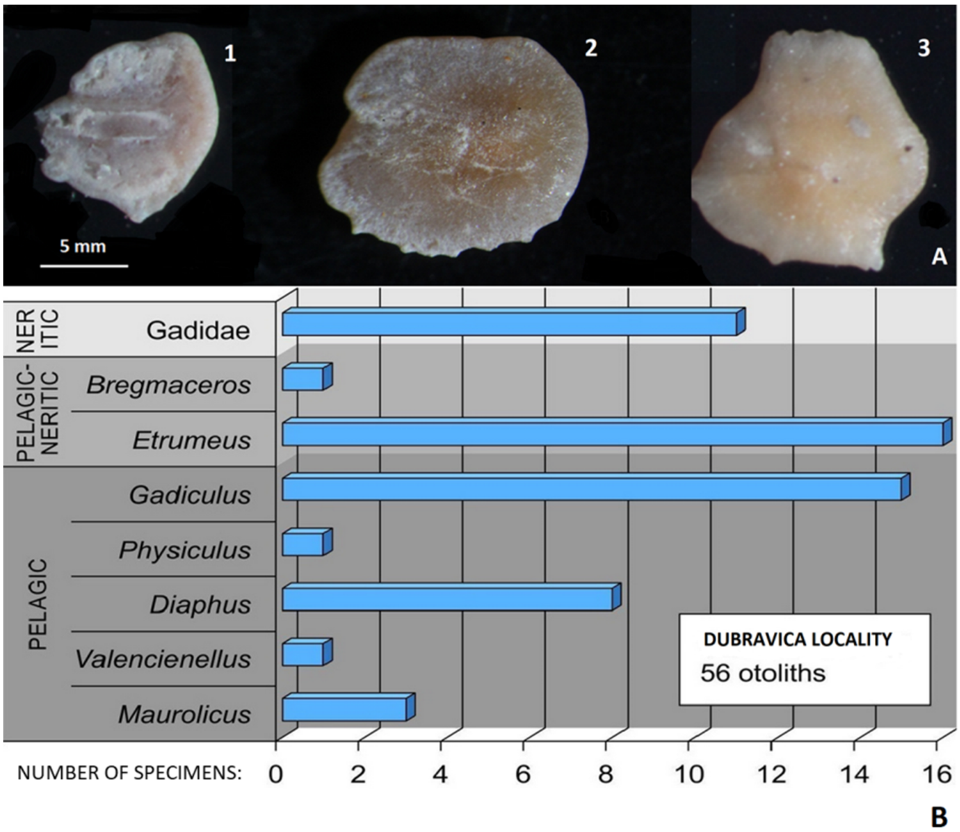

Figure 16. (**A**) Otholiths from the Middle Miocene deposits from the Dubravica locality, SW Medvednica Mt. (area 1 in Figure 3, for the localities see Figures 10 and 12): 1. *Bregmaceros* Thompson, 1840; 2. *Diaphus* C. H. Eigenmann and R. S. Eigenmann, 1890; 3. *Maurolicus* Cocco, 1838; (**B**) amount of the neritic, pelagic-neritic and pelagic taxa in otolith assemblage ([116], modified).

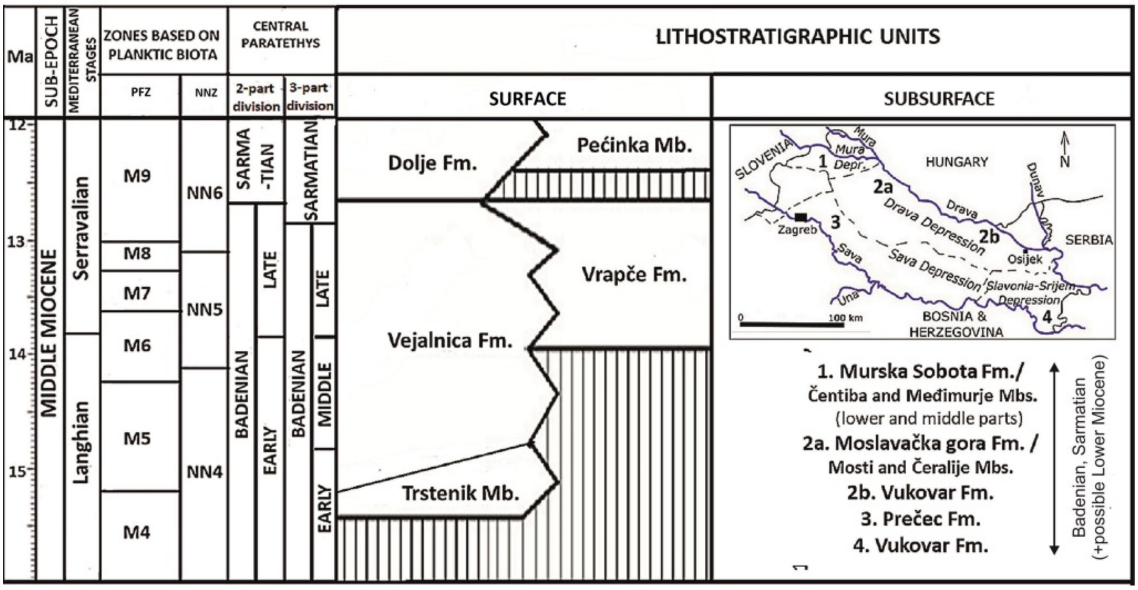

Figure 17. Correlation of chronostratigraphic, biostratigraphic and lithostratigraphic Middle Miocene units in the CPBS (after [4,13,51,132,133,148–152]). Vejalnica Formation is described on the basis of the Čučerje Realm sequence (with previously described basinal deposits); while Dolje Formation can be compared with the younger part of the formerly described Dolje Realm succession.

8. Paratethyan Migration Routes

As described in numerous papers (e.g., [1–4,21,22,25,26,153]) the Paratethys area was highly influenced by the global sea-level changes and tectonic activity controlling the deposition, resulting in paleogeographic changes and opening and closing of the open seaways which represented migration routes between the Paratethys, Mediterranean and western part of the Indian Ocean (Figure 18).

Figure 18. Marine connections and migration routes among the marine realms during the Miocene Epoch [154].

Due to the repeated opening and closing of the marine connections between the Paratethys and the neighboring marine areas, paleogeographic and biogeographic development of Paratethys and Mediterranean was different, and not always easy to compare with the Standard Stratigraphic Chart [155]. In the Paratethys, endemic fauna developed during the time of isolation and restricted communication with the neighboring marine areas. Therefore, different chronostratigraphic/geochronological charts for the Western, Central and Eastern Paratethys were established (e.g., [2,21,24,25]). During the high-stand periods, marine connections were open, enabling the "communication" and biota migration between marine areas. Planktonic and nektonic organisms, and their larval stages, can be a very useful tool in paleobiogeographic research and indicate a correlation of the migration routes with the Miocene marine flooding events. Examples of these indications can be found in papers based upon the microfossils (e.g., calcareous nannoplankton and diatoms in [156], calcareous nannoplankton in [7]), mollusks (e.g., bivalves in [32], gastropods in [156], gastropods—pteropods in [157]); and vertebrates—fishes (e.g., ([158] and references therein). Pteropod distribution in the Central Paratethys corresponds to the Middle Miocene marine flooding events; therefore, they can be helpful in considerations of possible migration routes of biota during the Middle Miocene transgressive-regressive cycles, e.g., see Figure 18 (e.g., [138,139,141–143,159]). The Badenian Stage (Langhian–Serravallian) in the Central Paratethys is marked by three transgressive-regressive cycles (see Figures 4 and 12).

The beginning of the Badenian (Langhian) corresponds to the transgressive-regressive cycle TB 2.3 in NN4 Zone (Figures 4 and 12), which is unclear and eroded in the various areas of the Paratethys (e.g., [33,160]). The next marine flooding in the Paratethys corresponds to the transgressive-regressive cycle TB 2.4. in the NN5 zone (see Figures 4 and 12), and [160] consider that this transgression covered vast areas of the Central Paratethys and marked the Badenian NN5 zone. This marine flooding connected the Paratethys with the Mediterranean and the western part of the Indian Ocean (e.g., [2,3,21–23,33]). The Central

Paratethys was connected with the Mediterranean via the supposed ”Trans-Tethyan-Trench-Corridor”, which was located in today’s area of Slovenia (e.g., [2,7,21–23,25,153,156,161,162]). There are differences in opinions on the possible seaways which acted as biota migration paths between the Central Paratethys and neighboring seas (e.g., [21–23,26,32–34,43,153,163,164] and references therein).

In the Badenian deposits of the Central Paratehys, including the Croatian part of the Pannonian Basin System, a “pteropod event” has been recorded by the presence of the species *Clio fallauxi* (Kittl, 1886), *Clio pedemontana* (Mayer, 1868), *Vaginella austriaca* (Kittl, 1886) and *Limacina valvatina* (Reuss, 1867) (e.g., [59,141–145,165]) (Figure 15). Species *C. fallauxi* is an Early Badenian index fossil (e.g., [141–144]), which is possibly recorded together with the species *C. pedemontana* in the vicinity of the supposed ”Trans-Tethyan-Trench-Corridor” [159]. The findings of these two species in the area close to this supposed marine corridor [59,159] could support the existence of the ”Trans-Tethyan-Trench-Corridor” during the Early Badenian, which acted as a migration route between the Mediterranean and the Central Paratethys during the NN4 and NN5 Zone (Figure 19). Index species *C. fallauxi* is recorded only in the Central Paratethys, and the species *C. pedemontana* is recorded also in the Mediterranean, Japan and the Caribbean, e.g., ([166] and references therein). The most distributed pteropod species in the Central Paratethys is *Vaginella austriaca*, recorded in the Central and Eastern Paratethys in the Karpatian and Badenian deposits (e.g., [142,143] and references therein), but also in the Northern Sea, Aquitaine Basin and the Mediterranean (e.g., [141,166] and references therein). Additionally, present pteropod species *Limacina valvatina* (Reuss, 1867) are recorded in the Paratethys throughout the Badenian (e.g., [142,143] and references therein).

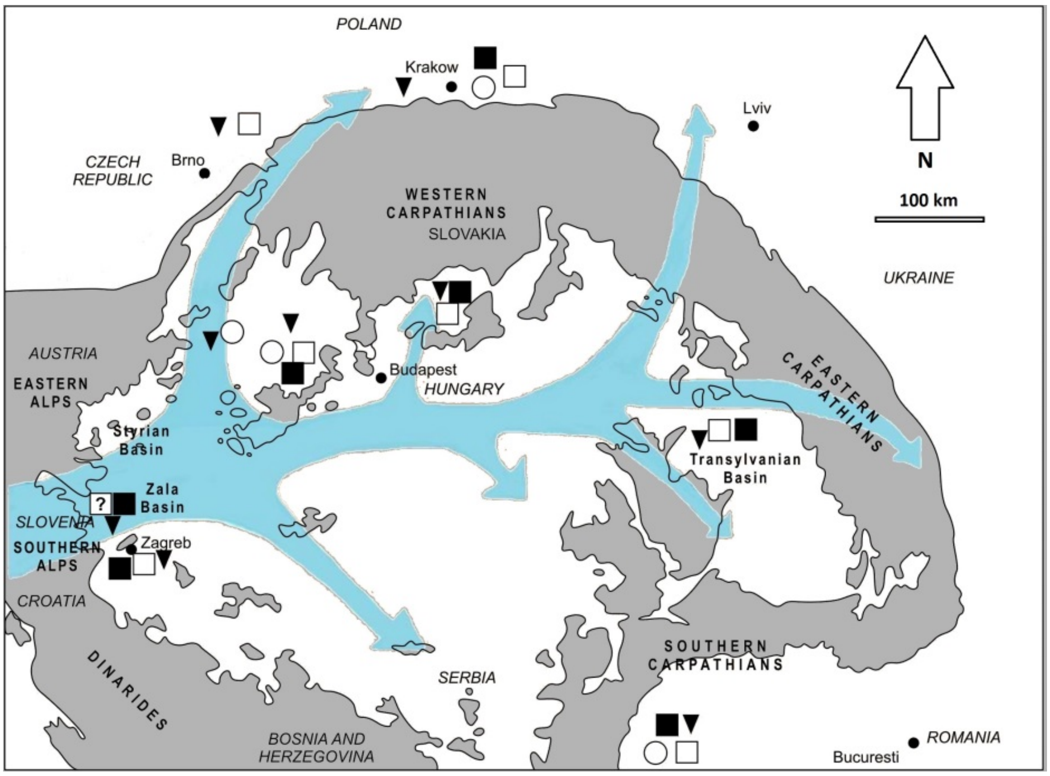

Figure 19. Distribution of pteropods: *Clio fallauxi* (Kittl, 1886) (white rectangulars), *Clio pedemontana* (Mayer, 1868) (black rectangulars), *Vaginella austriaca* Kittl, 1886 (black triangels) and *Limacina valvatina* (Reuss, 1867) (white circles), during the Early−Middle Badenian sensu [25] in the Paratethys. For references and localities see [59]. Paleogeographic map after [2].

The Badenian stage of the Central Paratethys is marked by the regression between the transgressive-regressive cycles TB 2.4 and TB 2.5 in the NN5 Zone (Figures 4 and 12) in the area of Paratethys and the Mediterranean (e.g., [21–23,160]). The marine connection between the Paratethys and the Mediterranean via the ”Trans-Tethyan-Trench-Corridor” was opened, and the connections on the east were closed (e.g., [21–23,25]). The Central and Eastern Paratethys were connected during this time ([34] and references therein). Significant evaporite deposits developed during this period known as the “Wielician crisis” from Poland to Romania, but also in the other parts of the Central Paratethys (e.g., [21,22,25,34,61,62] and references therein).

The last marine flooding of the entire Paratethys is recorded in the Late Badenian (see detailed divisions of the Badenian shown in Figure 4, Figure 12 and Figure S1), corresponding to the zone (transgressive-regressive cycle TB 2.5 in NN6 Figures 4 and 12) [2,21,22,153,160]. Several authors propose their opinions on the marine connections between the Paratethys and neighboring marine areas (e.g., [2,3,21,22,24,25,32,34,44,153]). The supposed ”Trans-Tethyan-Trench-Corridor”, as a marine connection between the Paratethys and the Mediterranean, according to several authors, was closed during the Late Badenian, but the exact time of the closure of this seaway is not known, and [156,167] consider that the ”Trans-Tethyan-Trench-Corridor” could have been an open marine connection to the Mediterranean until the end of the Badenian.

9. Discussion and Conclusions

Middle Miocene marine successions in northern Croatia originate from the SW margin of the epeiric Paratethys Sea. Therefore, near-shore littoral and inner shelf deposits dominate the area. They are characterized by coarse- to medium-grained clastic deposits, reefs and bioaccumulations. Fossil assemblages comprise a variety of benthic biota. Mechanical destruction and selective dissolution of the aragonite vs. calcite fossil shells point to the fresh-water influence in the vadose zone. Such deposits were found and described from many localities, and their age varies, pointing to the initial and terminal phases of the Middle Miocene transgressive-regressive cycles.

Deep (outer shelf-bathyal) Miocene marine deposits in the CPBS are sporadically found on and under the surface, near the fault zones. Subsurface data indicate the deposition in the elongate depressions, related to the long-lasting strike-slip fault zones. Depressions were filled with the clastic material eroded from the pre-Neogene basement, transported downslope together with the shallow marine sediment and mixed with the pelagic sediment deposited on the sea bottom. Such deposits, of marine origin, occur up to the EL-marker Rs7, which regionally represents the border between the Sarmatian and the Lower Pannonian (Serravallian/Tortonian) in the CPBS. Lithostratigraphic units comprising such deposits are a part of the Mosti Mb./Moslavačka gora Formation in the Drava Depression, the Prečec Formation in the Sava Depression, the Murska Sobota Formation in the Mura Depression and the Vukovar Formation in the Slavonia-Srijem Depression. Such areas, today located under the surface, were preferable environments for the local development of outer shelf/bathyal conditions. Consequently, in deeper parts of the basin, organic matter could be accumulated in reductive conditions, which is proven by the source rocks. Tectonics, starting with the 1st and especially 2nd transpressional phase in the CPBS, formed numerous structural traps, which are associated with reservoir and seal rocks.

The thickness of the Miocene marine successions in the depressions could reach 2000 m, locally even more, especially in the major strike-slip fault zones, such as the Northern Sava Depression Fault, and the Main Drava Fault, where long-lasting sinking characterized most of the Miocene Epoch (e.g., [10]).

However, some surface exposures of the Middle Miocene deposits from the marginal Paratethyan areas (e.g., Čučerje area and the vicinity of Marija Bistrica in the Medvednica Mt.; Kostajnica; the Sava and the Drava fault zones (see Figure 3) also show the pelagic influence. Surface exposures comprise the marls, argillaceous limestones and limestones, with planktonic assemblage dominating over the benthic biota.

The Čučerje Realm, in the central part of the Medvednica Mt. (Figure 10), today marked by a still active fault zone, comprises the outer shelf−bathyal deposits from at least two transgressive-regressive Badenian cycles, TB 2.4 and TB 2.5. Pelagic influence in the Middle Badenian (TB 2.4) can be recognized from the abundance of coccolithophores, planktonic foraminifers, dinoflagellates and pteropods, as seen from the previously described Vejalnica locality [59,65] (Figures 10, 12 and 15), while the high stand of the TB 2.5 cycle corresponds to the finding of the planktonic/benthic foraminiferal community at the nearby Sv. Barbara locality [134]. Fossils from the platy limestones at the Vejalnica locality are preserved selectively, depending on the hard parts mineralogy: aragonitic shells of pteropods and bivalves are not preserved, and they occur as casts and molds. In contrast, the calcitic coccoliths, foraminifer tests and ostracod carapaces are preserved, as well as the phosphatic fish scales. Such a dissolution pattern points to the deposition under the aragonite saturation horizon (today in temperate and warm regions under 500 m depth [85,168–171]). Benthic bivalves from this locality belong to the families Solemyidae and Lucinidae, known for the ability of hosting the sulfur bacteria as chemosymbionts and surviving in the oxygen depleted environments, up to the 6000 m (e.g., [59,172–174]. Therefore, the deposits from the Vejalnica locality point to the depth which locally exceeded a few hundred meters. Recognizing small pteropod casts and molds in the field was inevitable for the research at this locality because, due to the dissolution of their tests, pteropods were not previously found in wet-sieved samples.

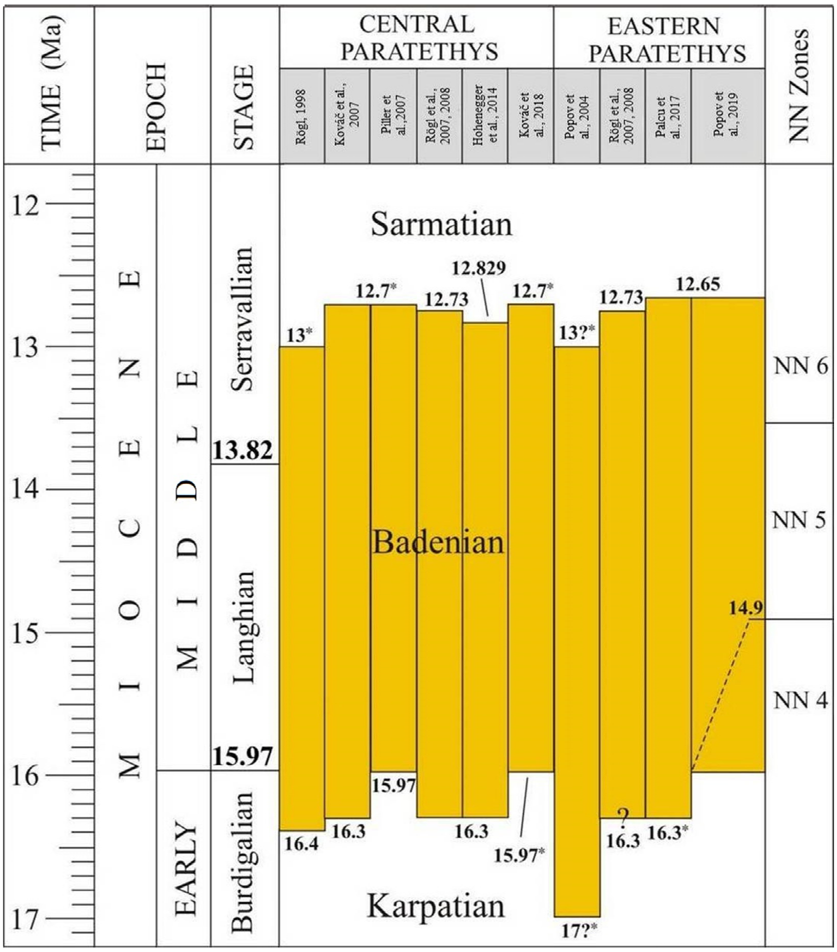

Figure 20. Absolute age of the Langhian/Serravallian, Karpatian/Badenian and Badenian/Sarmatian boundaries, proposed by the various authors. Asterisks (*) point to the ages derived from figures, not explicitly written in papers ([2,4,21,25,26,34,151,160,164,175]). For more information see Figure S1.

At the locality Marija Bistrica, situated near the fault zone in NE Medvednica Mt. (Figure 10), grey marls with partly redeposited coccolithophore assemblage were found [59,65]. The stratigraphic span of coccolithophores from these samples was determined as NN4-NN5. Therefore, the authors additionally studied the planktonic foraminifers, finding large orbulinas (*O. suturalis* and *O. universa*) together with small globigerinids, assemblage typical for the *Orbulina suturalis* Zone (M6 Plankton Zone, sensu [90]), or eventually with its transition into the *Fohsella peripheroacuta* Zone (M7 Zone). Both of these zones can be correlated with the NN5 Nannozone (sensu [88]) (see Figures 10, 11, 13 and 17).

Despite the complex stratigraphic studies, a lot of dilemmas occur considering the correlation of stratigraphic horizons, absolute age of the Miocene successions in the Paratethys Sea and their comparison with the Mediterranean and global stratigraphy (see Figures 20 and S1)

Depressed topographic forms, including troughs and trenches, can generally play an important role in communication between the separated marine basins during the transgressions. As they are often connected with the long-time active tectonic structures, modern prominent fault zones and negative relief forms may indicate the possible ancient migration routes, and point to the areas where to search for the evidence of such processes. Additionally, the depressions are the first to be flooded during the transgressive-regressive cycles and the last to emerge. Therefore, they preserve a more complete record of the complex Middle Miocene marine transgressions than the other marginal Paratethys areas and deserve to be investigated in detail.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences12030120/s1, Figure S1: A detailed stratigraphic division of the Badenian Stage in the Central and Eastern Paratethys, with the absolute age of the Langhian/Serravallian, Karpatian/Badenian and Badenian/Sarmatian boundaries, proposed by the various authors.

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