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Timing and mode of initial marine flooding in the southern Pannonian Basin: New U-Pb age constraints from the Prnjavor and Tuzla basin[☆]

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ABSTRACT

The Pannonian Basin in Central and Southeastern Europe is a huge landlocked basin delineated by Alpine-Carpathian-Dinarides chain. This extensional backarc basin originating by tectonic rifting at about 18 Ma, was successively flooded by the Central Paratethys Sea. The Slovenian Corridor along the Alpine-Dinarides junction enabled its communication with the Mediterranean Sea. Marine flooding along the southern margin of the Pannonian Basin – between the Styrian Basin in Austria and Velika Morava Basin in Serbia - is still poorly understood. While the conflicting biostratigraphic interpretations contribute to ongoing discussions on the timing and mode of this major environmental turnover, independent radiometric data are still rare. The present study contributes three new U-Pb zircon ages which are the very first such data on the Miocene marine transgression in northern Bosnia and Herzegovina. Datings from primary volcaniclastic deposits prove the middle Badenian age for marine transgression uniformly, with a 0.5 Ma eastwards-younging trend of its onset, dated at 14.6 Ma in Prnjavor Basin and at 14.1 Ma in the Tuzla Basin. This trend stays in line with the literature data suggesting a steady eastwards propagation of extension along the Pannonian Basin southern margin. Towards a better understanding of the interplay between tectonic and glacioeustatic forcing of the regional marine progression, a review of published stratigraphic data has been conducted, depicted correspondingly in four paleogeographic maps of ~1-Myr resolution. Building on these data, we bracket the initial gradual flooding interval to the late Burdigalian–early Serravallian (17 to 13.5 Ma) time interval, respectively, attaining up to 3.5 Myr overall duration in a step-wise manner. We infer fault growth and linkage as mechanisms controlling the hydrological pathways and thereby the direction of the transgression. This implies a transgression direction oblique to the main regional extensional direction. In some cases, local stress changes may lead to formation of sea pathways/gates opposite to the direction of extension. Although the tectonic phases were the main drivers in the creation of accommodation space, along the NE Dinarides, glacioeustasy driven by the global climate suspended the landward propagation of the coastline during sea-level low-stands at long obliquity nodes.

1. Introduction

Marine ingressions of epicontinental basins reflect the combined effects of regional geodynamics providing accommodation space by tectonic subsidence and the fluctuations of global climate forcing sea-level change (Einsele, 2000). The former process is critical for the

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initial phase of sea emergence, acting on a supra-Myr time-scale. In contrast, the second process dominates the regional paleogeographic history subsequent to marine flooding, governing shifts of the coastal zone at the scale of sub-Myr astronomical forcing (Bruno et al., 2024).

The extensional back-arc type Pannonian Basin (Fig. 1A), originated in the Early Miocene between the Dinarides, Alps, and Carpathians in Central Europe. It provides an ideal setting to investigate the interplay of these two processes on the regionally significant paleoenvironmental turnover from the long-lasting terrestrial conditions into the marine setting of the Central Paratethys Sea during Early-Middle Miocene times (Fig. 1B). However, the exact age and mode for the establishment of marine settings in its southern marginal area are still disputed (e.g. Pavelić and Kovačić, 2018; Brlek et al., 2020; Premec Fućek et al., 2023). Its semi-isolated, mostly shallow water environments often provide ambiguous biostratigraphic evidence, whereas independent time constraints are still scattered considering the huge geographic extent of the area.

We fill this gap by presenting new U-Pb ages from the Tuzla and Prnjavor basins in northern Bosnia and Herzegovina, situated along the marginal part of the Pannonian Basin flanking the NE Dinarides

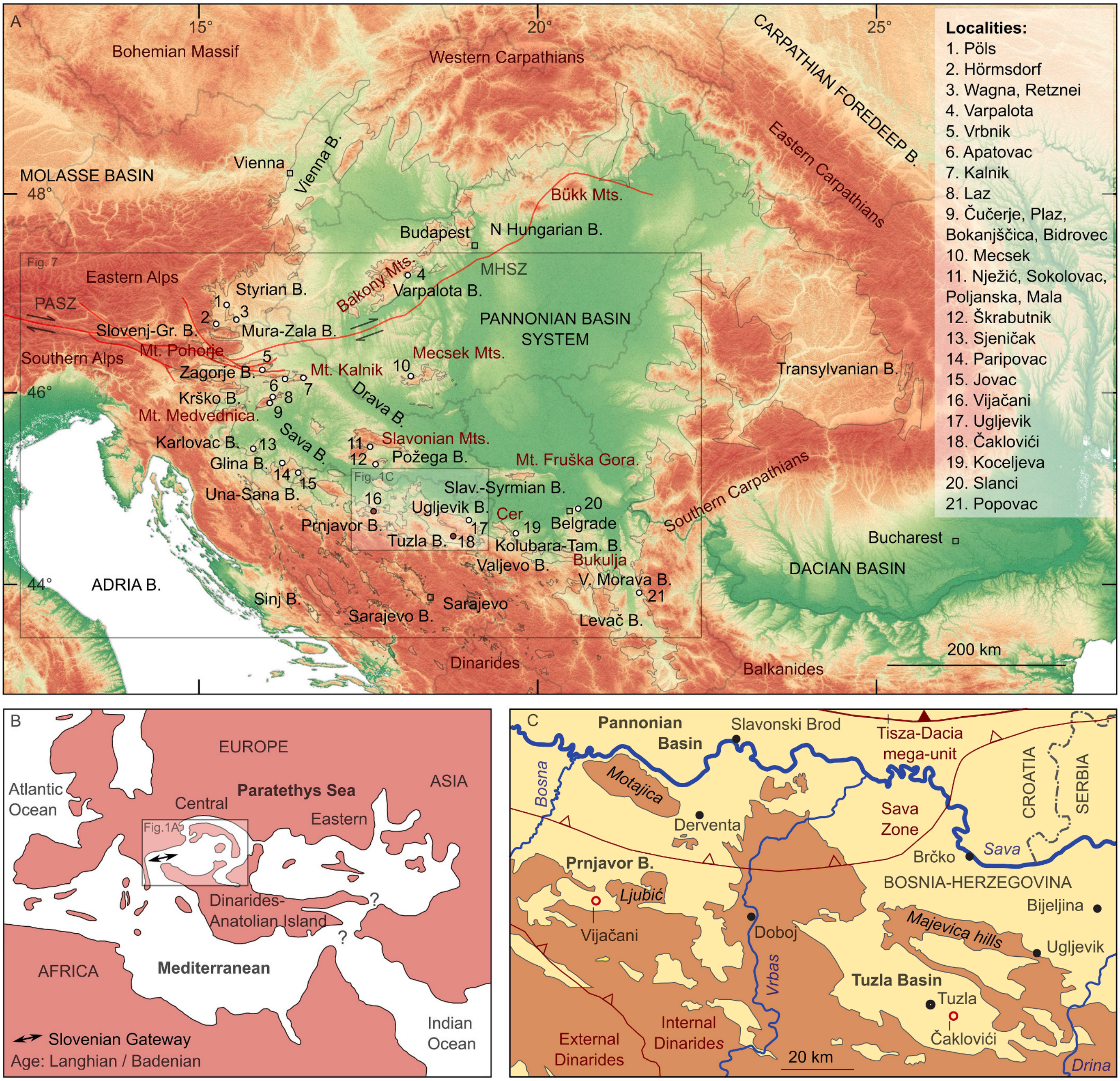

Fig. 1. Geographical and geological context of the study area. A: Location of the studied sections and subbasins/areas mentioned in text, in the context of Central Paratethys. The gray line marks the extent of the Neogene deposits of the Pannonian Basin System and intramountainous basins. Faults are after Schmid et al. (2020); Abbreviations: PASZ/MHSZ - Periadriatic/Mid-Hungarian Shear Zone. White dots are the location of stratigraphic sections reported in the literature from which volcaniclastics or bio-magnetostratigraphic records were studied as indicated in text. The dark red dots delineates the location of the Vijačani site in the Prnjavor Basin and Čaklovići section in the Tuzla Basin; B: Paratethys map modified after Rögl (1999). C: Simplified geological map (GMSFRY, 1970) showing the distribution of upper Oligocene to Quaternary sediments (yellow) with indicated positions of studied volcaniclastics. Tectonic units after Schmid et al. (2008, 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1A). Building on those results, we provide an in-depth review of the available radiometric, biostratigraphic, tectonic, as well as the global and local paleoclimatic data establishing currently the most accurate reconstruction of the SE-ward transgression in the Central Paratethys. Based on this evaluation, we present a series of new paleogeographic maps at ~1-Myr resolution depicting progression of marine flooding into the southern Pannonian Basin. Finally, we quantify the roles of tectonic, global and local climatic forcing in relative sea-level variations during the marine expansion in a landlocked basin system such as the Central Paratethys.

2. Geological setting and sampling site

2.1. Evolution of the Southern Pannonian Basin

The Pannonian Basin is an extensional back-arc basin in Central Europe, delimited by the Alps, Carpathians and Dinarides mountain chains (Fig. 1A). It has been formed as a consequence of geodynamic processes associated with convergence between the European and Adriatic plates, during the Neogene to Quaternary (e.g., Csontos, 1995; Fodor et al., 1999; Horváth et al., 2015). The three continental blocks, which were formed during pre-Neogene geodynamic events, directly underlie the Pannonian Basin. Their heterogeneities affected subsequent strain partitioning and Pannonian basin evolution (e.g., Fodor et al., 1998; Fodor et al., 2021). In the NW, ALCAPA Mega-Unit derived from the Adriatic block joining Europe following the closure of the Alpine Tethys in Cretaceous-Eocene times (e.g., Csontos, 1995; Schmid et al., 2008). To the *E*-SE, the Tisza-Dacia mega Unit includes a merged block that was previously detached from Europe. Due to the closure of the Neotethys Ocean and the subsequent Cretaceous-Eocene collision, this mega-unit is juxtaposed with the Dinarides and is involved in subsequent thick-skinned thrusting (e.g., Karamata, 2006; Schmid et al., 2008). The ALCAPA and Tisza-Dacia Mega Units are separated by a complex inherited shear zone, consisting of the Mid-Hungarian Fault Zone (MHFZ) and the Periadriatic Fault Zone (PFZ), the latter further continues almost through the entire Alps (e.g., Schmid et al., 2008; Fodor et al., 1999). This composite shear zone accommodated opposite rotations of ALCAPA (counterclockwise) and Tisza-Dacia (clockwise), and drove compartmentalization of extensional deformation affecting both units during the Neogene (e.g., Fodor et al., 1998; Balázs et al., 2018; Fodor et al., 2021).

The onset of rifting in Pannonian Basin is connected with extensive rhyolitic volcanism concerted along the MHFZ which was initiated at about 18 Ma (Figs. 1A, 2A; Lukács et al., 2018). Fodor et al. (2025a, 2025b) and (references therein) also links this phase to exhumation of the Pohorje and Rechnitz core complexes, followed by the initiation and rapid subsidence of the Styrian, Slovenj–Gradec and Mura–Zala basins (Fodor et al., 2008, 2020, 2021). The earlier extensional/transtensional deformational phase affecting the Pannonian Basin domain was triggered by a dextral lateral extrusion of the Eastern Alpine north of the PFZ (Heberer et al., 2017; Favaro et al., 2017). The escape tectonics have been controlled by the indentation and northward subduction of the Adriatic beneath the European lithosphere, beginning at about 20 Ma (Handy et al., 2015).

Synchronously or slightly later slab-rollback of the European plate towards the NE (e.g., Horváth and Royden, 1981; Horváth et al., 2006; Fodor et al., 2021) and probably also delamination of Adriatic mantle lithosphere towards the SW (e.g., Matenco and Radivojević, 2012; Löwe et al., 2023) are suggested to have caused the extension in the Pannonian realm, but also affecting the Dinarides (e.g., Schefer et al., 2011; Sant et al., 2018; Andrić-Tomašević et al., 2024), which in eastern areas of Pannonian Basin lasted into the Late Miocene (Balázs et al., 2016).

The Southern Alps nappe-stack extends south of the PFZ (Fig. 1A), representing the orogenic wedge detached from the subducting Adriatic crust (Handy et al., 2015). In its eastern part, it is tectonically partitioned, i.e., dissected by MHFZ faults. The original depositional area termed here collectively Zagorje Basin, is represented by syncline cores preserved from the Tunjice basin in central Slovenia, followed by Laško and Celje basins to the east, joining further eastwards the so-called Croatian Zagorje Basin (Ivančič et al., 2025; Grizelj et al., 2023; Avanić et al., 2021). After initially representing a constituent of the Hungarian Paleogene Basin (Báldi, 1986; Fodor et al., 2002), the Zagorje Basin became, in the Middle Miocene, an integral part of the Pannonian Basin (Horváth et al., 2015; Kováč et al., 2016). During the Oligocene and Middle Miocene, the Southern Alpine basins were with only few interruptions, connected to the Mediterranean Sea (Fig. 1B; Rögl, 1999). This marine gate termed the Slovenian Corridor, followed a still submerged eastern segment of the Southern Alps, into the Veneto foreland basin in NE Italy (Massari et al., 1986). In the Karpatian and Badenian (Fig. 2A, late Burdigalian to early Serravallian) after the emersion of the Alpine foreland basin, it became the only Central Paratethys connection to the open sea (Mandic et al., 2012, 2020). Its final closure due to tectonic uplift of the western Southern Alps gave rise to the Badenian-Sarmatian extinction-event and a short-term endemism-peak of marine relic-biota in the late Serravallian (Fig. 2A; ~13.8 Ma; BSEE; Harzhauser and Piller, 2007). Subsequently, in the Late Miocene this part of the South Alpine domain also became inverted by the N-S directed compression, regionally termed the Sava folding (Placer, 1998; Vrabec and Fodor, 2006; Ivančič et al., 2024, 2025).

The Dinarides follow further to the south, bounded by the Southern Alpine thrust front (Fig. 1A). This NW-SE striking fold-and-thrust belt, forms with more than 400-km-length the principal marginal zone of the southern Pannonian Basin. The Dinarides formed through subduction and closure of the Neotethys ocean between Adria- and Europe-derived continental units which was initiated during Middle Jurassic times (Pamić, 2002; Schmid et al., 2008; Handy et al., 2015). The main Cretaceous-Eocene mountain-building phase involved foreland-directed nappe stacking of Paleozoic basement, Jurassic ophiolites obducted onto the Paleozoic basement, and Permian to Eocene carbonate and siliciclastic sediments. In contrast, the nappes of the External Dinarides (Fig. 1A,C, lack ophiolites and Permian-Eocene sediments are dominated by carbonates (e.g., Korbar, 2009). The NE-E flank of the Dinarides is marked by the Sava suture dividing it from Tisza-Dacia and Europe towards the E ((Fig. 1C, e.g. Schmid et al., 2008). The Dinarides were affected by subsequent extensional phases that began during the late Oligocene (e.g., Casale, 2012; Erak et al., 2017), leading to the exhumation of metamorphic domes. This widespread extension initiated between 21 and 17 Ma (Schefer et al., 2011; Stojadinović et al., 2013) mainly affected the internal Dinarides inducing formation of depocenters in the hangingwalls (e.g., Andrić et al., 2015, 2017).

The basins along the southern margin of the Pannonian Basin (Fig. 1A) are situated on top of the Internal Dinarides and the Sava Zone (Fig. 1A,C, e.g. Una–Sana, Prnjavor, Ugljevik–Loznica, and Kolubara basins; see below). Only in the west, parts of the Krško–Sevnica and Karlovac–Glina basins are situated also on top of the External Dinarides (Ivančič et al., 2025). In the east, the Tuzla basin is fully restricted to the Internal Dinarides (Fig. 1C; Schmid et al., 2020). Finally, Kostolac and Velika Morava basins positioned over the Sava and Europe-derived, and Ophiolite and Dacian units, respectively, represent the easternmost constituents of the Pannonian Basin southern margin (Matenco and Radivojević, 2012).

Northwest of the external marginal zone, the Sava, Požega and Drava basins are delineated by ridges of unroofed Paleozoic cores such as Mt. Medvednica and Slavonian Mts. (Fig. 1A; van Gelder et al., 2015; Pavelić and Kovačić, 2018). This Dinarides-parallel striking basinal-complex regionally termed the North Croatian Basin, is considered as a sequence of southwestward backstepping, asymmetric rift-basins initiated at about 18 Ma (Pavelić et al., 2024). They formed above the Internal Dinarides (Mt. Medvednica and Mt. Kalnik), Sava zone (most of the Sava basin) and Tisza-Dacia mega-unit (northeastern Drava and Požega basins) (Schmid et al., 2020).

The presently studied Prnjavor and Tuzla basins (Fig. 1A,C), located

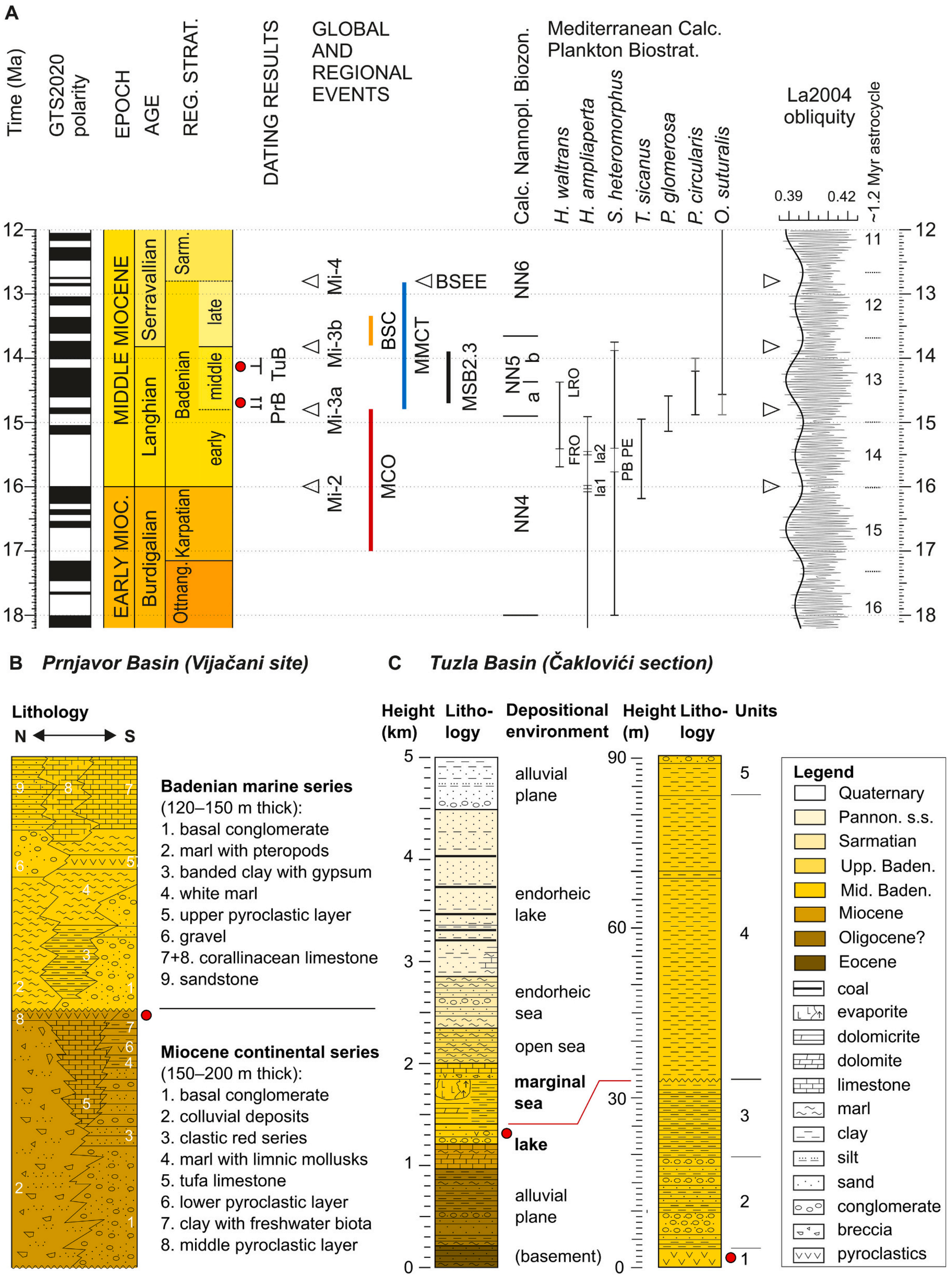

Fig. 2. A: Geological time scale with indicated geochronological results, showing regional and global events, biostratigraphic zonation and ranges mentioned in text, and long obliquity astrocycles coinciding with the glacioeustatic sea-level falls (compiled after Martini, 1971; Laskar et al., 2004; Abdul Aziz et al., 2008; John et al., 2011; Hilgen et al., 2012; Raffi et al., 2020; Turco et al., 2017; Lirer et al., 2019; Miller et al., 2020; this study). B–C: Overview of the main stratigraphic units with the location of the sampled volcaniclastics (red point) in B: Prnjavor Basin, Vijačani site (modified after Eremija, 1969) and C: Tuzla Basin, Čaklovići section (modified after Čičić et al., 1991 and Ćorić et al., 2018). Abbreviations: Reg. Strat. – Regional Stratigraphy, Mi – Miller event, MCO – Miocene Climatic Optimum, MMCT – Middle Miocene Climate Transition, BSEE – Badenian-Sarmatian Extinction Event, MSB – Megasequence B in John et al., 2011, Calc. – Calcareous, *H.* – *Helicosphaera*, *S.* – *Sphenolithus*, *T.* – *Trilobatus*, *P.* – *Praeorbulina*, *O.* – *Orbulina*, FRO/LRO – First/Last Regular (Common) Occurrence, PB – Paraacme Beginning, PE - Paraacme End, Ia – Influx, La2004 – Laskar et al., 2004, PrB – Prnjavor Basin, TuB – Tuzla Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in NE Bosnia and Herzegovina, are representing the external marginal zone of the southern Pannonian Basin.

2.2. Studied Basins

2.2.1. Prnjavor Basin

Prnjavor Basin is delimited by the Mt. Motajica to the north and Mt. Ljubić to the south (Fig. 1C). The former area is part of the Internal Dinarides' core-complex, unroofed by the southern Pannonian Basin synrift tectonics between 20 Ma and 14 Ma (Ustaszewski et al., 2010; Schefer et al., 2011). It is part of the Sava Zone representing the Late Cretaceous suture of the Neotethys (Vardar) Ocean and hosting a 27 Ma old granitoid pluton emplaced during the Oligocene break-off of the Adriatic slab beneath the European Tisza-Dacia block (Ustaszewski et al., 2010). Mt. Ljubić at the southern flank of the basin belongs already to the obducted Western Vardar ophiolite complex (Schmid et al., 2020). The youngest pre-Miocene rocks are represented by the Eocene flysch-like sandstones, marking the marine molasse deposition in the Internal Dinarides Foreland basin followed by the sea retreat in the Eocene.

Finaly, the deposition in the Prnjavor basin commenced about 20 Myr later in the Early or Middle Miocene, after a long-lasting hiatus. Its southern margin accommodates terrestrial and limnic conglomerates and sands, that grade upwards into lacustrine deposits, while the northern flank is mainly covered by colluvial fan deposits (Eremija, 1969; Fig. 2B). The continental, terrestrial to lacustrine succession transgressively overlays the basement and was likely deposited during the latest Early or earliest Middle Miocene, based on lithology and presence of fossil assemblages similar to neighboring regions (e.g. Pavelić and Kovačić, 2018). The basal unit is marked in its lower part by the coarse-grained red sandstones to conglomeratic sandstones with carbonate concretions whereas above the yellow pebbly sandstones prevail (Fig. 2B). This basal unit is followed by the transitional fluvio-lacustrine unit consisting of trough cross-bedded conglomerates and sandstones bearing freshwater biota, involving freshwater gastropods (*Melanopsis sostarici*, *Theodoxus* sp.) and dreissenid bivalves (*Andrusoviconcha* cf. *jadrovi*). On top, the lacustrine unit comprises platy marlstone, marly limestones, tufa limestones, yellow clays and sandstone likely bearing a freshwater fauna, and alternated volcaniclastic interlayers (Fig. 2B).

The marine deposits follow on top of continental succession by an angular unconformity. Based on the common planktonic foraminifera *Orbulina suturalis* and endemic pectinid bivalves such as *Pecten besseri* and *Aequipecten elegans*, a Middle Miocene (Badenian) age is determined (Eremija, 1969). The deposits consist of conglomerates and sandstones, lagoonal claystones with gypsum intercalations and bioclastic limestones. The claystone with mollusk fragments and foraminifera is found on the southern side of the basin.

2.2.2. Vijačani sampling site

The studied volcaniclastic layer, found at the southern basinal flank was previously investigated by Stangačilović (1969) and Eremija (1969). Termed by latter authors as the "trig point 331", after elevation mark in meter of the adjoined peak, it is intercalated to conglomerate on top of the continental series (Fig. 2B). The volcaniclastic layer with a thickness of about 50 cm, is outcropped near the motorway about 500 m SE of village Smolići in the municipality Donji Vijačani (WGS84 44.770373° 17.574191°, Fig. 1C).

2.3. Tuzla Basin

The Tuzla Basin is likewise situated in the Internal Dinarides, located about 50 km SE from the former basin (Fig. 1A,C). It is an about 56-km-long and up to 20-km-wide, WNW-ESE striking intramountain basin accommodating a 3500-m-thick sedimentary infill (Čičić et al., 1977, 1990, 1991; Čičić, 2002). Its basement, belonging to the Western Vardar Ophiolite Belt Zone is marked by the ophiolites obducted over the Drina-Ivanjica and Jadar-Kopaonik thrust sheets in the latest Jurassic and covered thereafter by Cretaceous to upper Eocene siliciclastic and carbonate deposits (Čičić et al., 1991; Schmid et al., 2008). The basin fill seems to represent only one continuous continental-marine-continental depositional megacycle, without main tectonic disruptions (Fig. 2C).

The age of up to 1800 m thick continental sediments beneath the initial marine ingression horizon, is approximated as Oligocene to Early Miocene, because of rare or lacking biostratigraphic markers (Fig. 2C). Still, the presence of congeriinae bivalves such as *Trigonipraxis kucici* in their topmost lower part ("Slavinovići Limestone", Kochansky-Devidé and Slišković, 1978), as well as finding of proboscidean elephant *Gomphotherium angustidens* in their upper part ("Variegated Series", Soklić and Malez, 1969), constrains the maximum age to 17 Ma (Fig. 2A, late Early Miocene) (e.g. De Leeuw et al., 2011).

The continental succession is directly overlain by the Middle Miocene marine deposits (Fig. 2C, Ćorić et al., 2018). Many exploratory drill-cores detected equivalent marine sediments superposing up to 600-m-thick rock-salt deposits ("Banded Series"). However, as the underlaying strata were never recovered, marine or continental deposits remained there badly constrained and controversial (Vrabac and Ćorić, 2008, Vrabac et al., 2011, 2022). Based on regional correlation, the salt precipitation event in the Tuzla Basin has been recently related with the early Serravallian Badenian Salinity Crisis (Fig. 2A, Báldi et al., 2017) or the latest Langhian sea-level fall (Mandic et al., 2019a). The latter correlations imply the rock-salt precipitation as postdating the onset of normal marine conditions in the Tuzla Basin, instead of predating it as suggested by the regional studies (Čičić et al., 1977, 1990, 1991; Čičić, 2002; Ćorić et al., 2018; Vrabac et al., 2003, 2022).

Becoming an embayment of the Pannonian Basin, Tuzla basin started to share its regional stratigraphic division and the general paleoenvironmental evolution. All major postdating regional environmental perturbations, such as the Paratethys restriction from the Mediterranean in the Middle Miocene ("Badenian-Sarmatian Extinction Event") or the emergence of endorheic Lake Pannon in the Late Miocene (Harzhauser and Piller, 2007; Piller et al., 2007), are recorded in the Tuzla Basin too (Figs. 2A,C). In particular, the Lake Pannon phase ends with several cycles of massive coal deposition in the southern Tuzla Basin during the Portaferrian (latest Pannonian), followed by the final return of terrestrial and alluvial environments in the Pliocene (Čičić et al., 1990, 1991). Thus, the 850-m-thick Middle Miocene marine succession (Badenian-Sarmatian) is overlain by a 1650-m-thick Upper Miocene Lake Pannon succession, topped by 500-m-thick alluvial deposits (Fig. 2C; Čičić et al., 1990; updated).

2.3.1. Čaklovići sampling site

The studied volcaniclastic layer marks the base of the Čaklovići section (WGS84 coordinates 44.50884°, 18.75055°, Fig. 1C, 2C). Previously studied by Ćorić et al. (2018) this section shows a shift from the continental ("Variegated Series") to the Middle Miocene marine deposits attributed to calcareous nannoplankton zone NN5. The section is located 7 km ESE from the city of Tuzla at the flank of the Čaklovići anticline in the southern Tuzla Basin (Čičić et al., 1990, 1991). The geochemistry and clay mineral composition of the 3-m-thick, grayish colored, altered vitroclastic tuff has been investigated by Badurina et al. (2021) and Šegvić et al. (2024). Based on increased content of highly vesicular pumices and geochemical fingerprint, the former study hypothesized its origin in the Bükkalja Volcanic Field of northern Hungary (Lukács et al., 2021). Above the sampled volcaniclastic layer, the section continues with an about 30-m-thick fining upward succession of freshwater fossil bearing lacustrine deposits. They comprise laminated, thinly bedded marlstone, intercalated in the lower 15 m by meter-thick conglomerate and sand packages indicating a deltaic depositional setting. Marine fossil bearing deposits follow with a 50-m-thick massive marlstone succession on top of an erosive discordance (WGS84 coordinates 44.508438°, 18.749712°). The top of the section shows a 7-m-thick coarsening upwards interval of massive marlstones, sandstones and conglomerates, marked by the presence of planktonic foraminifer *Orbulina suturalis* and calcareous nannoplankton *Sphenolithus heteromorphus* (Fig. 2A,C).

3. Methods

3.1. Samples and preparation

During the course of this study, zircon grains from three samples were dated. Two samples were taken in one 50-cm-thick volcaniclastic layer at Vijačani site in the Prnjavor Basin, sample Prnjavor 1 (PRV 1) from the lower part, and sample Prnjavor 2 (PRV 2) from the upper part. A third sample from the Tuzla Basin stems from the upper part of a 3-m-thick volcaniclastic layer at the base of the Čaklovići section.

Zircon grains were separated by standard techniques. The samples were crushed with a jaw crusher and disc mill to <500 μm, and the heavy minerals enriched by panning. Subsequently, zircon grains were handpicked under ethanol, mounted on double-sided tape, coated with gold, and their morphologies imaged by means of a scanning electron microscope (TESCAN VEGA2 SBH equipped with an Oxford SwiftED EDX-system, all at KIT Karlsruhe). Afterwards, the same grains were embedded with epoxy resin in 1-in. plastic rings, and grinded to expose their center parts. After polishing the zircons were additionally imaged by SEM to gain information about internal zoning patterns.

3.2. U-Pb-dating

Uranium-Th-Pb analyses were performed by laser ablation-sector-field inductively coupled plasma mass spectrometer (LA-SF-ICP-MS) during two sessions, using a 193 nm ArF Excimer laser (Analyte Excite+, Teledyne Photon Machines) coupled to a Thermo-Scientific Element XR instrument at KIT, Karlsruhe, Germany. Zircon grains of unknown age were analyzed together with the reference zircon material BB (primary standard), Plešovice, KA1, MudTank and SING, using the instrument conditions and tuning parameters listed in ESM-Table S1. Several grains were analyzed with multiple spots, in order to check for the presence of inherited components, and the effect of Pb loss. All raw data were corrected offline for daily instrumental drift and mass offset, using an in-house MS Excel© spreadsheet program (Gerdes and Zeh, 2006, 2009). Dating results of unknowns and reference materials are listed in ESM - Table S2, and presented in Tera-Wasserburg diagrams in Fig. 3, plotted by means of the software ISOPLOT 4.15 (Ludwig, 2012).

4. Results

4.1. U-Pb-dating

From each tephra sample a large number of zircon grains were analyzed in-situ by LA-SF-ICP-MS (ESM-Table S2c). All analyzed grains have perfect euhedral shapes and are closely intergrown with euhedral apatite and/or contain melt inclusions (Fig. 3). Zircon morphologies reveal significant differences among the samples. Zircon grains of samples PRV 1 and 2 commonly have aspect ratios of 2–4, and rarely >4, whereas these of CAK form mostly needles with aspect ratios >4 (Fig. 3). Overall, the euhedral shapes and elongated aspect ratios of the zircon grains suggest a volcanic origin, with minimal post-depositional reworking (e.g. Šamarija et al., 2026a). Zircon grains from all three samples yielded predominately Middle Miocene ages. The common Pb uncorrected analyses of the investigated samples, plot on regression lines that yield in Tera-Wasserburg diagrams lower intercept ^{206}Pb/^{238}U ages of 14.681 ± 0.043 Ma (PRV 1, $n = 126$), 14.584 ± 0.044 Ma (PRV 2, $n = 111$), and 14.120 ± 0.079 Ma (CAK, $n = 21$) (Fig. 3).

5. Discussion

5.1. Depositional age of regional marine transgression

Zircon grains from the volcaniclastic layer within the basal marine conglomerates of the Prnjavor Basin yielded ages (Fig. 3) of 14.681 ± 0.043 Ma (PRV 1) and 14.584 ± 0.044 Ma (PRV 2). The latter age provides a maximum age of ~14.6 Ma for the regional transgression, in accordance with the fossil record in marine sediments including *Orbulina suturalis* and *Helicosphaera waltrans* (Fig. 2A). In the Mediterranean sections, the former species has its first occurrence at the same age (Lirer et al., 2019), whereas the latter has its last occurrence at 14.4 Ma (Abdul Aziz et al., 2008). In consequence to such a young age constraint for the onset of marine conditions, continental deposition in the Prnjavor Basin might be well active as late as the middle Langhian (Fig. 2A,B, 4L, middle Badenian).

The U-Pb zircon data of 14.120 ± 0.079 Ma indicate that marine deposition in the Tuzla Basin occurred significantly later than in the Prnjavor Basin (Fig. 2A,C, 4M. The zircon age is in agreement with the biomagnetostratigraphically derived numerical age (~14.1 Ma) of the Paratethys marine flooding at the Ugljevik Section, located on the external flank of the Majevica peninsula sheltering the Tuzla embayment from the open sea in the Pannonian Basin (Fig. 1C, Mandic et al., 2019a). The date confirms a Middle Miocene age for the freshwater lacustrine deposition in the Tuzla Basin, previously set to Early Miocene (Čičić et al., 1990; Ćorić et al., 2018; Badurina et al., 2021). Such an age constraint confirms synchronicity of the marine transgression in the

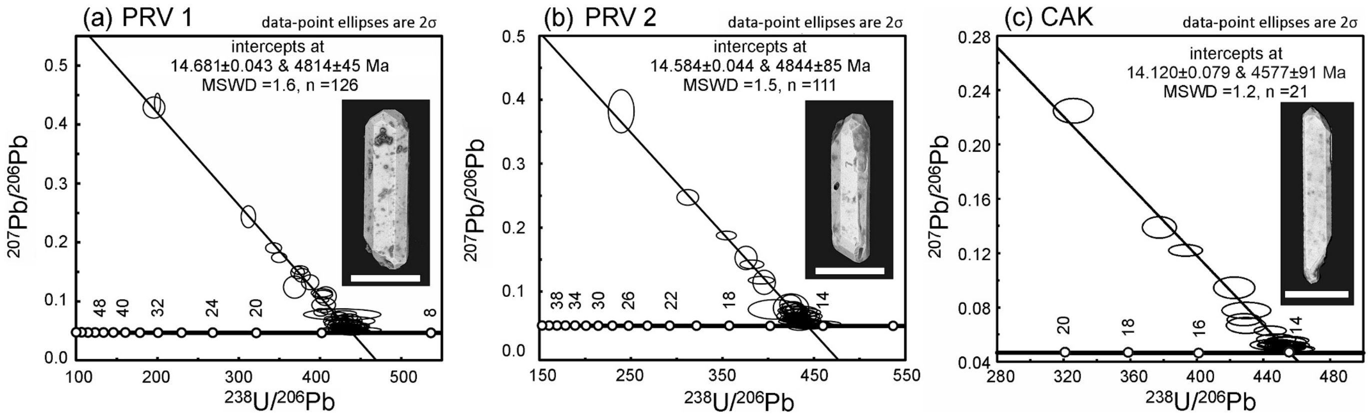

Fig. 3. Results of U-Pb dating of zircon grains from volcaniclastic sample PRV 1 and PRV 2 (a) and CAK (b) presented in Tera-Wasserburg diagrams. Inset: representative euhedral zircon grains showing intergrowth with apatite (dark gray minerals), white bar = scale = 100 μm.

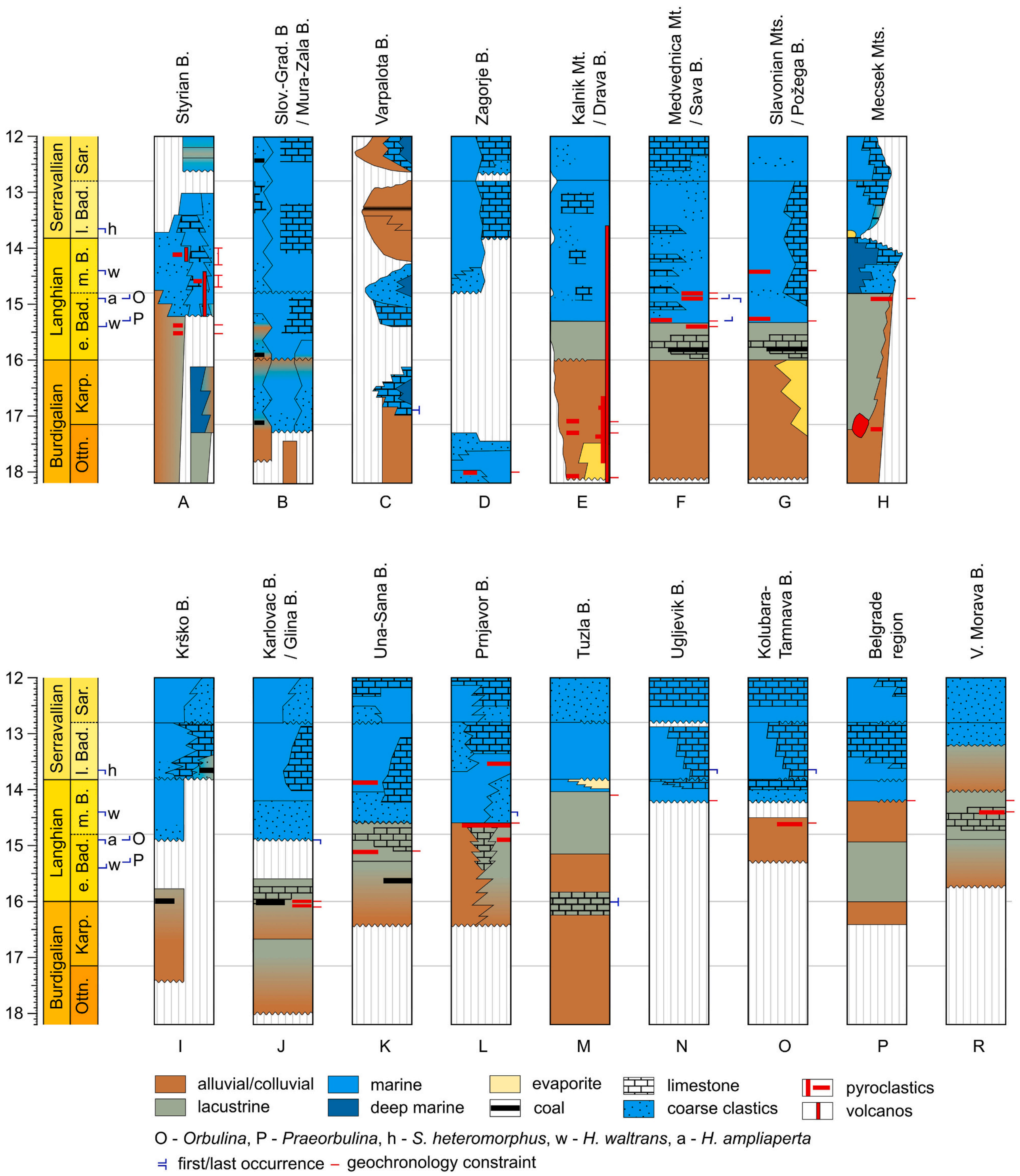

Fig. 4. Simplified lithostratigraphical columns for main studied basins with indicated stratigraphical constraints. A. Styrian basin - Gross et al., 2007; Sant et al., 2020; Piller, 2022; Dax et al., 2024; B. Slovenj Gradec / Mura-Zala b - Ivančić et al., 2018; Ivančič et al., 2025; C. Varpalota B. - Kókay, 1973; Mandic, 2003; Selmeczi et al., 2024; D. Zagorje B. - Avanić, 2012; Avanić et al., 2018, 2021; Brlek et al., 2023; this study (age of marine Lower Miocene, see text); E. Kalnik Mt. / Drava B. - Lučić et al., 2001; Mandic et al., 2012; Pavelić and Kovačić, 2018; Bigunac, 2022; Brlek et al., 2020, 2023; F. Medvednica Mt. / Sava B. - Vrsaljko et al., 2005, 2006; Pavelić and Kovačić, 2018; Premec Fućek et al., 2023; Trinajstić et al., 2023; Marković et al., 2021; Pavelić et al., 2024; Trinajstić, 2025; G. Slavonian Mts / Požega B. - Pavelić and Kovačić, 2018; Halamić et al., 2019; Brlek et al., 2020; Marković et al., 2021; Trinajstić, 2025; H. Mecsek Mts. - Sebe et al., 2019; Báldi, 2006; Báldi et al., 2002, 2017; Lukács et al., 2018; Selmeczi et al., 2024; I. Krško B. – Tomljenović and Csontos, 2001; Vrsaljko et al., 2005, 2006; Ivančič et al., 2025; J. Karlovac / Glina B - Tomljenović and Csontos, 2001; Benček et al., 2014; Magaš et al., 2014; Vrsaljko et al., 2005; Mandic et al., 2012; K. Una-Sana B. - Jovanović, 1972; Šikić, 1990a, Šikić, 1990b; L. Prnjavor B. - Eremija, 1969; Sofilj et al., 1984a, 1984b, this study; M. Tuzla B. - Vrabac et al., 2003; Čičić et al., 1990; Ćorić et al., 2018, this study; N. Ugljevik B. - Mandic et al., 2019a and references therein; O. Kolubara-Tamnava B. - Rundić et al., 2024 and references therein; P. Belgrade region - Mandic et al., 2019b and references therein; R. V. Morava B. – Dolić, 1980; Dolić et al., 1981; Sant et al., 2018; Bradić-Milinović and Vuković, 2024.

Tuzla-Ugljevik region (Fig. 1C; 2A, 4M,N). This implies that the marine rock-salt formation must likely be younger than the settling of the marine embayment in the Tuzla Basin and is bounded to the subsequent glacioeustatically forced sea-level fall marking the Langhian-Serravallian boundary. Indeed, the marine deposits directly underlaying rock-salt are marked by absence of *Helicosphaera waltrans* indicating the upper NN5 biozone with a maximum age of 14.3 Ma (Fig. 2A; Gašparič et al., 2019). In the Čaklovići section the latter species is likely absent (Ćorić et al., 2018), belonging therefore to the same biozone, as independently confirmed by our derived U-Pb zircon age of 14.1 Ma.

5.2. Towards a precise timing of the SPB marine ingression

In this chapter we discuss the significance of biostratigraphic,

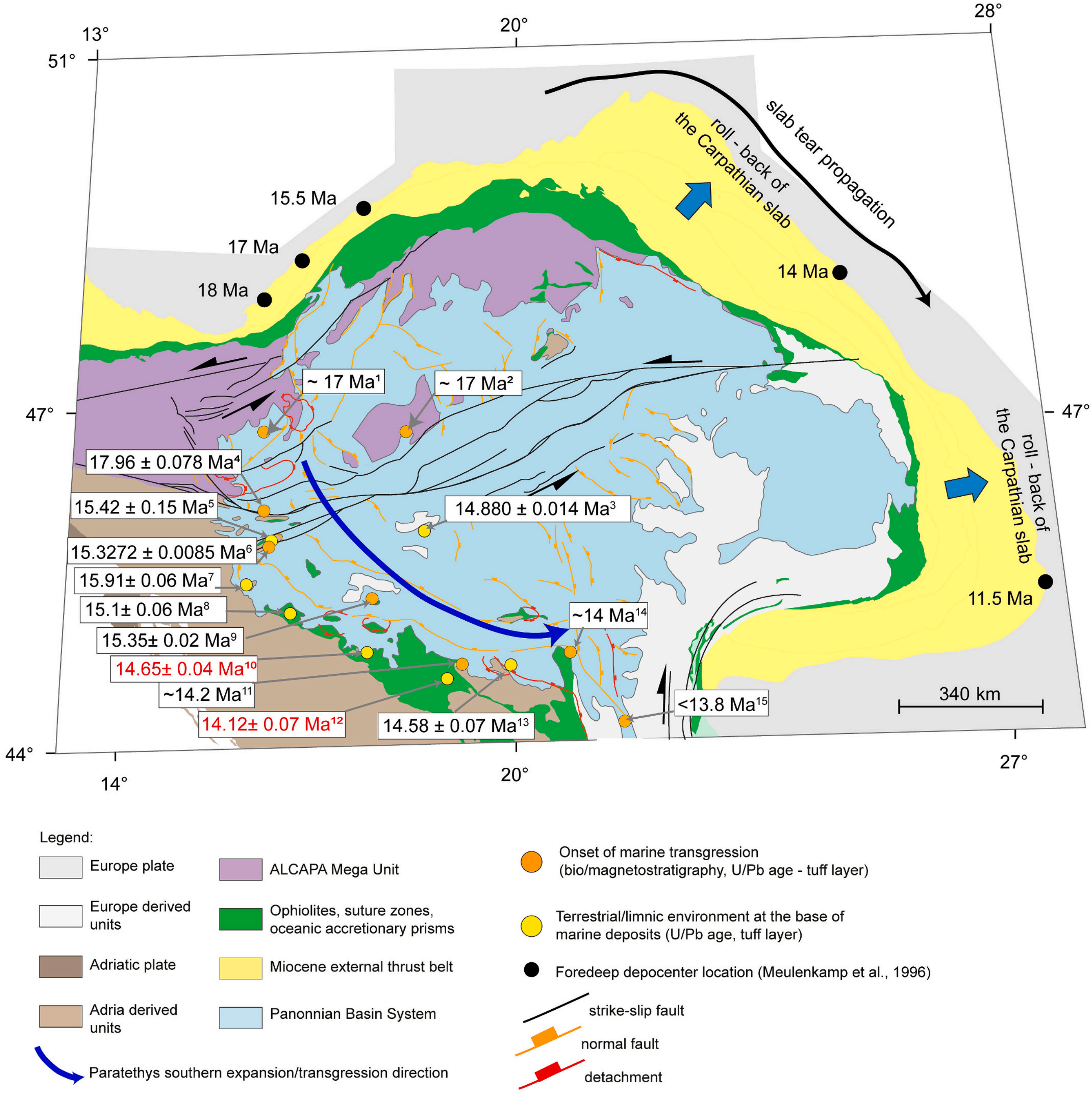

Fig. 5. Simplified geological map of Alpine-Carpathian-Dinarides system including Paratethys realm of the Pannonian Basin System (modified after Schmid et al., 2008). Fault patterns in red, orange and black from Fodor et al. (2021). Age of depocenter location in Alpine-Carpathian foredeep updated according to Piller et al. (2007). Ages indicated in white rectangles from: 1. Styrian B. - Spezzaferri et al., 2009; 2. Varpalota B. - Mandic, 2003; 3. Mecsek Mts. - Sebe et al., 2019; Lukács et al., 2018; 4. Vrbno - Brlek et al., 2023; 5. Laz - Marković et al., 2021; 6. Čučerje - Trinajstić, 2025; 7. Sjeničak - Mandic et al., 2012; 8. Jovac - Marković et al., 2021; 9. Škrabutnik - Brlek et al., 2020; 10. Vijačani - this study (PRV); 11. Ugljevik - Mandic et al., 2019a; 12. Čaklovići - this study (CAK); 13. Koceljeva - Rundić et al., 2024; 14. Slanci - Mandic et al., 2019b; 15. Popovac - Sant et al., 2018. Please note, that the Karpatian ages north of MHZ are here to delineate earlier transgressional phase affecting only the areas north of MHZ. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

magnetostratigraphic and radiometric data available from the sedimentary basins and areas along the southern margin of the Pannonian Basin, starting with the Styrian Basin in the west and ending with the Velika Morava Basin in the east (Figs. 1A, 4, 5). Distance between the most external numerically dated volcaniclastic layers (at Pöls, Austria and Popovac, Serbia) is about 580 km (Fig. 1A). More detailed data presentation for the discussed sections and sites is available from ESM-Table S3.

5.2.1. *Radiometric constraints*

Currently, the **Styrian Basin** (Figs. 1A, 4A, 5) stratigraphy is supported solely by Ar-Ar biotite and sanidine radiometric ages. The original calculations by Handler et al. (2006) have been subsequently recalculated by Sant et al. (2020) who contributed two additional ages for the marine transgression of the western Styrian Basin at Pöls at 14.3 Ma. The continental, coal-bearing deposition in this part of the basin, Ar-Ar dated to 15.4 Ma, apparently continued well into the middle Badenian. For the eastern Styrian Basin, which already represented a marine setting since the latest Early Miocene, the volcanic intercalations into the marine middle Badenian deposits with *Orbulina suturalis* and *Helicosphaera waltrans* have been Ar-Ar dated at Retznei quarry to 14.7 and 14.5 Ma (Handler et al., 2006; Sant et al., 2020; Gross et al., 2007; Hohenegger et al., 2009).

From the **Zagorje Basin** (Figs. 1A, 4D, 5) only one LA-ICP-MS U-Pb zircon age of 18.0 Ma is available from the Vrbno Member of the topmost Macelj Formation at Vrbno ~3 km S Trakoščan in NE Croatia constraining it to the early Ottnangian (lithostratigraphy after Avanić et al., 2021, sample 15a of Brlek et al., 2023). This represents the first numerical dating of the topmost marine deposits of the Slovenian–Hungarian Paleogene Basin followed by regional sea retreat and temporary closure of the Slovenian Corridor between the Central Paratethys and the Mediterranean (Pavelić, 2001; Mandic et al., 2012). Marine deposits superposing the Macelj Formation (i.e. Bednja and Crkovec Fm. of Avanić et al., 2021) have uncertain stratigraphic position. Radiometric dating of intercalated volcanic deposits shall demonstrate if they are representing the Ottnangian 3rd order sequence (Fig. 4D, e.g. Piller et al., 2007) or already the Badenian marine flooding of the southern Pannonian Basin (e.g. Ćorić et al., 2009; Brlek et al., 2020).

One of the most intensively radiometrically dated regions in the southern Pannonian Basin represents the **Mt. Kalnik** region (Figs. 1A, 4E, 5) at the western flank of the North Croatian Basin (NCB, Grizelj et al., 2023). There, alluvial complex underlaying lacustrine and marine Middle Miocene deposits (Pavelić et al., 2001; Mandic et al., 2012) is intercalated by massive volcaniclastics belonging to three eruptive events located in northern Hungary, at 18.1, 17.3 and 17.1 Ma (Brlek et al., 2023, 2024). Seven sites, one on the eastern and six on the western flank of the Mt. Kalnik inselberg, are constrained dominantly by highly precise CA-ID-TIMS U-Pb zircon, followed by Ar-Ar sanidine and by CA-ID-TIMS U-Pb zircon ages (Mandic et al., 2012; Brlek et al., 2020, 2023, 2024). These dates constrain the basal alluvial succession in the NCB to the Ottnangian (Fig. 2A; Piller et al., 2007; Pavelić et al., 2024).

From **Mt. Medvednica** (Figs. 1A, 4F, 5) likely in the western NCB, positioned about 40 km SW of the previous area, *syn*-rift depositional ages from four volcaniclastic layers are available. They were obtained by Ar-Ar volcanic glass and/or by highly precise CA-ID-TIMS U-Pb zircon dating (Marković et al., 2021; Trinajstić et al., 2023; Trinajstić, 2025). Lacustrine marl of Laz, Ar-Ar dated at 15.4 Ma is positioned about 120 m beneath the gradual transition into marine deposition (Pavelić et al., 2024). Lower part of the initial marine deposition represented by offshore marls have been U-Pb dated to 15.3 Ma at Čučerje by Trinajstić (2025), probably from lateral continuation of the volcaniclastic layer recorded in the neighboring partial section Bokanjščica by Premec Fućek et al. (2023). Upper part of the marine deposits at Čučerje partial section Plaz, represented by shallow water marine sands already bearing *Orbulina suturalis*, have been U-Pb dated to 14.9 Ma and 14.8 Ma, respectively (Ćorić et al., 2009; Marković et al., 2021; Premec Fućek et al., 2023; Trinajstić et al., 2023). Such a date challenges the Mediterranean astronomically tuned FO *Orbulina* event, set at 14.56 Ma (Fig. 2A; Lirer et al., 2019).

The **Slavonian Mts.** (Figs. 1A, 4G, 5) located in the eastern NCB provided ages for initial marine deposits in the southern Pannonian Basin similar to Mt. Medvednica. From a 5-m-thick tuff at Škrabutnik in Mt. Požeška gora intercalated about 17 m above the base of the Vejalnica Formation CA-ID-TIMS U-Pb zircon dating derived an age of 15.4 Ma (Brlek et al., 2020, Kopecká et al., 2022). Furthermore, its lateral equivalent provided dated by the same method provided an age of 15.3 Ma (ŠKR-3/21, Trinajstić et al., 2024; Trinajstić, 2025). Additionally, from a tuff of Nježić in Mt. Papuk Ar-Ar volcanic glass dating at 14.4 Ma allows a correlation of the interval bearing *Praeorbulina curva* and missing *Helicosphaera waltrans*, with the middle Badenian (Fig. 2A; Marković et al., 2021).

Freshwater lacustrine deposits of the **Karlovac-Glina** (Figs. 1A, 4J, 5) basin at the external margin of the Pannonian Basin, predating the Miocene marine transgression were dated on two sites. The western site (Sjeničak) provided the Ar-Ar sanidine age of 15.9 Ma, the eastern one (Paripovac) the Ar-Ar feldspar age of 16.0 Ma (Mandic et al., 2012). Such a date proved for the first time independently the absence of regional marine transgression before the onset of the Middle Miocene. Adjoining it to the southeast, the **Una-Sana** basin (Fig. 1A, 4K) exposes similar lacustrine deposits. There, one intercalated volcaniclastic layer provided the Ar-Ar volcanic-glass age of 15.1 Ma (Marković et al., 2021), even postdating the previously mentioned oldest age derived for the initial marine transgression in the eastern North Croatian Basin.

For the next 260 km, between the latter numerical age and the U-Pb zircon datum from the **Kolubara-Tamnava Basin** (Figs. 1A, 4O, 5), the corresponding data are still fully missing. Therefore, the present study of Prnjavor and Tuzla basins fills a substantial gape in numerical dating for the marine transgression on the southern margin of the Pannonian Basin. Recently published results from a drill-core in the SW part of Kolubara Basin, delivered a numerical age of 14.6 Ma for a volcanic tuff layer interstratified within continental clastics about 10 m below the marine basal conglomerate (Rundić et al., 2024).

Finally, 160 km south-eastwards, in the **Velika Morava Basin** (Figs. 1A, 4R, 5), the volcaniclastic layer intercalated with the freshwater marl succession in the cement quarry of Popovac, provided an age of 14.4 Ma. Additionally, the magnetostratigraphic data from the same section suggested that lacustrine deposition continued there at least until 14.1 Ma (Fig. 2A, Sant et al., 2018).

5.2.2. *Bio- and magnetostratigraphic age constrains*

During the Karpatian and Badenian, the Slovenian Corridor (Fig. 1B) was the only connection of the Central Paratethys to the open sea with the Mediterranean Sea (see above). Such a configuration is reflected in the distribution of its biota including important biostratigraphic markers such as planktonic foraminifera and calcareous nannoplankton. Therefore, the bioevents such as the first and the last occurrence of index species are anticipated to be quasi-synchronous between these two paleogeographic domains (Fig. 2A, Sant et al., 2017, 2019).

In the Central Paratethys, the most important bioevents on the marine Karpatian and Badenian deposits (Fig. 2A) are for the calcareous nannoplankton - FO *Helicosphaera waltrans* in the lower Badenian, LO *H. ampliaperta* (base NN5a) and LO *H. waltrans* (base NN5b) in the middle Badenian, and LO *Sphenolithus heteromorphus* (base NN6) in the upper Badenian. For the planktonic foraminifera these are FO *Trilobatus sicanus* (= *T. bisphericus*) in the uppermost Karpatian, FO *Praeorbulina glomerosa* in the lower Badenian, and the FO *P. circularis* and FO *O. suturalis* in the middle Badenian. Note however that the currently derived numerical age of the latter bioevent in the Central Paratethys with 14.9 Ma (Marković et al., 2021; Trinajstić et al., 2023) is challenging the Mediterranean one (14.6 Ma, Lirer et al., 2019), which evidently calls for revision (Fig. 2A).

Applying the latter stratigraphic concept combined with paleomagnetic data, Sant et al. (2017, 2020) proposed a revision of the Styrian Basin second marine transgression pulse placing it at 15.2 Ma, instead of the previously estimated 16.1 Ma (Hohenegger et al., 2009). Following this example, we are proposing here a revision of two sections in the North Croatian Basin, currently suggested to document the Karpatian marine transgression.

The 100-m-thick composite section Čučerje on Mt. Medvednica (Fig. 1A, 4F) with its subsections Bokanjščica (58 m) and Plaz (42 m), documents the initial marine transgression in this area. Its upper part with *Orbulina suturalis* and middle part with *Praeorbulina* sp. (Fig. 2A) were correlated with the early Badenian, whereas its lower part with *Helicosphaera waltrans* was set to uppermost Karpatian (Premec Fućek et al., 2023). Actually, the astronomically dated FO *H. waltrans* in the Mediterranean is dated to 15.7 Ma, whereas its first regular occurrence (FRO) starts at 15.4 Ma (Fig. 2A; Turco et al., 2017). Thus, the presence of this species already in the lowermost sample of the section, questions the Karpatian age of 16.1 Ma proposed by authors. Also, the level with *Praeorbulina* set by authors to 15.5 Ma, is essentially younger than 15.2 Ma (Lirer et al., 2019). Based on revised data, 15.7 Ma or 15.4 Ma must be considered as the maximum reliable age for the section, based on the FO and FRO *Helicosphaera waltrans* in the Mediterranean.

Such a biostratigraphic revision is highly supported by the current U-Pb dating of 15.3 Ma from an isolated site positioned 250 m W from the base of Bokanjščica partial section (Fig. 1A; Trinajstić, 2025). Although, its correlation to the section is hampered by bad outcrop conditions, the correlation to undated volcaniclastic layers indicated at 25 and 28 m height of the latter section (Premec Fućek et al., 2023) is well possible. Note however, that latter ages might stay in conflict with the radiometric age of the tuff level in the limnic deposits of nearby Laz on Mt. Medvednica predating the marine transgression (Fig. 1A; 15.4 Ma; Marković et al., 2021). As stated in the previous chapter, this tuff is positioned in the regional continental succession well below the actual flooding surface, suggesting potentially a much younger age for the NCB marine flooding (Pavelić et al., 2024). Yet, with the new data from Trinajstić (2025), even three radiometric datings from Mt. Medvednica and Slavonian Mts. support the hypothesis on the ~15.3 Ma age for the regional transgressive event set originally in Brlek et al. (2020), being consequently well established. Therefore, the age of the Laz volcaniclastic shall be ideally proven by the same radiometric method used for marine volcanoclastic layers to overcome the analytical uncertainties. In case the ~100 ka difference proves right, we might explain the controversy by increased depositional rates typical for marginal deltaic environments (Einsele, 2000).

The marine Mala site and the lacustrine Poljanska section (Fig. 1A) are positioned only ~5 m apart on the opposite sides of the Poljanska creek in NW Slavonian Mts. (Fig. 4G; Hajek-Tadesse et al., 2023). The former bears an assemblage of small sized planktonic foraminifera, sharing four species with the previously discussed Čučerje section (Premec Fućek et al., 2023). Except for the erratic presence of two probably reworked Paleogene species (*Globoturborotalita ouachitaensis* and *Paragloborotalia nana*; Spezzaferri et al., 2018; Leckie et al., 2018), all other species are normally present in the Badenian (Cicha et al., 1998; Rupp and Hohenegger, 2008; Hohenegger et al., 2009; Mandic et al., 2019b; Premec Fućek et al., 2023; this study). As marine Early Miocene deposits have never been established in this region, we interpret here the Mala site as a tectonically subsided block made of Badenian marine deposits.

5.3. *Paleogeography of the marine transgression*

The presented and discussed stratigraphic data facilitate as next a more precise reconstruction of the Miocene gradual marine flooding of the southern Pannonian Basin (Figs. 4, 5, 6). In particular the radiometric dating allows a consistent and independent control on timing of the changes in land-sea configuration, because the competence of marine stratigraphy in restricted basins, can be easily overestimated, providing the correlations ambiguous (Mandic et al., 2012; Kováč et al., 2018; this study).

Herein presented paleogeographic reconstructions (Figs. 4A-B) are centered to four glacioeustatic cycles recorded during the Miocene Climatic Optimum and Climatic Transition (Miller et al., 2020) coinciding with the placement of Karpatian and intra-Badenian boundaries (Figs. 2A, 4, 5; Piller et al., 2007; this study; see next chapter). The maps represent revisions of a number of previously published paleogeographic and sediment distribution maps including the study region such as Dax et al., 2024; Gross et al., 2007; Hámor, 1988; Ivančič et al., 2024; Kováč et al., 2003, 2007, 2017, 2018; Krstić et al., 2003, 2012; Mandic et al., 2012, 2019c; Palcu et al., 2015; Pavelić and Kovačić, 2018; Pavelić et al., 2024; Popov et al., 2004; Rögl, 1998, 1999; Sant et al., 2017, 2019; Rögl and Steininger, 1983; Vrsaljko et al., 2005; among others. Beyond that the georeferenced geological maps covering the study region have been consulted, such as 1:100.000 and 1:500.000 scale maps of former Yugoslavia, 1:100.000 of Hungary, and 1:200.000 of Austria, among others, along with other regional geological literature as cited in text and captions (Figs. 4 and 6).

5.3.1. *Karpatian (17.2–16.0 Ma)*

During our time window (Karpatian-Badenian) the only connection of Pannonian Basin to the open sea was the Slovenian Corridor, striking alongside the Southern Alpine Foreland Basin into the northern Mediterranean Sea (Fig. 6A; Massari et al., 1986; Rögl, 1999). It can be well assumed, that this connection was continuously active since the Karpatian, finally disrupted during the Badenian-Sarmatian transition (Fig. 2A; Harzhauser and Piller, 2007; Mandic et al., 2019a).

North of latter strait on the Eastern Alpine unit (Fig. 1A), biostratigraphically dated Karpatian initial marine sediments are present above continental deposits in the Styrian (Ebner and Sachsenhofer, 1995; Sachsenhofer et al., 1997; Spezzaferri et al., 2009; Hohenegger et al., 2009), Slovenj Gradec (NN4a, Ivančić et al., 2018), Mura-Zala (Márton et al., 2002; Kováč et al., 2003; Nádor et al., 2012; Fodor et al., 2013) basins, among others, superposing basement or Lower Miocene continental deposits (Fodor et al., 1998; Jelen and Rifelj, 2002, 2003; Ivančič et al., 2024, 2025). Those sediments can be more than 700 m thick in the Styrian Basin (Fig. 4A; Schreilechner and Sachsenhofer, 2007) and reach up to 300 m in Slovenj-Gradec Basin (Fig. 4B; Ivančić et al., 2018), documenting high sediment accumulation rates typical for rift basins. Conspicuously, the Karpatian transgression has not been recorded south of the Periadriatic–Donat–Balaton fault zone marking the contact with Southern Alps (Figs. 1A, 5; Fodor et al., 1998; Mandic et al., 2012; Ivančič et al., 2025).

The initial synrift deposits in the southern Pannonian Basin are dominated by alluvial conglomerates, sandstones and silts, pointing to strong erosion of uplifting core-complexes (Pavelić and Kovačić, 2018). Volcaniclastics intercalated to these continental deposits at Mt. Kalnik belonging to most intensively dated rocks to date, show there uniformly Ottnangian-Karpatian ages between 18.1 Ma and 17.1 Ma (Figs. 1A, 4E). Similar sediments are known from outcrops and drill cores in the whole NCB interpreted consequently as one uniform rift system accommodating huge alluvial plains, fed by the material from uplifting Internal Dinarides core-complexes (Pavelić et al., 2024). Dominantly reddish in colour and incorporating salina-lake deposits at Poljanska in Slavonian Mts. these deposits mark a conspicuous long-term, generally arid interval in the southern Pannonian Basin (Figs. 1A, 4G, 6A). Corresponding deposits are widely present in the southern Hungary likely underlaying the Miocene marine deposits (Figs. 4H, 6A; Horváth et al., 2015; Sebe et al., 2019; Selmeczi et al., 2024; Neubauer et al., 2025).

5.3.2. *Early Badenian (16.0–14.8 Ma)*

Despite a great number of biostratigraphic data suggesting the middle Badenian age for the initial marine flooding in NCB (Pavelić and Kovačić, 2018), the numerical ages of ~15.3 Ma from basal marine

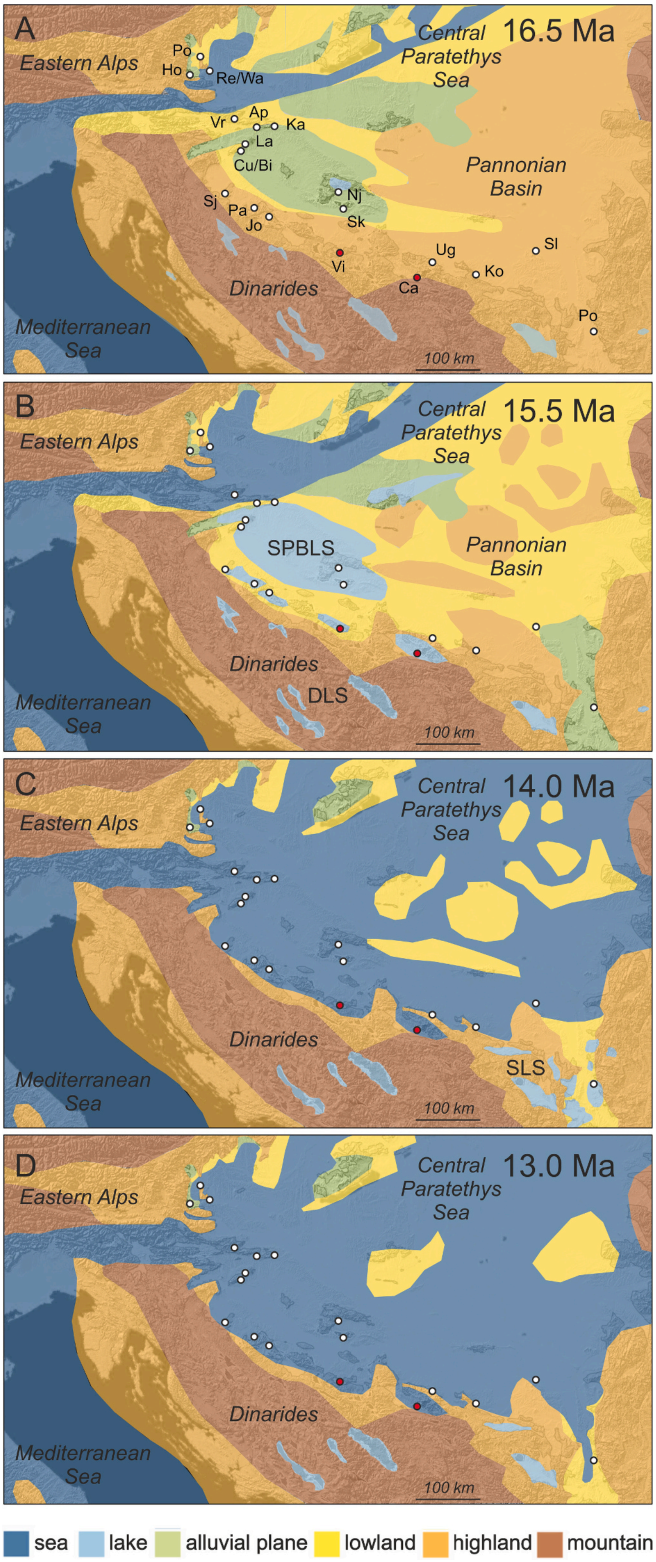

Fig. 6. Paleogeographic reconstruction of the southern Pannonian Basin step-wise marine flooding displaying the maximum sea extent for the indicated time windows. It is based on the present sediment distribution and its eroded/consumed record predicted along the Periadriatic – Mid-Hungarian tectonic zone. The fault pattern is from Fodor et al. (2021). Red dots are studied localities; white dots are geochronological calibration points based on literature data (see also Fig. 1A; see text and ESM-Table S3 for references). Abbreviations – Styrian B.: Po – Pöls, Ho – Hörmsdorf; Re/Wa – Retznei and Wagna; Zagorje B.: Vr – Vrbnik; Kalnik Mt.: Ap – Apatovac, Ka – Kalnik, Medvednica Mt.: La – Laz, Cu/Bi – Čučerje and Bidrovec; Karlovac-Glina B.: Sj – Sjeničak, Pa – Paripovac; Una-Sana B.: Jo – Jovac; Slavonian Mts.: Nj – Nježić, Sk – Škrabutnik; Prnjavor B.: Vi – Vijačani; Tuzla B.: Ca – Čaklovići; Ugljevik B.: Ug – Ugljevik; Kolubara-Tamnava B.: Ko – Koceljeva; Belgrade region: Sl – Slanci; Velika Morava B.: Po – Popovac. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

successions on Medvednica and Slavonian Mts. proves late early Badenian initiation of marine environment there (Fig. 1A, 2A, 4E,F, 6B; Brlek et al., 2020; Trinajstić, 2025). Such an age challenges a similar datum in lacustrine sediments on Medvednica, which might be explained by a methodological dating error (Ar-Ar vs. U-Pb) of the latter, or by high depositional rate in a deltaic setting of ∼120 cm/kyr or lateral facies shifts and co-existence of marine and lacustrine conditions in marginal settings. In general, the basin is understood as a broad and flat rift valley in front of the Dinarides Mountains encompassing Sava, Požega, and Drava basins (Pavelić et al., 2001, 2024; Tišljar, 1993; Pavelić and Kovačić, 2018; Rukavina et al., 2023; Bigunac, 2022). Such an interpretation is based on identical sedimentary successions across the NCB, suggesting formation of a large-size uniform lake environment (Fig. 6B). The latter was tentatively marked by iterative marine overspills from the Central Paratethys, based on the ostracod record, but estuarine biota typical for marine brackish conditions are truly absent (Mandic et al., 2012, 2019c). This NCB Lake must have been ultimately formed before the dam break, prompting the final ingression of marine water into the basin, because everywhere it shows transitional contacts to lacustrine deposits whereas the transgressive lags over the basement are missing (Pavelić et al., 2024; Pavelić and Kovačić, 2018). Based on data from Mecsek Mts., the NCB lake was probably connected to that area (Fig. 4H, 6B, Sebe et al., 2019; Selmeczi et al., 2024; Neubauer et al., 2025).

Before reaching its full size a greater number of smaller lakes might have existed, bounded to areas of elevated subsidence (Rukavina et al., 2023). Such a scenario prompted the separation of the slightly brackish Southern Pannonian Lake System (SPLS) from the fresh water Dinarides Lake System (DLS) coexisting in the intramountainous valleys of the southern adjoining mountain range (Fig. 6B; Mandic et al., 2019c).

Badenian period has been characterized by major pulse in extension which already during Karpatian started dissecting the NE Dinarides into a series of tectonic windows (e.g., Mt. Medvednica, Mt. Motajica, Mt. Cer, Mt. Bukulja, Figs. 1A,C). There, the metamorphic cores were exhumed along low-angle detachments (Ustaszewski et al., 2014; Stojadinović et al., 2013). The large offsets provided accommodation space for the coming marine invasion of Central Paratethys, affecting the major depocenters such as Sava or Drava basins (Balázs et al., 2016). The secondary brittle structures developed on the tectonic islands, might provide accommodation space for lacustrine basins, leading to coeval marine and lake depositional systems, although the available data depict those mainly bounded to marginal mountainous areas.

For example, in the early Badenian, the radiometric and biostratigraphic data points to coexistence of lacustrine and marine environments in the Styrian basin. There, but also elsewhere north of the Donat and Balaton faults (Tari, 1994; Fodor et al., 2013, 2021; Nyíri et al., 2021), the Styrian unconformity is marked by angular disconformity between Lower and Middle Miocene deposits well exposed in the Wagna Section in its eastern sub-basin (Gross et al., 2007; Hohenegger et al., 2009). The second, Middle Miocene marine transgression was biomagnetostratigraphically constrained there by the FO *Praeorbulina* to 15.2 Ma pointing to a long sea retreat since the late Karpatian forced regression (Fig. 2A; Sant et al., 2020). In the western Styrian Basin limnic deposition was radiometrically dated to 15.4 Ma and 15.5 Ma, the overlaying marine deposits at 14.3 Ma and 14.0 Ma (Sant et al., 2020). This suggests the parts of the western Styrian basin might have preserved the continental settings into the middle Badenian. In Karpatian this part of the Styrian Basin was largely continental (Figs. 4A, 6B, Gross et al., 2007; Dax et al., 2024).

5.3.3. Middle Badenian (14.8–13.8 Ma)

The middle Badenian (Figs. 2A, 6C) is in general biostratigraphically marked by the FO of *Orbulina* (Hohenegger et al., 2014; Pavelić and Kovačić, 2018), radiometrically dated on Mt. Medvednica to 14.9 Ma (Trinajstić et al., 2023). Such a date coincides with the LO *Helicosphaera ampliaperta* marking the onset of biozone NN5 (Martini, 1971). Previously applied Mediterranean FO *Orbulina* at 14.56 Ma (e.g. Šegvić et al., 2023) is correspondingly downshifted in the present study (Fig. 2A). The previous magnetostratigraphic dating from the Mediterranean (Abdul Aziz et al., 2008; Lirer et al., 2019) might likely need revision.

The biostratigraphic constraint of 14.9 Ma for the gradual transition from lacustrine to marine conditions was established in the Sokolovac (Gornji Vrhovci) section on Mt. Papuk (Fig. 1A; Pavelić et al., 1998; Ćorić et al., 2009). Corresponding transitional marine environment at Škrabutnik dated older to 15.3 Ma and set into the topmost NN4 zone (Fig. 2A, 4G; early Badenian; see also previous chapter) has been described from the southern Slavonian Mts with biotic assemblages and geochemical data, proving high nutrient inputs and increased freshwater impact (Brlek et al., 2020; Kopecká et al., 2022). Neighboring section in the same region dated to NN5a showed in contrast a distinctive middle Badenian fauna with *Orbulina suturalis* marking already established stable; fully marine middle Badenian conditions (Kopecká et al., 2022).

Our new data from the Prnjavor Basin in northern Bosnia and Herzegovina (Figs. 1A,C, 4L), show in contrast no transitional facies between the limnic and marine deposits. The volcaniclastics dated at 14.7 Ma and 14.6 Ma, underlaying the basal conglomerates (Fig. 2B; Eremija, 1969) fully constrain the lower part of the middle Badenian and coincide with the marine calcareous plankton assemblages with *Orbulina suturalis* and *Helicosphaera waltrans*. This coincides with the data from northwestwards adjoining Una-Sana and Karlovac-Glina basins (Figs. 1A, 4J,K) demonstrating the presence of lacustrine deposits through the Karpatian and early Badenian with radiometric ages ranging from 16.0 Ma to 15.1 Ma (Mandic et al., 2012; Marković et al., 2021).

In contrast to western parts of the southern Pannonian Basin, further to the east the marine onset occurs consistently after the LRO *Helicosphaera waltrans* dated in Mediterranean at 14.36 Ma (Fig. 2A; Abdul Aziz et al., 2008), in the upper part of the middle Badenian. This event has been initially biomagnetostratigraphically dated to ∼14.2 Ma at Ugljevik (Figs. 1A, 4N, 5; 6C; Mandic et al., 2019a). The later outcrop shows a continuous marine middle-late Badenian succession making it the excellent reference section for that interval. Further to the east, based on marine calcareous plankton quantitative study, the same aged basal marine transgressive interval has been detected at Slanci, near Belgrade (Figs. 1A, 4P, 5, 6C, Mandic et al., 2019b). There (Fig. 6C), the marine deposits overlay limnic succession of the Serbian Lake System (SLS) although the character of their boundary is not well understood due to the lack of outcrops in that area (Krstić, 1996; Dolić, 1997).

The record of the initial marine transgression on Mt. Fruška Gora (Fig. 1A) is marked by the presence of *Orbulina suturalis* and benthic foraminifera assemblage of the Lagenidae Zone (Rundić et al., 2013). However, the absence of calcareous nannoplankton data currently prevents a more precise setting within the middle Badenian interval. Furthermore, data defining the nature of the marine transgression and the age of continental deposits below it, are likely missing (Rundić et al., 2013). In contrast, recently published results from the SW part of Kolubara-Tamnava Basin (Fig. 1A, 4O), based on radiometric dating (14.58 Ma) of tuff interstratified within pre-marine continental clastics, along with the biostratigraphic record from initial marine deposits identical to Ugljevik and Slanci, suggest, the onset of the regional Badenian transgression at ∼14.2 Ma (Rundić et al., 2024).

Our data from the Tuzla Basin (Figs. 1C, 2C, 3, 4M) likely set the initial marine transgression to the late middle Badenian. The volcaniclastic layer dated at 14.1 Ma is intercalated to deltaic lacustrine conglomerates grading upward to limnic silt and clay followed continuously by marine marls. The calcareous plankton assemblage set to upper NN5, is in line with our radiometric dating (Fig. 2A).

5.3.4. Late Badenian (13.8–12.7 Ma)

This interval represents the final flooding of the southern Pannonian Basin by the Paratethys Sea marked by its inflow into the Velika Morava basin, documented by marine deposits reaching southwards to the area of Kruševac (Figs. 1A, 4R, 5, 6D; Anđelković et al., 1991). Slightly northward in the Popovac cement quarry near Paračin, SLS deposits have been radiometrically dated at 14.4 Ma with topmost level in the section astronomically tuned at 14.2 Ma (Sant et al., 2018). The latter succession is overlain by about 350 m of continental SLS deposits. Near Paraćin, as well as, in many other marine sites along the Velika Morava Basin, exclusively late Badenian sediments have been detected based on micro- and macropaleontological data, superposing basement rocks and continental deposits or alternating with the latter (Figs. 1A, 4R, 5, 6D; Petronijević, 1967; Dolić et al., 1981; Bradić-Milinović and Vuković, 2024).

5.4. Glacioeustatic vs. tectonic forcing of the transgression

Karpatian and Badenian ages (Fig. 2A) are coinciding with the global period of intensive climate change termed the Miocene Climate Optimum (MCO, 17.0–14.8 Ma) and the subsequent Middle Miocene Climate Transition (MMCT, 14.8–12.8 Ma) (Fig. 2A; Miller et al., 2020). The climate variation was orbitally forced at 400 kyr with maxima probably

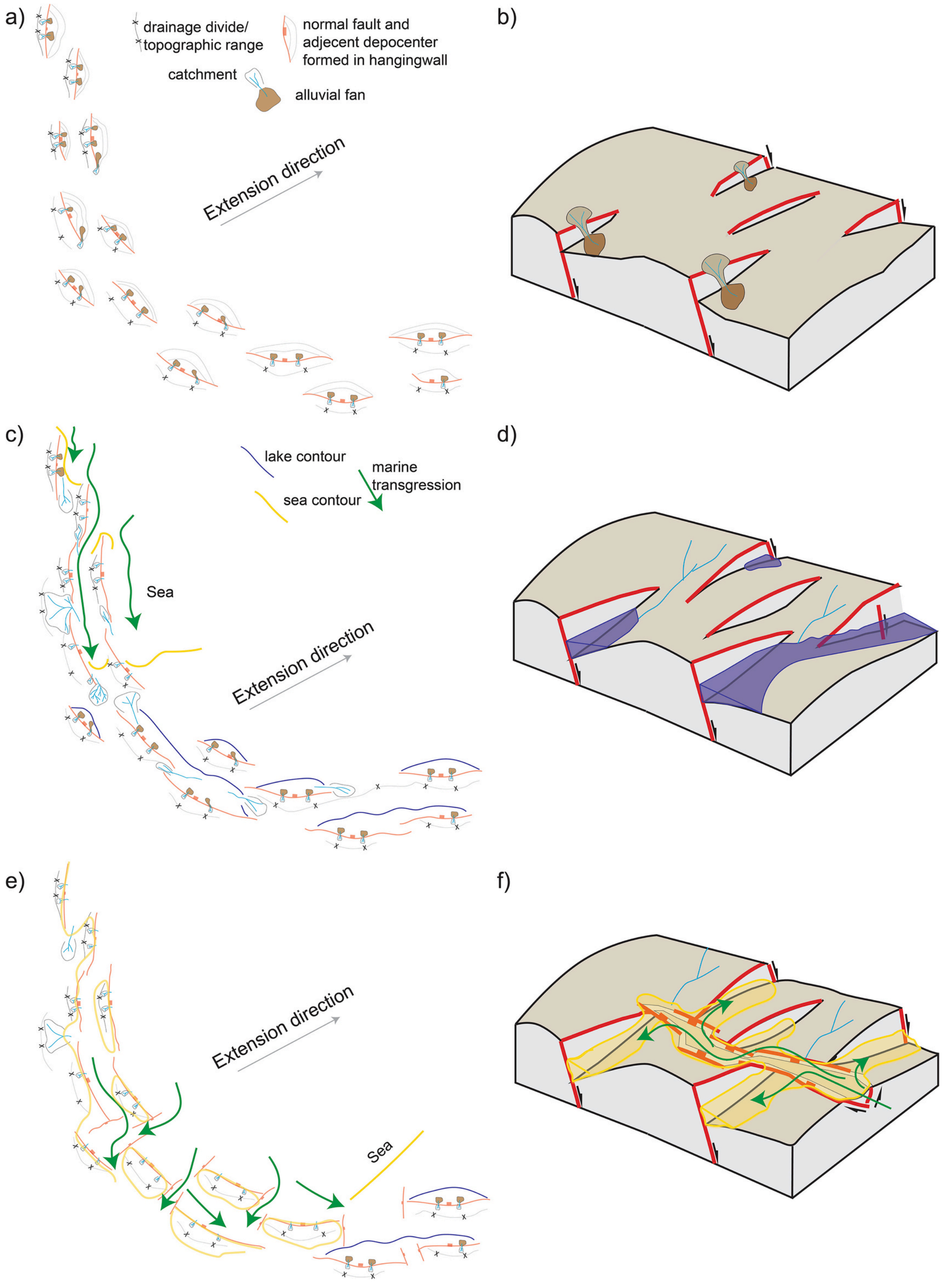

Fig. 7. Fault propagation and linking mechanism controlling basin connectivity and overall transgression direction. See detailed explanation in text.

prompting the last ice-free world in geological history. The major glacioeustatic sea-level falls termed Miller-events (Mi) coinciding with the long tilt minima, occurred at million-years-scale and supported boundary definitions of several standard and regional geological chronostratigraphic units (Piller et al., 2007; Hilgen et al., 2012). Hence, the Karpatian-Badenian (Burdigalian–Langhian, Early–Middle Miocene) boundary (16 Ma) marked by a 40 m sea-level fall, correlates with Mi2. Lower-middle Badenian transition roughly correlates with the Mi3a expressed by a 30 m fall (14.8 Ma). Middle–Upper Badenian (Langhian–Serravallian) boundary correlates with Mi3b expressed by a 50 m fall (13.8 Ma). Finally, the Badenian–Sarmatian boundary coincides roughly with a 20 to 30 m fall at 12.8 Ma (Mi4). After MMCT the Eastern Antarctic Ice Cap (EAIC) became permanent and the deep-sea temperature remained stable and low (<5 °C), causing the end of dynamic Early–Middle Miocene sea level change (Miller et al., 2020). Note that the current synthesis of Badenian chronostratigraphy (Kováč et al., 2018) advocates its twofold subdivision with the lower part identical to the standard Langhian stage (Raffi et al., 2020; Fig. 2A). The seismic data from the Styrian and Vienna basin demonstrate however the Badenian threefold architecture in line with its herein adopted subdivision (Figs. 2A, 4; Harzhauser et al., 2020; Siedl et al., 2020; Dax et al., 2024).

Independent of global eustatic changes, regional diachronous tectonic activity (Matenco and Radivojević, 2012; Balázs et al., 2016; Fodor et al., 2021) likely influenced relative sea levels across the Pannonian realm by raising or lowering coastal areas and affecting the basin volumes. By reviewing the available published and our new dates for the expansion of the Central Paratethys a stepwise south-southeastward trend has been observed (Figs. 1A, 4, 5, 6). During the first step in the latest Early Miocene (Karpatian), the marine realm invaded previously terrestrial depositional environments and land masses in the Styrian, Slovenj Gradec and Mura-Zala basins, located north of the Mid-Hungarian line (Sant et al., 2020; Fodor et al., 2021). This region was strongly affected by *E*-directed lateral extrusion (also known as escape of the Eastern Alps; Ratschbacher et al., 1991) and subsequent rotation of the underlying ALCAPA Megaunit (e.g., Fodor et al., 1998, 1999). This led to extension and exhumation of Alpine nappes (Pohorje, Rechnitz, at around 21–18 Ma; Dunkl and Demény, 1997) and formation of the intramountain basins in the immediate hangingwall (e.g., Strauss et al., 2001; Fodor et al., 2021). It is still unclear the contribution of the Carpathian slab roll-back to extension during this phase.

The limited extent of this transgression can be attributed to two possible explanations. First, synchronous or earlier transpressional tectonic events along the Periadriatic fault and Mid-Hungarian Shear zone (e.g., Fodor et al., 1998, 1999; Wölfler et al., 2011) were responsible for creating a "wall" that prevented further marine transgression to the south at this point. Second, although also affected by the initial phase of extension (Schefer et al., 2011; Stojadinović et al., 2013; Toljić et al., 2013; Andrić-Tomašević et al., 2024) pre-existing likely higher topography south of the Mid-Hungarian Shear zone stayed above sea level (Figs. 1A, 5, 6A,B). The increased elevation along the Mid-Hungarian zone has already inferred from the northward-directed paleotransport direction supplying Miocene remnant of the North Hungarian Paleogene Basin (Sztanó, 1994).

Styrian unconformity relates to regional tectonic phase of Eastern Alps coinciding with the glacioeustatic Mi2 sea-level fall at ~16 Ma (Fig. 2A, 4; Dax et al., 2024). Their combined effects by these forces affected the tectonic block tilting, sea retreat from the marginal environments and long-term increased erosion levels for up to 800 kyr in the Styrian Basin (Fig. 4A; Sant et al., 2020). In basinal depocenters the sedimentation probably continued (Hohenegger et al., 2009; Dax et al., 2024).

Coevally with the aforementioned extensional phase (21–17 Ma, if not earlier, in some cases ~27 Ma), the Dinarides (Fig. 1A; e.g., Schefer et al., 2011; Erak et al., 2017) were also affected by extension. This was represented by numerous metamorphic cores that started their exhumation along low-angle detachments (e.g., Studenica and Kopaonik metamorphic cores, Schefer et al., 2011, Cer, Löwe et al., 2023, Jastrebac, Erak et al., 2017, Bosansko Škriljavo Gorje, Casale, 2012). As a consequence, a large number of lakes form in the local topographic minima developed in the hanging walls of the faulted domains (Fig. 1A, e.g., Valjevo-Mionica Basin, Šamarija et al., 2026b; Ibar Basin, Andrić-Tomašević et al., 2025; Sarajevo-Zenica Basin, Andrić et al., 2017; Pranjani Basin, Andrić-Tomašević et al., 2021; Sava, Požega and Drava Basins Pavelić and Kovačić, 2018). At first, these lakes were internally drained, i.e., endoreic, acting as a local base levels and trapping sediments eroded from the immediate footwall and local drainage (e.g., Kováč et al., 2018; Andrić-Tomašević et al., 2021; Pavelić et al., 2024).

However, over time, field observations indicate that some previously isolated lakes are beginning to communicate with each other (Figs. 1A, e.g., Sava, Požega and Drava, basins, Pavelić and Kovačić, 2018; Sinj and Drniš basins, Neubauer et al., 2016).

The potential mechanisms responsible for the hydrological connection between intramountain basins, which could be later used by the sea to flood basins closer to the Pannonian realm, may be structurally induced drainage integration (e.g., Spencer and Pearthree, 2001; Cowie, 1998; Geurts et al., 2018). In the tectonically active region, as in the study area, it is expected that extensional fault growth and structural linkage of adjacent fault segments affect the topography of intra-basin areas, leading to basin hydrological linkage close to its strike (Fig. 7; e.g., Gawthorpe and Leeder, 2000; Cowie et al., 2006; Geurts et al., 2018).

According to this model early rifting creates isolated depocenters in the hangingwall of the normal fault (Figs. 7A,B). These were supplied by alluvial fans along the immediate footwall, which is observed in the Pannonian realm (Pavelić and Kovačić, 1999; Pavelić et al., 2001, 2024; Andrić et al., 2017; Andrić-Tomašević et al., 2021). As faults propagate and begin to interact with adjacent fault segments, the accommodation space increases and includes segmented half-graben depocenters connected by transfer zones (Figs. 7C,D, e.g., Gawthorpe and Hurst, 1993). These zones, e.g., relay ramps form low elevation corridors that facilitate across the fault hydrological pathways, allowing axial flows to enter neighboring halfgraben. The subsequent fault growth and active subsidence not only increase the accommodation space but also dissect the topography, providing new hydrological pathways along and across the fault strike.

It is noteworthy that locally recorded changes in the extensional field led to brittle deformation in some cases, oblique to perpendicular to the major low-angle detachments, which could cut through the previous topography, providing a new hydrological path connected intramountain basins in the direction perpendicular/oblique to the strike (Figs. 7E,F). It is noteworthy that recorded shifts of up to 90° in the extensional stress field (e.g., Ilić and Neubauer, 2005; Mladenović et al., 2014; Porkoláb et al., 2019) produced faults cutting the low-angle detachments (e.g., Schefer et al., 2011; Stojadinović et al., 2013) and preexisting topography, potentially creating new hydrological pathways at the angle to its strike. This would allow connection with the basins in the hinterland-backstep direction. Such changes are in the Dinarides are recorded in the area of Kopaonik, Bukulja, Cer, and V. Morava Basin (Fig. 1A, where older structures resulting from N(NE)-S(SE) extension (~21–17 Ma, Schefer et al., 2011; Löwe et al., 2023) were overprinted by E-W directed extensional structures (Schefer et al., 2011; Andrić-Tomašević et al., 2024).

Taking all together, the overall transgressive trend would not follow extensional direction (in this case towards N-NE) but will have orientation parallel to oblique to the basin bounding fault strike (in our study area overall direction is towards SE to E) (Figs. 5 and 7).

Following mechanism described above, the continuation of extension and fault growth allowed for a further southward expansion of the Central Paratethys marine domain by subsidence, starting with Zagorje Basin in the early Badenian (Figs. 1A, 4D; Ivančič et al., 2025), continued by the flooding of the NCB at 15.3 Ma in the late early Badenian (Figs. 1A, 4E-G; Brlek et al., 2020), and succeeding with the peripheral Dinarides during the middle Badenian (Fig. 1A, 4I-P, 14.9–14.6 Ma from Krško to Prnjavor and 14.2–14.1 Ma from Ugljevik to Belgrade; this study). The reason for this delay is twofold. First, the observed diachroneity in transgression-regression cycles between individual basins during the Badenian (early, middle, and late) can be related to the migration of extension (Balázs et al., 2017a, 2017b). However, constraints on subsidence rates in individual basins along the NE Dinarides are lacking, therefore, this hypothesis still needs to be tested. Second, that diachronous accommodation space creation may be influenced by local parameters such as fault length, relative fault positions, inherited structures, lithological variations, pre-existing topography, karstification, height of the sill (Jackson and Rotevatn, 2013; Matenco et al., 2016; Geurts et al., 2018; Jackson et al., 2017; Eskens et al., 2025).

Previous authors already suggested Carpathian slab roll-back to be a dominant driver of extension during Badenian-Sarmatian times (e.g., Balázs et al., 2016; Fodor et al., 2025a, 2025b). Continued subduction lengthens the subducted slab, increasing slab pull (e.g., Duretz et al., 2014), triggering rollback, and producing trench retreat and extension in the upper plate (e.g., Xue et al., 2022). This process overtakes control on tectonic processes resulting in E-NE extension migration observed both north and south of MHZ (e.g., south of MHZ, it lasted between 15 and 9–8 Ma, Balázs et al., 2016; Fodor et al., 2021, 2025a, 2025b), while the contraction was still ongoing in the Carpathians. Considering previous models on the Carpathian slab tearing, we expect along strike variable slab roll back and thereby extensional rates. Previous authors, suggested slab tear propagation along the Carpathian chain which passed by Mid-Hungarian zone around early to middle Badenian (Fig. 5; Meulenkamp et al., 1996; Oszczypko and Oszczypko-Clowes, 2012; Jipa, 2018). As the tear propagates, it leads to increase in slab pull, and likely roll back and extension, as the larger portions of the slab remain hanging on the smaller surface area (Maiti et al., 2024). This would mean that during and after Badenian times, the stronger slab-roll back was affecting the Pannonian Basin domain south of Mid-Hungarian zone. Interestingly, this temporarily and spatially correlates with the period of the marine transgression and its propagation to the south observed in our study area.

Above-described evolution was coeval with major see-level changes, i.e. with the third-order sea-level cycle MSB2.3 (~14.7–13.9 Ma, John et al., 2011). Subsequently, the major sea level drop at Mi3b, forced the pausing of the transgression in the area of Belgrade. Thus, after a "significant delay" the marine transgression reached finally the Velika Morava Basin at ~13.5 Ma within the late Badenian transgressive pulse (Figs. 1A, 4R, 6D, Dolić, 1980).

Taking all together the marine realm spread over a distance of about 600 km (Fig. 1A) from Styrian Basin to Velika Morava Basin within ~3.5 Myr leading to average transgression rates of 170 km/Myr. This represents however not a continuous process, because the transgression is additionally controlled by the sea level variation forcing breaks induced by the relative sea level falls and acceleration during the relative sea level rises. It is noteworthy that the Pannonian Basin domain includes numerous subbasins whose accommodation space is influenced by temporal and spatial variations in tectonic forces, heterogeneous pre-existing structural fabrics, and pre-existing topographic variations. Even though Early Miocene diffuse extension affected a wider area of Dinarides and Pannonian Basin, the strong compartmentalisation of these areas would prevent a single eustatically driven transgressive phase from flooding the entire area within couple of 10^5–10^6 years. It is simply because the local connections (gateways) between these basins did not open coevally. This likely hindered the flooding wave coming from the Mediterranean through the Slovenian Gate from reaching its maximal extent already in the Karpatian.

6. Conclusions

Three new U-Pb zircon ages provided for the very first time numerical radiometric data on the Central Paratethys marine transgression in Bosnia and Herzegovina, setting it uniformly to the middle Badenian. The latter time interval coincides with the massive eastward expansion of the marine setting in the Pannonian Basin and correlates with the peak of extensional synrift tectonics expressed by boosting of core complex exhumation along its southern margin, delineated by the Internal Dinarides and the Sava Zone. Beyond that, the achieved dates prove the trend of eastwards younging of the extension along the Dinarides strike. Hence, in the west, marine transgression was dated in the Prnjavor Basin to 14.8 Ma and 14.6 Ma, whereas in the east, age of 14.1 Ma from the Tuzla Basin is half a million year younger, and it is even younger by at least 0.3 Ma further to the southeast.

The latter pattern stays well in accordance with published radiometric and biostratigraphic data assigning the marine flooding of NCB complex at about 15.3 Ma, whereas in the basins between Ugljevik and Belgrade marine environments were not established before 14.1 Ma. Fitting this pattern, at the western tip of the southern Pannonian Basin, marine deposition in the Styrian Basin commenced at 17 Ma (Karpatian), followed by subsequent, marine transgression of the Zagorje Basin shortly after 16 Ma (early Badenian). In contrast, at the eastern tip of the southern Pannonian basin in the Velika Morava Basin the marine deposits are exclusively late Badenian in age, i.e. younger than 13.8 Ma, in accordance with the synrift stage remaining active there until 11 Ma. Taking the distance of 600 km between the Styrian Basin and southern Velika Morava Basin and traveling time of 3.5 Ma, given by the difference between transgression onsets in those two basins, the average southeastward progression of the Pannonian Basin extension front attains roughly 170 km/Myr.

In summary, the general trend (mode) of marine expansion in the Central Paratethys is stepwise. The tectonic phases associated with the major regional processes, including the extrusion of the Eastern Alps and the Carpathian slab roll back, induced the time transgressive creation of accommodation space. This provided a space for a southward expansion of the marine realm across the mid-Hungarian Shear zone at the Karpatian-Badenian transition. The subsequent acceleration of extension following the Carpathian rollback led to eastward-to-southeastward-directed "collapse" of previously mountainous domains, creating space for the expansion of the marine environment. Although the tectonic phases were the main drivers in the creation of accommodation space, i.e. lowering the elevation, along the NE Dinarides, the climate and eustasy controlled the availability of water. Consequently, the global sea level fall induced by Mi3b cooling led to stalled SE-wards marine expansion, despite active subsidence induced by extension.

The radiometric data supporting the observing trends and interpretations are still tremendously scattered, qualifying the region by far understudied. We hope the present study will inspire the next stage of regional geochronological studies, facilitating a more distinct view and better understanding of regional and global processes governing environmental change in such landlocked basins.

CRediT authorship contribution statement

Oleg Mandic: Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Nevena Andrić-Tomašević:** Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Robert Šamarija:** Visualization, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **Stjepan Ćorić:** Validation, Resources, Methodology, Investigation, Writing – review & editing. **Ljupko Rundić:** Validation, Conceptualization, Writing – review & editing. **Armin Zeh:** Validation, Supervision, Resources, Methodology, Writing – review & editing. **Davor Pavelić:** Validation, Investigation, Writing – review & editing. **Sejfudin Vrabac:** Validation, Resources, Investigation. **Patrick Grunert:** Validation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2026.105532.

Data availability

Data will be made available on request.

References

Abdul Aziz, H., Di Stefano, A., Foresi, L.M., Hilgen, F.J., Iaccarino, S.M., Kuiper, K.F., Lirer, F., Salvatorini, G., Turco, E., 2008. Integrated stratigraphy and ^{40}Ar/^{39}Ar chronology of early Middle Miocene sediments from DSDP Leg 42A; Site 372 (Western Mediterranean). Palaeogeogr. Palaeoclimatol. Palaeoecol. 257, 123–138. https://doi.org/10.1016/j.palaeo.2007.09.013.

Anđelković, M., Eremija, M., Pavlović, M., Anđelković, J., Mitrović-Petrović, J., 1991. Paleogeography of Serbia. The Tertiary [in Serbian with English Summary]. Institute for Regional Geology and Paleontology; Faculty of Mining and Geology. University of Belgrade.

Andrić, N., Fügenschuh, B., Životić, D., Cvetković, V., 2015. The thermal history of the Miocene Ibar Basin (Southern Serbia): new constraints from apatite and zircon fission track and vitrinite reflectance data. Geol. Carpath. 66, 37–50.

Andrić, N., Sant, K., Matenco, L., Mandic, O., Tomljenović, B., Pavelić, D., Hrvatović, H., Demir, V., 2017. The link between tectonics and sedimentation in asymmetric extensional basins: inferences from the study of the Sarajevo-Zenica Basin. Mar. Pet. Geol. 83, 305–332. https://doi.org/10.1016/j.marpetgeo.2017.02.024.

Andrić-Tomašević, N., Simić, V., Mandic, O., Životić, D., Suárez, M., García-Romero, E., 2021. An arid phase in the Internal Dinarides during the early to middle Miocene: Inferences from Mg-clays in the Pranjani Basin (Serbia); Palaeogeogr.; Palaeoclimat. Palaeoecol 562, 110–145. ISSN 0031-0182. https://doi.org/10.1016/j.palaeo.2020.110145.

Andrić-Tomašević, N., Simić, V., Životić, D., Nikolić, N., Pavlović, A., Kluge, T., Beranoaguirre, A., Smit, J., Bechtel, A., 2024. Tectonically induced travertine deposition in the Levač intramountain basin (Central Serbia). Sedimentology 71, 1214–1244. https://doi.org/10.1111/sed.13171.

Andrić-Tomašević, N., Walter, B.F., Simić, V., Raza, M., Životić, D., Novaković, Ž., Kolb, J., Gerdes, A., Beranoaguirre, A., 2025. Contributions of arid climate and hydrothermal fluid flow on sedimentation in saline alkaline lakes: insight from the Ibar intramountain basin (Southern Serbia). Depositional Rec. 11, 1029–1062. https://doi.org/10.1002/dep2.70017.

Avanić, R., 2012. Litostratigrafske Jedinice Donjeg Miocena Sjeverozapadne Hrvatske [Lower Miocene Lithostratigraphic Units from North-Western Croatia – In Croatian]. Unpubl. PhD Thesis. Faculty of Science; University of Zagreb, p. 162.

Avanić, R., Kovačić, M., Pavelić, D., Peh, Z., 2018. The Neogene of Hrvatsko Zagorje. In: Tibljaš, D., Horvat, M., Tomašić, N., Mileusnić, M., Grizelj, A. (Eds.), 9th Mid-European Clay Conference; Conference book - Field Trip Guide book; Zagreb, pp. 128–129.

Avanić, R., Pavelić, D., Pécskay, Z., Mikinić, M., Tibljaš, Wacha, L., 2021. Tidal deposits in the early Miocene Central Paratethys: the Vučji Jarek and Čemernica members of the Macelj formation (NW Croatia). Geol. Croatica 74, 41–56. https://doi.org/10.4154/gc.2021.06.

Badurina, L., Šegvić, B., Mandic, O., Slovenec, D., 2021. Miocene tuffs from the Dinarides and Eastern Alps as proxies of the Pannonian Basin lithosphere dynamics and tropospheric circulation patterns in Central Europe. J. Geol. Soc. Lond. 178. https://doi.org/10.1144/jgs2020-262.

Balázs, A., Matenco, L., Magyar, I., Horváth, F., Cloetingh, S., 2016. The link between tectonics and sedimentation in back-arc basins: New genetic constraints from the analysis of the Pannonian Basin. Tectonics 35, 1526–1559. https://doi.org/10.1002/2015TC004109.

Balázs, A., Burov, E., Matenco, L., Vogt, K., Francois, T., Cloetingh, S., 2017a. Symmetry during the syn- and post-rift evolution of extensional back-arc basins: the role of inherited orogenic structures. Earth Planet. Sci. Lett. 462, 86–98. https://doi.org/10.1016/j.epsl.2017.01.015.

Balázs, A., Granjeon, D., Matenco, L., Sztanó, O., Cloetingh, S., 2017b. Tectonic and Climatic Controls on Asymmetric Half-Graben Sedimentation: Inferences from 3-D Numerical Modeling. Tectonics 36, 2123–2141. https://doi.org/10.1002/2017TC004647.

Balázs, A., Matenco, L., Vogt, K., Cloetingh, S., Gerya, T., 2018. Extensional polarity change in continental rifts: Inferences from 3-D numerical modeling and observations. J. Geophys. Res. Solid Earth 123, 8073–8094. https://doi.org/10.1029/2018JB015643.

Báldi, T., 1986. Mid-Tertiary Stratigraphy and Paleogeographic Evolution of Hungary. Akadémiai Kiadó, Budapest, p. 293.

Báldi, K., 2006. Paleoceanography and climate of the Badenian (Middle Miocene; 16.4-13.0 Ma) in the Central Paratethys based on foraminifera and stable isotope (δ18 O and δ13 C) evidence. Int. J. Earth Sci. 95, 119–142.

Báldi, K., Benkovics, L., Sztanó, O., 2002. Badenian (Middle Miocene) basin development in SW Hungary: subsidence history based on quantitative paleobathymetry of foraminifera. Int. J. Earth Sci. (Geol. Rundsch.) 91, 490–504. https://doi.org/10.1007/s005310100226.

Báldi, K., Velledits, F., Ćorić, S., Lemberkovics, V., Lőrinz, K., Shevelev, A., 2017. Discovery of the Badenian evaporites inside the Capathian Arc: implications for global climate change and Paratethys salinity. Geol. Carpath. 68, 193–206. https://doi.org/10.1515/geoca-2017-0015.

Benček, Đ., Bukovac, J., Magaš, N., Šimunić, A., 2014. Osnovna geološka karta RH 1: 100.000; list Karlovac L 33–92. Hrvatski geološki institut Zagreb.

Bigunac, D., 2022. Taložni i dubinski odnosi donjomiocenskih naslaga i Slavonsko-Srijemskoj; Dravskoj i Savskoj depresiji. Unpubl. PhD. University of Zagreb; Faculty of Mining; Geology and Petroleum Engineering, p. 213. https://repozitorij.rgn.unizg.hr/object/rgn:1986/FILE0/download. accessed online on 6 April 2026.

Bradić-Milinović, Vuković, S., 2024. Stratigraphic implications of the Middle Miocene of the Despotovac area: recognition of two geological formations. Geol. An. Balk. Poluostrva 85, 5–22. https://doi.org/10.2298/GABP240314004B.

Brlek, M., Kutterolf, S., Gaynor, S., Kuiper, K., Belak, M., Brčić, V., Holcová, K., Wang, K. L., Bakrač, K., Hajek-Tadesse, V., Mišur, I., Horvat, M., Šuica, S., Schaltegger, U., 2020. Miocene syn-rift evolution of the (Carpathian-Pannonian Region): new constraints from Mts. Kalnik and Požeška gora volcanoclastic record with regional implications. Int. J. Earth Sci. 109, 2775–2800. https://doi.org/10.1007/s00531-020-01927-4.

Brlek, M., Tapster, S.R., Schindlbeck-Belo, J., Gaynor, S.P., Kutterolf, S., Hauff, F., Georgiev, S.V., Trinajstić, N., Šuica, S., Brčić, V., Wangg, K.-L., Lee, H.-Y., Beier, C., Abersteiner, A.B., Mišur, I., Peytcheva, I., Kukoč, D., Németh, B., Trajanova, M., Balen, D., Guillong, M., Szymanowski, D., Lukács, R., 2023. Tracing widespread early Miocene ignimbrite eruptions and petrogenesis at the onset of the Carpathian-Pannonian Region silicic volcanism. Gondwana Res. 116, 40–60. https://doi.org/10.1016/j.gr.2022.12.015.

Brlek, M., Trinajstić, N., Gaynor, S., Kutterolf, S., Schindlbeck-Belo, J., Šuica, S., Wang, K.-L., Lee, H.-Y., Watts, E., Georgiev, V.G., Brčić, V., Špelić, M., Mišur, I., Kukoč, D., Schoene, B., Lukács, R., 2024. Spread and frequency of explosive silicic volcanism of the Carpathian-Pannonian Region during early Miocene: Clues from the SW Pannonian Basin and the Dinarides. J. Volcanol. Geotherm. Res. 45, 108215. https://doi.org/10.1016/j.jvolgeores.2024.108215.

Bruno, L., Demurtas, L., Magri, D., Michelangeli, F., Rittenour, T., Hong, W., Rossi, V., Vaiani, S.C., Vecchi, A., Amorosi, A., 2024. Sedimentary response of the Po Basin to Mid-late Pleistocene glacio-eustatic oscillations. Quat. Sci. Rev. 344, 109005. https://doi.org/10.1016/j.quascirev.2024.109005.

Casale, G.M., 2012. Core Complex Exhumation in Peri-Adriatic Extension and Kinematics of Neogene Slip along the Saddle Mountains Thrust. Unpubl. PhD study. University of Washington, p. 93. https://digital.lib.washington.edu/server/api/core/bitstreams/846cbbf2-4aa8-458b-a459-8ee33a8d059e/content (accessed on 28 Oct 2025).

Cicha, I., Rögl, F., Rupp, C., Čtyroká, J., 1998. Oligocene – Miocene foraminifera of the Central Paratethys. Abh. Senckenb. Naturforsch. Ges. 549, 1–325.

Čičić, S., 2002. Geološki sastav i tektonika Bosne i Hercegovine. Earth Science Institute, Sarajevo.

Čičić, S., Stevanović, P., Soklić, I., Atanacković, M., Eremija, M., Milojević, R., Jovanović, Č., Bušatlija, I., Raić, V., Laušević, M., 1977. Kenozojske periode. Geologija Bosne i Herzegovina; Vol. 3; Geoinžinjering; Sarajevo.

Čičić, S., Mojićević, M., Jovanović, Č., Tokić, S., Dimitrov, P., 1990. Osnovna geološka karta SFR Jugoslavije 1:100.000; list Tuzla. Savezni geološki zavod, Beograd.

Čičić, S., Mojićević, M., Jovanović, Č., Tokić, S., Dimitrov, P., 1991. Osnovna geološka karta SFR Jugoslavije 1:100.000; Tumač za list Tuzla. Savezni geološki zavod, Beograd.

Ćorić, S., Pavelić, D., Rögl, F., Mandic, O., Vrabac, S., Avanić, R., Jerković, L., Vranjković, A., 2009. Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System; Central Paratethys). Geol. Croatica 62, 31–43.

Ćorić, S., Vrabac, S., Đulović, I., Babajić, E., 2018. Donji miocen i donji baden na profilu Čaklovići u Tuzlanskom bazenu. 17. Kongres geologa Srbije; Vrnjačka Banja 17–20. Maj. 2018.; knjiga apstrakata, pp. 115–120.

Cowie, P.A., 1998. Normal fault growth in three-dimensions in continental and oceanic crust. In: Roger Buck, W., Delaney, P.T., Karson, J.A., Lagabrielle, Y. (Eds.), Faulting and Magmatism at Midocean Ridges. American Geophysical Union Monograph 106, pp. 325–348.

Cowie, P.A., Attal, M., Tucker, G.E., Whittaker, A.C., Naylor, M., Ganas, A., Roberts, G.P., 2006. Investigating the surface process response to fault interaction and linkage using a numerical modelling approach. Basin Res. 18, 231–266.

Csontos, L., 1995. Tertiary tectonic evolution of the Intra-Carpathian area: a review. Acta Vulcanol. 7, 1–13.

Dax, F., Sachsenhofer, R.F., Schreilachner, M.G., Tari, G., 2024. The Styrian Basin: An overview with new insights from seismic data. In: Tari, G.C., Kitchka, A., Krézsek, C., Lučić, D., Markič, M., Radivojević, D., Sachsenhofer, R.F., Šujan, M. (Eds.), The Miocene Extensional Pannonian Superbasin, Vol. 1. Regional Geology. Geological Society, London. https://doi.org/10.1144/SP554-2023-194. Special Publications; 554.

De Leeuw, A., Mandic, O., Krijgsman, W., Kuiper, K., Hrvatović, H., 2011. A chronostratigraphy for the Dinaride Lake System deposits of the Livno-Tomislavgrad Basin: the rise and fall of a long-lived lacustrine environment in an intra-montane setting. Stratigraphy 8, 29–43.

Dolić, D., 1980. Skica miocena Pomoravlja i Levačko-Beličkog basena. Symposium de géologie regionale et paleontologie — Institut de geologie regional et de paleontologie Faculte des mines et de geologie Universite de Belgrade, pp. 373–380.

Dolić, D., 1997. Lake Miocene near Belgrade. Geol. An. Balk. Poluostrva 61, 15–49.

Dolić, D., Kalenić, M., Marković, B., Dimitrijević, M., Radoičić, R., Lončarević, Č., 1981. SFRJ Osnovna geološka karta 1:100 000. Tumač za list Paraćin K 34–7. Federal Geological Institute of Yugoslavia, Beograd.

Dunkl, I., Demény, A., 1997. Exhumation of the Rechnitz Window at the border of Eastern Alps and Pannonian basin during Neogene extension. Tectonophysics 272, 197–211.

Duretz, T., Gerya, T.V., Spakman, W., 2014. Slab detachment in laterally varying subduction zones: 3-D numerical modeling. Geophys. Res. Lett. 41, 1951–1956. https://doi.org/10.1002/2014GL059472.

Ebner, F., Sachsenhofer, R., 1995. Paleogeography; subsidence and thermal history of the Neogene Styrian Basin (Pannonian basin system; Austria). Tectonophysics 242, 133–150.

Einsele, G., 2000. Sedimentary Basins. Evolution; Facies and sediment Budget. Springer; Berlin; Heidelberg; New York.

Erak, D., Matenco, L., Toljić, M., Stojadinović, U., Andriessen, P., Willingshofer, E., Ducea, M.N., 2017. From nappe stacking to extensional detachments at the contact between the Carpathians and Dinarides - the Jastrebac Mountains of Central Serbia. Tectonophysics 710–711, 162–183. https://doi.org/10.1016/j.tecto.2016.12.022.

Eremija, M., 1969. The Neogen between Motajica and Ljubić (Prnjavor basin) in Bosnia. Geol. Glasnik; Sarajevo 13, 38–140.

Eskens, L.H.J., Andrić-Tomašević, N., Kumar, A., Scheck-Wenderoth, M., 2025. Spatiotemporal growth of Seismic-Scale Syn-Flexural Normal Faults in the German Molasse Basin. Basin Res. 37, e70016. https://doi.org/10.1111/bre.70016.

Favaro, S., Handy, M.R., Scharf, A., Schuster, R., 2017. Changing patterns ofexhumation and denudation in front ofan advancing crustal indenter; TauernWindow (Eastern Alps). Tectonics 36, 1053–1071. https://doi.org/10.1002/2016TC004448.

Fodor, L., Jelen, B., Márton, E., Skaberne, D., Čar, J., Vrabec, M., 1998. Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic Line and surrounding area – implication for Alpine-Carpathian extrusion models. Tectonics 17, 690–709. http://onlinelibrary.wiley.com/doi/10.1029/98TC01605.

Fodor, L., Csontos, L., Bada, G., Györfi, I., Benkovics, L., 1999. Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: A new synthesis of paleostress data. In: Durand, B., Jolivet, L., Horváth, F., Séranne, M. (Eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. Geological Society; London; Special Publications 156, pp. 295–334. https://doi.org/10.1144/GSL.SP.1999.156.01.15.

Fodor, L., Jelen, B., Márton, E., Rifelj, H., Kraljić, M., Kevrić, R., Márton, P., Koroknai, B., Báldi-Beke, M., 2002. Miocene to Quaternary deformation; stratigraphy and paleogeography in Northeastern Slovenia and Southwestern Hungary. Geologija 45, 103–114.

Fodor, L.I., Gerdes, A., Dunkl, I., Koroknai, B., Pécskay, Z., Trajanova, M., Horváth, P., Vrabec, M., Jelen, B., Balogh, K., Frisch, W., 2008. Miocene emplacement and rapid cooling of the Pohorje pluton at the Alpine-Pannonian-Dinaric junction: a geochronological and structural study. Swiss J. Earth Sci. 101 (Supplement 1), 255–271. https://doi.org/10.1007/s00015-008-1286-9.

Fodor, L., Uhrin, A., Palotás, K., Selmeczi, I., Tóthné Makk, Á., Riznar, I., Trajanova, M., Rifelj, H., Jelen, B., Budai, T., Muráti, J., Koroknai, B., Mozetič, S., Nádor, A., Lapanje, A., 2013. A Mura–Zala-medence vízföldtani elemzést szolgáló földtani-szerkezetföldtani modellje (Geological and structural model of the Mura–Zala Basin and its rims as a basis for hydrogeological analysis). Magyar Állami Földtani Intézet Évi Jelentése; 2011; 47–91; 6 melléklet (in Hungarian with English abstract).

Fodor, L., Márton, E., Vrabec, M., Koroknai, B., Trajanova, M., Vrabec, M., 2020. Relationship between magnetic fabrics and deformation of the Miocene Pohorje intrusions and surrounding sediments (Eastern Alps). Int. J. Earth Sci. 109 (4), 1377–1401. https://doi.org/10.1007/s00531-020-01846-4.

Fodor, L., Balázs, A., Csillag, G., Dunkl, I., Héja, G., Jelen, B., Kelemen, P., Kövér, S., Németh, A., Nyíri, D., Selmeczi, I., Trajanova, M., Vrabec, M., Vrabec, M., 2021. Crustal exhumation and depocenter migration from the Alpine orogenic margin towards the Pannonian extensional back-arc basin controlled by inheritance. Glob. Planet. Chang. 201. https://doi.org/10.1016/j.gloplacha.2021.103475, 103475.

Fodor, L., Balázs, A., Oravecz, É., Harangi, Sz, Cloetingh, S., Gerya, T., Lukács, R., 2025a. Migration of deformation; basin subsidence; magmatism in extensional basins: comparative constraints from numerical models and observations (Pannonian Basin). In: EGU General Assembly 2025; Vienna; Austria; 27 April – 2 May 2025. EGU25–16095. https://doi.org/10.5194/egusphere-egu25-16095.

Fodor, L., Balázs, A., Oravecz, É., Harangi, Sz, Cloetingh, S., Gerya, T., Lukács, R., 2025b. Migration of deformation; basin subsidence; magmatism in the extensional Pannonian Basin: good fit between numerical models and observations. In: Virág, A., Cserép, B., Molnár, K., Szemerédi, M. (Eds.), 15th Assembly of Petrology and Geochemistry; Nagybörzsöny – Banská Štiavnica; 2–4 October 2025. Book of Abstracts; 32–35. ISBN 978-963-8361-64-6. https://geochem.hu/conf/15kgvgy/abstracts.html.

Gašparič, R., Hyžný, M., Jovanović, G., Ćorić, S., Vrabac, S., 2019. Middle Miocene decapod crustacean assemblage from the Tuzla Basin (Tušanj; Bosnia and Herzegovina); with a description of two new species and comparison with coeval faunas from Slovenia. Palaeontol. Electron. 22.1.9A, 1–21. https://doi.org/10.26879/894.

Gawthorpe, R.L., Hurst, J.M., 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. J. Geol. Soc. Lond. 150, 1137–1152. https://doi.org/10.1144/gsjgs.150.6.1137.

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Res. 12, 195–218.

Gerdes, A., Zeh, A., 2006. Combined U-Pb and Hf Isotope LA-(MC) ICP-MS analyses of Detrital Zircons: Comparison with SHRIMP and New Constraints for the Provenance and Age of an Armorican Metasediment in Central Germany. Earth Planet. Sci. Lett. 249, 47–61. https://doi.org/10.1016/j.epsl.2006.06.039.

Gerdes, A., Zeh, A., 2009. Zircon formation versus zircon alteration–new insights from combined U–Pb and Lu–Hf in situ LA-ICP-MS analyses; and consequences for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt. Chem. Geol. 261, 230–243. https://doi.org/10.1016/j.chemgeo.2008.03.005.

Geurts, A.H., Cowie, P.A., Duclaux, G., Gawthorpe, R.L., Huismans, R.S., Pedersen, V.K., Wedmore, L.N.J., 2018. Drainage integration and sediment dispersal in active continental rifts: a numerical modelling study of the central Italian Apennines. Basin Res. 30, 965–989. https://doi.org/10.1111/bre.12289.

GMSFRY, 1970. Geological Map of the SFR Yugoslavia; scale 1:500.000. Federal geological Institute, Belgrade.

Grizelj, A., Milošević, M., Miknić, M., Hajek-Tadesse, V., Bakrač, K., Galović, I., Badurina, L., Kurečić, T., Wacha, L., Šegvić, B., Matošević, M., Čaić-Janković, A., Avanić, R., 2023. Evidence of early Sarmatian volcanism in the Hrvatsko Zagorje Basin; Croatia: Mineralogical; geochemical and biostratigraphic approaches. Geol. Carpath. 74, 59–82. https://doi.org/10.31577/GeolCarp.2023.02.

Gross, M., Fritz, I., Piller, W.E., Soliman, A., Harzhauser, M., Hubmann, B., Moser, B., Scholger, R., Suttner, T.J., Bojar, H.-P., 2007. The Neogene of the Styrian Basin - Guide to Excursions. Joannea Geol. Paläont. 9, 117–193.

Hajek-Tadesse, V., Wacha, L., Horvat, M., Galović, I., Bakrač, K., Grizelj, A., Mandic, O., Reichenbacher, B., 2023. New evidence for early Miocene palaeoenvironmental changes in the North Croatian Basin: Insights implicated by microfossil assemblages. Geobios. https://doi.org/10.1016/j.geobios.2023.01.005.

Hámor, G. (Ed.), 1988. Neogene Palaeographic Atlas of Central and Eastern Europe. Hungarian Geological Institute.

Handler, R., Ebner, F., Neubauer, F., Bojar, V., Hermann, S., 2006. 40Ar/39Ar dating of Miocene tuffs from the Styrian part of the Pannonian Basin; Austria: an attempt to refine the basin stratigraphy. Geol. Carpath. 57, 483–494.

Handy, M.R., Ustaszewski, K., Kissling, E., 2015. Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity; slab gaps and surface motion. Int. J. Earth Sci. 104, 1–26. https://doi.org/10.1007/s00531-014-1060-3.

Harzhauser, M., Piller, W.E., 2007. Benchmark data of a changing sea. Palaeogeography; Palaeobiogeography and events in the Central Paratethys during the Miocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 253, 8–31. https://doi.org/10.1016/j.palaeo.2007.03.031.

Harzhauser, M., Kranner, M., Mandic, O., Strauss, P., Siedl, W., Piller, W.E., 2020. Miocene lithostratigraphy of the northern and Central Vienna Basin (Austria). Aust. J. Earth Sci. 113 (2), 169–199.

Heberer, B., Neubauer, F., Genser, J., Lee Reverman, R., Fellin, M.G., Dunkl, I., Zattin, M., Seward, D., Brack, P., 2017. Postcollisional cooling history of the Eastern and Southern Alps and its linkage to Adria indentation. Int. J. Earth Sci. 106, 1557–1580. https://doi.org/10.1007/s00531-016-1367-3.

Hilgen, F.J., Lourens, L.J., Van Dam, J.A., 2012. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), A Geologic Time Scale 2012. Elsevier, Amsterdam, pp. 923–978.

Hohenegger, Rögl F., Ćorić, S., Pervesler, P., Lirer, F., Roetzel, R., Scholger, R., Stingl, K., 2009. The Styrian Basin: a key to the Middle Miocene (Badenian/Langhian) Central Paratethys transgressions. Aust. J. Earth Sci. 102, 102–132.

Hohenegger, J., Ćorić, S., Wagreich, M., 2014. Timing of the Middle Miocene Badenian stage of the Central Paratethys. Geol. Carpath. 65, 55–66.

Horváth, F., Royden, L., 1981. Mechanism for the formation of the intra-Carpathian basins: a review. Earth Evol. Sci. 13, 307–316.

Horváth, F., Bada, G., Szafian, O., Tari, G., Adam, A., Cloetingh, S., 2006. Formation and deformation of the Pannonian Basin: constraints from observational data. Geol. Soc. Lond. Mem. 32, 191–206. https://doi.org/10.1144/GSL.MEM.2006.032.01.1.

Horváth, F., Musitz, B., Balázs, A., Végh, A., Uhrin, A., Nádor, A., Koroknai, B., 2015. Evolution of the Pannonian basin and its geothermal resources. Geothermics 53, 328–352. https://doi.org/10.1016/j.geothermics.2014.07.009.

Ilić, A., Neubauer, F., 2005. Tertiary to recent oblique convergence and wrenching of the Central Dinarides: constraints from a palaeostress study. Tectonophysics 410, 465–484. https://doi.org/10.1016/j.tecto.2005.02.019.

Ivančić, K., Trajanova, M., Ćorić, S., Rožic, B., Šmuc, A., 2018. Miocene paleogeography and biostratigraphy of the Slovenj Gradec Basin: a marine corridor between the Mediterranean and Central Paratethys. Geol. Carpath. 69, 528–544. https://doi.org/10.1515/geoca-2018-0031.

Ivančič, K., Bartol, M., Marinšek, M., Kralj, P., Mencin Gale, E., Atanackov, J., Horvat, A., 2024. A review of the Neogene formations and beds in Slovenia; Western Central Paratethys. Geologija 67, 193–215. https://doi.org/10.5474/geologija.2024.009.

Ivančič, K., Bartol, M., Marinšek, M., Kralj, P., Mencin Gale, E., Atanackov, J., Trajanova, M., Horvat, A., 2025. Stratigraphy and structure of the Slovenian part of the Pannonian Superbasin: A brief overview. In: Tari, G.C., Kitchka, A., Krézsek, C., Lučic, D., Markić, M., Radivojević, D., Sachsenhofer, R.F., Šujan, M. (Eds.), The Miocene Extensional Pannonian Superbasin, Vol. 1. Regional Geology. Geological Society, London. https://doi.org/10.1144/SP554-2023-190. Special Publications; 554.

Jackson, C.A.-L., Rotevatn, A., 2013. 3D Seismic Analysis of the Structure and Evolution of a Salt-Influenced Normal Fault Zone: a Test of competing Fault Growth Models. J. Struct. Geol. 54, 215–234. https://doi.org/10.1016/j.jsg.2013.06.012.

Jackson, C.A.-L., Bell, R.E., Rotevatn, A., Tvedt, A.B., 2017. Techniques to Determine the Kinematics of Synsedimentary Normal Faults and Implications for Fault Growth Models. Geol. Soc. Lond. Spec. Publ. 439, 187–217. https://doi.org/10.1144/SP439.22.

Jelen, B., Rifelj, H., 2002. Stratigraphic structure of the B1 Tertiary tectonostratigraphic unit in eastern Slovenia. Geologija 45, 115–138.

Jelen, B., Rifelj, H., 2003. The Karpatian in Slovenia. —. In: Brzobohatý, R., Cicha, M., Kováč, M., Rögl, F. (Eds.), The Karpatian: A Lower Miocene Stage of the Central Paratethys. Masaryk University, Brno, pp. 133–139.

Jipa, D.C., 2018. Large-scale along-arc sedimentary migration in the Carpathian Foredeep. A paleogeographic approach. Palaeogeogr. Palaeoclimatol. Palaeoecol. 505, 140–149.

John, C.M., Karner, G.D., Browning, E., Leckie, R.M., Mateo, Z., Carson, B., Lowery, C., 2011. Timing and magnitude of Miocene eustasy derived from the mixed siliciclastic-carbonate stratigraphic record of the northeastern Australian margin. Earth Planet. Sci. Lett. 304, 455–467. https://doi.org/10.1016/j.epsl.2011.02.013.

Jovanović, Č., 1972. Prilog poznavanju geologije tercijarnih sedimenata između Une i Vrbasa. Geol. glasnik Sarajevo 16, 5–26.

Karamata, S., 2006. The geological development of the Balkan Peninsula related to the approach; collision and compression of Gondwana and Eurasian units. In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. Geological Society London Special Publications 260, pp. 155–178.

Kochansky-Devidé, V., Slišković, T., 1978. Miocenske kongerije Hrvatske; Bosne i Hercegovine. Palaeontol. Jugoslav. 19, 1–98.

Kókay, J., 1973. Faziostratotypen der Bantapusztaer Schichtengruppe. In: Papp, A., Rögl, F., Senes, J. (Eds.), M2 Ottnangien. Die lnnviertler; Salgotarjaner Bantapusztaer Schichtengruppe und die Rzehakia Formation. Chronostratigraphie und Neostratotypen 2; 227-249; Bratislava.

Kopecká, J., Holcová, K., Brlek, M., Scheiner, F., Ackerman, L., Rejšek, J., Milovský, R., Baranyi, V., Gaynor, S., Galović, I., Brčić, V., Belak, M., Bakrač, K., 2022. A case study of paleoenvironmental interactions during the Miocene climate Optimum in southwestern Paratethys. Glob. Planet. Chang. 211, 103784. https://doi.org/10.1016/j.gloplacha.2022.103784.

Korbar, T., 2009. Orogenic evolution of the external Dinarides in the NE adriatic region: a model constrained by tectonostratigraphy of upper cretaceous to Paleogene carbonates. Earth Sci. Rev. 96, 296e312.

Kováč, M., Andreyeva-Grigorovich, A.S., Brzobohatý, R., Fodor, L., Harzhauser, M., Oszczypko, N., Pavelić, D., Rögl, F., Saftić, B., Sliva, L., Stránik, Z., 2003. Karpatian Paleogeography; Tectonics and Eustatic changes. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), The Karpatian. A Lower Miocene Stage of the Central Paratethys. Masaryk University, Brno, pp. 49–72.

Kováč, M., Andreyeva-Grigorovich, A., Bajraktarević, Z., Brzobohatŷ, R., Filipescu, S., Fodor, L., Harzhauser, M., Nagymarosy, A., Oszczypko, N., Pavelić, D., Rögl, F., Saftić, B., Sliva, L., Studencka, B., 2007. Badenian evolution of the Central Paratethys Sea: paleogeography; climate and eustatic sea-level changes. Geol. Carpath. 58, 579–606.

Kováč, M., Plašienka, D., Soták, J., Vojtkoa, R., Oszczypko, N., Less, L., Ćosović, V., Fügenschuh, B., Králiková, S., 2016. Paleogene palaeogeography and basin evolution of the Western Carpathians; Northern Pannonian domain and adjoining areas. Glob. Planet. Chang. 140, 9–27. https://doi.org/10.1016/j.gloplacha.2016.03.007.

Kováč, M., Hudáčková, N., Halásová, E., Kováčová, M., Holcová, K., Oszczypko-Clowes, M., Báldi, K., Less, Gy, Nagymarosy, A., Ruman, A., Klučiar, T., Jamrich, M., 2017. The Central Paratethys palaeoceanography: a water circulation model based on microfossil proxies; climate; and changes of depositional environment. Acta Geol. Slovaca 9, 75–114.

Kováč, M., Halásová, E., Hudáčková, N., Holcová, K., Hyžný, M., Jamrich, M., Ruman, A., 2018. Towards better correlation of the Central Paratethys regional time scale with the standard geological time scale of the Miocene Epoch. Geol. Carpath. 69 (3), 283–300. https://doi.org/10.1515/geoca-2018-0017.

Krstić, N. (Ed.), 1996. Neogene of Central Serbia, 19. Special Publication of Geoinstitute, pp. 1–83.

Krstić, N., Savić, Lj., Jovanović, G., 2012. The Neogene Lakes on the Balkan Land. Geol. an. Balk. poluos. 73, 37–60.

Krstić, N., Savić, L., Jovanović, G., Bodor, E., 2003. Lower Miocene lakes of the Balkan Land. Acta Geol. Hung. 46, 291–299.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285. https://doi.org/10.1051/0004-6361:20041335.

Leckie, R.M., Wade, B.S., Pearson, P.N., Fraass, A.J., King, D.J., Olsson, R.K., Premoli Silva, I., Spezzaferri, S., Berggren, W.A., 2018. Taxonomy; biostratigraphy; and phylogeny of Oligocene and lower Miocene Paragloborotalia and Parasubbotina. In: Wade, B.S., Olsson, R.K., Pearson, P.N., Huber, B.T., Berggren, W.A. (Eds.), Atlas of Oligocene Planktonic Foraminifera, vol. 46. Cushman Foundation for Foraminiferal Research; Special Publication, pp. 125–178.

Lirer, L., Foresi, L.M., Iaccarino, S.M., Salvatorini, G., Turco, E., Cosentino, C., Sierro, F. J., Caruso, A., 2019. Mediterranean Neogene planktonic foraminifer biozonation and biochronology. Earth Sci. Rev. 196, 102869. https://doi.org/10.1016/j.earscirev.2019.05.013.

Löwe, G., Prelević, D., Ustaszewski, K., 2023. A first attempt at a provenance study in the Jadar block (Serbia) by means of U-Pb zircon geochronology. Geol. An. Balk. Poluostrva 84, 17–31. https://doi.org/10.2298/GABP230303005L.

Lučić, D., Saftić, B., Krizmanić, K., Prelogović, E., Britvić, V., Mesić, I., Tadej, J., 2001. The Neogene evolution and hydrocarbon potential of the Pannonian Basin in Croatia. Mar. Pet. Geol. 18, 133–147.

Ludwig, K.R., 2012. User's Manual for Isoplot 3.75. Berkeley Geochronological Center. Special Publication No. 5.

Lukács, R., Harangi, S., Guillong, M., Bachmann, O., Fodor, L., Buret, Y., Dunkl, I., Sliwinski, J., van Quadt, A., Peytcheva, I., Zimmerer, M., 2018. Early to Mid-Miocene syn-extensional massive silicic volcanism in the Pannonian Basin (East-Central Europe): Eruption chronology; correlation potential and geodynamic implications. Earth Sci. Rev. 179, 1–19. https://doi.org/10.1016/j.earscirev.2018.02.005.

Lukács, R., Guillong, M., Bachmann, O., Fodor, L., Harangi, S., 2021. Tephrostratigraphy and Magma Evolution based on combined Zircon Trace Element and U-Pb Age Data: Fingerprinting Miocene Silicic Pyroclastic Rocks in the Pannonian Basin. Front. Earth Sci. 9, 615768. https://doi.org/10.3389/feart.2021.615768.

Magaš, N., Bukovac, J., Benček, Đ., 2014. Osnovna geološka karta RH 1:100.000. Tumač za list Karlovac L 33-92. Hrvatski geološki institut Zagreb.

Maiti, G., Koptev, A., Baville, P., Gerya, T., Crosetto, S., Andrić-Tomašević, N., 2024. Topography response to horizontal slab tearing during retreating oblique continental collision: insights from 3D thermomechanical modelling. J. Geophys. Res. Solid Earth 129. https://doi.org/10.1029/2024JB029385 e2024JB029385.

Mandic, O., 2003. Bivalves of the Karpatian in the Central Paratethys. In: Brzobohaty, R., Cicha, I., Kovac, M., Rögl, F. (Eds.), The Karpatian – A Lower Miocene Stage of the Central Paratethys. Masaryk University Brno, Brno, pp. 217–227.

Mandic, O., De Leeuw, A., Bulić, J., Kuiper, K., Krijgsman, W., Jurišić-Polšak, Z., 2012. Paleogeographic evolution of the Southern Pannonian Basin: 40Ar/39Ar age constraints on the Miocene continental series of northern Croatia. Int. J. Earth. Sci. (Geol. Rundsch.) 101, 1033–1046. https://doi.org/10.1007/s00531-011-0695-6.

Mandic, O., Sant, K., Kallanxhi, M.-E., Ćorić, S., Theobalt, D., Grunert, P., De Leeuw, A., Krijgsman, W., 2019a. Integrated bio-magnetostratigraphy of the Badenian reference section Ugljevik in southern Pannonian Basin - implications for the Paratethys history (middle Miocene; Central Europe). Glob. Planet. Chang. 172, 374–395. https://doi.org/10.1016/j.gloplacha.2018.10.010.

Mandic, O., Rundić, Lj, Ćorić, S., Pezelj, D., Theobalt, D., Sant, K., Krijgsman, W., 2019b. Age and mode of the middle Miocene marine flooding of the Pannonian Basin - constraints from Central Serbia. Palaios 34, 71–95. https://doi.org/10.2110/palo.2018.052.

Mandic, O., Hajek-Tadesse, V., Bakrač, K., Reichenbacher, B., Grizelj, A., Mikinić, M., 2019c. Multiproxy reconstruction of the middle Miocene Požega palaeolake in the Southern Pannonian Basin (NE Croatia) prior to the Badenian transgression of the Central Paratethys Sea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 516, 203–219. S0031-0182(18)30430-9.

Mandic, O., Schneider, S., Harzhauser, M., Danninger, W., 2020. Bivalves from the Innviertel Group of Allerding in the North Alpine Foreland Basin (lower Miocene; Upper Austria). Neues Jahrb. Geol. P.-A. 297 (1), 47–100. https://doi.org/10.1127/njgpa/2020/0914.

Marković, F., Kuiper, K., Ćorić, S., Hajek-Tadesse, V., Kučenjak, M.H., Bakrač, K., Pezelj, Đ., Kovačić, M., 2021. Middle Miocene marine flooding: New 40Ar/39Ar age constraints with integrated biostratigraphy on tuffs from the North Croatian Basin. Geol. Croatica 74, 237–252. https://doi.org/10.4154/gc.2021.18.

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.), Proceedings of the II Planktonic Conference, 2. ed. Tecnoscienza, Roma, pp. 739–785.

Márton, E., Fodor, L., Jelen, B., Márton, P., Rifelj, H., Kevrić, R., 2002. Miocene to Quaternary deformation in NE Slovenia: complex paleomagnetic and structural study. J. Geodyn. 34, 627–651.

Massari, F., Grandesso, P., Stefani, C., Zanferrari, A., 1986. The Oligo-Miocene Molasse of the Veneto-Friuli region; Southern Alps. Giorn. Geol.; ser. 3 48 (1–2), 235–255.

Matenco, L., Radivojević, D., 2012. On the formation and evolution of the Pannonian basin: constraints derived from the orogenic collapse recorded at the junction between Carpathians and Dinarides. Tectonics 6939.

Matenco, L., Munteanu, I., ter Borgh, M., Stanica, A., Tilita, M., Lericolais, G., Dinu, C., Oaie, G., 2016. The interplay between tectonics; sediment dynamics and gateways evolution in the Danube system from the Pannonian Basin to the western Black Sea. Sci. Total Environ. 543 (Part A), 807–827.

Meulenkamp, J.E., Kovac, M., Cicha, I., 1996. On late oligocene to pliocene depocentre migrations and the evolution of the Carpathian-Pannonian System. Tectonophysics 266, 301–317.

Miller, K.G., Browning, J.V., Schmelz, W.J., Kopp, R.E., Mountain, G.S., Wright, J.D., 2020. Cenozoic Sea-level and cryospheric evolution from deep- sea geochemical and continental margin records. Sci. Adv. 6. https://doi.org/10.1126/sciadv.aaz1346 eaaz1346.

Mladenović, A., Trivić, B., Antić, M., Cvetković, V., Pavlović, R., Radovanović, S., Fügenschuh, B., 2014. The recent fault kinematics in the westernmost part of the Getic nappe system (Eastern Serbia): evidence from fault slip and focal mechanism data. Geol. Carpath. 65, 147–161. https://doi.org/10.2478/geoca-2014-0010.

Nádor, A., Lapanje, A., Tóth, Gy, Rman, N., Szőcs, T., Prestor, J., Uhrin, A., Rajver, D., Fodor, L., Muráti, J., Székely, E., 2012. Transboundary geothermal resources of the Mura-Zala basin: joint thermal aquifer management of Slovenia and Hungary. Geologija 55, 209–224. https://doi.org/10.5474/geologija.2012.013.

Neubauer, T.A., Mandic, O., Harzhauser, M., 2016. The freshwater mollusk fauna of the Middle Miocene Lake Drniš (Dinaride Lake System; Croatia): a taxonomic and systematic revision. Aust. J. Earth Sci. 108, 15–67.

Neubauer, T., Mandic, O., Sebe, K., 2025. The Early–Middle Miocene freshwater mollusk fauna of the Mecsek Mts. (S Hungary): a biogeographic stepping stone. Bull. Geosci. 100, 319–357. https://doi.org/10.3140/bull.geosci.1948.

Nyíri, D., Tőkés, L., Zadravecz, Cs, Fodor, L., 2021. Early postrift confined turbidite systems in a supra-detachment basin: Implications for the early to Middle Miocene basin evolution and hydrocarbon exploration of the Pannonian basin. Glob. Planet. Chang. 203, 103500. https://doi.org/10.1016/j.gloplacha.2021.103500.

Oszczypko, N., Oszczypko-Clowes, M., 2012. Stages of development in the Polish Carpathian Foredeep basin. Cent. Eur. J. Geosci. 4, 138–162.

Palcu, D.V., Tulbure, M., Bartol, M., Kouwenhoven, T.J., Krijgsman, W., 2015. The Badenian–Sarmatian Extinction Event in the Carpathian foredeep basin of Romania: Paleogeographic changes in the Paratethys domain. Glob. Planet. Chang. 133, 346–258.

Pamić, J., 2002. The sava-vardar zone of the Dinarides and hellenides versus the Vardar Ocean. Eclogae Geol. Helv. 95, 99e113.

Pavelić, D., 2001. Tectonostratigraphic model for the North Croatian and North Bosnian sector of the Miocene Pannonian Basin System. Basin Res. 13, 359–376. https://doi.org/10.1046/j.0950-091x.2001.00155.x.

Pavelić, D., Kovačić, M., 1999. Lower Miocene alluvial deposits of the Požeška Mt. (Pannonian Basin; Northern Croatia): cycles; megacycles and tectonic implications. Geol. Croatica 52, 67–76.

Pavelić, D., Kovačić, M., 2018. Sedimentology and stratigraphy of the Neogene rift-type North Croatian Basin (Pannonian Basin System; Croatia): a review. Mar. Pet. Geol. 91, 455–469.

Pavelić, D., Miknić, M., Sarkotić Šlat, M., 1998. Early to Middle Miocene facies succession in lacustrine and marine environments on the southwestern margin of the Pannonian Basin System (Croatia). Geol. Carpath. 49, 433–443.

Pavelić, D., Avanić, R., Bakrač, K., Vrsaljko, D., 2001. Early Miocene Braided River and Lacustrine Sedimentation in the Kalnik Mountain Area (Pannonian Basin System; NW Croatia). Geol. Carpath. 52, 375–386.

Pavelić, D., Kovačić, M., Vrsaljko, D., Avanić, R., 2024. Alluvial-lacustrine-marine complex of Mount Medvednica: the early syn-rift deposition and palaeogeography (early to Middle Miocene; North Croatian Basin). Rudarsko-geološko-naftni zbornik 39, 65–85. https://doi.org/10.17794/rgn.2024.1.7.

Petronijević, Ž., 1967. Srednjomiocenska i donjosarmatska (štajerska) fauna sisara Srbije. Palaeont. jugoslavica 7, 1–157.

Piller, W.E. (Ed.), 2022. The lithostratigraphic units of Austria: Cenozoic Era(them) Abhandlungen der Geologischen Bundesanstalt, 76. Wien, p. 357.

Piller, W.E., Harzhauser, M., Mandic, O., 2007. Miocene Central Paratethys stratigraphy – current status and future directions. Stratigraphy 4, 151–168.

Placer, L., 1998. Structural meaning of the Sava folds. Geologija 41, 191–221.

Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G., Kovác, M., 2004. Lithological-Paleogeographic maps of Paratethys. 10 Maps late Eocene to Pliocene. Cour. Forschungsinst. Senck. 250, 1–46.

Porkoláb, K., Kövér, S., Benkó, Z., Héja, G.H., Fialowski, M., Soós, B., Spajić, N.G., Đerić, N., Fodor, L., 2019. Structural and geochronological constraints from the Drina-Ivanjica thrust sheet (Western Serbia): implications for the Cretaceous–Paleogene tectonics of the Internal Dinarides. Swiss J. Geosci. 112, 217–234. https://doi.org/10.1007/s00015-018-0327-2.

Premec Fućek, V., Galović, I., Mikša, G., Hernitz Kučenjak, M., Krizmanić, K., Hajek-Tadesse, V., Matošević, M., Pecimotika, G., Zlatar, S., 2023. Paleontological and lithological evidence of the late Karpatian to early Badenian marine succession from Medvednica Mountain (Croatia); Central Paratethys. Int. J. Earth. Sci. (Geol. Rundsch.) 112, 1–30. https://doi.org/10.1007/s00531-022-02264-4.

Raffi, I., Wade, B.S., Pälike, H., 2020. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), Geologic Time Scale 2020. Elsevier, Amsterdam, pp. 1141–1215.

Ratschbacher, L., Frisch, W., Linzer, H.G., Merle, O., 1991. Lateral extrusion in the Eastern Alps; part 2.: structural analysis. Tectonics 10, 257–271. https://doi.org/10.1029/90TC02623.

Rögl, F., 1998. Paleogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). Ann. Naturhist. Mus. Wien 99A, 279–310.

Rögl, F., 1999. Mediterranean and Paratethys. Facts and Hypotheses of an Oligocene to Miocene Paleogeography (short overview). Geol. Carpath. 50, 339–349.

Rögl, F., Steininger, F., 1983. Vom Zerfall der Tethys zu Mediterran und Paratethys. Ann. Naturhist. Mus. Wien 85/A, 135–163.

Rukavina, D., Saftić, B., Matoš, B., Kolenković Močilac, I., Premec Fuček, V., Cvetković, M., 2023. Tectonostratigraphic analysis of the syn-rift infill in the Drava Basin; southwestern Pannonian Basin System. Mar. Pet. Geol. 152, 106235. https://doi.org/10.1016/j.marpetgeo.2023.106235.

Rundić, Lj, Knežević, S., Rakijaš, M., 2013. Badenian marine transgression: new evidence from the Vrdnik coal basin (northern Serbia). Geol. An. Balk. Poluostrva 74, 9–23. https://doi.org/10.2298/GABP1374009R.

Rundić, Lj, Gajić, V., Ćorić, S., Stefanović, J., Batočanin, N., Radisavljević, M., Prelević, D., 2024. Timing and facies analysis of the Middle Miocene Badenian flood deposits in southern Central Paratethys—insights from KC-4 borehole; western Serbia. Int. J. Earth. Sci. (Geol. Rundsch.) 113, 1067–1094. https://doi.org/10.1016/10.1007/s00531-024-02430-w.

Rupp, C., Hohenegger, J., 2008. Paleoecology of planktonic foraminifera from the Baden-Sooss section (Middle Miocene; Badenian; Vienna Basin; Austria). Geol. Carpath. 59, 425–445.

Sachsenhofer, R.S., Lankreijer, A., Cloething, S., Ebner, F., 1997. Subsidence analysis and quantitative basin modelling in the Styrian Basin (Pannonian Basin System; Austria). Tectonophysics 272, 175–196.

Sant, K., Palcu, D., Mandic, O., Krijgsman, W., 2017. Changing seas in the Early-Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy. Terra Nova 29, 273–281. https://doi.org/10.1111/ter.12273.

Sant, K., Mandic, O., Rundić, Lj, Kuiper, K.F., Krijgsman, W., 2018. Age and evolution of the Serbian Lake System: integrated results from Middle Miocene Lake Popovac. Newsl. Stratigr. 51, 117–143. https://doi.org/10.1127/nos/2016/0360.

Sant, K., Palcu, D.V., Turco, E., Di Stefano, A., Baldassini, N., Kouwenhoven, T., Kuiper, K.F., Krijgsman, W., 2019. The mid-Langhian flooding in the eastern Central Paratethys: integrated stratigraphic data from the Transylvanian Basin and SE Carpathian Foredeep. Int. J. Earth. Sci. (Geol. Rundsch.) 108, 2209–2232. https://doi.org/10.1007/s00531-019-01757-z.

Šamarija, R., Andrić-Tomašević, N., Mandic, O., Zeh, A., Mužek, K., Pavelić, D., Schwotzer, M., 2026a. U-Pb Dating of volcaniclastic deposits from the Sinj Basin: Implications for Provenance and the Tectono-Sedimentary Evolution of the External Dinarides. Int. J. Earth Sci. (Geol. Rundsch.) 115, 27. https://doi.org/10.1007/s00531-026-02567-w.

Šamarija, R., Andrić-Tomašević, N., Mandic, O., Zeh, A., Potić, B., Arifović, A., Schwotzer, M., 2026b. Delayed onset of regional aridification during global climate cooling: insights from the Miocene Valjevo-Mionica Basin; southeastern Europe. Glob. Planet. Chang. (in review). this volume.

Sant, K., Kuiper, K.F., Rybar, S., Grunert, P., Harzhauser, M., Mandic, O., Jamrich, M., Sarinova, K., Hudackova, N., Krijgsman, W., 2020. ^{40}Ar/^{39}Ar geochronology using high sensitivity mass spectrometry: examples from middle Miocene horizons of the Central Paratethys. Geol. Carpath. 71 (2), 166–182. https://doi.org/10.31577/GeolCarp.71.2.5.

Schefer, S., Cvetković, V., Fügenschuh, B., Kounov, A., Ovtcharova, M., Schaltegger, U., Schmid, S.M., 2011. Cenozoic granitoids in the Dinarides of southern Serbia: age of intrusion; isotope geochemistry; exhumation history and significance for the geodynamic evolution of the Balkan Peninsula. Int. J. Earth. Sci. (Geol. Rundsch.) 100, 1181–1206. https://doi.org/10.1007/s00531-010-0599-x.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M., Ustaszewski, K., 2008. The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss J. Geosci. 101 (1), 139–183. https://doi.org/10.1007/s00015-008-1247-3.

Schmid, S.M., Fügenschuh, B., Kounov, A., Matenco, L., Nievergelt, P., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenovic, B., Ustaszewski, K., van Hinsbergen, D.J.J., 2020. Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. Gondwana Res. 78, 308–374. https://doi.org/10.1016/j.gr.2019.07.005.

Schreilechner, M.G., Sachsenhofer, R.F., 2007. High resolution sequence stratigraphy in the Eastern Styrian Basin (Miocene; Austria). Aust. J. Earth Sci. 100, 164–184.

Sebe, K., Selmeczi, I., Szuromi-Korecz, A., Hably, L., Kovács, Á., Benkó, Z., 2019. Miocene syn-rift lacustrine sediments in the Mecsek Mts. (SW Hungary). Swiss J. Geosci. 112, 83–100. https://doi.org/10.1007/s00015-018-0336-1.

Šegvić, B., Lukács, R., Mandic, O., Strauss, P., Badurina, L., Guillong, M., Harzhauser, M., 2023. U-Pb zircon age and mineralogy of St. Georgen halloysite tuff shed light on the timing of the middle Badenian transgression; ash dispersal and paleoenvironmental conditions in the Central Vienna Basin; Austria. J. Geol. Soc. Lond. 180/2. https://doi.org/10.1144/jgs2022-106 jgs2022-106.

Šegvić, B., Badurina, L., Braga, A.E., Mandic, O., Werts, K., Doyle, E., Slovenec, D., Marković, F., Slivšek, G., Demir, V., 2024. Mobility patterns of rare earth elements in diagenetically altered vitric tuff shaped by illite-smectite. Clay Clay Miner. 72 (e14), 1–18. https://doi.org/10.1017/cmn.2024.21.

Selmeczi, I., Fodor, L., Lukács, R., Szepesi, J., Sebe, K., Prakfalvi, P., Sztanó, O., Less, Gy., 2024. Lower and Middle Miocene. In: Babinszki, E., Piros, O., Csillag, G., Fodor, L., Gyalog, L., Kercsmár, Zs., Lukács, R., Sebe, K., Selmeczi, I., Szepesi, J., Sztanó, O. (Eds.), Lithostratigraphic units of Hungary II. – Cenozoic formations; 52–116. Supervisory Authority for Regulatory Affairs (SARA), Hungary. ISBN 978-963-671-328-7. https://sztfh.hu/downloads/foldtan/cenozoic_online.pdf.

Siedl, W., Strauss, P., Sachsenhofer, R.F., Harzhauser, M., Kuffner, T., Kranner, M., 2020. Revised Badenian (middle Miocene) depositional systems of the Austrian Vienna Basin based on a new sequence stratigraphic framework. Aust. J. Earth Sci. 113 (1), 87–110. https://doi.org/10.17738/ajes.2020.0006.

Šikić, K., 1990a. Osnovna geološka karta Republike Hrvatske; list Bosanski Novi 1: 100.000; L 33–105. Hrvatski geološki institut Zagreb, 2014.

Šikić, K., 1990b. Osnovna geološka karta Republike Hrvatske 1:100.000. Tumač za list Bosanski Novi 1:100.000, L 33-70. Hrvatski geološki institut Zagreb, 2014.

Sofilj, J., Marinković, R., Pamić, J., 1984a. Osnovna geološka karta SFR Jugoslavije 1: 100.000; list Derventa. Savezni geološki zavod, Beograd.

Sofilj, J., Marinković, R., Pamić, J., Đorđević, D., 1984b. Osnovna geološka karta SFR Jugoslavije 1:100.000; Tumač za list Derventa. Savezni geološki zavod, Beograd.

Soklić, I., Malez, M., 1969. Ein Fund der Art Mastodon angustidens in der bunten Folge bei Tuzla (mittleres Miozän). Bull. Sci. Cons. Acad; Yougosl. A 14 (11–12), 380–382.

Spencer, J.E., Pearthree, P.A., 2001. Headward erosion versus closed-basin spillover as alternative causes of Neogene capture of the ancestral Colorado River by the Gulf of California. In: The Colorado River: Origin and Evolution: Grand Canyon; Arizona; Grand Canyon Association Monograph, 12, pp. 215–219.

Spezzaferri, S., Coric, S., Stingl, K., 2009. Palaeoenvironmental reconstruction of the Karpatian–Badenian (Late Burdigalian–Early Langhian) transition in the Central Paratethys. A case study from the Wagna Section (Austria). Acta Geol. Pol. 59, 523–544.

Spezzaferri, S., Olsson, R.K., Hemleben, C., Wade, B.S., Coxall, H.K., 2018. Taxonomy; biostratigraphy; and phylogeny of Oligocene and lower Miocene Globoturborotalita. In: Wade, B.S., Olsson, R.K., Pearson, P.N., Huber, B.T., Berggren, W.A. (Eds.), Atlas of Oligocene Planktonic Foraminifera, vol. 46. Cushman Foundation for Foraminiferal Research; Special Publication, pp. 231–268.

Stangačilović, D., 1969. Podvodni vulkanizam u Prnjavorskom basenu (Bosna). Zapisnici Srpskog geološkog drustva za 1964.; 1965.; 1966. i 1967. godinu; 689–694.

Stojadinović, U., Matenco, L., Andriessen, P.A.M., Toljić, M., Foeken, J.P.T., 2013. The balance between orogenic building and subsequent extension during the Tertiary evolution of the NE Dinarides: Constraints from low-temperature thermochronology. Glob. Planet. Chang. 103, 19–38. https://doi.org/10.1016/j.gloplacha.2012.08.004.

Strauss, P., Wagreich, M., Decker, K., Sachsenhofer, R.F., 2001. Tectonics and sedimentation in the Fohnsdorf-Seckau (Basin Miocene; Austria): from a pull-apart basin to a half-graben. Int. J. Earth. Sci. (Geol. Rundsch.) 90, 549–559. https://doi.org/10.1007/s00531000018.

Sztano, O., 1994. The tide-influenced Pétervására Sandstone; early Miocene; northern Hungary: Sedimentology; paleogeography and basin development. Geol. Ultraiect. 120, 1–155.

Tari, G., 1994. Alpine Tectonics of the Pannonian Basin. Unpubl. PhD. Thesis. Rice University, Texas; USA, p. 501.

Tišljar, J., 1993. Sedimentary bodies and depositional models for the Miocene oil-producing areas of Ladislavci; Beničanci and Obod. Nafta 44 (10), 531–542.

Toljić, M., Matenco, L., Ducea, M.N., Stojadinović, U., Milivojević, J., Đerić, N., 2013. The evolution of a key segment in the Europe-Adria collision: the Fruška Gora of northern Serbia. Glob. Planet. Chang. 103, 39–62.

Tomljenović, B., Csontos, L., 2001. Neogene-Quaternary structures in the border zone between Alps; Dinarides and Pannonian basin (Hrvatsko zagorje and Karlovac basin; Croatia). Int. J. Earth. Sci. (Geol. Rundsch.) 90, 560–578. https://doi.org/10.1007/s005310000176.

Trinajstić, N., 2025. Tefrostratigrafija i petrogeneza vulkanoklastičnih naslaga donjo do srednjomiocenskog kiselog vulkanizma Karpatsko-panonske regije. Unpublished PhD Thesis. Univ. Zagreb, p. 396. https://repozitorij.pmf.unizg.hr/object/pmf:15120.

Trinajstić, N., Brlek, M., Gaynor, S.P., Schindlbeck-Belo, J., Šuica, S., Avanić, R., Kutterolf, S., Wang, K.-L., Lee, H.-Y., Holcová, K., Kopecká, J., Baranyi, V., Hajek-Tadesse, V., Bakrač, K., Brčić, V., Kukoč, D., Milošević, M., Mišur, I., Lukács, R., 2023. Provenance and depositional environment of Middle Miocene silicic volcaniclastic deposits from Mt. Medvednica (North Croatian Basin; Carpathian-Pannonian Region). J. Volcanol. Geotherm. Res. 443, 107917. https://doi.org/10.1016/j.jvolgeores.2023.107917.

Trinajstić, N., Brlek, M., Schindlbeck-Belo, J., Tapster, S.R., Kutterolf, S., Avanić, R., Šuica, S., Brčić, V., Kukoč, D., Rybar, S., Šarinová, K., Milošević, M., Mišur, I., 2024. Characterizing the ~15.3 Ma explosive eruption: Insights from volcaniclastic deposits across the Pannonian Basin and the Dinarides. 10th Neogene of Central and South-Eastern Europe Abstract Volume; May 27 to 31; 2024 in Podčetrtek. Geološki zavod Slovenije, Slovenia, p. 81.

Turco, E., Hüsing, S., Hilgen, F., Cascella, A., Gennari, R., Iaccarino, S.M., Sagnotti, L., 2017. Astronomical tuning of the La Vedova section between 16.3 and 15.0 Ma. Implications for the origin of megabeds and the Langhian GSSP. Newsl. Stratigr. 50, 1–29. https://doi.org/10.1127/nos/2016/0302.

Ustaszewski, K., Kounov, A., Schmid, S.M., Schaltegger, U., Frank, W., Krenn, E., Fügenschuh, B., 2010. Evolution of the Adria-Europe plate boundary in the northern Dinarides - from continent-continent collision to back-arc extension. Tectonics 29. https://doi.org/10.1029/2010TC002668. TC6017.

Ustaszewski, K., Herak, M., Tomljenovic, B., Herak, D., 2014. Neotectonics of the Dinarides–Pannonian Basin transition and possible earthquake sources in the Banja Luka epicentral area. J. Geodyn. 82, 52–68. https://doi.org/10.1016/j.jog.2014.04.006.

van Gelder, I.E., Matenco, L., Willingshofer, E., Tomljenović, B., Andriessen, P.A.M., Ducea, M.N., Beniest, A., Gruić, A., 2015. The tectonic evolution of a critical segment of the Dinarides-Alps connection: Kinematic and geochronological inferences from the Medvednica Mountains; NE Croatia. Tectonics 34, 1952–1978. https://doi.org/10.1002/2015TC003937.

Vrabac, S., Ćorić, A., 2008. Revizija "Karpata" Tuzlanskog bazena sa osvrtom na stratigrafski polozaj sone formacije. Geološki glasnik Sarajevo 37, 71–81.

Vrabac, S., Coric, S., Ferhatbegovic, Z., 2003. The Karpatian in Bosnia and Herzegovina. In: Brzobohatý, R., Cicha, I., Kováč, M., Rögl, F. (Eds.), The Karpatian. A Lower Miocene Stage of the Central Paratethys. Masaryk University; Brno, pp. 141–144.

Vrabac, S., Ferhatbegović, Z., Đulović, I., Bijedić, Dž, 2011. Findings of marine fossils in salt formation of the salt rock reservoir Tetima near Tuzla (in Bosnian/Serbian/Croatian). In: Zbornik radova III kongresa geologa BiH Sarajevo, pp. 53–60.

Vrabac, S., Ćorić, S., Đulović, I., Bošnjak, M., Babajić, E., Hrvatović, H., Rundić, L.J., Jovanović, G., Dervišević, R., Renovica, R., Ustalić, S., 2022. Field trip guidebook [9th NCSEE International Workshop; Tuzla]. J. Fac. Min. Geol. Civ. Eng. Tuzla 1, 55–75. https://doi.org/10.51558/2303-51612022.1.1.55.

Vrabec, M., Fodor, L., 2006. Late Cenozoic tectonics of Slovenia: Structural styles at the northeastern corner of the Adriatic microplate. In: Pinter, N., Grenerczy, Gy, Weber, J., Stein, S., Medak, D. (Eds.), The Adria microplate: GPS Geodesy; Tectonics; and Hazards. NATO Science Series IV; 61; 151–168. Springer.

Vrsaljko, D., Pavelić, D., Bajraktarević, Z., 2005. Stratigraphy and Palaeogeography of Miocene Deposits from the marginal Area of Žumberak Mt. and the Samoborsko Gorje Mts. (Northwestern Croatia). Geol. Croatica 58 (2), 133–150.

Vrsaljko, D., Pavelić, D., Miknić, M., Brkić, M., Kovačić, M., Hećimović, I., Hajek-Tadesse, V., Avanić, R., Kurtanjek, N., 2006. Middle Miocene (Upper Badenian/Sarmatian) palaeoecology and evolution of the environments in the area of medvednica Mt. Geol. Croat. 59/1, 51–63.

Wölfler, A., Kurz, W., Fritz, H., Stüwe, K., 2011. Lateral extrusion in the Eastern Alps revisited: refining the model by thermochronological; sedimentary; and seismic data. Tectonics 30, 1–15. https://doi.org/10.1029/2010TC002782.

Xue, K., Schellart, W.P., Strak, V., 2022. Overriding plate deformation and topography during slab rollback and slab rollover: Insights from subduction experiments. Tectonics 41. https://doi.org/10.1029/2021TC007089 e2021TC007089.