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A review of the Neogene formations and beds in Slovenia, Western Central Paratethys

Pregled neogenskih formacij in plasti v Sloveniji, zahodna Centralna Paratetida

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Abstract

Neogene sedimentary successions are found in eastern and northeastern Slovenia. Their formation was closely related to the evolution of the western part of the Pannonian Basin System and the Central Paratethys; it was influenced by global transgressive and regressive cycles as well as by global, regional and local tectonics. Several formations and beds were defined within the Neogene sedimentary successions which can be found in three separate areas. The first one includes the formations north of two major fault systems, the Periadriatic Fault System and the Mid-Hungarian Zone, which were associated with the Mura-Zala and the Styrian Basins, respectively. Successions south of these major faults are not formally connected to any of the major basins and developed in two distinct parts: a strip between Tunjice and Kozjansko to the north and the Krško area to the south. From the Egerian to the early Badenian, different areas exhibit different types of sedimentation, whereas from the middle Badenian onwards, sedimentation in different zones is partly comparable, depending on the type of depositional environment. Egerian and Eggenburgian sediments are only found south of the above-mentioned major fault zones, whereas Karpatian sedimentation only occurred north of them. Sediments in both areas are characterized by alternation of shallow marine, brackish and terrestrial sedimentation. In contrast, sedimentary environment in the Badenian evolved from a terrestrial, mainly fluvial environment with alluvial fans, through a transitional stage (delta and lagoon) to a shallow and deep marine environment. The Sarmatian sequences reflect a brackish environment with decreasing salinity and continue into extensive Pannonian delta systems that gradually fill the basins from west to east. The formations that correspond to the Pannonian in the Mura-Zala Basin can be correlated with the formations in the Krško area. The Pliocene is characterized by terrestrial sedimentation with the formation of rivers and lakes in the newly established intramontane basins.

Izvleček

Neogenska sedimentna zaporedja so prisotna v severovzhodnem in vzhodnem delu Slovenije. Njihov nastanek je vezan na razvoj zahodnega dela Panonskega bazena in Centralne Paratetide ter posledično na globalno, regionalno in lokalno tektonsko aktivnost ter globalne transgresijsko-regresijske cikle. Sedimentna zaporedja so opredeljena v več formacijah in plasteh, ki so se razvijala na treh večjih ločenih območjih. Prvo je severno od Periadriatskega preloma in Srednjemadžarske prelomne cone, kjer je bila sedimentacija vezana na Mursko-Zalski in Štajerski bazen. Neogenska zaporedja južno od omenjene prelomne cone so se razvijala na dveh ločenih območjih, v pasu od Tunjic do Kozjanskega ter na območju Krškega in niso del nobenih večjih bazenov. Od egerija do spodnjega badenija se sedimentna zaporedja med različnimi območji izrazito razlikujejo, medtem ko je sedimentacija od srednjega badenija dalje na različnih območjih delno primerljiva. Egerijski in eggenburgijski sedimetni so prisotni le južno od prelome cone, ottnangijske in karpatijske sedimente pa najdemo le severno od nje. V obeh primerih je sedimentacija potekala v plitvomorskem in brakičnem okolju ter na kopnem. Bolj enoten je bil razvoj od badenija dalje, ko je transgresija povzročila poplavitev celotnega ozemlja, kar je omogočilo razvoj podobnega sedimentacijskega okolja v različnih območjih. Sprva kopensko, predvsem rečno okolje z aluvialnimi vršaji se je nadaljevalo v prehodno okolje z deltami in lagunami, ki ga je hitro poplavilo morje Centralna Paratetida. Sarmatijska zaporedja odražajo brakično okolje z zmanjšano slanostjo, ki so počasi prehajala v obsežne sisteme panonskih delt. Te so postopoma zapolnjevala porečja od zahoda proti vzhodu, kar je omogočilo korelacijo formacije v Mursko-Zalskem bazenu in na območju Krškega. V pliocenu je značilna kopenska sedimentacija z nastankom rek in jezer v novo nastalih intramontanih bazenih.

Introduction

The Miocene rocks and sediments, deposited in the Pannonian Basin System (PBS) are found in the eastern and north-eastern parts of Slovenia. They are often present in distinct locations that stretch in an E-W or NW-SE direction. In the Miocene, sedimentation took place in three separate depositional units. In the north-eastern part, north of the Periadriatic Fault System (PFS) and Mid-Hungarian Zone (MHZ), south of it and in the Krško area. Sedimentation north of the PFS and MHZ was subjected to the development of two larger basins, the Mura-Zala and Styrian Basins (Fig. 1). The Mura-Zala Basin represented one of the deepest depressions of the PBS (Fodor et al., 2002), covering most of north and northeast Slovenia in the Miocene (Drobne et al., 2008) (Fig. 1). The Styrian Basin was formed northwest of the Mura-Zala Basin - the boundary between these two basins in the present-day Slovenia is still not defined. It is described in Austria, where the boundary represents the South Burgenland Swell (Hasenhüttl et al., 2001). Each of these two basins is divided into smaller basins. The westernmost part, the Slovenj Gradec Basin, is connected to the Mura-Zala Basin (Ivančič et al., 2018a), while the northernmost part, the Ribnica-Selnica Trough, was subjected to the sedimentation of the Styrian Basin (Gašparič & Hyžný, 2014). The second sedimentation unit was located south of the PFS

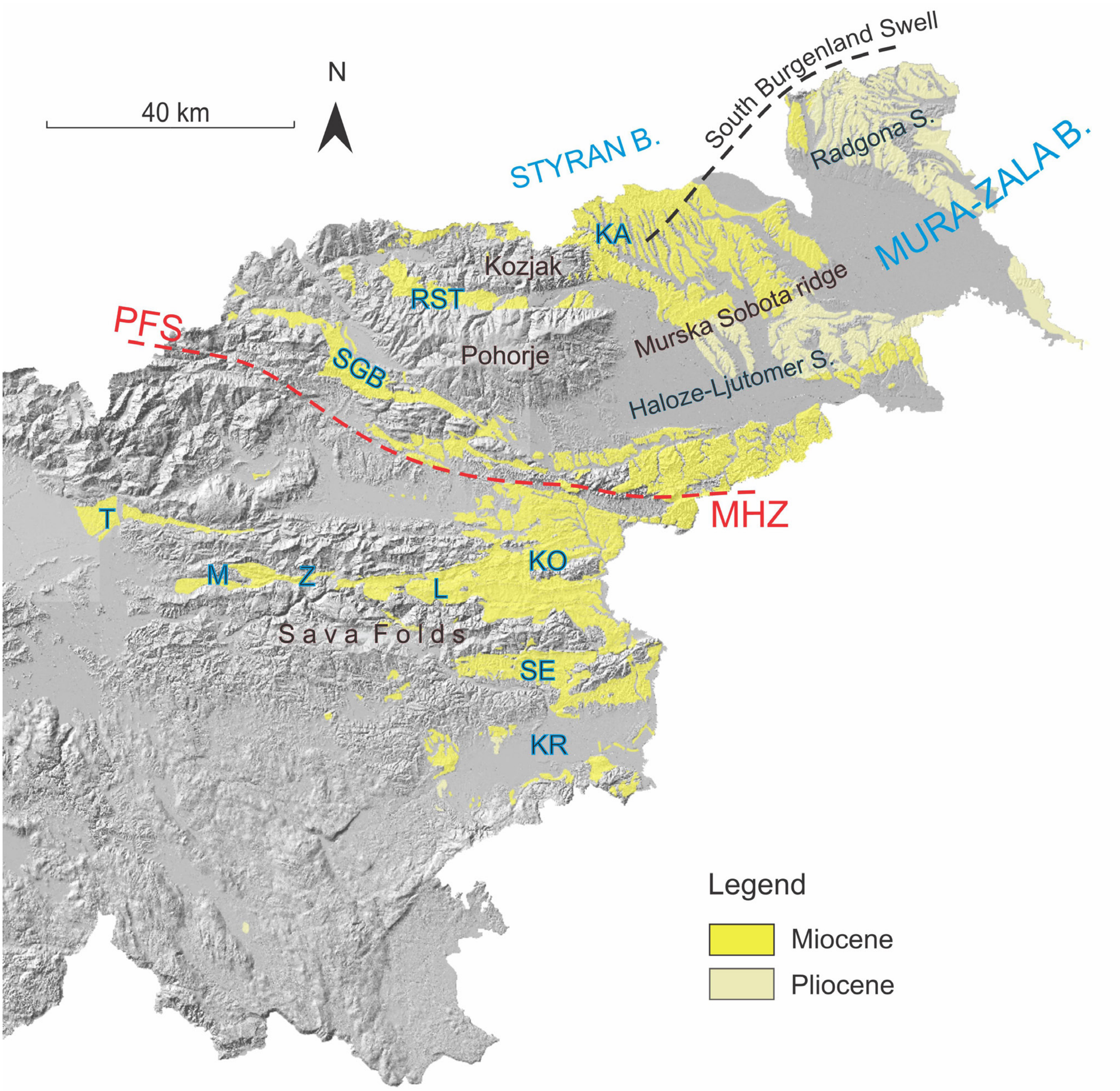

Fig. 1. Distribution of the Miocene and Pliocene rocks in Slovenia. Explanatory notes: B – Basin, KA – Kungota area, KO – Kozjansko area, KR – Krško area, L – Laško area, M – Moravče area, RST – Ribnica Selnica Trough, S – Subbasin, SE – Senovo area, SGB – Slovenj Gradec Basin, T – Tunjice area, Z – Zagorje area (modified after Buser, 2010).

and MHZ. Today, the Miocene rocks are exposed in several parallel running facies belts (structurally forming cores of synclines) between Tunjice in the west through Moravče, Laško and Zagorje to Kozjansko in the east. The third unit is located in the south-east of the Sava Folds and represents the Krško area, which developed independently of the other two (Poljak, 2017a). At various times, the areas were either isolated and experienced unique development or connected and characterized by uniform sedimentation.

Individual sedimentary sequences are combined into groups of strata, members and formations. Some formations are defined in several different regions (e. g., Laško formation, which is known from the area of Tunjice, Laško, Kozjansko and Krško), while other strata and members are associated to a single area (e. g., Radlje beds, which only occur in in the Ribnica-Selnica Trough). Synrift, post-rift and compressional tectonic phases along with eustatic changes have created various terrestrial, shallow- and deep-water sedimentary environments. Each formation represents a particular type of sedimentary fill, characterized by a specific tectonic phase in a particular time interval (Jelen et al., 2006).

This paper presents all the Neogene sedimentary formations described in Slovenia in the transitional zone between the rising Alps and Dinarides on one side and the extensional PBS on the other. Their occurrence is strongly related to local, regional and global tectonic activity. Sedimentary succession has been extensively studied in a wide range of specific areas, but this knowledge has not yet been summarized into an integral picture. This paper aims to improve the general understanding of sedimentary processes taking place during the Neogene.

Structural overview

Northeastern Slovenia lies at the junction of four tectonic units: the PBS, the Southern Alps, the Eastern Alps and the Dinarides. The area is part of the broader collision zone between the African and Eurasian plate, characterized by a triple junction of the European Plate, the Adriatic Microplate and the Pannonian Lithosphere (Brückl, 2010). The deep lithospheric structure is not definitively known, with possible southward subduction of the European plate, northward subduction of the Adriatic plate or a combination of both. The area is split into two distinct zones of somewhat different Cenozoic tectonic evolution by the PFS and the MHZ. The PFS, which transitions into the MHZ, with its northernmost edge delineated by the Balaton Fault. The ALCAPA megaunit, composed of Adria-derived allochthons, underwent eastward lateral extrusion during the Neogene (Vrabec & Fodor, 2006; Schmid et al., 2020 and references therein; Fodor et al., 2021 and references therein).

The zone to the north of the PFS-MHZ line, comprising the ALCAPA megaunit is composed of late Early to Late Cretaceous age Eoalpine generally top-to-north thrust and nappe system of Adria-derived allochthons, generally composed of pre-Permian metamorphic rocks, with upward decreasing metamorphic grade, and overlying Permian to Mesozoic successions (Schmid et al., 2020 and references therein). The basement underwent extensive extensional tectonic deformation in the Miocene, as the result of subduction, slab breakoff and rollback in the Carpathians, the consequent crustal thinning and the formation of the Pannonian Basin and the subsequent mantle upwelling and thermal subsidence of the basin. Extensional tectonics in NE Slovenia initiated at 25–23 Ma (Eggerian), peaking at 19–15 Ma (Eggenburgian to Badenian) and ceasing by 12–11 Ma (Late Sarmatian to early Pannonian) (Fodor et al., 2002, 2021). Extension resulted in the crustal thinning driven along low-angle detachment faults and the formation of an asymmetric metamorphic core complex. It comprises the Pohorje and Kozjak domes, in which the metamorphic basement outcrops at the surface. To the east, the Murska Sobota extensional block or ridge moved eastward and subsided along the Pohorje and Kozjak detachments. Further still to the east, the Transdanubian Range moved east and subsided along the Baján detachment (Fodor et al., 2021). To the west of the Pohorje dome, the structure of the much smaller-scale extensional blocks is somewhat uncertain. The Pohorje and Kozjak domes are separated by the Lovrenc and Primož Faults. The (supradetachment) extensional basins formed both along the higher-angle normal faults that sole to the detachments and the detachments themselves, transitioned from terrestrial in the early Neogene (Eggenburgian to Karpatian, 19–17.25 Ma) into near-shore and bathyal in the Middle Miocene (Badenian, 15.97–12.8 Ma) (Fodor et al., 2021). Deformation subsequently migrated eastwards towards the Transdanubian Range in Hungary. In NE Slovenia, the most important basins include the Slovenj Gradec Basin located west of the Pohorje dome, the Ribnica-Selnica Trough, which formed along the Lovrenc and Primož Faults, separating the Pohorje and Kozjak domes, the Radgona Subbasin, which lies to the north of the Murska Sobota ridge, the Ljutomer Subbasin, also known as the Haloze-Ljutomer-

Budafa Subbasin located south of the Murska Sobota ridge, and the Mura-Zala Basin, which lies east of the Murska Sobota ridge (Fodor et al., 2002, 2021). The extensional tectonic regime persisted until the Sarmatian, after which the region underwent thermal subsidence, as evidenced by the deposition of a further, 1–2 km thick post-tectonic succession of sediments (Fodor et al., 2002). Neogene sediment total thickness reaches up to ~3000 m in the Radgona Subbasin, and more than 5000 m in the Ljutomer Subbasin (Gosar, 2005).

In the latest Miocene and in the Pliocene, the region underwent an inversion of the tectonic regime, with extensional structures reactivated as compressional and transpressional, and extensional basins undergoing inversion (Fodor et al., 2002). The inversion only affected the southern part of the area, including the Ljutomer Subbasin, with the reverse Ljutomer and Haloze North and South faults and the dextral strike-slip Donat Fault (Atanackov et al., 2021), and associated large-scale folds, including the Ormož-Selnica Anticline and smaller-scale folds, such as the Petišovci Anticline.

South of the PFS-MHZ line, the basement is composed of the Adria-derived (eastward extension of the) South Alpine unit, which comprises top-to-south thrust and nappe system composed mostly of Late Paleozoic (Carboniferous and Permian) clastics and Mesozoic carbonates. The South Alpine unit itself is thrust to the south over the External Dinarides, with the two units separated by the South Alpine Thrust Front (Placer, 2008; Schmid et al., 2020). The External Dinarides are a late-Eocene to early-Oligocene top-to-the south thrust / fold and thrust system, composed of Adria-derived allochthons, mostly of the Slovenian carbonate platform and later the Dinaridic carbonate platform, to a much lesser extent the Slovenian Basin, overlain in the western part by Eocene to Oligocene flysch (Placer, 2008; Schmid et al., 2020). The easternmost part of SE Slovenia comprises the transitional zone into the Internal Dinarides along the thinned Mesozoic carbonate platform margin and transition into basinal successions and ophiolites of the Internal Dinarides (Placer, 2008). The basement was dissected by extensional tectonics, at least in SE Slovenia and into Croatia where the structure is well known (Krško Basin), beginning in the early Neogene, continuing until the late Neogene (Tomljenović & Csontos, 2001; Poljak, 2017a). Successions of Neogene marine sediments locally exceeds 1000 m, e.g. ~1500 m in the Globoko Basin (Poljak, 2017b). A Middle to Late-Miocene stress field change to a generally N-S compression resulted in the formation of the Sava Folds (Placer, 1998). This is a fold and thrust belt of E-W to ENE-WSW trending large scale folds, in general east of the Ljubljana Basin and the Žužemberk Fault, reaching east into Croatia. An extension of the Sava Folds to the west into the External Dinarides is strongly suspected (Rižnar, 2009). The formation of the Sava Folds may be asynchronous, post-Sarmatian in the north (Placer, 1998) and post middle-Pannonian in the south (Gosar & Janežič, 2006; Poljak, 2017b; Atanackov et al., 2018). The folds are confirmed active in the south-southeastern part of the Sava Folds (Poljak, 2017a; Atanackov et al., 2018).

Basins North of the Periadriatic Fault System and Mid-Hungarian Zone

Two different series of Neogene sediments have developed in Slovenia. The first to the north, and the second to the south of the PFS and MHZ. In the north, the sedimentary environment is mainly subjected to the development of the Styrian and Mura-Zala Basins. These areas have been influenced by the ongoing tectonic activity in the northern depositional areas. In the southern region, the sedimentary record is variable and does not conform to the large basin framework observed in the north. Neogene tectonic activity influenced the sediments, which are now found in isolated areas (Fig. 1) that were deposited separately from the southern part until the Badenian, when both parts were flooded by the Central Paratethys.

Formations and beds, Associated with the Styrian Basin

The specific area in Slovenia that was subjected to sedimentation in the Styrian Basin has not yet been defined. Furthermore, it is not defined where the border between the Styrian and Mura-Zala Basin is. It is defined by the South Burgenland Swell, but its continuation into the Slovenian area is not clear (Fodor et al., 2002). Fossil remains in the **Ribnica-Selnica Trough** indicate a similarity with the type of sedimentation in the Styrian Basin during the Karpatian transgression (Gašparič & Hyžný, 2014), where conglomerate layers alternate with sandstones and siltstones (Pavšič & Horvat, 2009). The main uncertainty is in the designation of the **Kungota area,** which is, to some extent, the border area between the Steirischer Schlier (Kreuzkrumpel Formation) of the Styrian Basin and the Haloze Formation of the Mura-Zala Basin (Hohenegger et al., 2009; Maros et al., 2012). On the one hand, sedimentation in the Kungota area resembles sedimentation to the

Wagna section (Rijavec, 1965), and the tectonic structures of the Kungota area suggest a connection to the Styrian Basin (Kralj et al., 2009). On the other hand, the sediments in the Kungota area indicate similarities to sedimentation in the Mura-Zala Basin (Fodor et al., 2002; Jelen et al., 2006; Fodor et al., 2011; Maros et al., 2012). This suggest that these two basins might be connected during the Karpatian transgression. However, detailed sedimentological and palaeontological analyses are still missing.

Radlje beds

The oldest Miocene sediments on the northern side of the PFS and the MHZ can be found in northern Slovenia, by the Austrian border, near Radlje ob Dravi (Fig. 2). The strata consist of conglomerate and sandstones, whose Eggenburgian age is questionable (Mioč & Žnidarčič, 1977). The conglomerate and gravel are full of metamorphic rocks fragments, indicating proximity to the hinterland and fluvial sedimentation (Mioč & Žnidarčič, 1977). This corresponds to the Radl Beds of the Eibiswald Formation, whose Ottnangian deposits are interpreted as alluvial fans and proximal delta facies (Stingl, 1994). However, as the Radlje beds have not been explored in the past or in the recent, their evolution and connection with the surrounding basins is not yet defined.

Formations and Beds, Associated with the Mura-Zala Basin

In the Mura-Zala Basin, the Neogene sedimentation began in the Karpatian and continued to the Pliocene. The sedimentation was strongly influenced by tectonic activity and started in the Early

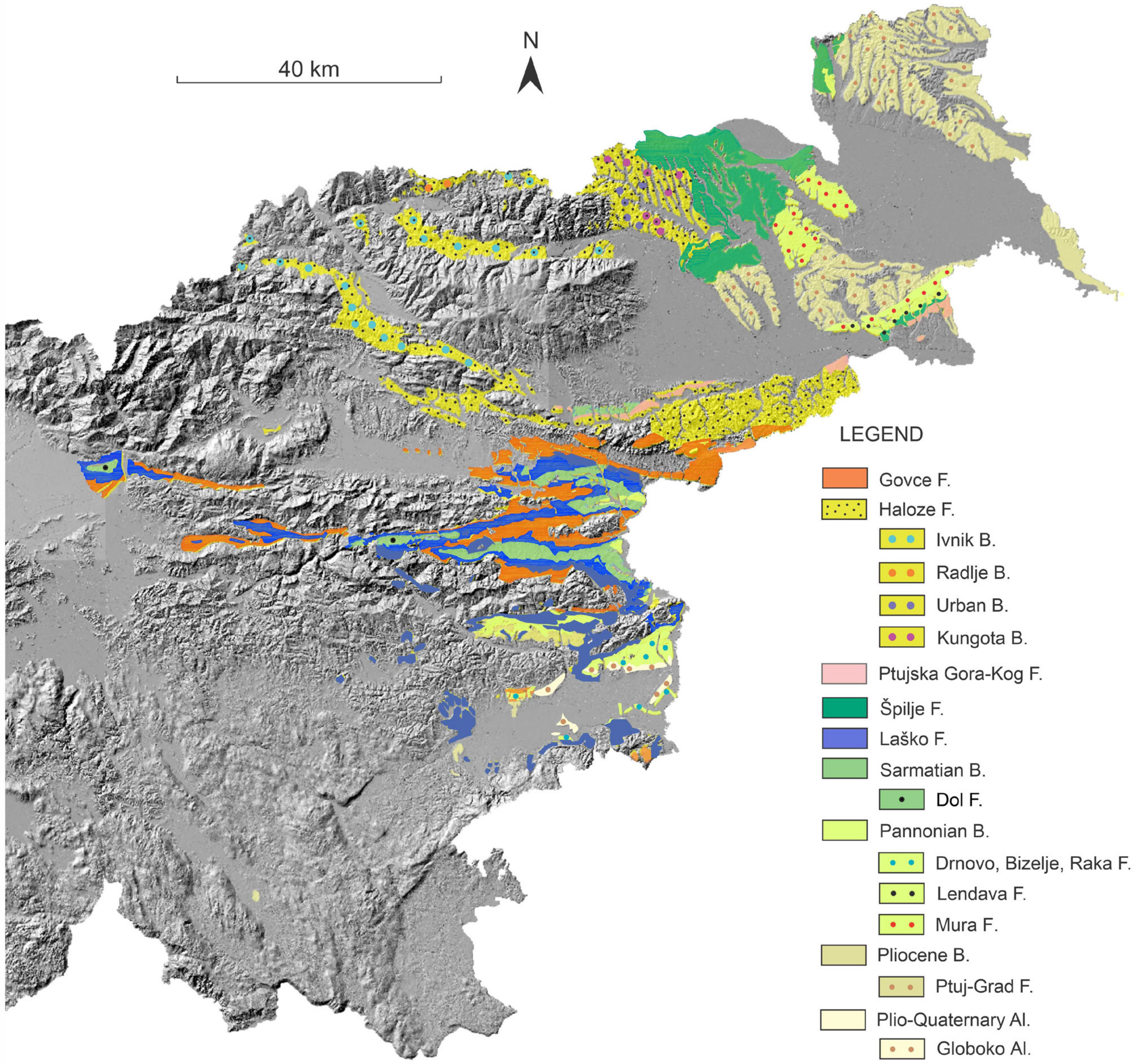

Fig. 2. Distribution of the Miocene formations in Slovenia. Explanatory notes: F – Formation, B – Bed, Al – Alloformation (modified after Buser, 2010).

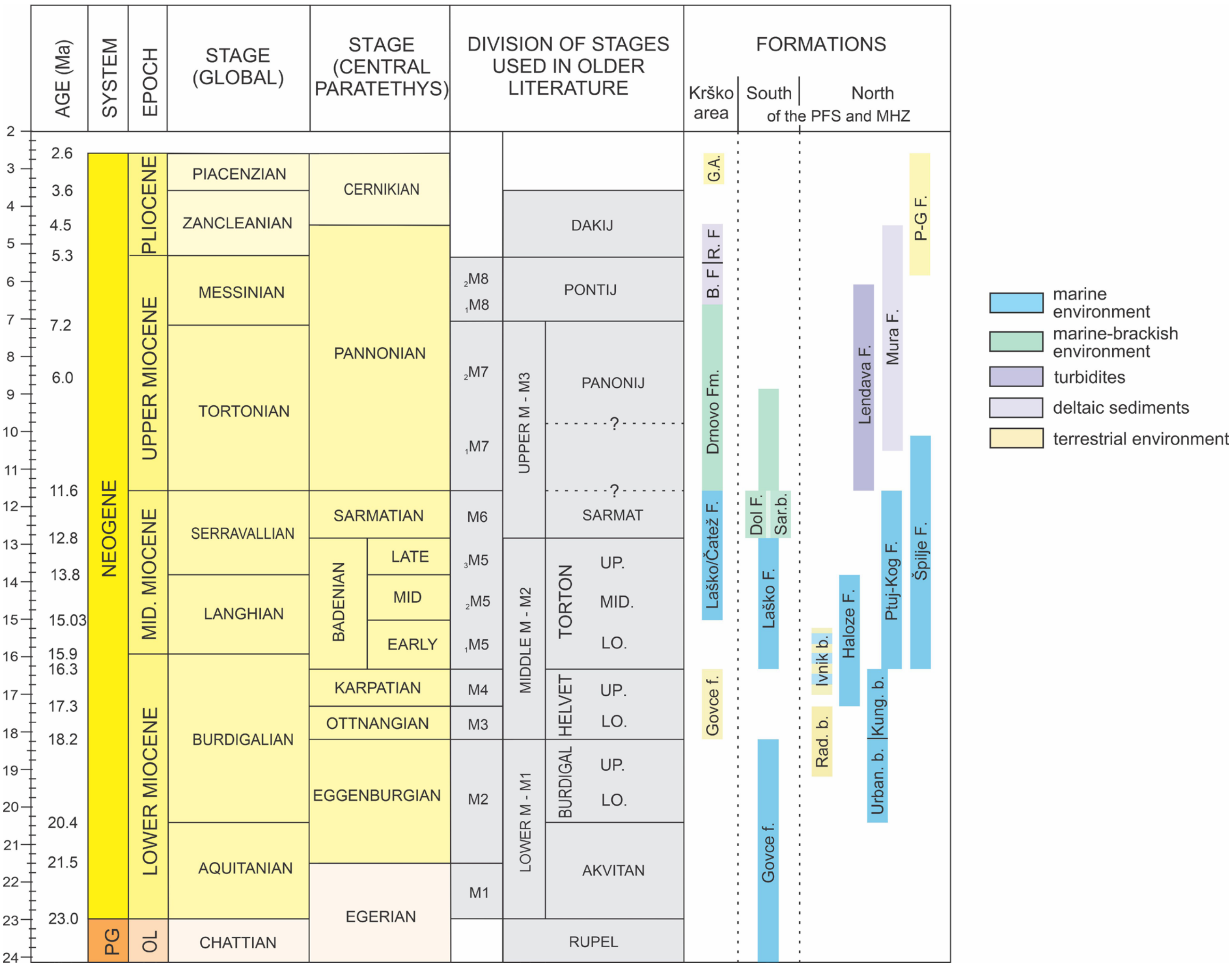

Fig. 3. Correlation of formations described in the paper with the stratigraphic time scale in the Central Paratethys (modified after Rögl et al., 2007 and Hohenegger et al., 2014). Explanatory notes: B.F. – Bizeljsko Formation, R.F – Raka Formation, G.A. – Globoko Alloformation, P-G F. – Ptuj-Grad Formation, Rad. B. – Radlje beds, Sar. b. - Sarmatian beds.

Miocene extension, which led to the thinning of the crust and the formation of half-grabens (Jelen et al., 2006). The filling of the half-grabens was associated with different tectonic phases (post-rift, syn-rift); therefore, several formations were defined, namely the Haloze, Ptujska gora - Kog, Špilje, Lendava, Mura and Ptuj-Grad Formations. Besides those, informal names of beds in particular areas are used in older literature, namely the Ivnik, Urban and Kungota beds (Jelen et al., 2006), which today are attributed to the Haloze Formation.

The Haloze Formation (Karpatian – early Badenian)

Description: Initial sedimentation in the Mura-Zala Basin covered the pre-Cenozoic basement. Alternation of conglomerates, sandstones, muddy breccia with fossils such as oyster shells indicate first infilling of the grabens in the Karpatian (Fodor et al., 2011). In the Slovenj Gradec Basin, initial Karpatian sedimentation starts with the basal conglomerate and muddy breccia and continues with alternating layers of conglomerate, sandstone, siltstone and marlstone of terrestrial character (Ivančič et al., 2018b). Sedimentation continued with the deposition of finer-grained sediments of the Central Paratethys. Nannoplankton assemblages point to functioning connection of Central Paratethys with the Mediterranean Sea (Ivančič et al., 2018a). The Haloze Formation is divided into several members: Plešivec-Urban, Stoperce-Kungota, and Neraplje-Cirknica (Jelen & Rifelj, 2011) as well as into specific beds: Ivnik, Haloze and Urban, which are described in greater detail below. The thickness of sediments is over 1300 m (Fodor et al., 2011) and are located north of the PFS (Fig. 1). The formation extends from the Karpatian to the lower Badenian.

Sedimentation: The Haloze Formation represent the infilling of the half-grabens formed in the first syn-rift phase of the PBS formation (Maros et al., 2012). Regression-transgression cycles alternated twice in the Central Paratethys at this time (Kováč et al., 2018), and strongly affected the PBS, especially the marginal parts (Pavelić & Kovačić, 2018; Ivančič et al., 2018b). Marine transgression caused sedimentation in the shallow marine, near-coast environment, with the deposition of sands, marls and lithothamnium nodules integrated with conglomerate (Maros et al., 2012). Gradually, a deepening of the sea and open-marine sedimentation is indicated by the deposition of sandstones, siltstones and marlstone (Maros et al., 2012). Volcanic activity in the surrounding area resulted in the deposition of tuff layers, called the **Ranca tuff layer** in the Kungota area (Fodor et al., 2011; Maros et al., 2012).

Correlation: Regression stage between the Karpatian/Badenian boundary is not yet defined in the Haloze Formation (Fodor et al., 2011). In the Wagna and Katzengraben sections, distinguished angular discordance can be observed, namely the Styrian Unconformity (Hohenegger et al., 2009). The regression stage between the Karpatian/Badenian boundary is defined by coarse-grained high-energy fluvial sediments (Jelen & Rifelj, 2003, 2005; Jelen et al., 2006; Fodor et al., 2011). The beginning of the early Badenian transgression is characterized by the formation of transitional environment (e.g., lagoonal, deltaic; Ivančič et al., 2018b). The formation represents lateral variation of the Tekeres Formation in Hungary (Fodor et al., 2011).

The Ivnik beds

Description: Initial sedimentation of the Ivnik beds represents basal conglomerates of Karpatian age, which indicate the first infilling of the basin. Regression stage between the Karpatian/Badenian boundary is defined in the Slovenj Gradec Basin, where it is characterized by swamps with thick layers of coal (Ivančič et al., 2018a). Sedimentation continues with deposition of conglomerate, which is gradually replaced by sandstones and, further on, marly siltstones (Ivančič et al., 2018a). Sediments are defined in the Slovenj Gradec Basin and Ribnica-Selnica Trough (Fig. 2). In both areas, sedimentation took place form the Karpatian to the end of early Badenian. The thickness of the Ivnik layers is over 1200 m (Ivančič et al., 2018a).

Sedimentation: Detailed sedimentological, geochemical and paleontological analyses indicate three regression-transgression periods between the Karpatian and the end of the early Badenian (Ivančič et al., 2018a). The three depositional sequences can be correlated to the global third order sequence cycles (TB 2.2, TB 2.3, TB 2.4; cf. Haq et al., 1988; Hardenbol et al., 1998). All three transgressions point to an active marine connection with the Mediterranean Sea. The first Badenian transgression is well defined in the sedimentary successions with lowstand and highstand system tract defined and sedimentation described in detail in Ivančič et al. (2018a).

Correlation: Sedimentation of the Ivnik beds in the Slovenj Gradec Basin and Ribnica-Selnica Trough have specific differences in their sedimentary input. While the sediments in the Slovenj Gradec Basin originated from the south-west, west and subordinately form the south (Ivančič et al., 2018b), the main input into the Ribnica-Selnica Trough originated from the Pohorje Mountains (Mioč, 1978). According to the above, the two basins were probably separated by a barrier in the Karpatian and early Badenian in the form of the partly uplifted Pohorje tectonic block (Trajanova, 2013; Ivančič et al., 2018a), but detailed investigations are still missing. The Ivnik beds in the Slovenj Gradec Basin shows similarities in depositional environment and represent time equivalent with the Haloze Formation (Ivančič et al., 2018a), while in the Ribnica-Selnica Trough with the Styrian Basin (Gašparič & Hyžný, 2014).

The Urban beds

Description: The Burdigalian age (Fig. 3) of the Urban layers is well supported in Rijavec (1965). They are divided into two parts: lower and upper Urban beds. The sediments discordantly cover the Paleozoic basement. In the lower part, breccia (with tonalite and gneiss blocks) is overlain by mica, sandy marlstone, mica carbonate sandstone, and marlstone. Rare conglomerate occurs. Microfossil remains such as foraminifera, ostracod and echinoderms indicate a marine environment. The upper part of the Urban beds consists of conglomerate, sandy marlstone, sand, sandstone and tuff. Microfauna in both parts is similar. The thickness of the Urban beds is over 500 m (Rijavec, 1965). They occur near the Urban hill, NW of Maribor (Fig. 2).

Sedimentation: Sediments were deposited in open-marine environment and indicate similarities to the beds in the Styrian basin (Rijavec, 1965). According to the latest research (Jelen & Rifelj, 2011; Fodor et al., 2011, Maros et al., 2012), the Urban beds are Karpatian in age and belong to the Plešivec-Urban Member of the Haloze Formation.

The Kungota beds

Description: The Kungota beds are well described in Rijavec (1965). They occur in the Kungota area (Fig. 1) and overlie the Urban beds. The lower part of the Kungota beds is composed of conglomerate, sandstone, and marl with clay interlayers. On top of the marlstone, a tuff layer occurs. Microfossils including foraminifera, ostracods and echinoderms indicate Helvetian age (Fig. 3). The fauna differs from that in the Urban beds. The upper part of the Kungota beds is similar to the lower ones but does not contain any tuff layers. The thickness of the Kungota beds is over 400 m (Rijavec, 1965).

Sedimentation: Sedimentation took place in shallow marine environment (Rijavec, 1965). According to research (Jelen & Rifelj, 2011; Fodor et al., 2011; Maros et al., 2012) the Kungota beds are part of the Stoperce-Kungota Member of the Haloze Formation, which also includes the Ranca tuff bed.

The Ptujska Gora – Kog Formation (early Badenian – Sarmatian)

Description: The sedimentary succession of the Ptujska Gora – Kog Formation is composed of conglomerate, gravel, breccia, sandstone, sand, sandy silt, silty marl, marlstone, clayey marl, limestone and dolomite with insertion of coal layers (Jelen & Rifelj, 2011; Maros et al., 2012). It comprises sediments form early Badenian to Sarmatian and can be found in a thin belt southwest northeast of Haloze (Fig. 2).

Sedimentation: Ptujska-Gora Kog Formation is an informal lithostratigraphic unit, which is not commonly used in the literature. Sediments were deposited in various sedimentation environment from shallow marine, nearshore, brackish to fluvial environment (Maros et al., 2012). They represent the filling of the basin in the post-rift and first compressional phase in the PBS (Maros et al., 2012).

The Špilje Formation (early Badenian – early Pannonian)

Description: The Špilje Formation consist mainly of muddy and sandy sediments. In the Kungota area, the beginning of sedimentation is characterized by an unconformity (Rijavec, 1965), where the sediments discordantly overlay Karpatian sediments. The sedimentary succession starts with the basal conglomerates, which represent the first deposits in the basin and are overlain by sandstone, sand, marl, litothamnium limestone and marl (Žnidarčič & Mioč, 1989; Fodor et al., 2011). The thickness of the Špilje Formation is up to 1600 m (Fodor et al., 2011). The sandy beds in the area of Lenart were investigated in two discrete levels which were biostratigraphically assigned to the early-late Badenian (Bartol, 2009). Late Badenian lithothamnium limestones occur in a strip between the Pesnica and Drava Faults and north of the Pesnica Fault as rhodolithic conglomerates and individual rhodoids (Bartol, 2009). They consist of red algae and abundant bryozoans, corals, gastropods, bivalves, sea urchins and other reef-dwelling organisms.

Sedimentation: The sediments were deposited in the basin, formed during the syn- and post-rift phases of the PBS from the early Badenian to the early Pannonian (Jelen & Rifelj, 2005; Bavec et al., 2005; Jelen et al., 2006). Sedimentation took place in shallow and deep marine environment enabling the formation of sandy turbidites (Fodor et al., 2011).

The connection to the transgressive-regressive periods was defined in the vicinity of Lenart, where sediments were correlated with the sea-level lowstand between eustatic cycles TB2.3 and TB2.4 (after Haq et al., 1988). A change from a deeper water depositional system to the sandy-turbiditic regime suggests the formation of restricted sub-basins, as does the contemporaneous reduction in the number of planktonic foraminifera (Fodor et al., 2002). The overlying middle Badenian marls contain diverse nannofossil assemblages (Bartol, 2009) and several horizons enriched in pteropods (Mikuž et al., 2012a), which is consistent with a fully marine environment and functioning marine connections with the surrounding areas.

The sandy and marly beds in the Mura-Zala Basin dated to the boundary of nannofossil biozones NN5 and NN6 (Bartol & Pavšič, 2005; Bartol, 2009) were deposited during the sea-level lowstand at the transition between 3rd order cycles TB 2.4 and TB 2.5. The late Badenian nannofossil assemblages are diverse and enriched in genera that indicate warm water, suggesting a pelagic sedimentary environment and a functioning connection with the Mediterranean (Bartol, 2009; Bartol et al., 2014). Warm hemipelagic environment and connection to Mediterranean in early Badenian indicate also discoasters and pteropods (Bartol & Pavšič, 2005; Mikuž et al., 2012b).

Correlation: Recent research (Jelen & Rifelj, 2011; Fodor et al., 2011) describes the Špilje Formation as one of the formations in the Mura-Zala Basin. The sediments are found in the area between Lenart and Špilje (Fig. 2). Based on the micro- and macrofauna and the lithological similarities with the sediments of the Vienna Basin, the sedimentary succession of the Špilje Formation has been correlated with the sediments of the Vienna Basin (Rijavec, 1965; Kuščer, 1967). Rhodoids represent a littoral reef facies deposited in shallower parts of the basin (Šikić et al., 1979).

The Lendava Formation (Pannonian)

Description: In most cases, the Lendava Formation overlays the Špilje Formation, however in some localities, it overlays the pre-Tertiary beds. The formation consists of up to a few meters thick stack of layers of basal conglomerates at the bottom, the sequence continues with large amounts of sands and sandstones, which represent turbiditic sequences, and in the upper part of the formation, sandy muddy and silty marl and marlstone, clay and marly clay prevail (Jelen & Rifelj, 2011; Fodor et al., 2011). The thickness of sandy turbidites reaches up to 1000 m (Fodor et al., 2011). Sediments of the Lendava Formation are outcroping in small areas north and west of Ormož (Fig. 2).

Sedimentation: The Lendava Formation was defined based on seismic profiles and includes Pannonian sediments, which represent diachronous deposits of a large delta system. They include prograding delta and shelf-slope deposits (fine-grained sediments), and also sandy turbidites between the delta fronts and the deep basin (Jelen & Rifelj, 2003; Bavec et al., 2005; Fodor et al., 2011; Maros et al., 2012). The Lendava Formation is followed by delta front sediments of Mura Formation (Jelen et al., 2006).

Correlation: In general, in Hungary, the lateral equivalents are: Algyo Formation, Ujfalu Formation and Zagyva Formation (Fodor et al., 2011; Maros et al., 2012), while in Austria, they are: the Schichten von Loipersdorf in Unterlamm, Stegersbacher Schichten, Jennersdorfer Schichten, Taborer Schotter in Süsswasser-Kalk (Gross, 2003; Gross et al., 2008).

The Mura Formation (Pannonian)

Description: The Pannonian clastic sediments of the Mura Formation consist of poorly lithified interlaminated or massive silt, clayey silt, sandy silt and marl. In the overlying upward coarsening Pontian succession interlaminated and interbedded sand and silt become more abundant, and locally, gravelly sand and sandy gravel, and coal seams occur (Fodor et al., 2011; Maros et al., 2012).

Sedimentation: The Mura Formation was defined based on seismic profiles. It contains pro-delta and transitional pro-delta to delta front sediments, representing a diachronous continuation of the deltaic sequence from the Lendava Formation (Jelen et al., 2006) (Fig. 4). In the uppermost section coal seams and organic matter occur and indicate the presence of swamps and the transition of environment into delta plain. The delta front deposits form an interconnected sand body that extends in a subsurface area of 22.128 km^2 and yields economically important amount of thermal water (Mioč & Ogorelec, 1991; Kralj, 2001b; Nádor et al., 2012; Šram et al., 2015).

Post-rift subsidence and the ongoing compressional phase (Huismans et al., 2001) of the southwest Pannonian Basin System during upper Pannonian (ex. Pontian) resulted in the retreat of the Lake Pannon toward the east. Fluvial systems draining from the west toward the east and southeast formed diverse deltaic environments along the coastline, and eventually infilled the body of standing water (Kralj, 1995; Jelen et al., 2006; Fodor et al., 2011; Maros et al., 2012; Kováč et al., 2017). The Mura Formation consists of sediments deposited in pro-delta, pro-delta to delta front, delta front and delta plain environment. Jelen and Rifelj (2011) have subdivided the Mura Formation into the Presika-Petišovci Member and the Cogetinci-Kuzma Member. Both members have rather similar lithology and thickness amounting up to 1200 m (Pleničar, 1970; Mioč & Ogorelec, 1991; Kralj, 1995, 2001a; Nádor et al., 2012; Šram et al., 2015).

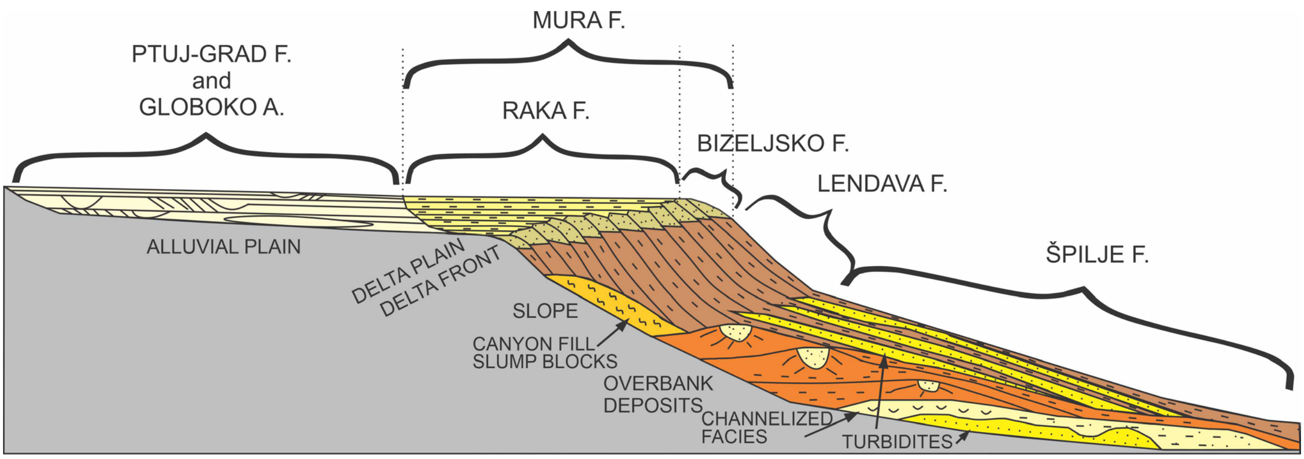

Fig. 4. Distribution of several formations of the Mura-Zala Basin and in the Krško area in relation to the sedimentation environment (modified after Neal et al., 1993). Explanatory marks: F – Formation, A – Alloformation.

The Ptuj-Grad Formation (Pliocene)

Description: The beginning of the Ptuj-Grad Formation is characterized by coal deposits on the alluvial plain (Fig. 4). Generally, the formation consists of alternation of sand, silt, clay marl, lignite and gravel sediments and include numerous gravel bodies of Late Miocene to Pliocene (Maros et al., 2012). Meandering accretions are mainly composed of gravelly sand or sandy gravel, and flood plain deposits of gravelly-silty sand and sand interbedded with silty and clayey fine-grained sediments. The formation includes also extrusive basalt, lava flows, basalt- pyroclastics and subvolcanic basaltic rocks (Maros et al., 2012). In the vicinity of the settlement of Grad, alkali basaltic autoclastic, volcaniclastic and mixed fluvial-volcaniclastic deposits outcrop as erosional remnants of maar, tuff ring and tuff cone. Further to the east of Goričko, the Pliocene deposits are overlain by Early Quaternary gravel, sandy gravel and sand with minor intercalations of fine-grained sediments (Pleničar, 1970; Kralj, 1995).

Sedimentation: As the upper Pannonian deltaic sedimentation prograded toward the east, the Pliocene environment in north-eastern Slovenia changed to terrestrial and dominated by braided and meandering river systems (Kralj, 1995, 2001a). A system of alluvial fans developed, and further to the east, it evolved into a system of braided and meandering rivers.

The formation of the Ptuj Member is still poorly understood, although it has been assumed to be related to the meandering system of the Drava-Drau paleo flow draining into the Ptuj-Lutomer Depression. Rare occurrences of coal indicate the existence of peat swamps (Žnidarčič & Mioč, 1989).

Depositional environment and sedimentary successions of the Grad Member are more complex and closely related to the subsidence of the Styrian Basin and Mura-Zala Basin, and in particular, the Radgona-Radkersburg Depression. The Grad member is assumed to have developed as a result of the drainage systems of Mura-Mur, Zala and Krka-Kerka paleo-streams. Several measured imbrications indicate nearly west-to-east flow directions (Kralj, 1995).

Correlation: Alkali basaltic volcanism is about 3 Ma old and closely related to the Pliocene occurrences in the Styrian Basin and Little Hungarian Plain (Winkler, 1926; 1927; Poulditis, 1981; Kralj, 1995, 2001a; 2010; Martin & Németh; 2004). The early fluvial sedimentation occurred along the South-Burgenland Swell infilling the Radgona-Radkersburg Depression as well.

Formations and beds south of the Periadriatic Fault System and Mid-Hungarian Zone and in Krško area

South of the PFS and MHZ, sedimentation from the Egerian to the Pliocene took place in two separate depositional units. The first extends from Tunjice in the west to Kozjansko in the east, and the second is in the Krško area. Today the sediments are preserved in several isolated areas, which were connected during the Egerian, Eggenburgian and Badenian as part of the Central Paratethys. While the sedimentary successions in the Early Miocene and Badenian were united by the transgression of the Central Paratethys, the Sarmatian and Pannonian sediments are not associated with any specific formation. In the Krško area in particular, several new formations have been defined within the Pannonian, which are shown in the newly published Geological map of the Krško area and described in the Explanatory notes (Poljak, 2017a, b).

The Govce formation (late Egerian, Eggenburgian)

Description: In the area of Zagorje the sequence starts with basal conglomerates and gravel with keratophyre pebbles and Lepidocyclina limestone (Kuščer, 1967). Basal beds are covered by blueish marly clay interchanging in the overlying beds with sand and sandstone that dominate the upper part of the sequence. Sand beds also include keratophyre and carbonate gravel. Locally the sedimentary sequence continues with sandy limestone and occasionally contains *Lepidociclyna*. It is overlain by litothamnian limestone of Lower Miocene age. The upper part of the sequence contains thin coal layers in sand beds (Kuščer, 1967). Formation development varies laterally. In the Tunjice Hills, a 380 m sequence starts with the Govce clay containing sand and sandstone, continues as interchanging marlstone and claystone beds covered by conglomerate and ends with sand and sandstone (Vrabec, Mi., 2000). In the Krško area, the succession starts with silicate-carbonate pebbles and continues with several tens of meters of silicate-carbonate gravel and sand, sandstone, marl, marlstone, tuff and coal (Verbič, 1995; Dozet et al., 1998; Poljak, 2017a). In the area of Kozjansko, the Govce formation comprises a 500–600 m thick sequence of predominantly carbonate conglomerates and sand, sandstone, marl, marlstone, tuff and coal (Aničić et al., 2002). In the surroundings of the Maclje Mountain, the Govce beds contain well lithified green glauconitic Maclje sandstone of Eggenburgian age (Aničić et al., 2002). Marlstone in the Kozjansko area contain numerous calcitic nannoplankton of early and late Egerian, and the upper part could be attributed to the Eggenburgian (Pavšič & Aničić, 1998, 2000). The Govce formation comprises the oldest Miocene deposits in Slovenia. The formation includes poorly lithified sediments of Oligocene and Lower Miocene (Egerian and Eggenburgian) age (Buser, 1978, 1979; Aničić & Juriša, 1985a, 1985b). It has been determined in Tunjice (Premru, 1980; Vrabec, Mi. 2000), Moravče, Sava folds (Hamrla, 1954; Kuščer, 1967), Krško (Poljak, 2017a), Kozjansko (Pavšić & Aničić, 1998; Aničić et al., 2002) and Žetale (Jelen & Rifelj, 2011). The Govce beds lie discordantly on Pre-Cenozoic basement (Kuščer, 1967; Vrabec, Mi., 2000; Poljak, 2017a) or on Paleogene clastic sediments known as the Sivica and Pletovar formation, as well as on Oligocene volcanic rocks (Buser, 1978, 1979; Aničič et al., 2002). According to the correlation with surroundings basins, the sediments of the Govce formation in Krško area are presumably Ottnangian age (Poljak, 2017a).

Sedimentation: Lower Miocene age has been assigned based on foraminifera (Kuščer, 1967). The lower portion of the Govce formation was deposited in littoral environment while the upper part developed in brackish system. However, an abundance of pentalites in Kozjanko area indicate a decrease in salinity in the upper Egerian (Pavšič & Aničić, 1999). In Krško area, the formation is determined based on resemblance to the Govce beds in the Sava Folds, sediments were deposited in fluvial, swamp and lacustrine environment (Poljak, 2017a).

The Laško formation (Badenian)

Description: Sediments of the Laško formation discordantly overlapped the Govce formation in the Krško Basin (Poljak, 2017a) and in the Laško area (Kuščer, 1967). The formation is divided into two parts: Laško marl, and lithothamnium limestone (Buser, 1978; Aničić et al., 2002; Bavec et al., 2005). In the Tunjice area, the Laško formation consists of conglomerates present in the beginning of succession, and alternation of course to fine grained sandstones and siltsotnes (Vrabec, Mi. et al., 2014; Rojnik, 2015). In the Zagorje area, the succession starts with the basal conglomerate, composed of pebbles of eroded Govce beds, and continues with sandstone (with quartz and keratophyre grains), sandy and marly limestone and marl. The top of the succession is characterized by lithothamnium limestone of varying thickness defined as biosparite with rare grains of quartz with foraminifera, lithothamnium, bryozoan, and echinoderms (Strgar, 2003). The abundance of the biogenic component in the sediments is described in the Kozjansko area as well (Aničić et al., 2002). It occurs locally in two levels: below and above the Laško marl (Munda, 1951). Sediments are described as Badenian and in Krško area as Sarmatian age as well (Poljak, 2017a), and are outcropping in wider area from Tunjice, Laško, Zagorje, Kozjansko, Senovo and Krško (Fig. 1).

The Laško marl is rich in bivalve and gastropod macrofossils. Lithothamnium limestone and Laško marl gradually alternate into Sarmatian clay in the area between Hrastnik and Laško (Munda, 1951; Kuščer, 1967) and in the Krško Basin (there is no strict boundary; Poljak, 2017a).

Sedimentation: Sedimentation took place in shallow marine, nearshore, and shoreface environment in the Middle Miocene. A prominent gastropod species *Pereiraeia gervaisi* was found in several localities near Šentjernej reflecting warm shallow water marine environment (Mikuž, 1999). Warm and humid paleoenvironmental conditions are also defined in Tunjice area (Ivančič et al., 2024). Most specimens were dated biostratigraphically to the upper part of the middle Badenian (Bartol et al., 2014), some accompanying nannofossil assemblages were enriched with *Braarudosphaera bigelowii*, which is able to tolerate freshwater influences (Bartol et al., 2008). This could reflect a sea-level lowstand at the boundary of 3rd order cycles TB 2.4 and TB 2.5. Late Badenian foraminiferal assemblages suggest a complex sedimentary environment with outer shelf to bathyal water depths in the Planina Syncline and shallow, nutrient rich and cool water in the Kozjansko area (Oblak Brown, 2006).

Correlation: The formation is described by various authors, south of the PFS and MHZ (Munda, 1951; Hamrla, 1954; Kuščer, 1967; Aničić et al., 2002; Strgar, 2003; Poljak, 2017a). The lithothamnium limestone of Laško formation is macroscopically similar to the lithothamnium limestone of Govce formation (Kuščer, 1967). Stratigraphic equivalent of the Laško marl represents *Šentjur micritic limestone* in the Celje area and Motnik Syncline. It contains remains of pelagic foraminifers and does not contain fragments of lithothamnium algae (Buser, 1979; Aničić et al., 2002).

The Dol formation / Sarmatian beds (Sarmatian)

Description: The Sarmatian sequence generally consists of conglomerate, gravel, sandstone and clayey layers in the lower part and continues with sandy and clayey marl, calcarenite, sandstone, sand and quartz sandstone. In the upper part, mica sand with interlayers of clayey marl prevail (Kuščer, 1967; Žnidarčič & Mioč, 1989; Aničić, 1990; Aničić et al., 2002). The calcareous sandstone is dominated by the remains of lithothamnium and other reef organisms (Buser, 1979; Premru, 1983). The Dol formation is described in the Tunjice and Zagorje areas (Placer, 1998, 1999; Vrabec, Mi. et al., 2014), while in the Kozjansko and Laško area, Sarmatian sediments are not formalized into a specific lithostratigraphic unit. In the Zagorje Syncline, these layers represent the deepest part of the depression. In the Tunjice area, the formation consists of clay, which represents the boundary between the Badenian and the Sarmatian sediments, covered by sand and calcarenite with the gastropods *Cerithium*. The thickness of the Sarmatian succession is up to 400 m (Pavšič & Horvat, 2009). In the Krško Basin, Sarmatian beds overlay Badenian layers in places, but occasionally Sarmatian strata are absent and Pannonian marlstones lie directly on Badenian beds. For this reason, the Sarmatian beds, when present in the Krško Basin, are included into the Laško formation (Poljak, 2017a; Poljak et al., 2016).

Sedimentation: The Sarmatian sediments were deposited in a brackish environment (Rijavec, 1965; Žnidarčič & Mioč, 1989, Aničić et al., 2002). Extensive micropaleontological analyses of foraminifera (Oblak Brown, 2006), ostracods and nanoplankton (Marinšek et al., 2022) were carried out in the Kozjansko area. Based on the ostracod analysis, it was interpreted that the predominant environment was marine to brackish. The ostracod assemblage indicates a lower to middle Sarmatian age. Silicoflagellates in the Tunjice area indicate a marine environment with low inflow and shallowing of the basin. The later is confirmed with a decrease of plankton as well as an increase of epilitic and epiphytic forms (Horvat, 2004). Seashore fossils suggest a good connection of the Central Paratethys with the Indopacific in the early Sarmatian (Pavšič & Horvat, 2009).

Correlation: According to the macro- and microfauna and the lithological profiles in the Špilje area, the Sarmatian Beds are similar to the strata in the Vienna Basin (Rijavec, 1965; Kuščer, 1967).

The Čatež Formation (Badenian, Sarmatian)

Description: The lower part of the succession contains breccias and conglomerates with carbonate matrix and dolomite pebbles, deposited on the pre-Neogene basement. Conglomerate include dolomite, carbonate, chert and marl pebbles. The succession continues with lithothamnium limestone (rudstone), characteristic of shallow marine environments. The Čatež Formation is determined in the north slope of the Gorjanci hills and is divided into the limestone Badenian part and the clastic Sarmatian part (Rižnar et al., 2002).

Sedimentation: The rudstone interchanges with white litothamnium limestone (bindstone) typical of low energy deeper marine environment. It is overlain by somehow deeper water (up to 100 m depth) calcarenite (packstone). The Sarmatian beds are represented by alternation of marlstones, marls and gravel with calcarenite layers, indicating tectonically controlled sedimentation. Foraminiferal assemblages indicate a brackish environment (Rižnar et al., 2002).

The Drnovo Formation (Pannonian)

Description: The formation overlays Sarmatian beds or lies transgressively on Badenian beds or on pre-Cenozoic basement. It consists of Pannonian (including ex. Pontian) marls. The basal part is composed of thin bedded carbonate siltstones, they are followed by poorly lithified sediments (dolomite-calcite silts to siltstones). Towards the upper part, the clay and quartz minerals predominate. (Poljak, 2017a). The Drnovo Formation is defined in the Krško Basin and is generally found in the southern part of the Orlica Mountains and the Krško Hills. Sediments are usually deposited on Laško marls or Litothamnian limestones, but in some specific cases it can be found on Mesozoic limestones (Poljak, 2017a). The thickness of the Pannonian part of the formation is up to 300 m, and the ex. Pontian part up to 200 m. The age of the formation was defined on the basis of gastropods, molluscs and ostracods (Poljak, 2017a).

Sedimentation: Sediments cover the marine-brackish sediments of the Sarmatian or pre-neogene basement and are deposited in freshwater and lake environment (Poljak, 2017a).

Correlation: In the Croatian Zagorje, west of the Krško area, the deposits consist of alternations of sand, silt, marl, and clay of upper Pannonian age, where a turbiditic environment was present (Pikija, 1982).

The Bizeljsko Formation (upper Pannonian)

Description: Sediments of the Bizeljsko Formation are deposited concordantly on sediments of the Drnovo Formation. It consists of an alternation of marl and sand with rare intermediate layers or lenses of gravel. The mineral composition of the formation is identical to that of the Drnovo Formation, and it mostly consists of quartz (Lapajne, 1975). In some upper layers, little pockets of unlithified and well rounded gravel can be found.

They are composed of magmatic and metamorphic rocks originated from the Eastern Alps (Trajanova, 2006). The upper Pannonian age is determined by the ostracod microfauna. The thickness of the beds is up to 800 m (Poljak, 2017a).

Sedimentation: Sedimentation took place in a deltaic environment, containing sediments from the delta front (Fig. 4). Ostracod assemblages indicate a brackish environment with varying energy levels ranging from high and low (Marinšek et al, 2023). Individual sandy layers show evidence of synsedimentary slumps with the presence of rip-up clasts (Poljak, 2017a).

The Raka Formation (upper Pannonian)

Description: The formation consists of almost pure (up to 99 %) quartz sand and only occasionally are some marl lenses are present. In places, thin and irregular beds of oxidized clay sediments can be found. The uppermost Pannonian age of the sediments was determined based on mollusks and ostracods microfauna. The maximum thickness is 500 m. Within the Raka Formation, The Globoko Member occurs, composed of gravel, sand, silt, and clay with coal (Poljak, 2017a).

Sedimentation: Sedimentation took place in a deltaic environment and include delta plain sediments (Fig. 4).

Pliocene - Quaternary Alloformations

Description: The terrestrial sediments of the “Plio-Quaternary” unit comprising gravely, sandy, and muddy sediments are often pedogenized (Šikić et al., 1979; Verbič et al., 2000; Poljak, 2017a). The gravelly part is characterized as non-carbonate and carbonate gravel of Sava and Savinja River provenance (Verbič, 2004; Mencin Gale, 2021) preserved in several terraces (Poljak, 2017a; Mencin Gale et al., 2019a, 2019b, 2024). The thickness of the unit in the Krško Basin (Globoko claypit) is estimated at 30 m (Poljak, 2017a) and in Velenje Basin at 205 m (Brezigar et al., 1985). In the area of Krško Basin, the unit is formally described as the **Globoko Alloformation**. The first attempts at estimating the age of the unit were based on the geological knowledge of the adjacent regions and stratigraphical position and yielded a Pliocene-Lower Pleistocene age (Pleničar & Ramovš, 1954; Šikić et al., 1979). This was later revised to 1–2 Ma based on morphostratigraphy (Kuščer, 1993; Verbič, 2004). The first attempt of absolute dating of the Globoko Alloformation at the Globoko claypit locality employed optically stimulated luminescence (OSL), which yielded a minimum age of 306 000 years ± 2σ (Bavec, 2000), however, the capability of the dating method and sediment properties do not render reliable results (Bavec & Poljak, 2013). Further attempts included dating using terrestrial cosmogenic nuclide (TCN) on the Libna Hill which yielded a minimum of 1.8 Ma (Cline & Cline, 2013; Cline et al., 2016). The latest results of TCN dating at several locations in the basin indicate the Globoko Alloformation spans the time interval from the latest Pliocene to Middle Pleistocene (Cline et al., 2018, personal communication). The latest studies of the “Plio-Quaternary” unit were performed not only in Krško Basin (Mencin Gale, 2021) but also in Slovenj Gradec, Nazarje (Mencin Gale et al., 2019b), Celje, Drava-Ptuj (Mencin Gale et al., 2019b) and Velenje Basin (Mencin Gale et al., 2024). These studies encompass geomorphological, sedimentological, provenance analysis, and in the case of the Velenje Basin also the chronological analysis of the “Plio-Quaternary” unit and represent one step closer to formalizing the newly called Plio-Early Pleistocene unit. Sediments of this unit are characterized by several different facies including matrix and clast supported gravel, massive and cross-bedded fine- to coarse-grained sands and massive fines (silt and clay), in parts containing dropstones.

The Plio-Early Pleistocene unit is followed by the Quaternary sediments encompassing Middle-Late Pleistocene and Holocene deposits. These deposits generally exhibit a less weathered character, higher carbonate content and better preserved morphology (Mencin Gale et al., 2019a, 2019b, 2024; Mencin Gale, 2021).

Sedimentation: The Plio-Early Pleistocene deposits are characterized as a terrestrial succession of f luvial deposits preserved in terrace staircases (Verbič, 2002, 2004; Poljak, 2017a; Mencin Gale et al., 2019a, 2019b, 2024; Mencin Gale, 2021) or buried in the central part of the basins (e.g. Krško Basin; Poljak, 2017a). Generally, sediments from the Plio-Early Pleistocene were deposited in f luvi-al or alluvial/colluvial fan settings. Interpretation of sedimentary environment is limited due to the poor quality of outcrops and can be only deduced in a few localities. In the Krško Basin, a braided river system was interpreted, characterized by typical features like channel lag, overbank, or abandoned channel deposits (Mencin Gale, 2021). Shorter sections from the Drava-Ptuj Basin might also indicate a braided river system based on their lithofacies assemblages (Mencin Gale et al., 2019b). In the Velenje Basin, the sections suggest a wandering (intermediate category between the braided and meandering river systems) and meandering river system (Mencin Gale et al., 2024) and also lacustrine and swamp sedimentation (Brezigar et al., 1985).

In the Krško Basin, two formal nomenclatures of the Quaternary alloformations and allomembers are currently available. Verbič (2004) discriminates between three Pleistocene (**Dobrava, Brežice** and **Drnovo Alloformations**) and four Holocene terraces (uniform Vrbina Allomember; part of the Drnovo Alloformation). Poljak (2017) on the other hand describes **Brezina, Sotla, Krka, Sava** and **Dobrava Alloformations**, each further divided into several allomembers. The age constraints of Quaternary units using optically stimulated luminescence, infrared stimulated luminescence, ^{14}C, U/Th, and terrestrial cosmogenic nuclides are summarized by Mencin Gale (2021). The age of the unit in the Velenje Basin was constrained by isochron-burial dating using cosmogenic ^{26}Al and ^{10}Be which yielded an age 2.7 ± 0.3 Ma (Mencin Gale et al., 2024), which is in excellent agreement with the biostratigraphic data (Rakovec, 1968, Debeljak, 2017; Drobne et al., 2017).

Correlation: In general, the comparison of the Plio-Early Pleistocene unit between Slovenj Gradec, Nazarje, Velenje, Celje, Drava-Ptuj, and Krško Basins exhibits differents extent of the deposits.

In the Velenje and Slovenj Gradec Basins Plio-Early Pleistocene unit strongly prevail over younger Middle-Late Pleistocene surfaces, distinguishing them from the Nazarje, Celje, and Drava-Ptuj intramontane basins nearby. This could be due to specific tectonic changes, meaning that Pliocene-Quaternary fluvial sequence can serve as an important marker of tectonic processes (Mencin Gale et al., 2024).

In the Krško Basin, correlation with cross-border area is suggested by fossil material. No fossil material was found in the "Plio-Quaternary" unit of the Krško Basin. However, the "Plio-Quaternary" unit was also mapped in the near-border area in northwest Croatia (Zagreb region), where some fossil material was found in Majdačko selo consisting of unionids and melanopsids of Pliocene age (Šikić et al., 1979). This indicates that the »Plio-Quaternary« sediments represent the lateral equivalent of upper *Viviparus* beds (Šimunić & Avanić, 1985). It is, however, possible that the fauna was re-worked as the age determination is in contradiction with stratigraphic Bistra unit (Zagreb area), which indicates Pleistocene age (Bakrač & Koch, 1999, Grizelj et al., 2017).

Discussion

Marine connection of individual areas

There are prominent differences in the Central Paratethys transgression and regression stages between the individual basins north and south of the PAF and the MHZ. In the southern basins, Neogene sedimentation started in the Egerian and continued to Eggenburgian, where the Govce formation is described. In the northern basins, the Eggerian and Eggenburgian sediments are not defined, and this transgression has not reached the Krško area either. However, the Govce formation is described in the Krško area as well, but sediments were deposited in Ottnangian in terrestrial environment, based on similarities with sediments in the Medvednica Mountains (Čorić et al., 2009; Poljak, 2017a). The fact that the transgression in the Egerian and Eggenburgian did not reach the area north of the PFS and the MHZ as well as south of the central Sava folds (Fig. 5) suggests that the transgression was of lesser extent, or the local tectonic uplift (or delayed subsidence) of individual blocks prevented the northward and southward spreading of the Central Paratethys.

Prominent paleogeographic changes led to variable sedimentation in the late Early Miocene. Ottnangian sedimentation took place only in the Krško area, where Ottnangian/Karpatian alluvial, lacustrine and even marine sediments have been described (Verbič, 1995; Dozet et al., 1998; Rižnar, 2005; Poljak, 2017a). Karpatian transgression influenced sedimentation in the basins north of the PFS and the MHZ (Fig. 5) and caused the first marine transgression in the Early Miocene. The nanoplankton assemblages in the Slovenj Gradec Basin and the decapod crustacean fauna in the Ribnica Selnica Through indicate a marine connection with the Mediterranean Sea in the Karpatian (Gašparič & Hyžný, 2014; Ivančič et al., 2018a). In the areas south of the PFS and the MHZ, the Ottnangian and Karpatian sediments are not defined.

While Karpatian marine sedimentation continued in the Badenian in the Mura-Zala Basin (Maros, 2012), the early Badenian transgression correlated with TB 2.3 (Haq et al., 1988) is defined only in the Slovenj Gradec Basin (Ivančič et al., 2018a). Nanoplankton assemblages point to the connection with the Mediterranean Sea (Ivančič et al., 2018a). The extent of the transgression towards the west is not yet defined (Fig. 5). South of the PFS and MHZ, the early Badenian transgression has been proven in the Kozjansko area (Aničić et al., 2002) and presumable in the Tunjice and Moravče area.

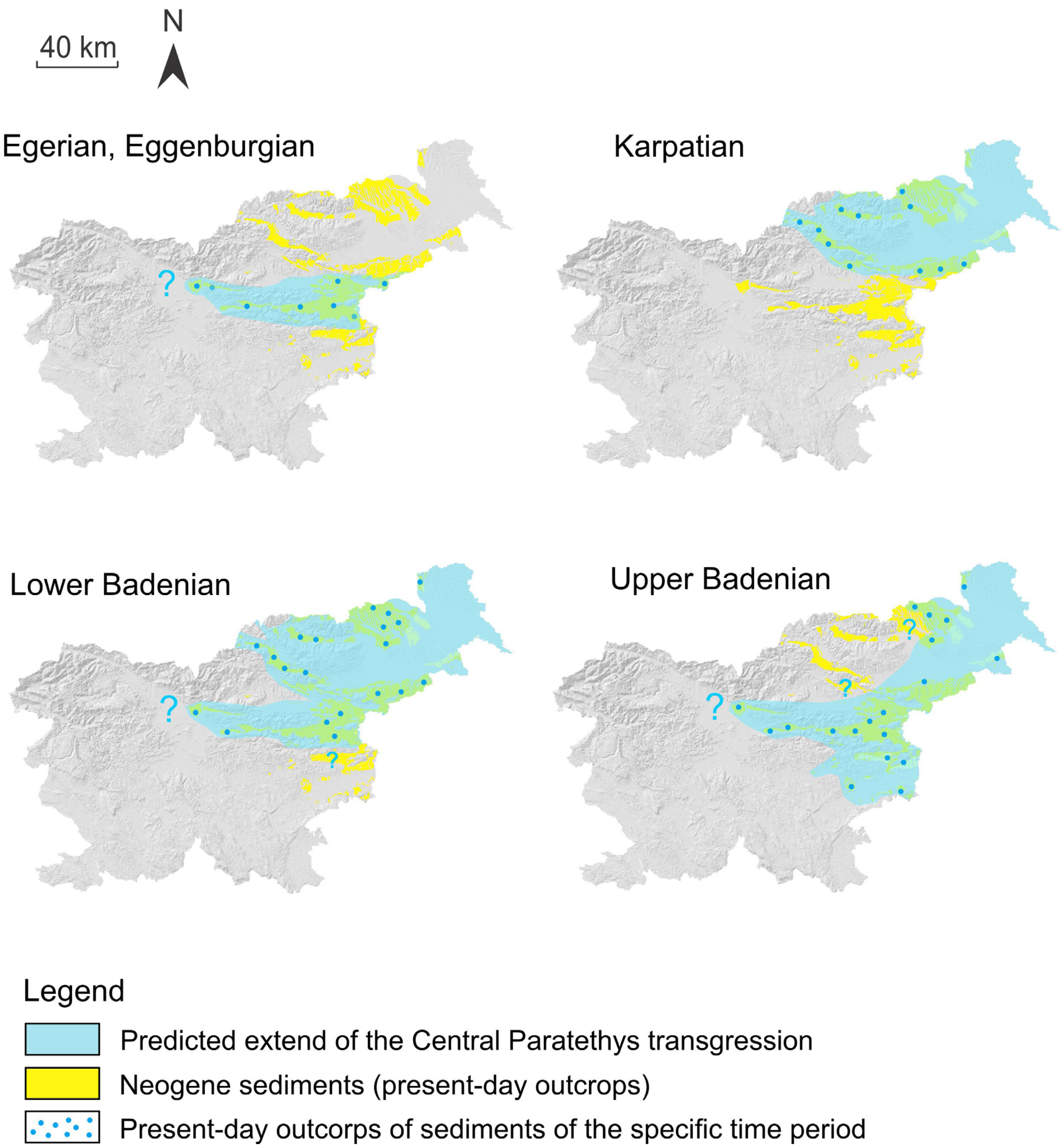

Fig. 5. Transgressions of the Central Paratethys in the Slovenian area, through the Early and Middle Miocene stages: blue colour indicates presumed extension of the Central Paratethyan transgression, yellow colours indicate distribution of actual outcrops of Neogene sediments.

At the end of the early Badenian, widespread palaeogegographic changes led to a cassation of Miocene sedimentation in the Ribnica Selnica Through, the Slovenj Gradec Basin and Kungota area due to the exhumation of the Pohorje Tectonic Block (Trajanova, 2013). The subsequent transgression of the Central Paratethys in the late Badenian caused the flooding of the areas north and south of the PFS and MHZ, as well as the Krško area (Fig. 5). Marine sedimentation continued in the Sarmatian, but the gradual filling of the basin and the cassation and closure of the marine connection to the open sea caused first brackish and later deltaic and terrestrial sedimentation in the Pannonian with the deposition of fine-grained sediments, white intercalations of coarse-grained sediments and coal.

Different names of lithological units

The difficulty in comparing beds and formations in various areas sometimes lies in the different naming of the individual lithological units. More precise investigations have rarely been carried out, so usually only the descriptive field name of the unit has been established, which is sometimes inaccurate. With coarse-grained sediments, this problem is not so pressing, as the names of the units can be determined fairly accurately in the field. The problem arises when fine-grained sediments or different types of limestone and calcarenites are present. For example, the term lithothamnium limestone is commonly used in the literature, but sometimes the name is not appropriate because of the involvement of different fossils. In several places, the terms lithotamnium limestone, calcarenite or algal limestone are used. Rarely, lithothamnium limestone is defined more precisely (bindstone, rudstone) (Rižnar et al., 2002). The difficulties in defining lithothamnium limestone have been emphasised by various authors (Fuchs, 1894; Mikuž et al., 2014; Poljak, 2017a). Within the Badenian there are several layers of lithotamnium limestones, which are not precisely dated. It is possible that the lithothamnium limestone belongs to different 3rd order sequence cycles, but without detailed sedimentological, stratigraphical and especially paleontological analyses, it is impossible to distinguish between them. Similar uncertainty with the commonly used term Laško marl (Laški lapor), which is present in more than one undefined horizon (bellow and over lithothamnium limestone). Moreover, the name Laško marl is commonly used for thicker sequences of silty sediments.

Correlation of different fauna between separate basins

Palaeontological studies are occasionally well documented in individual areas, but they have rarely been compared with neighboring basins. The exception is a small part of Kozjansko area, which contains Pannonian sediments and has been the subject of a few studies (Stevanović & Škerlj, 1989, Aničić et al., 2002, Marinšek et al., 2022). The ostracod and mollusk fauna of the Kozjansko area can easily be correlated to the Bizeljsko Formation in the Krško area. In both areas an abundant ostracod assemblage, which assigned to the upper Pannonian (ex."Pontian") stage, can be found. The assemblage includes some characteristic species like *Bakunella anae, Bakunella dorsarcuata, Hemicytheria Croatica* and *Camptocypria acranasuta and* can be correlated with the Croatian Mt. Medvednica and the Styrian Basin (Sokač, 1972; Gross, 2008). Correlations with the fauna in the Mura-Zala basin are still missing.

Formalising the "Plio-Quaternary" unit

The informal "Plio-Quaternary" unit has been a matter of debate for what is now a long while. This unit represents the onset of the youngest terrestrial sedimentation, marked by successions of clastic sediments abundant in central, southern and eastern Slovenia. Rare adequate exposures and subsurface data, strong weathering and degraded geomorphological characteristics have prevented research on the composition, provenance, genesis and age of the "Plio-Quaternary" fluvial terrace sequences in Slovenia, resulting in scarce relevant data in the past (Pleničar & Ramovš, 1954; Brezigar et al., 1985, 1987; Markič & Rokavec, 2002; Bavec et al., 2003; Verbič, 2004; Bavec & Poljak, 2013; Poljak, 2017a). The lack of knowledge concerning these units constitutes a scientific gap in the stratigraphy of the region, which limits our understanding of the Quaternary evolution of the entire pan-Alpine region.

The latest studies of the "Plio-Quaternary" unit in Slovenj Gradec, Nazarje, Velenje, Celje, Drava-Ptuj and Krško Basins followed multi-methodological approach (Mencin Gale et al., 2019a, 2019b; Mencin Gale, 2021) and provided the basic ground for formalizing the alloformations. However, except in Velenje and Krško Basin, no numerical age dating is available, which is the main aim of the future studies and the main condition for formalizing the sequence.

Conclusions

The Neogene period is characterized by significant paleoenvironmental, structural, paleogeographical and climatic changes. During this period, different depositional environments evolved which resulted in the deposition of several formations. Their composition reflects sea level fluctuations, which influenced not only the sedimentation processes, but also the connection of the Central Paratethys with the Mediterranean Sea and the open ocean. Such connections were established through the so-called Trans Tethyan (Slovenian) Corridor during the Karpatian and Badenian transgressions. While formations in the Mura-Zala Basin (Haloze, Špilje, Lendava, Ptuj-Grad, Ptuj-Kog, Mura) were defined primarily on the basis of seismic profiles, the formations in other parts were defined on the basis of biostratigraphic correlations. The oldest sediments are described south of the PFS as the Govce formation, which includes largely silty marl deposits of Egerian and Eggenburgian age that were deposited in a shallow marine to brackish environment. Ottnangian and Karpatian sediments are only present north of the PFS and the MHZ. Ottnangian sediments, known as the Radlje layers, consist mainly of conglomeratic successions, deposited in fluvial environments. The Haloze Formation consists of fine- to coarse-grained sediments of Karpatian age deposited in terrestrial, transitional and shallow marine environments. According to new data, it comprises the Urban, Kungota and Ivnik beds. The Badenian transgressions flooded the entire study area. The Špilje and Ptujska Gora – Kog Formation are described in the Mura-Zala Basin, while the Laško and Čatež Formations are defined south of the PFS and MHZ; their successions consist of comparable sediments. Sedimentation begins with conglomerate layers overlain by sand, silt and marl with interbedded limestone layers. Sarmatian sediments are deposited concordantly on Badenian. South of the PFS and the MHZ, the Dol formation is described, comprises conglomeratic, sandy, silty and marly layers, deposited in marine and brackish environment. During the Pannonian, the Lendava, Mura and Ptuj-Grad formations were deposited in the Mura-Zala Basin. The sediments were initially deposited in a turbiditic and later in a deltaic environment where deposition of clayey, silty and sandy sediments prevail. South of the PFS and the MHZ, Pannonian sediments are present in the Kozjansko and Krško area. While sediments are not described in any formation in the Kozjansko area, the Drnovo, Bizeljsko and Raka Formations are defined in the Krško area. In this area, the sandy and silty sediments were initially deposited in a brackish environment which evolved towards a deltaic setting. Pliocene and Quaternary formations are only well defined in the Krško area, with the Globoko Alloformation consisting of non-carbonate gravel, sandy and silty layers.

Many uncertainties remain obscuring the overall structure of the studied part of the PBS and its sedimentary evolution during the Neogene due to lack of research. This review provides some guidelines for further research with the aim of expanding our knowledge of:

- the precise age of individual formations,
- stratigraphic, paleontological, and sedimentological correlations between different formations,
- temporal and spatial description of the Trans-Tethyan Trench corridor,
- standardization of different names/descriptions of similar lithological units,
- formalization of the Plio-Quaternary units.

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