Lithostratigraphic units in the Drava Depression (Croatian and Hungarian parts) – a correlation

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The lithostratigraphic division and correlation is one of the most common stratigraphic divisions. It is strictly connected with lithological content of the rocks or deposits. Sometimes lithostratigraphic units, especially in rank of formations and members, can be approximately correlated with particular chronostratigraphic units in range of stages or sub-stages, i.e. lithosratigraphic units have synchronous borders. In other cases, the borders are asynchronous. Croatian and Hungarian lithostratigraphic units in the Drava Depression are analysed here as well as the possibility of their correlation. Such correlation scheme can be useful in comparison of different units, especially because the Croatian part is based on approximately synchronous, and Hungarian on asynchronous borders between units. Moreover, the Drava Depression in this region is an important hydrocarbon production province where lithostratigraphic correlation is widely used, even across state borders. The presented lithostratigraphic scheme, it's lithological descriptions and correlation could help in any geological research or evaluation in the entire analysed depression.

Key words: lithostratigraphy, Drava Depression, Croatia, Hungary

1. Introduction

The entire Drava Depression covers the surface area of about 12 000 square km, where approximately 9 100 belong to the Croatia (Figure 1). Generally, the Neogene and Quaternary rocks and deposits defined the subsurface volume known as the Drava Depression. The total thickness can reach more than 7 000 m in the central part of that depression.[38] In Ng-Q complex a sporadic occurrences of volcanic rocks of Middle Miocene stage as well as fluvial and lacustric sediments of Lower Miocene can be found. However, the most part consists of Middle Miocene, Upper Miocene and Pliocene clastic and biogenic sediments and Pleistocene and Holocene sediments and deposits.

The basement of the Drava Depression is represented with rocks of significantly different lithology assemblage and chronostratigraphic assemblage. Those are mostly carbonates (limestone and dolomite), metamorphites (amphibolite, schist and gneiss) and magmatites (granite, gabbro) from Mesozoic and Palaeozoic eras. However, that basement is not part of Croatian lithostratigraphy nomenclature of the Drava Depression.

The analysed chronostratigraphic and lithostratigraphic units of the Drava Depression are based on numerous well and seismic data. There are several regional papers where ranks and lithostratigraphic units are defined. In Croatian part the most famous source is ref.[43] internal study and later dissertation[34] where he proposed the formal lithostratigraphic nomenclature in the Drava Depression. The most available and reliable source of the Croatian lithostratigraphic nomenclature in the Croatian part of the Pannonian Basin System

Fig. 1. Area that approximately covers the Drava Depression
Sl. 1. Približno područje prostiranja Dravske depresije

(CPBS) is given in ref.[38]. In Hungarian part, several sources were used here (refs.[11,12,33]) with lithostratigraphical columns and correlation through several geological provinces in the Hungarian part of the Pannonian Basin System (HPBS). This analysis is based on time intervals that encompassed particular serie, stages and sub-stages during Neogene and Quaternary, and that are given in refs.[5,18].

Moreover, in the Croatian part of the western Drava Depression the lithostratigraphic division had been made according with lithostratigraphy of the Sava Depression, which are both corresponding. Those two areas together represented the most southern (south-western) part of the PBS and shared similar depositional processes and environments.

2. Lithological description of pre-Neogene basement rocks

Magmatic and metamorphic rocks in Croatian part are named as “temeljno gorje” what means “the basement”. Those are mostly granite, gabbro as well as cataclised and hydrothermal altered metamorphites, mostly of amphibolitic and greenschist facies (Figure 2). The age is often only approximated, due to numerous orogeneses that masked or destroyed characteristic mineral paragenesis. Some metamorphic periods had been dated from[4] using samples from the Moslavačka gora Mt., who described granite as younger than metamorphic rocks, i.e. on 90±5, 64 and 62 Ma. Furthermore, in ref.[25] are described several magmatic and metamorphic complexes and ofiolitic rocks in the CPBS as Mesozoic. Other author[7] dated gabbro and serpentinite on NW sides of the Majevica and Trebovac Mts as Upper Cretaceous. When Mesozoic carbonate sediments are present between the magmatic and metamorphic rocks and Neogene-Quaternary infill they are called “podloga tercijara” what means “Tertiary basement” – a name that is a relic of an older stratigraphical division. Those in the CPBS are mainly limestones and dolomites (Figure 2), often cataclised and weathered into breccias and conglomerates. Their Mid-

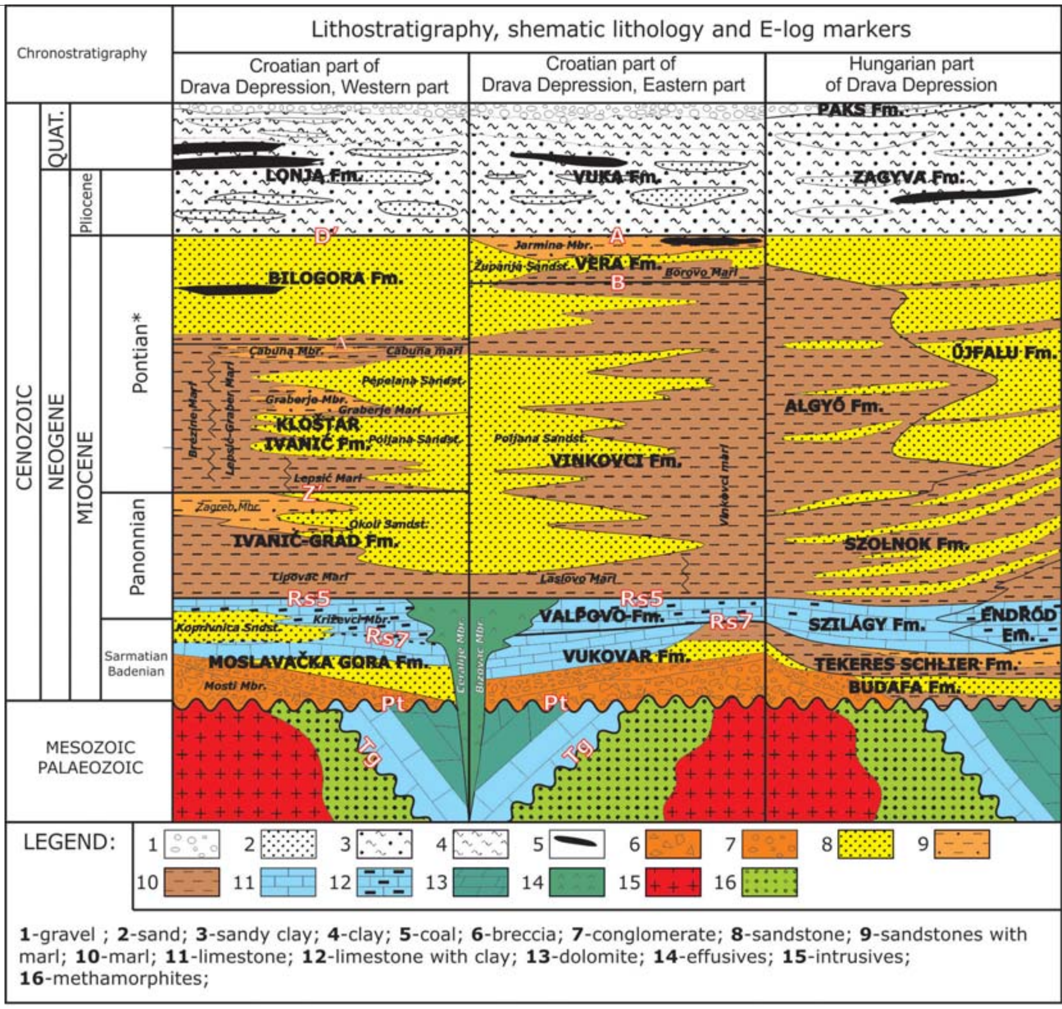

Fig. 2. A schematic representation of the correlation of units between Croatian and Hungarian parts of the Drava Depression, modified after refs.11,12,34,38 (thicknesses are not in scale).

Sl. 2. Shematski prikaz litološkog sastava i korelacije jedinica između hrvatskog i mađarskog dijela Dravske depresije, modificiran prema[11,12,34,38] (debljine nisu u mjerilu).

dle Triassic (i.e., Ladinic) age is often proven from algae genus *Dasicladacea*, i.e. *Diplopora annulata SCHAFHÄUTL* and *Teutloporella sp.* and correlation with Mesozoic outcrops on present-day mountain like Papuk (refs.[9,10]).

3. Lithostratigraphic units of approximately Middle Miocene to Lower Pannonian serie/substage

Sediments of Middle Miocene (and very locally Lower Miocene) represent the period of overall marine transgression in the entire PBS. They are deposited over Palaeozoic or Mesozoic unconformities. Lower Miocene extension locally started in Ottnangian and Karpatian (ref.[30]) with development of smaller fluvial and lacustric environments, where some sporomorphs taxons are characteristic just for Central Paratethys (e.g.[20,29]). However, overall marine transgression and forming of the Central Paratethys (e.g.[17,18,31,32,39]) started in Badenian when present-day mountains in Northern Croatia, like Medvednica and Psunj Mts., were isolated islands. Numerous smaller rhomboidal (pull-apart) basins were regularly created onto sea bottom, and the largest was the Bjelovar Subdepression (e.g.[15,16]). The sediment thicknesses reached several hundred meters[19]. The weathering and cataclising were especially strong into shallow sea and inland, where the main siliciclastic and carbonate (*Coralinacea* and *Briozoa* reefs) detritus sources were located. The dominant depositional mechanisms were alluvial fans. The Late Badenian sea-level rise, resulted from re-opening of the Indo-pacific seaway[31], caused flooding of uplifted blocks on many places in the Drava Depression. The boundary in the base of Upper Badenian deposits may be compared with the acknowledged Middle Badenian unconformity, and is considered as a syn-rift/post-rift boundary[8,26].The disintegration of the Central Paratethys started in the Uppermost Badenian, when this large palaeo-sea lost connections with Indo-Pacific and Palaeo-Mediterranean (e.g.[17]), and during Pannonian had been closed into brackish the Lake Pannon[13] that later disintegrated into smaller lacustric, fresh-water regional lakes[18] mostly covers today's depression or basins into PBS.

In the Croatian part of the Drava Depression, western part, Miocene sediments up to Lower Pannonian belong to the Moslavačka gora Formation (Figure 2), which is divided into older the Mosti Member (sporadically Lower Miocene, Badenian and Sarmatian) and younger the Križevci Member (approximately of Lower Pannonian age). Electro-log (abbreviation e-log or EL) borders “Tg” or “Pt” are borders between Moslavačka gora Fm. and pre-Neogene basement. EL-marker Rs5 divided Moslavačka gora Fm. and Ivanić Grad Fm. in the top. Badenian sediments are dominantly coarse breccia, conglomerates and coarse to medium-grained sandstones. Sometimes those can be green coloured sandstones, due to coloured mica (chlorite and glauconite) content, representing so-called “hybrid type of green sandstones” (described as lithotype, e.g.[24,35]). They are indicator of weak reductive environments in sea of normal salinity, what plays an important role in preservation of organic matter and genesis of source rocks in Upper Badenian, Sarmatian and Lower Pannonian. Those periods are also characterised with pelitic, dominantly calcitic rocks like (marlitic) limestones and marl, mostly deposited over lithoral areas. Consequently, it is very hard to distinguish borders between stages of Badenian, Sarmatian and Pannonian, so the only EL-marker Rs5 is recognised onto resistivity curves as border between Lower and Upper Pannonian. Sporadically EL-marker Rs7 can be distinguished but not in the whole part of this segment. Locally Lower Pannonian can include several sequences of marlitic sandstones or, rarely, sandstones, what indicate on changes in dominant depositional mechanism. The Mosti Member is mostly represented with sandstone, breccia and breccia-conglomerate, and locally tuffite or tuffitic sandstones. In Sarmatian entire area is covered with calcitic marl. The Križevci Member (also named as Croatica-deposits after characteristic fossil shell *Radix croatica*) is lithologically marl and clayey limestone in different ratios. The Koprivnica Sandstones are a lateral equivalent of the Križevci Member but only with the dominant lithology being sandstones. Sporadically effusive rocks of Badenian to Lower Pannonian age are present and as named as the Ćeralije Member.

In Croatian part of the Drava Depression, eastern part, Miocene sediments up to Lower Pannonian can be divided into two formations. These are THE VUKOVAR and THE VALPOVO FORMATIONS (Figure 2). As in western part the border with pre-Neogene basement is defined by EL-border “Tg” or “Pt” and Rs5 separates the Valpovo Formation from younger, Upper Pannonian one. Border between Vukovar and Valpovo formation is defined by EL-border Rs7. THE VUKOVAR FORMATION is represented by coarse grained sediments (breccias and conglomerates) at its base with sandstones and limestone in its upper part which approximately belongs to Sarmatian. THE VALPOVO FORMATION is similar to the Križevci Member and is mostly comprised of clayey limestone.

In Hungarian part the Miocene sediments up to Sarmatian belong into four lithostratigraphic formations. Those are the Budafa, the Tekeres Schlier, the Szilágy and the Endröd Formations (Figure 2). Lacustrine clayey marls and sandstones represent the transition from Karpatian brackish water to Badenian fully marine conditions.[33] These are overlain by coarse clastics (sands, sandstones, and conglomerates) that were deposited from foreshore to near shore areas. This heterogonous interval is named the Budafa Formation, which can reach thickness of 600-700 m. It is overlaid by regressive sediments of dark grey, sandy siltstones and marls named as the Tekeres Schlier Formation, which formed in shallow marine environment (rarely exceeds 200–400 m). The Late Badenian is represented by the Szilágy Fm. (the Turritella–Corbula Clay-marls in alteration with the Lithothamnion Limestones and the Leitha Limestones, originated from shallow marine, near shore or littoral zones.[33] Chronostratigraphically lateral equivalent or younger is the Endröd Fm., composited mostly from dominantly pelitic sediments of Badenian like dark grey calcareous marls that gradually turn into clayey marls of hemipelagic origin.

4. Lithostratigraphic units of approximately Late Pannonian substage

In the Late Pannonian (9.3–7.1 Ma) the Drava Depression was elongated brackish lake filled by turbidites that interrupted basin pelitic sedimentation (e.g.[18]). The eastern part probably represented the marginal area where turbiditic events dominant in the CPBS and delta and prodelta sedimentation, which prevailing in the HPBS, met each other and resulted in sometimes in lithological units that can not be correlated regionally. It is also the main reason why lithostratigraphic nomenclature in the Croatian part of the Drava Depression differs in the western and eastern parts.

Generally, during the Late Miocene the entire PBS was an open lake system with active inflows and outflows (e.g.1). In[31,32,39] and others describes Late Pannonian as period when sedimentation was active in different brackish and fresh water depressions. Different species of Ostracodes, Silicoplacentines and Foraminifers indicated mostly on shallow and brackish water environment.

In the Croatian part of the Drava Depression, western part that age belongs to the Ivanić-Grad Formation (Figure 2), which is also biostratigraphically named as *Banatica-deposits* after characteristic fossil shell *Congeria banatica*. EL-marker Rs5 is border with older the Moslavačka gora Formation, where EL-marker Z' is border with younger the Kloštar Ivanić Formation. That formation is divided into the oldest Lipovac Marl, follow with the Zagreb Member or laterally equivalent Okoli Sandstones. The Lipovac Marl is the oldest member, represented with calcitic marl, sandy marl with sandstone, marl and calcite-clayey marls, marlitic clay and clayey marl, clay limestone and silty clay. The younger Zagreb Member (somewhere marl, calcitic or clayey, i.e. the Zagreb Marl) consists of different parts of fine-grained sandstone and marl, i.e. marlitic sandstone and sandy marl. The Okoli Sandstones are laterally equivalent of the Zagreb Member, where sandstones dominate with rarely intercalations of marls.

In the Croatian part of the Drava Depression, eastern part that age belongs to the base of the VINKOVCI Formation (Figure 2). Bottom part of the Vinkovci Formation, just above EL-marker Rs5 is composed of dominantly pelitic sediments, i.e. marls which belong to the Laslovo Marl and its lateral equivalent the Vinkovci Marl. Sandstones only dominate in Poljana Sandstones.

In the Hungarian part sediments of Upper Pannonian mostly belong to the Szolnok Formation (Figure 2), which included several series of fine-grained sandstones of turbiditic origin. These are supposed to be formed mainly on turbidite fan lobes and sheets.[1,28] The thickness of individual sandstone bodies usually varies in the range of 3–10 m, and they are separated by 2–20 m thick intercalations of marls. The thickness of the whole turbiditic succession, however, shows great variation depending on the topography of the basin floor. That it pinches out towards the basin margins and is significantly thinner above basement highs, while it can reach 1 500 m in the deepest parts of the depressions.[33]

5. Lithostratigraphic units of approximately Pontian stage

Like during the most of Pannonian in Pontian stage (7.1-5.6 Ma) the depositional characteristics and environments remained same, i.e. dominated with distant transport of huge volume of clastics where (a) the main clastic source areas were located to the distant north-east, (b) a turbiditic transport mechanism is active along the deepest lake floor, and (c) an absence of large delta and prodelta environments on southern margins of the PBS (e.g.[18,42]). In fact, there are some new results (e.g.[21,22]) stated strong indicators of smaller alluvial fans activity on the margins (hinterlands) of Pannonian and especially Pontian lakes into CPBS, but the volume of deposited detritus, compared with turbidites, is negligible. Generally, the most volume of psammitic sediments is still deposited in the deepest parts, transported by turbidites from the Eastern Alps.[18,30,39] In northern and especially eastern parts some sediment can be deposited from deltas came from north or north-west, which are interpreted as the depositional mechanism for the most of today Hungary at the end of Miocene.

Pelitic sediments are deposited in periods between activities of two currents. Some salinity changes can be connected with establishing of connection between Pannonian and Dacian basins[39], what resulted in caspi-brackish environment and fauna (e.g.[31,32]). However, at the end of Pontian such connection is closed and fossil relicts indicated again the fresh water environment.

In the Croatian part of the Drava Depression, western part Lower Pontian sediments are named the Kloštar Ivanić Formation (Figure 2), or also *Abichi-deposits* after characteristic fossil shell *Paradacna abichi*. The oldest sediment belongs to member the Lepsić Marl, followed by the Poljana Sandstones, the Graberje Marl, the Pepelana Sandstones and the Cabuna Marl. Locally the Brezine Marl is a member that can substitute all mentioned members in the case when only impermeable sediments are deposited (e.g., in the S and SE of the Bjelovar Subdepression). Lower border with the Ivanić Grad Formation is EL-marker Z'. EL-marker Δ is approximately upper border (recognised inside the Cabuna Marl) with the Bilogora Formation. Lithologically it is alternation of different sandstones and marls. Marlitic members are mostly lithological homogenous, except locally the upper part of Lepsić Marl. In the youngest the Cabuna Marl clayey component is dominant. Sandstone members are often intercalated with marls, especially the Poljana Sandstones inside the Bjelovar Subdepression, where the sandstone is almost completely absent on the south and southeast. The thickness can vary between several tens of meters (the marl members) and several hundred meters (the sandstone members, the Brezine Marl). Sediments of Upper Pontian are named as the Bilogora Formation (Figure 2), i.e. as the Rhomboidea-deposits after fossil shell Congeria rhomboidea. That formation is not divided into members. EL-marker Δ is border with older Kloštar Ivanić Formation and EL-marker D' with younger the Lonja Formation. Thickness is mostly larger then from previous formation, and in the deeper parts can reach more than 500 m. The older sediments are mostly clayey marl, and rarely poorly consolidated sandstones.

In the Croatian part of the Drava Depression, eastern part Lower Pontian and a part of the Upper Pontian still belong to the aforementioned THE VINKOVCI FORMATION (Figure 2) and its members. Only the uppermost part is divided by EL-marker B that separates Vinkovci Formation from THE VERA FORMATION (Figure 2). It is divded into Borovo Marl at the base, Županja Sandstones and Jarmina Member at the top which is separated from younger sediments by EL-marker A.

In the Hungarian part silty clayey marls and siltstones are widespread all over the basin above the turbiditic succession, in connection with the approaching delta slope. The delta sediments of approximately Pontian age are the mostly known as the Algyö Formation (Figure 2). Fine grained slope sediments contain up to 2–40 m thick lentoid sandy intercalations of different mass flow origin.[33] The thickness of the strongly progradational delta slope reflects palaeo-water depth[27] and varies from 50 m to several hundred metres. According to reflection seismic sections the slope angle also changed from rather gentle and ramp-like, to steep in the deepest depressions.[36] The mostly younger or synchronous formation with previous one is the Újfalu Formation (Figure 2). That is characterised with thick sandstones were accumulated mostly on the delta front and delta plain as distributary mouth bar, channel fill or wave-reworked shore-face deposits. Due to the high rate of subsidence a very thick (700 – 1 000 m) aggradational units of that formation was formed reflecting several episodes of minor relative lake-level oscillations.[33]

6. Lithostratigraphic units of approximately Pliocene and Quaternary serie/system

The Pliocene (5.6–2.6 Ma) and Quaternary (2.6–0.0 Ma) were periods of the second transpressional phase in the Croatian part of the Pannonian Basin System[18], during which the most of negative (mainly flower) structures were uplifted, in many cases forming anticlinal hydrocarbon traps. The water environment was greatly reduced, being only sporadically lacustrine and evolving into Quaternary marshes, river alluviums and predominantly continental loess. In fact the entire Pannonian Basin System is divided on many fresh water lakes[31,32,39], which were gradually filled with fluvial and continental sediments. Sedimentation is characterised with sand and clay, and in deeper lakes it is silt, marl and even carbonate. The local lacustric clastic environments can be characterised with smaller deltas of the Gilbert type (this delta type is described, e.g., in[35]). Due to smaller depositional environments, often restricted onto kilometre scale those formations are not divided into members, because lithologically they very hardly can correlated onto scale lower than rank of formation. Although some “conditional” markers had been outlined and proposed in the Sava Depression where in[37] authors mentioned that deposits younger than EL-marker α’ (Pliocene base) can be divided with EL-marker Q’ between Lower and Middle Pleistocene (i.e. between impermeable sediments in the base and unconsolidated deposits of mostly sands and gravels into top). Later authors in[6] recognised marker Q’, but also H into Lower Pliocene. Recent work in researching lithofacieses and possibility to define regional EL-marker in Pliocene and Quaternary sediments of the Sava Depression had been based onto neural network calculation and consequent mapping.[2,3]

In the Croatian part of the Drava Depression, western part this sediments and deposits lithostratigraphically belongs to the Lonja Formation (Figure 2), margined in base with EL-marker D’. The thickness varies from 10 to more than 1 000 meters in some parts. In the deepest parts it is represented by sandy clays and silts. Other parts are dominantly filled with clay with sand intercalations. Gravel, sand and clay with lignite intercalations (cm-m dimensions) are deposited only in the central part. Lithification is very poor and is further decreasing in younger parts (unconsolidated sediments). The top part of the formation consists of Holocene loess, clay, gravel, and sand.

The counterpart eastern part of the Croatian part of the Drava Depression is THE VUKA FORMATION (Figure 2). A thickness of this unit is somewhat smaller than in the western part but can still be significant. Similar lithology comprised of clays, sands and silts in the deeper part and dominantly sands and gravel in the topmost part can be observed.

In the Hungarian part that part mostly encompasses the Zagyva Formation (Figure 2) defined in the Pliocene and older Quaternary, and the Paks Formation (Figure 2) during Quaternary. The flooded delta plain gradually gave way to an alluvial plain, on which thin-bedded, often variegated silty clays, occasionally lignites alternate with sand beds a few metres thick. The fine grained deposits are of floodplain, wet plain and shallow lacustrine (pond) origin, while sands mainly represent fluvial channel fills. The thickness of this unit is about 300–400 m in the Drava Depression, but elsewhere it was considerably eroded during the Pliocene.[33]

7. Discussion and Conclusion

This review is based on numerous published sources that described the lithostratigraphical units in ranks of formations and members and lithology in the Drava Depression. The analysed space belongs to two countries, Croatia and Hungary. Consequently, two lithostratigraphic nomenclatures where developed that are different in two main principles: (a) borders of Croatian formation are mostly approximately synchronous (i.e., they are considered that have been deposited in wide area during the periods lasting 10^3-10^4 years); (b) borders of Hungarians formations are mostly asynchronous, i.e. they are consider as lithological borders that were deposited over wide area in the period on the scale 10^5-10^6 years. It means that correlation between Croatian and Hungarian formations cannot be unambiguous, i.e. generally one formation in the Croatian part of the Drava depression laterally corresponds to one or more Hungarian formation and oppositely.

Moreover, the regional EL-markers described in the Croatian part of the Drava Depression are not always present or recognisable onto e-logs. EL-marker that can be traced in almost all parts of the depression is Z', whilst other ones can be masked by erosional or tectonical unconformities. It depends on type and depth of depositional environment and tectonical displacement in the time and after deposition.

Of special interest are the two Upper Miocene formations named as Ivanić-Grad and Kloštar Ivanić. Both of them represent monotonous alternation of sandstones and marls, and are results of turbiditic events and lacustric environments. As the lithological differentiation is only criteria for selection of lithostratigraphic units it would be appropriate to propose to merge those two formations into one. Maybe as that unit would be typical for the Drava Depression, the appropriate name could be the Drava Formation.[40,41] As the completely same lithological situation is valid for the Sava Depression there could be also proposed new formation like the Sava Formation can be proposed[40,41], which would replace Ivanić-Grad and Kloštar Ivanić Formations.

Depositional environments though Neogene and Quaternary had been very similar in both part of the Drava Depression (Croatian and Hungarian). Only difference came from different Upper Miocene model of clastics sedimentation generally developed in those two countries. In Croatian the most part of Miocene sedimentation is described as turbiditic dominant with minor influence of delta plains or alluvial fans. Oppositely, during the most of Miocene in Hungary is modelled the domination of different delta environments (delta and prodelta fans), which migrated through the space and time. However, the lithology in different (sub)stages is very similar. The eastern part of the Drava Depression is areas where those two environments met each other. The presented Croatian and Hungarian lithostratigraphic units can be correlated using proposed correlation table and given dominant lithological descriptions of lithostratigraphic units in this paper.

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