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The Neogene of Hrvatsko Zagorje

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The origin of the oldest Neogene rocks of the Hrvatsko Zagorje region is related to the coastal area of the Central Paratethys in the Late Eocene when, due to the continental collision of Eurasia with Africa and India, the Tethys split into Paratethys and the Mediterranean Sea (RÖGL, 1996, 1998). In the Late Eocene, Oligocene and Early Miocene, the marine sedimentation continued only in the northern part of Hrvatsko Zagorje, that is, in the Hrvatsko Zagorje Basin (HZB - north of the Kalnik Mt.). During this period, the southern part of Hrvatsko Zagorje, as a northwestern part of the North Croatian Basin (NCB) was predominantly the land area while the marine sedimentation started in the Early, and, according to some geologists, only in the Middle Badenian when these two basins had been connected (AVANIĆ et al., 1990; ŠIMUNIĆ, AN. et al., 2000; PAVELIĆ et al., 2001, 2002; VRSALJKO et al., 2006; ĆORIĆ et al., 2009; AVANIĆ, 2012; BRLEK et al., 2016; MARKOVIĆ, F., 2017; PAVELIĆ & KOVAČIĆ, 2018).

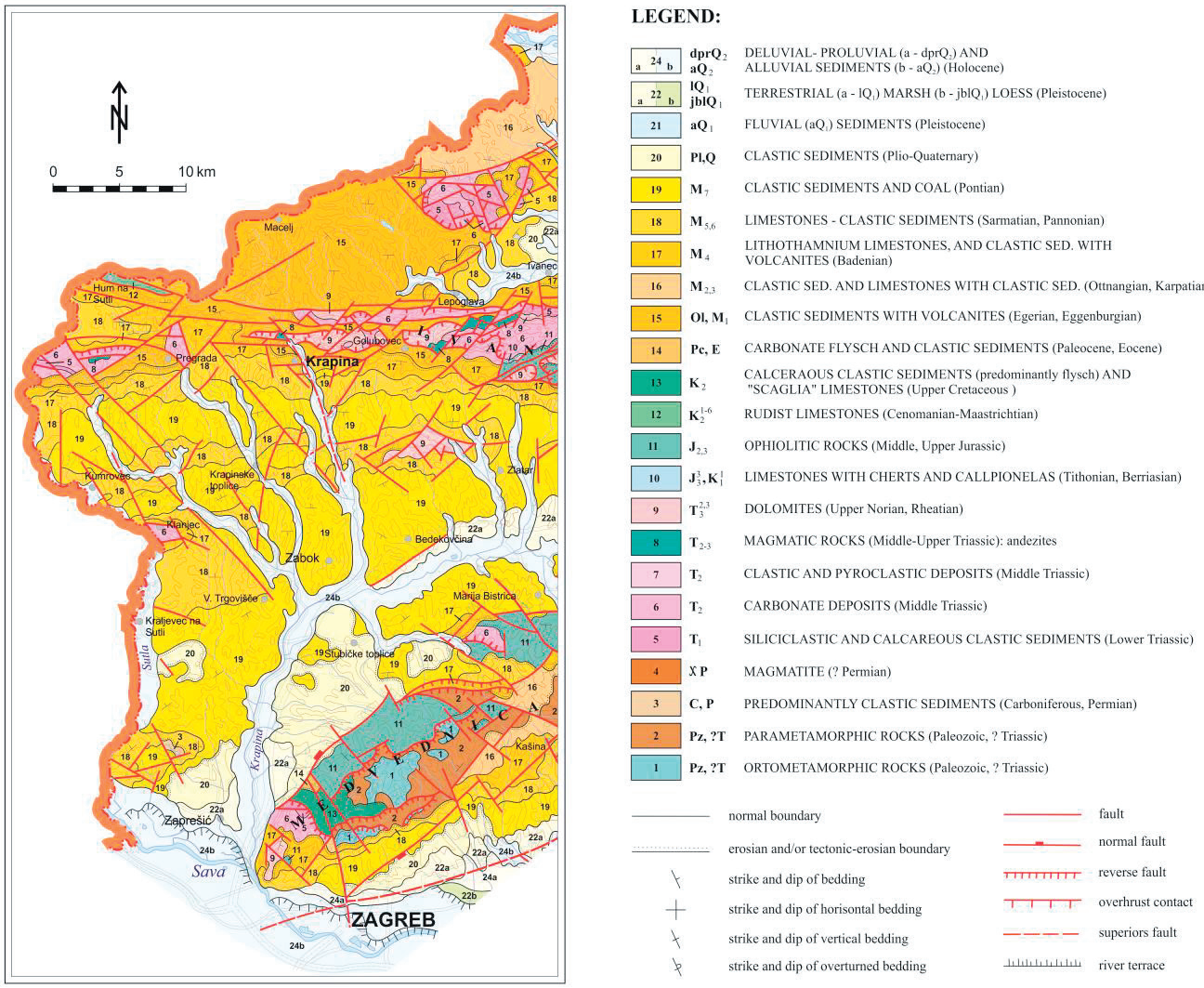
The oldest sedimentary rocks on the surface are located in the northern part of Hrvatsko Zagorje in the area of the Ravna Gora Mt. These Oligocene–Miocene rocks overlie the shallow water marine sediments of the Keglević Fm. of the Middle to Late Eocene age (ŠIMUNIĆ, AN. et al., 2000). After the Eocene there occurred a short emersion followed by marine transgression during the Kiscellian stage characterized by deposition of sediments of the Meljan Fm. In the beginning, the clayey limestones and calcarenites reflect deposition in the littoral and afterwards, until the Early Egerian, deposition continued in the prodelta environment with marls and sandstone intercalations (AVANIĆ et al., 2007). A sedimentation with prograding tendencies continued into the Late Egerian with prodelta and coastal deposition of sands and marls, followed by the delta pyroclastics and conglomerates of the Golubovec Fm. The significant supply of terrigenous material is also indicated by the fragments of coal that have been eroded from the floodplains or delta plains and transported into the coastal environment. The existence of several layers of brown coal is recorded in numerous coal mines in the area between Pregrada and Krapina as well as along the Strahinščica and Ivanščica Mts., and the eastern parts of the Kalnik Mt. (AVANIĆ et al., 1990; MARKOVIĆ, S., 2002). Due to the collision of the Adriatic plate and the European foreland (SCHMID et al., 1989), the regional stress characterized by the main NS compression axis with EW extension occurred during the Oligocene and Miocene. Within the stress zone of the Hrvatsko Zagorje Basin, the Donat and Rogaška fault systems with dextral strike slips were formed, representing the eastern continuation of the Periadriatic lineament (ŠIMUNIĆ, AN. & PAMIĆ, 1993; TOMLJENOVIĆ & CSONTOS, 2001). Associated to these fault systems is occurrence of synsedimentary volcanism in the Egerian (andesite and pyroclastic rocks of the Golubovec Fm.) and Eggenburgian (tuffs of the Macelj Fm.).

After the emersion at the end of the Egerian in the HZB, the onset of the Eggenburgian was marked by a transgression and deposition of sands, glauconitic sands and pyroclastics of the Vučji Jarek Mb. of the Macelj Fm. in the coastal environment, coinciding with the sea level rise in the Central Paratethys (STEININGER & WESSELY, 2000; AVANIĆ, 2012). Further relative sea level rise in this area caused the deposition of clayey and sandy silts of the transitional zone between the shelf and the shoreface environment of the Čemernica Mb. In the Late Eggenburgian, the uplifted parts of Strahinščica, Ivanščica and Ravna Gora Mts. were intensely weathered. The rivers had eroded and transported the coarse-grained terrigenous material that was finally deposited in the fan delta, prodelta, and shoreface environments (Lipni Vrh Mb.). At the end of the Eggenburgian and beginning of the Ottnangian there was a further rise of the sea level between the shelf and the coastal area under the tidal influences and the presence of volcanic activity (Vrbno Mb.). Sands deposited in the coastal area were characterized by cross-bedding while those accumulated on tidal flats and in tidal channels contain intercalations of layers and laminae of silts and clay. The transitional zone is characterized by marls intercalated with sandstone while only marls accumulated on the shelf. Volcanic activity at the end of Eggenburgian is indicated by tuffs, and bentonite clays originated from the subsequent alteration of the pyroclastics of the Vrbno Mb. During, and, especially, in the Late Ottnangian, deposition of calcitic silts and tuffs was followed by silty sands of the transition zone of the Bednja Fm., indicating a regressive sequence. The further relative sea level fall has been recorded in the Karpatian by the deposition of sand and gravel in the coastal area (Crkovec Fm.).

During the Ottnangian in the area of Kalnik and Medvednica Mts. (NCB), gravels with lens of sand and silts of the alluvial environment of Daranovci Fm. have been deposited (AVANIĆ et al., 1995; PAVELIĆ et al., 2001). The prevalence of coarse-grained sediments in the Early Ottnangian is related to the occurrence of the

main normal faults, i.e. the extensions within the basins, accompanied with formation of half-graben of the early syn-rift phase (PAVELIĆ et al., 2001). From the Late Ottnangian to the Karpatian (ĆORIĆ et al., 2009) and, according to the latest data, to the Middle Badenian (MARKOVIĆ, F., 2017; PAVELIĆ & KOVAČIĆ, 2018) a freshwater lake developed in that area (Glavnica Fm.). In the lower part of the Glavnica Fm. congerian limestones with coal layers (Vukov Dol Mb.) represent the deposition on the littoral, while marls and tuffs were deposited in the deeper lake, as well as marls with laminae and layer sands in prodelta (Koščević Mb.). Mostly the upper part of the formation, delta front and prodelta conglomerates with lenses and intercalations of sands and siltites of the Franci Mb. occur (AVANIĆ, 1997). The occurrence of pyroclastic rocks in the Ottnangian, Karpatian and Early Badenian was related to syn-rift processes (PAVELIĆ et al., 2001; MARKOVIĆ, F., 2017). The depositional sequence in the NCB from the littoral, through the deeper lake to the delta sediments suggests the the sucession of deepening and subsequent shallowing. Due to the Early Badenian transgression in the Central Paratethys (RÖGL, 1996; SANT et al., 2017) in the area of the HZB, after a short emersion, there was a period of deposition of coarse-grained material in the shoreface area and formation of the Trstenik Mb. (AVANIĆ, 2012). It was later followed by a further deepening characterized by a deposition of marls in the shelf area of the Vejalnica Fm. By this transgression both the HZB and the NCB have been connected. The transition from the lacustrine into the marine deposition was gradual (AVANIĆ, 1997). Depending on the local tectonics and sea level oscillation in the area of the Hrvatsko Zagorje region during the Middle and Late Badenian the coastal parts were characterized by biocalcirudites and biocalcarenites of the Vrapče Fm. while in the offshore area marls of the Vejalnica Fm. prevailed. More rarely, marls may contain intercalations of coarse-grained sediments that represent shallow water material reworked by storms and transported by strong currents toward the offshore (AVANIĆ, 1997).

At the end of the Badenian, isolation of the Pannonian Basin started which in the beginning of the Sarmatian resulted by formation of a marine environment characterized by reduced salinity. Sarmatian sediments in the Hrvatsko Zagorje region usually conformably overlie Badenan sediments. They are represented by shallow-water conglomerates, calcarenites and limestones of the Pećinka Fm. or by horizontally laminated pelitic sediments of the Dolje Fm. deposited in somewhat deeper marine environment. The very end of the Sarmatian is characterized by shallowing of the marine environment due to the basin inversion (TOMLJENOVIĆ & CSONTOS, 2001). Pannonian sediments mostly conformably overlie Sarmatian deposits, and indicate a new transgressive-regressive cycle (PAVELIĆ & KOVAČIĆ, 2018). Their deposition took place in the newly formed brackish Lake Pannon. The oldest Pannonian sediments in the southern part of Hrvatsko Zagorje are composed of the platy clayey limestones of the Croatica Fm. deposited in the lake littoral. These sediments overlie sands with pebbles of the St. Matej Mb. deposited in the delta environment only in the north part of the Medvednica Mt. Clayey limestones of the Croatica Fm. gradually change into marls of the Medvedski Breg Fm. deposited in a deeper lake environment. At the beginning of the Pannonian the river clastic systems prograded from the northern and northwestern directions in the northern part of Hrvatsko Zagorje, spreading in the Middle Panonnian to its southern part forming sandy to silty sediments of the Andraševec Fm. Their accumulation commenced in a deeper lake environment, indicating the onset of the closing of the lake. The late Pannon Lake depositional phase was characterized by a regression indicated by predominantly sandy sediments of the delta of the Nova Gradiška Fm. That ended in the latest Pannonian by sedimentation of the delta and alluvial plain sediments of the Pluska Fm. During the Pliocene the area of Hrvatsko Zagorje was an alluvial plain with minor freshwater lakes and swamps. Geological map of the area is shown on Fig. 2, while geological column is on Fig. 3.



LEGEND:

24 a b	$dprQ_2$ aQ_2	DELUVIAL- PROLUVIAL (a - $dprQ_2$) AND ALLUVIAL SEDIMENTS (b - aQ_2) (Holocene)
22 a b	lQ_1 $jblQ_1$	TERRESTRIAL (a - lQ_1) MARSH (b - $jblQ_1$) LOESS (Pleistocene)
21	aQ_1	FLUVIAL (aQ_1) SEDIMENTS (Pleistocene)
20	Pl,Q	CLASTIC SEDIMENTS (Plio-Quaternary)
19	M_7	CLASTIC SEDIMENTS AND COAL (Pontian)
18	$M_{5,6}$	LIMESTONES - CLASTIC SEDIMENTS (Sarmatian, Pannonian)
17	M_4	LITHOTHAMNIUM LIMESTONES, AND CLASTIC SED. WITH VOLCANITES (Badenian)
16	$M_{2,3}$	CLASTIC SED. AND LIMESTONES WITH CLASTIC SED. (Ottnangian, Karpatian)
15	Ol, M_1	CLASTIC SEDIMENTS WITH VOLCANITES (Egerian, Eggenburgian)
14	Pc, E	CARBONATE FLYSCH AND CLASTIC SEDIMENTS (Paleocene, Eocene)
13	K_2	CALCERAOUS CLASTIC SEDIMENTS (predominantly flysch) AND "SCAGLIA" LIMESTONES (Upper Cretaceous)
12	K_2^{1-6}	RUDIST LIMESTONES (Cenomanian-Maastrichtian)
11	$J_{2,3}$	OPHIOLITIC ROCKS (Middle, Upper Jurassic)
10	J_2^3, K_1^1	LIMESTONES WITH CHERTS AND CALLPIONELAS (Tithonian, Berriasian)
9	$T_3^{2,3}$	DOLOMITES (Upper Norian, Rheatian)
8	T_{2-3}	MAGMATIC ROCKS (Middle-Upper Triassic): andezites
7	T_2	CLASTIC AND PYROCLASTIC DEPOSITS (Middle Triassic)
6	T_2	CARBONATE DEPOSITS (Middle Triassic)
5	T_1	SILICICLASTIC AND CALCAREOUS CLASTIC SEDIMENTS (Lower Triassic)
4	X P	MAGMATITE (? Permian)
3	C, P	PREDOMINANTLY CLASTIC SEDIMENTS (Carboniferous, Permian)
2	Pz, ?T	PARAMETAMORPHIC ROCKS (Paleozoic, ? Triassic)
1	Pz, ?T	ORTOMETAMORPHIC ROCKS (Paleozoic, ? Triassic)

normal boundary
erosian and/or tectonic-erosian boundary
strike and dip of bedding
strike and dip of horisontal bedding
strike and dip of vertical bedding
strike and dip of overturned bedding

fault
normal fault
reverse fault
overhrust contact
superiors fault
river terrace

Figure 2. Geological map of the northwestern part of Croatia modifed according to the Geological Map of the Republic of Croatia 1:300000 (HGI-CGS, 2009).

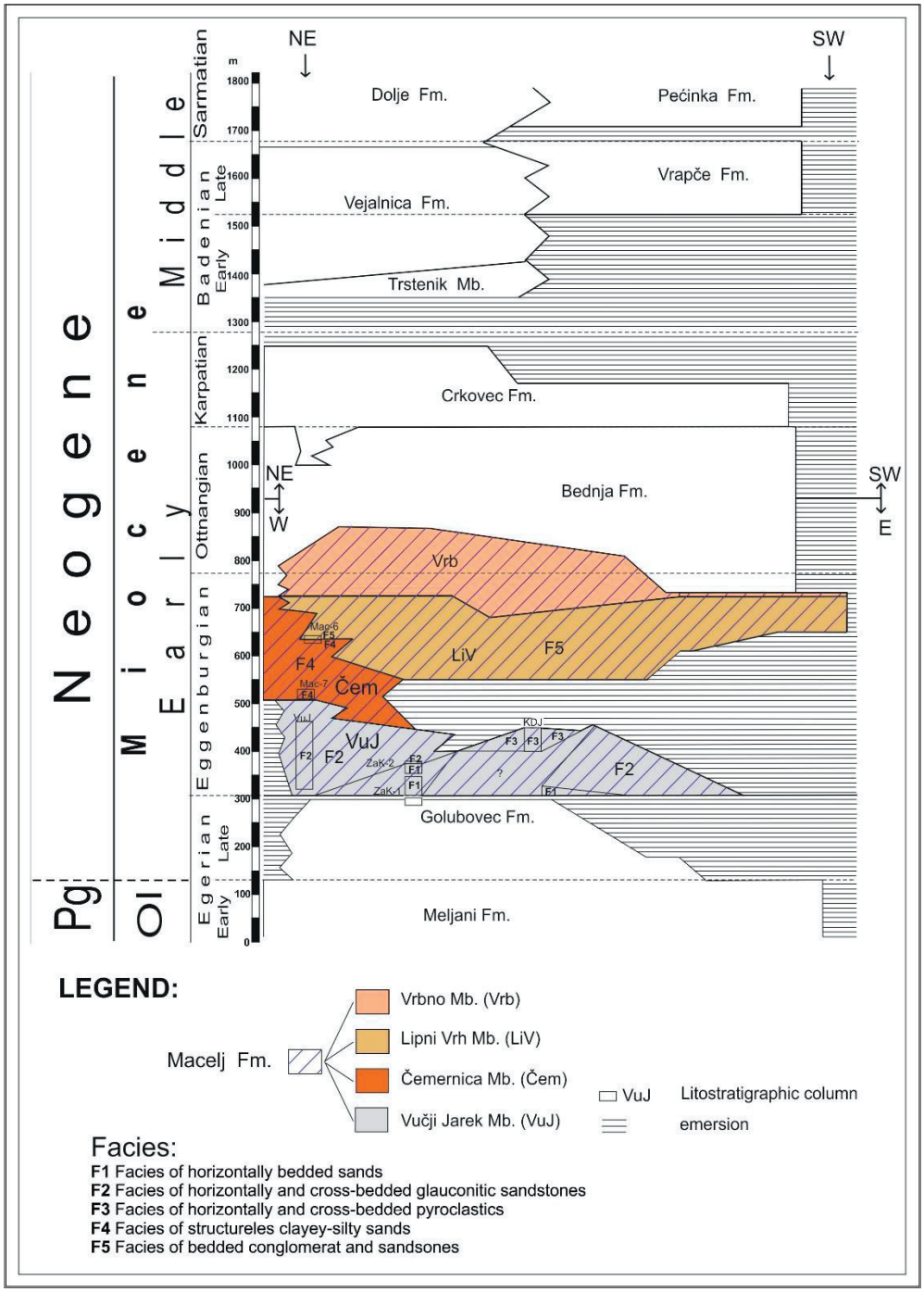


Figure 3. Schematic column of the Oligocene - Middle Miocene lithostratigraphic units of Hrvatsko Zagorje Basin (modified after AVANIĆ, 2012).