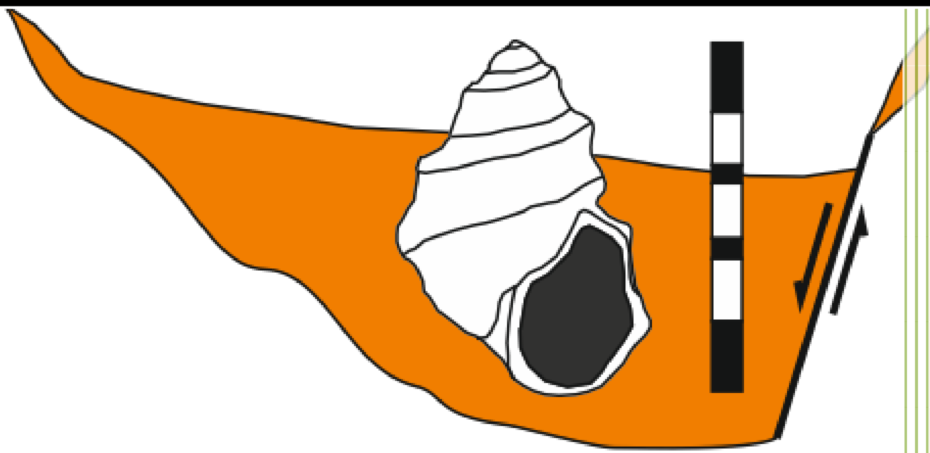
20–24 May 2016
Zagreb / Croatia

RCMNS Interim Colloquium 2016
Croatian Geological Society Limnogeology Workshop

Lake – Basin – Evolution



Field Trip Guidebook

Zagreb 2016

RCMNS IC 2016 & CGS Limnogeology Workshop

LAKE - BASIN - EVOLUTION

20 - 24 May 2016, Zagreb, Croatia

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Lake – Basin – Evolution

Stratigraphy, Geodynamics, Climate and Diversity of Past and Recent Lacustrine Systems

Field Trip Guidebook

Hrvatsko geološko društvo / Croatian Geological Society
Zagreb 2016
ISBN 978-953-59036-0-4

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Preface

Lacustrine basins are dynamic depositional systems depending on regional climate and geodynamic settings. Their isolation may lead to diversification of endemic faunas that complicate biostratigraphic correlations and palaeoecological assessments. Even today, age constraints for a number of prominent lacustrine complexes are inadequately resolved. Improved time resolution relies on the thorough integration of multiproxy data.

For that reason, the Regional Committee on Mediterranean Neogene Stratigraphy (RCMNS) decided to devote a special Interim Colloquium to this particular topic. The Dinarides area of Croatia provides the ideal geological setting of an active fold and thrust belt that separated the Mediterranean and Paratethys basins and recorded an extended history in lacustrine deposition. Those basins offer spectacular examples how geodynamic processes controlled duration and depositional modes in lacustrine systems. Several of the Neogene-Quaternary lakes became evolutionary hotspots. Large-scale research projects such as the Lake Ohrid deep drilling (SCOPSCO, PI Thomas Wilke), the Freshwater Gastropods of the European Neogene (FreshGEN, PI Mathias Harzhauser), the Pontocaspian biodiversity Rise and Demise (PRIDE, PI Frank Wesselingh), and the Evolution of the Paratethys (NWO, PI Wout Krijgsman) show the interest in lacustrine systems and biotic evolution within.

The Croatian Geological Society (CGS) represents the key partner responsible for the on-site organization of this meeting, which became integrated into its CGS Limnogeology Workshop. Beside RCMNS and CGS as parent organisations, a great number of national and international scientific bodies and companies became active supporters and sponsors of the meeting – University of Zagreb (Faculty of Mining, Geology and Petroleum Engineering, Faculty of Science), Croatian Natural History Museum, Natural History Museum Vienna, INA-Industrija nafte, Zagreb Tourist Board, Croatian Geological Survey, Croatian Academy of Sciences and Arts, International Union of Sedimentologists, and International Union of Geological Sciences.

The 2016 RCMNS Interim Colloquium and CGS Limnogeology Workshop will bring together a variety of experts and disciplines in lacustrine basin research. Stratigraphers, sedimentologists, structural geologists, paleontologists, biologists and geochemists will present current results from their ongoing research and will share their experience. This will lead to new cooperations still better integrating the constantly growing knowledge toward a new synthesis of the still underexplored field of limnogeology.

The Organization Team

Program

EXCURSION 1 - PANNONIAN BASIN

Friday, 20 May

08:00	45.807012, 15.964435	Departure - University of Zagreb (RGNF, Pierottieva 1)
09:00	45.933949, 16.087004	Planina Gornja
10:40	45.958022, 16.090484	Laz Bistrički
11:30	46.000854, 15.969803	Mirti / Hruševec
12:30	45.980145, 15.986237	Lunch in Donja Stubica
14:00	46.024894, 15.922667	Hum Zabočki
15:30	45.820291, 15.857016	Kostanjek
17:00	45.807012, 15.964435	Arrival - as departure

EXCURSION 2 - DINARIDES

Sunday, 22 May

08:00	45.807012, 15.964435	Departure - University of Zagreb (RGNF, Pierottieva 1)
10:00	44.880323, 15.618544	Plitvice (Croatia)
14:00	43.849984, 15.629439	Lake Vrana (Croatia)
16:30	43.723310, 16.594943	Lučane (Sinj Basin / Croatia)
19:00	43.741006, 16.633863	Hrvace - Pension Vrba

Monday, 23 May

08:00	43.741006, 16.633863	as above
09:30	43.730639, 17.022426	Mandek (Livno Basin / Bosnia-Herzegovina)
11:30	43.741771, 17.086560	Tušnica (as above)
14:00	43.709919, 17.182881	Ostrožac (Tomislavgrad Basin / BH)
15:30	43.650897, 17.216894	Cebara (as above)
17:30	43.971637, 17.235321	Fatelj (Kupres Basin / BH)
19:00	43.948524, 17.188723	Kupres - Hotel Adriaski

Tuesday, 24 May

08:00	43.948524, 17.188723	as above
09:00	43.997662, 17.518516	Gračanica (Bugojno Basin / BH)
12:30	44.140301, 18.120600	Greben / Kakanj (Sarajevo-Zenica Basin / BH)
14:00	44.133401, 17.937542	Lašva (as above)
14:30	44.148444, 17.951676	Janjići (as above)
15:30	44.133945, 17.926670	Dinner - Titanik (Lašva)
21:00	45.807012, 15.964435	Arrival - as departure

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PART 1 / EXCURSION 1

By Marijan Kovačić, Oleg Mandic and Bruno Tomljenović
With contributions by Frane Marković, Klaudia Kuipers, Valentina Hajek Tadesse, Koraljka Bakrač and Tamara Đerek

Miocene paleo-lakes of the southwestern Pannonian Basin

1. Introduction: History of lacustrine environments in the SW Pannonian Basin

Lakes dominated the Miocene paleoenvironmental history of the SW Pannonian Basin in NW Croatia (Fig. 1 and 2). In particular, the lacustrine deposition lasted in the area for more than 12 myr, making about two thirds of the basin history (Fig. 2). The lake deposition shows thereby two principal phases. First one relates to the Early to Middle Miocene Dinaride Lake System (DLS), the second one to the Late Miocene and Pliocene Lake Pannon and Lake Slavonia systems.

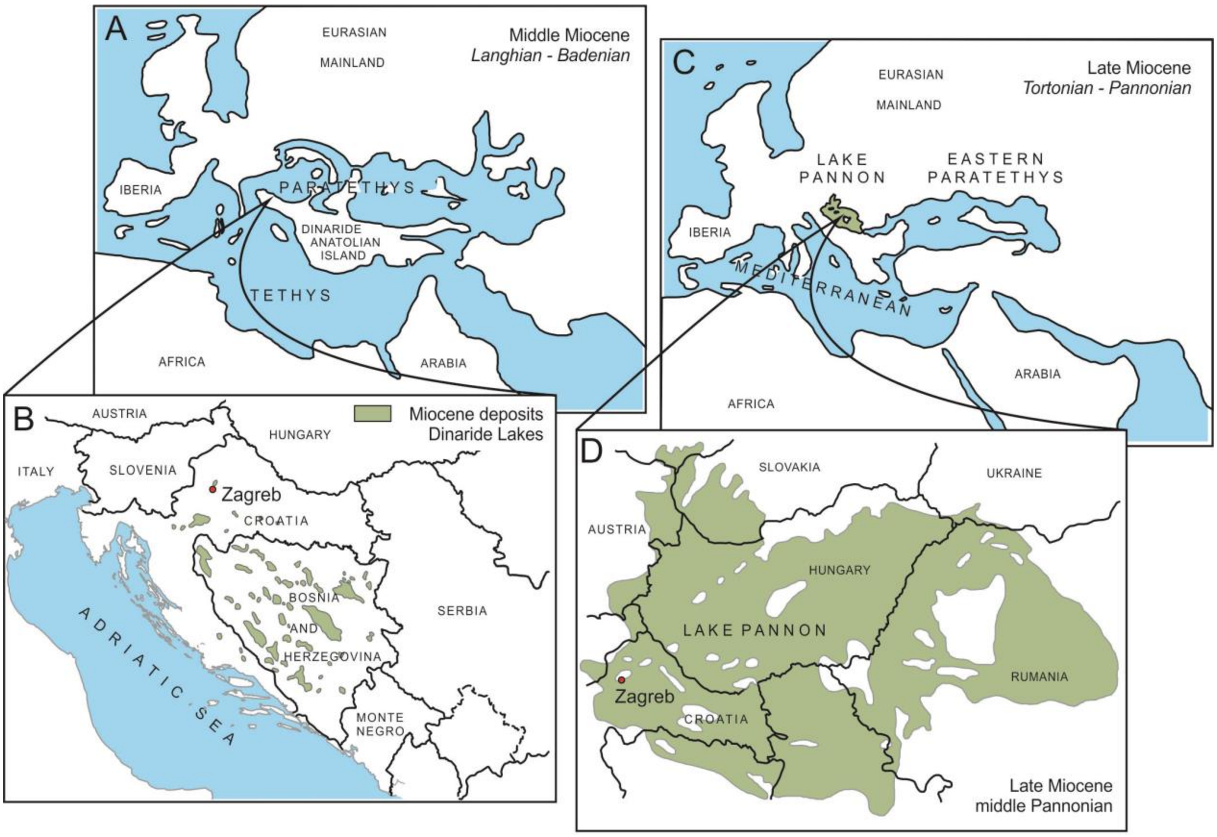


Fig. 1. Middle Miocene (A) and Late Miocene (C) paleogeographic maps of the Paratethys. Detail maps below show distribution of Dinaride Lake System (B) and Lake Pannon (D) deposits (modified from Harzhauser & Mandic, 2010 and references therein).

DLS represented isolated lakes that settled the intra-mountain basins of the Dinarides with a peak density during the Miocene Climate Optimum (de Leeuw et al., 2012). Their retreat coincided roughly with the marine flooding of the SW Pannonian Basin by the Paratethys Sea that commenced between 15 and 14 Ma (Mandic et al., 2012; Fig. 1A-B) The latter was a huge epicontinental sea originated around the Eocene–Oligocene transition north of the just elevated Alpine-Dinarides-Pontides fold-and-thrust belt (Fig. 1A).

The eastward retreat of that sea, only 3 myr later, by the end of the Middle Miocene, installed the brackish, long-living Lake Pannon in the area, famous for its species-rich, endemic, sub-aquatic fauna (Neubauer et al., 2015) (Fig. 1 C-B). Lake Slavonia represented finally the installation of fully freshwater conditions marked by the major extinction of brackish fauna and an endemic radiation of freshwater species (Mandic et al., 2015). The recent terrestrial phase installed with the final climate deterioration due to initial Quaternary glaciation.

However, the presented paleoenvironmental evolution reflects not only the regional climate evolution of the late Cenozoic but, still more important, the geodynamic history of the Pannonian basin, a classical Central European back-arc basin that originated between 21 and 18 Ma at the junction between the Alpine, Dinarides and Carpathian orogens

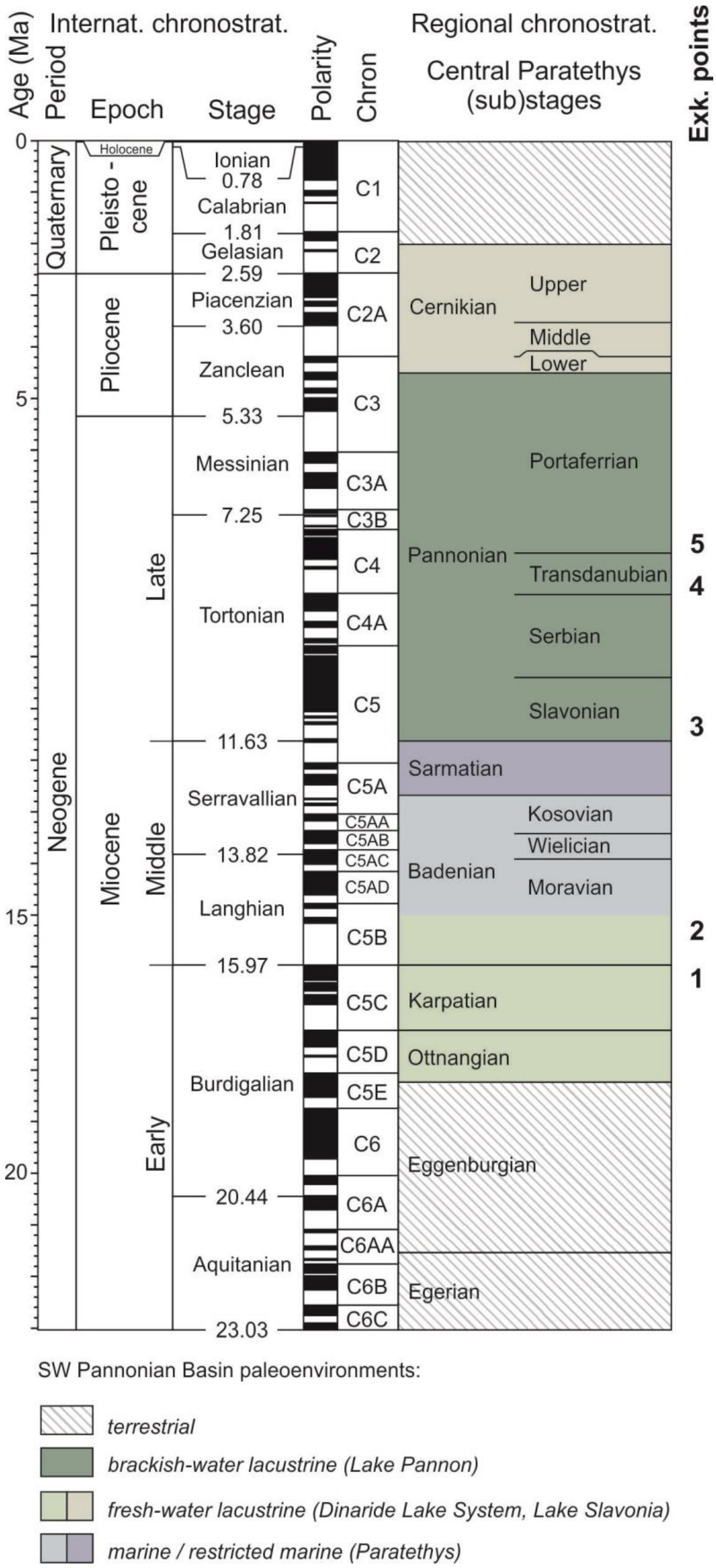


Fig. 2. Chronostratigraphic correlation table after Hilgen et al. (2012), with updated Central Paratethys correlation, and indicated history of paleoenvironmental change in the SW Pannonian Basin.

(Horvath et al., 2015; Fig. 3). Its formation is related to a rapid roll-back of the Carpathian and Dinaride slabs, attached to the European continent and to the Adriatic microplate, respectively (Matenco & Radivojević, 2012; Fig. 3). The start of syn-rift tectonics therein coincides with the initiation of alluvial and lacustrine deposition in its southern domain (Fig. 4). The installation of Lake Pannon marks, in contrast, the initiation of post-rift tectonic regime in the area (Horvath et al., 2015).

Sava depression is the deepest structure at the SW margin of Pannonian Basin. This is a NW-SE striking half-graben locally filled by more than 5 km of predominantly siliciclastic Neogene and Quaternary deposits (Fig. 3 and 4). Its sedimentary infill shows three depositional megacycles separated by compressional phases dated to the late Middle Miocene, the Miocene–Pliocene transition and the early Pleistocene. The first cycle comprises up to 2-km-thick DLS and Central Paratethys deposits, the second cycle includes up to 2.5-km-thick Lake Pannon sediments, whereas the third cycle shows finally up to 0.9-km-thick Lake Slavonia deposits. Only this third cycle is absent in the region of Mt. Medvednica, where terrestrial deposition started already with the retreat of Lake Pannon around the Miocene–Pliocene transition.

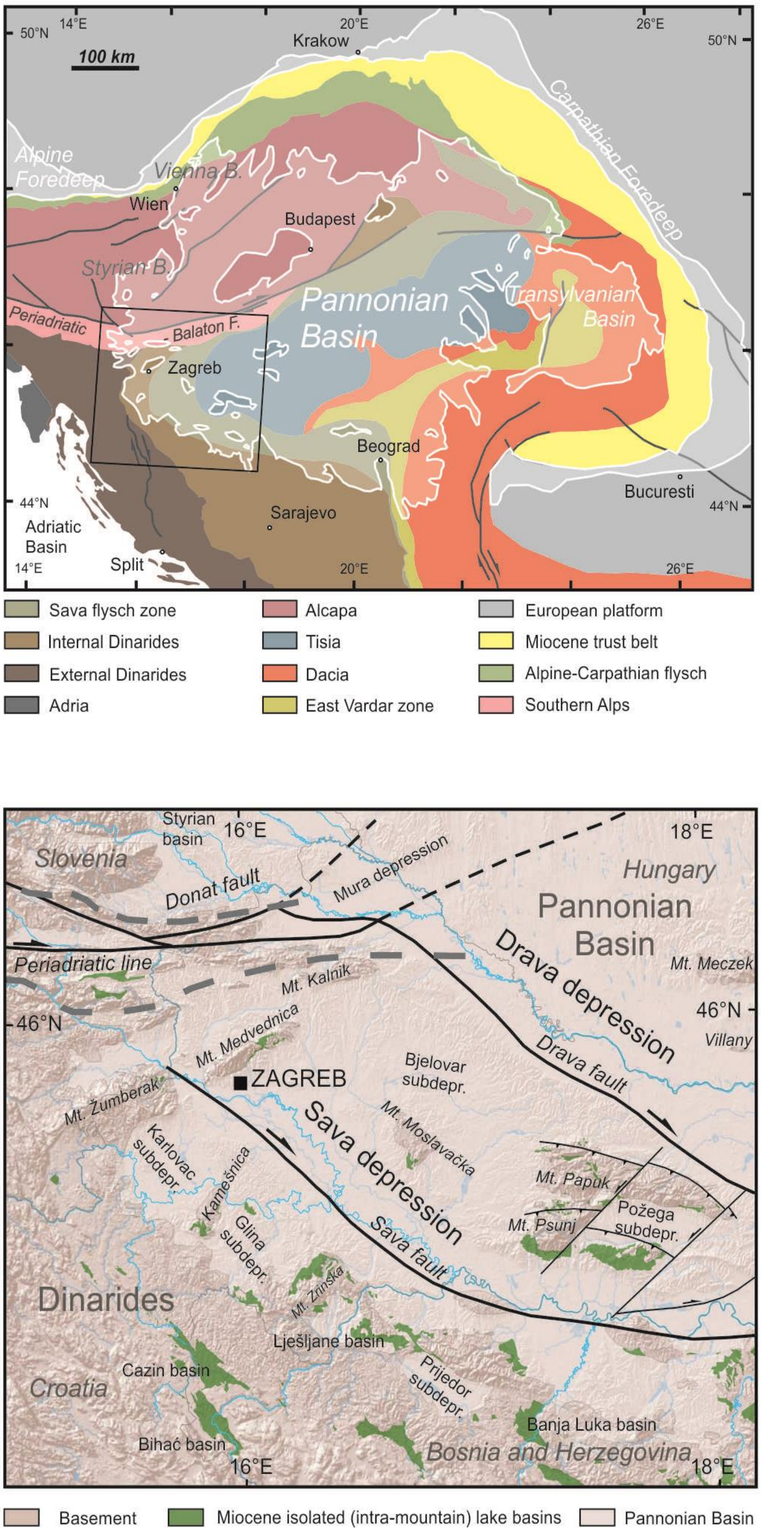
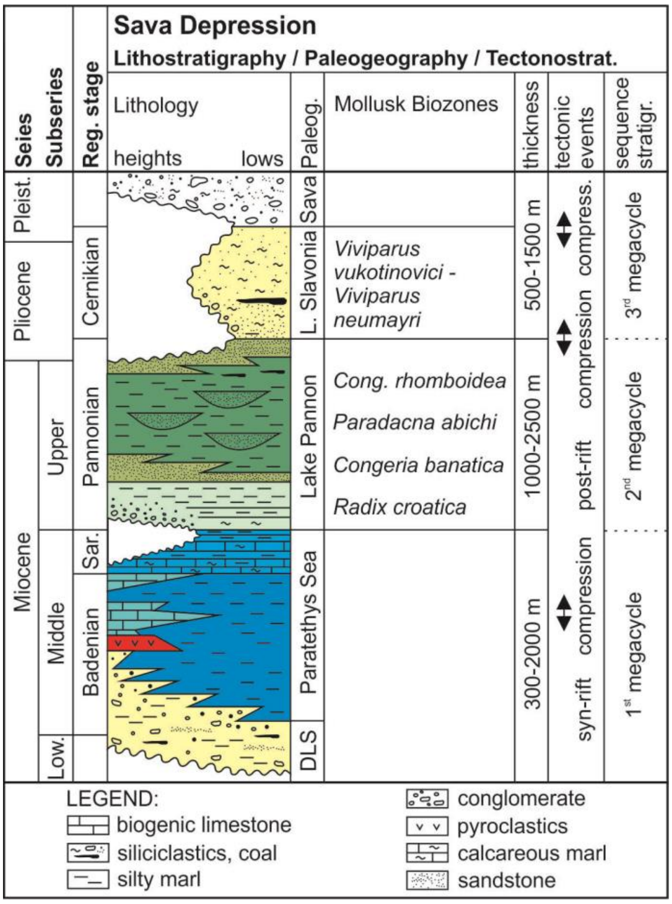


Fig. 3. Map above shows the position of Neogene Paratethys basins in the tectonic framework of the Alpine-Carpathian-Dinarides fold and thrust system (modified from Mandic et al., 2012 and references therein). Lower map shows tectonic setting of the SW Pannonian Basin and the distribution of Neogene deposits.

Fig. 4. Sketch showing the depositional history of the Sava depression and adjoining areas. Note that at the northern margin of the depression and in the Hrvatsko Zagorje region Lake Slavonian deposits are missing because of the southwards and eastwards back-stepping of the lacustrine deposition (modified from Mandic et al., 2015 and references therein).



2. Structural characteristics of Mt. Medvednica and surrounding area

Bruno Tomljenović

The Mt. Medvednica, with neighboring "inselbergs" of Mts. Kalnik and Ivanščica in Hrvatsko Zagorje, lies in the Dinarides–Alpine–Pannonian basin transition zone, formed during the Neogene–Quaternary at the SW termination of the Zagorje–Mid-Transdanubian Shear Zone. The present day structural architecture of this area mostly resulted from the latest Miocene–Quaternary shortening, which led to the formation of km-scale E- to ENE-striking anticlines and synclines bounded by NW- and SE-dipping reverse faults. As a rule, cores of anticlines expose pre-Neogene rocks of the Dinarides and South Alpine affinity, while the intervening synclines are occupied by up to 2.5 km thick Miocene–Quaternary sediments. Locally, these structures are bounded or cross-cut by NW-striking dextral and NE-striking sinistral faults (Fig. 5).

In its central part, Mt. Medvednica is an asymmetric antiform composed of pre-Neogene basement rocks in its core (Paleozoic and Mid-Cretaceous metamorphics, Jurassic ophiolitic mélange and Senonian-Paleocene shallow marine to basinal sequences), which are unconformably covered by Neogene and Quaternary sediments. However, due to generally N–S directed shortening, active since the latest Miocene until the present time, the structural position of Miocene sediments around the

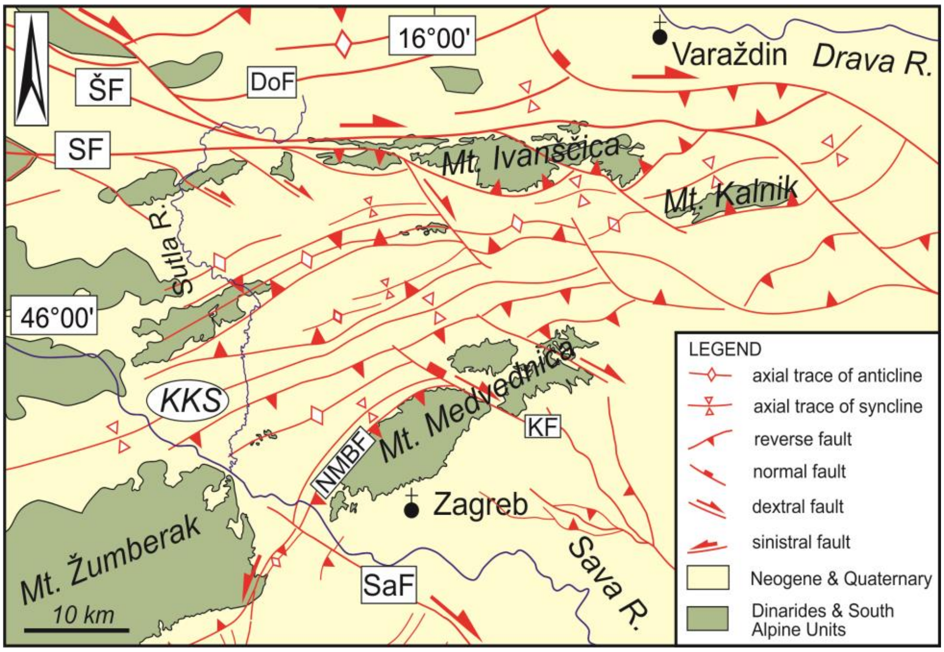


Fig. 5. Map of latest Neogene–Quaternary structures in the Dinarides-Alpine-Pannonian basin transition zone (modified from Tomljenović & Csontos, 2001 and references). Abbreviations: ŠF-Šoštanj fault., DoF-Donat f., SF-Sava f. in Slovenia, KKS-Konjščina – Krško syncline, NMBF-North Medvednica Boundary f., KF-Kašina f. and SaF-Sava f. in Croatia.

Medvednica antiform is not uniform. In the north-eastern part, i.e., to the NE of the Kašina Fault (KF in Fig. 5), Miocene sediments unconformably superpose the NW and SE limb of the antiform. By contrast, in the central and south-western part, to the SW of the Kašina Fault, Miocene sediments are exposed only along the SE limb of the antiform at elevation between 200 and 400 m, while on the NW limb these sediments are hidden in the footwall of the North Medvednica Boundary Fault (NMBF in Fig. 5) and buried below an about 400 m thick pile of Pliocene–Quaternary sediments deposited in the core of the neighboring Stubica-Zaprešić syncline (Fig. 6).

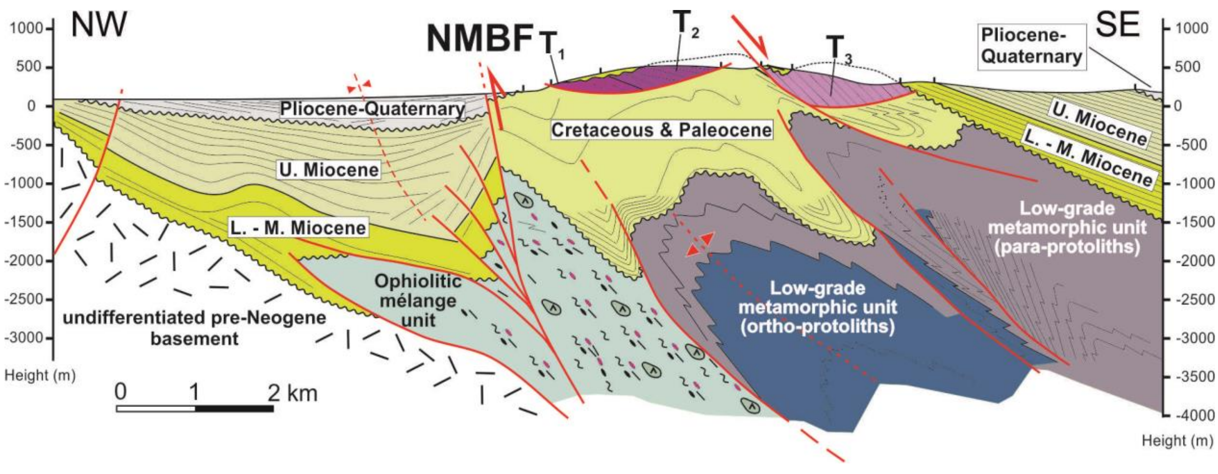
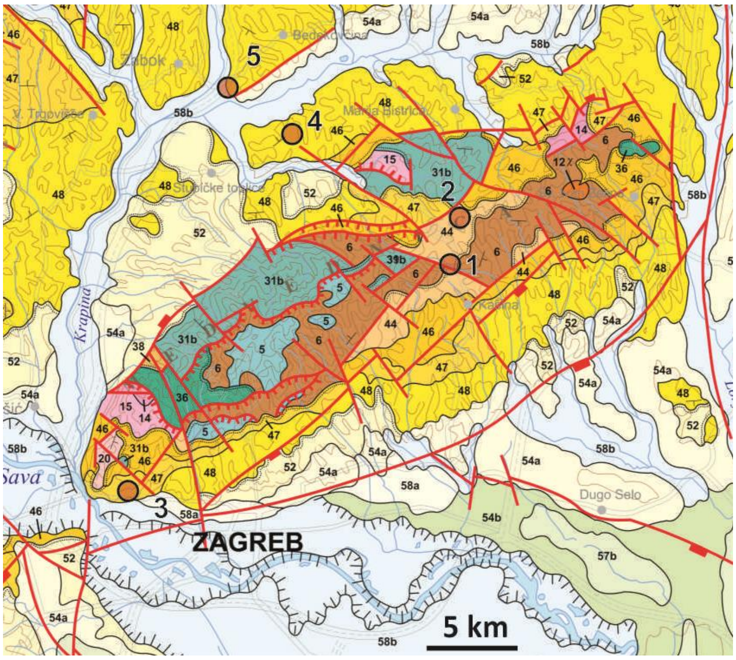


Fig. 6. Geological profile across the SW end of Mt. Medvednica (after Tomljenović, 2002).

3. Excursion points



LEGEND

58b	Holocene - alluvial deposits	Pannonian Basin terrestrial phase
58a	Holocene - deluvial and proluvial deposits	
57b	Holocene - marsh deposits	
54b	Pleistocene - marsh loess	
54a	Pleistocene - terrestrial loess	
52	Pliocene-Pleistocene - clastics	
48	**middle-late Pannonian - lacustrine deposits**	Pannonian Basin lacustrine and marine phase
47	Sarmatian-**early Pannonian -** clastics / **carbonates**	
46	Badenian - marine deposits	
44	**Ottnangian-early Badenian - freshwater deposits**	
36	Upper Cretaceous - carbonates	Internal Dinarides basement rocks
31b	Jurassic - ophiolites	
20	Upper Triassic - dolomite	
15	Middle Triassic - carbonates	
14	Lower Triassic - clastic rocks	
12	Permian? - magmatic rocks	
6	Paleozoic-Triassic? - parametamorphic rocks	
5	Paleozoic-Triassic? - orthometamorphic rocks	

Fig. 7. Geological map (Croatian Geological Institute M 1:300,000) showing regional setting of the study area and the position of excursion points: 1 - Planina, 2 - Laz, 3 - Kostanjek, 4 - Mirti, 5 - Hum

Outcrops with Pannonian Basin related lacustrine deposits are concentrated in the vicinity of Zagreb along the southeastern slope of Mt. Medvednica (Fig. 7). Already in the Miocene, this mountain was a topographic high as suggested by a ring-like, coast-parallel distribution of sediments deposited during transgression/regression depositional cycles. The oldest Miocene deposits are concentrated to its central part, getting ever younger away from the mountain, i.e., towards the neighboring Sava Depression. Almost continuous lacustrine deposition of the southwestern Pannonian Basin was disturbed only by a single Paratethys ingression during the Middle Miocene (Badenian and Sarmatian (15–12 Ma). We will demonstrate the content of the older (18–15 Ma) lacustrine and alluvial deposits in two points - Planina Gornja (Chapter 3.1) and Laz Bistrički (Chapter 3.2) superposing directly the Paleozoic core of Mt. Medvednica. A short history of the the younger, Lake Pannon related lacustrine cycle, is displayed in three localities (in stratigraphic order) - Kostenjak (Slavonian; Chapter 3.3), Mirti (Transdanubian; Chapter 3.4) and Hum Zabočki (Portaferrian; Chapter 3.4). Whereas the first one represents the SW slope of Mt. Medvednica, located in the western suburbs of Zagreb, the other two are located at the southern and the northern limbs of the Konjščina syncline in Hrvatsko zagorje, respectively (See Fig. 5 for the location of Konjščina syncline).

POINT 1. PLANINA - Pre-Badenian alluvial and lacustrine Miocene

Locality:	Planina Gornja
WGS84 coordinates:	45.936502° N, 16.083457° E
Age:	Burdigalian–Langhian (Ottnangian–Badenian, Early–Middle Miocene)
Lithostratigraphy:	Glavnica Formation / Vukov Dol Member

Introduction

The study area represents the central and slightly depressed part of Mt. Medvednica mostly composed of Miocene sediments that separate the exhumed Paleozoic inselberg core in two parts. The outcrops are distributed along the brook Vukov Dol running from the village Planina Gornja to the southeast. They are easily accessible by a road that follows the stream course.

Up to 125-m-thick lacustrine and alluvial series of Glavnica Formation is composed in Vukov Dol of colored conglomerates and sands, dark gray marl, bedded silicified limestones and coal lenses (Polić, 1935; Basch, 1983; Avanić et al., 1995; Dedić et al., 2014). Limestone and marl of the Vukov Dol Member bear abundant but badly preserved mollusk fauna dominated by dreissenid bivalves, identified in Kochansky-Devidé & Slišković (1978) as *Trigonipraxis boeckhi* and *Androsoviconcha neumayri*. The succession superposes strongly folded late Paleozoic metasandstone and limestone. The Middle Miocene marine deposits following transgressively on top of the Glavnica Formation are present south of the Vukov Dol area.

The succession of Planina Gornja mapped by Polić (1935) starts with one about 10-m-thick unit comprising (from base to top) basal conglomerates, gray and red clay, gray sand and gray marl (Fig. 8). Coal and dark clay facies with unionid and dreissenid bivalves is locally present therein. The next unit has about the same thickness and bears a hard, silicified, well bedded, dreissenid limestone, used regionally as a building stone. Following unit is made by yellowish and grayish marl with abundant and well-preserved plant remains, representing the topmost Miocene unit of the Planina Gornja - Vukov Dol area. To the southwest, a very thick fining upward series of conglomerates, sandstones and yellowish marls with small dreissenid bivalves (compare with the next point) is present on top of latter marls. This lacustrine succession terminates with the Badenian marine marls and corallinacean limestones.

The original stratigraphic correlation with the Oligocene, based on macro-flora (Polić, 1935), was later corrected to Ottnangian and Karpatian (Basch, 1983, Avanić et al., 1995, Dedić et al., 2014). Lately, Mandic et al. (2012) extended the time-window of the initial southern Pannonian Basin freshwater deposition into the Middle Miocene (18–15 Ma; compare with the next point).

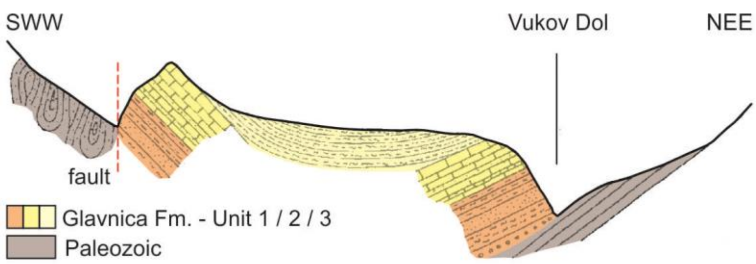


Fig. 8. Original, schematic cross-section through the Gornja Planina valley by Polić (1935, partly modified) showing succession of the Lower to Middle Miocene, freshwater lacustrine Glavnica Formation (see text for detail explanation of the unit contents).

Fig. 9. Studied outcrop behind the Vukov Dol watermill E of Planina Gornja.

Dreissenid limestone of the Vukov Dol Mb.

Outcrop is located behind a small watermill adjacent to the main road to Planina Gornja (Fig. 9). It is a part of the cliff of the southern Vukov Dol shore. The succession shows transition from a dark mudstone into the dreissenid limestone. The beds dip by 28° to the SSW (220°).

The succession starts with 50-cm-thick dark brownish silty clay to clayey silt without macrofossils (Fig. 10). The clayey unit is overlain by a 140-m-thick transitional interval of limy marl grading upward to marly limestone. Bedding ranges from 10 to 35 cm, the bedding planes are planar, marked by an increased clayey component. Scattered, small-sized dreissenid bivalves are present on bedding planes. Fresh surfaces are dark gray, the oxidized ones light gray in color.

The beige-weathered, 145-m-thick, dreissenid limestone makes the upper part of the section. It is composed of four equally thick beds. Bedding surfaces are planar; internally the packages show fine wavy bedding. The limestone is organic rich, dark brown in color on fresh surfaces, bearing partly abundant plant remains and ostracods. The sediment was originally made by accumulated dreissenid shells which were subsequently leached and partly recrystallized. Besides, the sediment is strongly affected by silicification processes and compaction. Considering their few-centimeter size and trigonal shape, the poorly preserved dreissenids resemble at best *Trigonipraxis boeckhi*.

The succession reflects shallowing upward trend of the depositional environment from profundal, low energy and badly oxidized environment in the base to the shallow water, turbulent, littoral depth marked by the shell bed installation.

The valley of Vukov Dol exposes the hard dreissenid limestone in many places along its course that roughly follows their bed-strike (Fig. 11). One road outcrop, located about 70 m to the east from the watermill, exposes the entrance of a small, abandoned mine work and

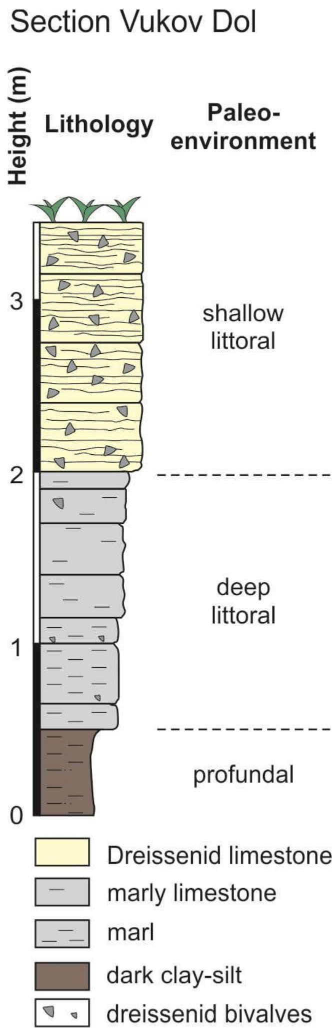


Fig. 10. Section logged at the Vukov Dol watermill showing a shallowing-upward succession marked by the installation of dreissenid limestone on top.

shows a thin coal seam intercalating the dreissenid limestone. Additionally, in some of the outcrops along the road or at the neighboring slopes of the valley the dreissenid limestone alternates with fine-grained sandstones.

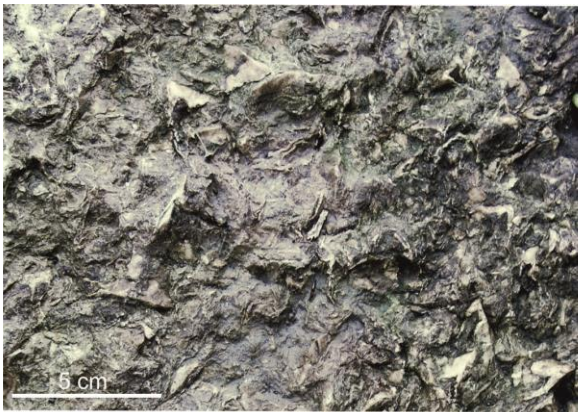


Fig. 11. Dreissenid limestone with densely packed recrystallized shells of *Trigonipraxis boeckhi*.

POINT 2. LAZ - Age constraint on disintegration of the initial Pannonian Basin lake system

Marijan Kovačić, Frane Marković, Klaudia Kuiper, Valentina Hajek-Tadesse, Koraljka Bakrač, Tamara Đerek, Oleg Mandic

Locality:	Laz Bistrički
WGS84 coordinates:	45.939735° N, 16.079466° E
Age:	Early Langhian (early Badenian, Middle Miocene)
Lithostratigraphy:	Glavnica Formation / Koščević Member

Introduction

The road outcrop (Fig. 12), located at the southern entrance of the village Laz, displays marl of the Koščević Member and Glavnica Formation (Dedić et al., 2014). The lacustrine series, well exposed along the road Zagreb–Marija Bistrica between villages Kašina and Laz, is directly overlain by initial marine deposits of the Paratethys Sea (Basch, 1981, 1983).

Fig. 12. The outcrop of marls with tuff layer (red line) at the Laz locality.

The mollusk data presented below are from Vrsaljko et al. (2015), the taxonomy follows Neubauer et al. (2016). The species-level data on terrestrial macro-flora are from Đerek (2015).

Lithology and fossil content

The exposed succession is 5-m-thick and consists of horizontally bedded marls and silty marls intercalated by one 2–3-cm-thick, normally graded, brown or dark green altered tuff layer (Fig. 13). The marls are finely bedded (1–5 cm scale), grey or yellow colored, horizontally laminated or bioturbated. They contain 35–50% carbonate component. Non-carbonate component consists of quartz, chlorite, illit-muscovite, kaolinite, smectite and smektit/illite. The tuff is

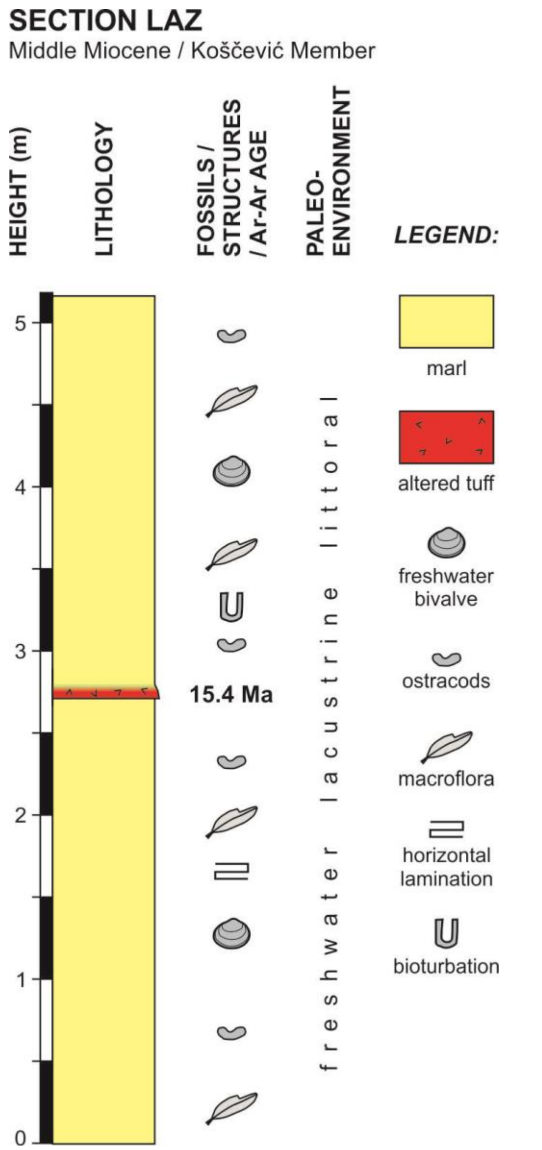


Fig. 13. Log of the marls with tuff layer, which proves their Middle Miocene age, and fossil community suggesting lacustrine freshwater environment and subtropic climate.

altered into bentonite composed of smectite, heulandite (zeolite) and sanidine (Fig. 14).

Along the entire section the marls are very rich in fossil leaves of terrestrial macro-flora including *Myrica lignitum*, *Daphnogene polymopha, Podogonium knorii, Pinus taedaeformis*, and *Quercus lonchitis* (Fig. 15). Additionally, small bivalves (*Pisidium* sp., *Illyricocongeria* sp.) and gastropods (*Gyraulus* sp.) are present. Also, several ostracod taxa were recorded in the succession belonging to families Candonidae, Cyprididae, and Leptocytheridae. Palynomorphs are dominated by pollen grains of conifers (*Pinus* sp. and *Cathaya* sp.). Additionally, few pollen grains of the broad-leaf tree *Pterocaryapollenites stellatus* and the spores of fern families Pteridaceae (*Verrucingulatisporites rugosus*) and Polypodiaceae (*Polypodiisporites favus*) were detected.

Paleoecology and depositional setting

Mollusk fauna includes taxa restricted to freshwater conditions (*Pisidium* sp. and *Gyraulus* sp.; e.g., Welter-Schultes, 2012). In contrast, the findings of few leptocytherid carapaces and the presence of brackish-water tolerant chlorophycean algae *Botryococcus* sp., may indicate an increased water-salinity. Although, leptocytherids are mostly known from marine settings, they are also capable to colonize freshwater ecosystems, such as the ancient Lake Ohrid in the Hellenides (e.g., Namiotko et al., 2012). Therefore, the freshwater lacustrine setting, suggested by the mollusks, is still a sound conclusion for the investigated section.

The presence of pulmonate gastropods (*Gyraulus* sp.) indicates a shallow-water littoral setting. Occurrence of chlorophycean algae points to deposition within the photic zone. The ostracod assemblages represent a mixture of deep-water and shallow-water species. Their poor preservation, an effect of reworking processes, suggests increased water-energy at time

Fig. 14. 2-3-cm-thick layer of dark green altered tuff from Laz section.

Fig. 15. *Daphnogene* sp., a fossil leaf of the laurel family (Lauraceae) from the Laz section.

of deposition. In contrast, the preservation of terrestrial macro-flora implies deposition in predominantly low-energy setting, accompanied by an increased sediment-accumulation rate. Abundant plant fragments and silty material proves terrestrial influence, but lack of sandy and coarse grained material regards this influence as minor.

In conclusion, marly sediments of the Laz section were deposited in a freshwater lake at littoral depth, below the wave base, not very far from the coast-line. The composition of fossil macro-flora and palynomorphs (paleotropical elements *Verrucatosporites* sp. and *Leiotriletes* sp.; Stuchlik, 1994) suggests a subtropical climate.

Radiometric age and geochemical classification of the tuff

According to $^{40}Ar/^{39}Ar$ dating of extracted sanidine grains, the age of the tuff layer is 15.42 ± 0.15 Ma. The microelement content of the tuff suggests according to Winchester and Floyd (1977), a trachitic composition of the pyroclastic material. Documentation on that geochronological and mineralogical data will be presented in the PhD study by second author (FM).

Such an age of the tuff layer evidences an early Langhian (early Badenian, Middle Miocene) deposition for the freshwater lacustrine sediments at Laz. It implies that the ingression from the Paratethys did not rich the area before the Middle Miocene and the presence of marine Lower Miocene deposits can be indeed disregarded in the SW Pannonian Basin as suggested previously by Mandic et al. (2012). Such result stays in accordance with the marine plankton data (Ćorić et al., 2009), pointing out, that the start of the regional marine ingression was younger than 14.91 Ma, postdating consequently the Karpatian-Badenian transition in the Paratethys by more than 1 myr.

POINT 3. - KOSTANJEK - Disintegration of the Paratethys Sea and the origin of Lake Pannon

Locality:	Kostanjek (Podsused / Zagreb)
WGS84 coordinates:	45.821016° N, 15.855741° E
Age:	Sarmatian–Pannonian (Middle–Late Miocene)
Lithostratigraphy*:	Dolje, Kostanjek (="*Croatica*"), and Medvedski breg Formation

* Note: The present lithostratigraphic classification is after Dedić et al. (2014), except for their Croatica Formation. The latter term, based on a fossil gastropod name (*Radix croatica*), should be replaced by a geographic name following recommendation of the International Stratigraphic Guide (Salvador, 1994). Thus, we replace it now with the term Kostanjak Formation and propose the present section for the stratotype (Fig. 16). Its stratigraphic interval equals the informal unit *croatica* Beds of Jenko (1944) and the *Radix croatica* Zone of Moos (1944). Vrsaljko (1999) recommended already former section as potential stratotype of the *croatica* Beds. The Medvedski breg Formation corresponding to

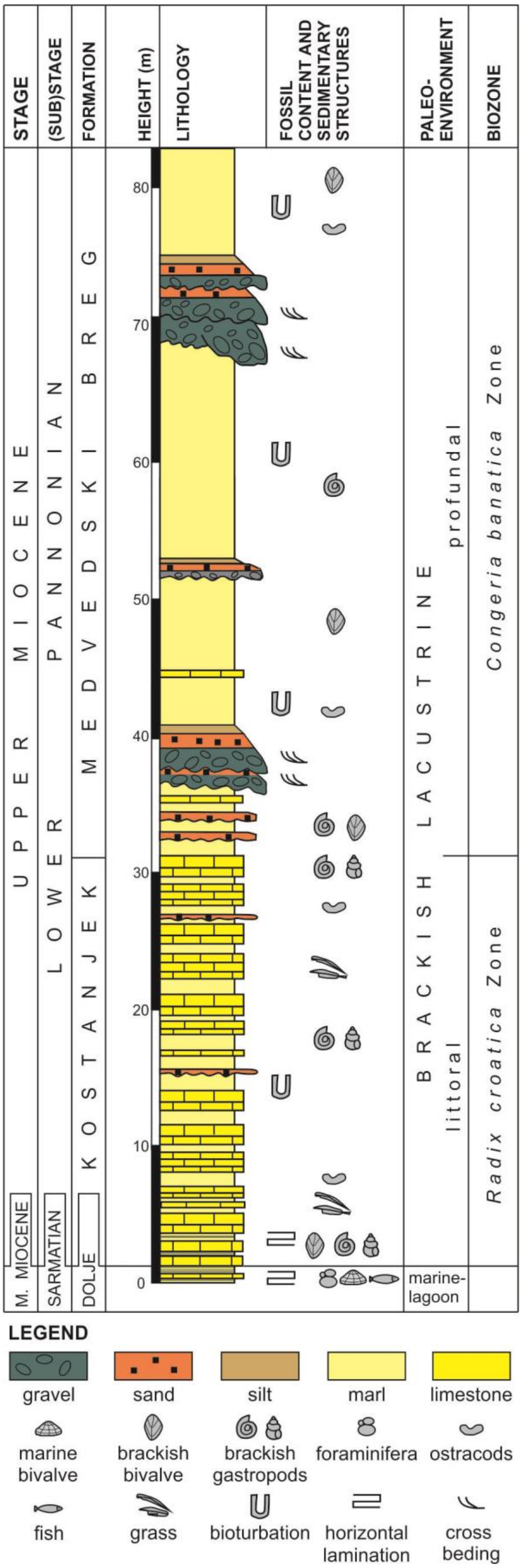


Fig. 16. Geological column of the early Pannonian *croatica* and *banatica* beds at the Kostanjek locality.

the informal regional unit *banatica* Beds and correlating with the *Congeria banatica* Zone is present in the upper part of section Kostanjak.

Introduction

The locality is situated at the SW tip of Mt. Medvednica in the westernmost suburb area of Zagreb. It is an abandoned marl quarry of the former cement factory Podsused mined into the Kostenjak hill. The area is not only an industrial monument but also a large-scale landslide. At present, the quarry is devastated, covered by debris and largely vegetated. Despite, small outcrops are still available allowing insight to parts of the 83-m-thick Miocene succession, described in detail by Vrsaljko (1999) and Kovačić & Grizelj (2006). Previously, Papp (1956) correlated the upper part of the succession with the Vienna Basin letter stages C/D.

The section starts with the late Sarmatian Dolje Formation, followed continuously by Pannonian deposits of the lower Slavonian Kostanjek Formation and the upper Slavonian Medvedski breg Formation (Fig. 16). The Middle Miocene Sarmatian part was deposited in the restricted-marine Paratethys Sea, the Upper Miocene Pannonian part in the brackish-water Lake Pannon. The transition is marked by the disappearance of marine fossil taxa.

Point A: Sarmatian-Pannonian transition

In the lower part of the quarry only one meter of the Dolje Formation is exposed (Fig. 16). They are represented by horizontally laminated silty marl and marl which consists of rhythmical alternation of dark and light laminae. Dark laminae contain an increased amount of organic matter, while the light laminae are rich in carbonate mineral. The fossil assemblage consists of small bivalves (*Ervilia* sp.), fish, ostracods and miliolid foraminifera.

The Kostanjek Formation is 30-m-thick and mostly composed of horizontally bedded marly

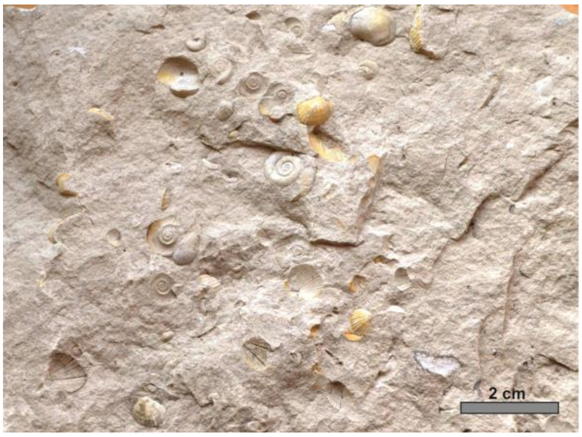


Fig. 17. Platy limestone from the lower part of the Kostanjek section with pulmonate gastropods *Gyraulus* and *Radix*. The fossil community indicates an almost pure freshwater, shallow littoral environment of early Pannonian age.

limestones and calcite rich massive marls. In the first 2–3 m, the limestone intercalates with up to 30-cm-thick layers of laminated marls, while in the middle and upper part, up to 5-cm-thick layers and lenses composed of loosely consolidated and poorly sorted sand were observed. The limestones and marls contain plant fragments and association of endemic, lacustrine mollusks and ostracods. Within the mollusk assemblage, most frequent are pulmonate gastropods *Radix croatica* and *Gyraulus* sp. (Fig. 17), while *Hungarocypris* sp., *Amplocyopris* sp., *Loxoconcha* sp., and *Candona* sp. dominate the ostracod assemblage.

The horizontally laminated marls from the lower part of the Kostanjek section were deposited from suspension in a relatively deep, calm and protected environment. Varve-like lamination suggests seasonal changes in sedimentation. The fossil association points to Sarmatian age and restricted marine character of the sedimentary environment.

In contrast, the fossil association of the Kostanjek Formation suggests deposition at littoral-sublittoral depth of the Lake Pannon, characterized by a very low water-salinity. The gradual change of lithology and the sharp change of the fossil assemblage indicate a continuity of deposition at the Middle-Late Miocene boundary along with an abrupt transformation from restricted marine to lacustrine environment, marked by a disappearance of foraminifera and marine gastropods.

Point B: Open lake marls and gravels with *Congeria banatica*

Marls and gravels of the Medvedski breg Formation overlay continuously the Kostanjek Formation. Their thickness at the Kostanjek section is about 50 m (Fig. 16). Calcite rich marls dominate the entire succession. They are massive or bioturbated and contain an autochthonous mollusk assemblage dominated by dreissenid (*Congeria banatica*) and cardiid (*Lymnocardium* sp.) bivalves (Fig. 18). In the abundant ostracod assemblage the most frequent are *Candona* sp., *Cypria* sp., *Hemicytheria* sp., and *Cyprideis* sp.

Cross-stratified gravel with sand lenses occurs in three horizons of the Medvedski breg Formation. They show erosional lower and gradational upper boundaries. The gravel is trough cross-stratified, normally graded and clast-supported. It is composed of up to 15 cm-large,

Fig. 18. Massive marl from the middle part of the Kostanjek section with *Congeria banatica*, which indicates a deep-water brackish lacustrine environment of early Pannonian age.

sub-angular to sub-rounded cobbles of metamorphic and volcanic rocks, spilite, biocalcarenite, dolomite and mollusk-shell bioclasts.

According to its fauna the Medvedski breg Formation was deposited in a sublittoral, brackish-water, lacustrine environment. The vertical succession and replacement of the *Radix croatica* with the *Congeria banatica* assemblage indicates a deepening and salinity-increase upwards trend from an almost freshwater shallow-littoral environment to a deeper basin brackish-lacustrine environment.

The marls represent autochthonous deposition from suspension. Mineralogically and structurally immature gravels and sands represent clastic material transported from locally uplifted areas to the lake by rivers and torrents, which most probably formed a fan delta.

POINT 4. MIRTI - Lake Pannon middle age – Transdanubian forced regression

Locality:	Mirti / Hruševec
WGS84 coordinates:	46.000836° N, 15.969852° E
Age:	Transdanubian / middle Pannonian (late Tortonian, Late Miocene)
Lithostratigraphy:	Andraševec Formation

Introduction

Small abandoned sandpit is located alongside the road of Mirti in the village Hruševec, 2 km N of the city of Donja Stubica, on the northern slopes of Mt. Medvednica. It exposes deposits of the Andraševec Formation (Kovačić et al., 2009, Dedić et al., 2014), comprising the brackish-water, endemic Lake Pannon mollusk fauna of the Transdanubian (middle Pannonian, Late Miocene) *Paradacna abichi* Zone (Bakrač et al., 2012). Outcrop was studied in detail by Kovačić et al. (2004).

The succession dips by 20° to the north and belongs to the southern limb of the Konjščina Syncline. The lower part of the 50-m-thick succession (Fig. 19) is made by marls with sandy and silty intercalations (Facies F1). Its upper part exposes strongly deformed sandy and silty deposits (Facies F2).

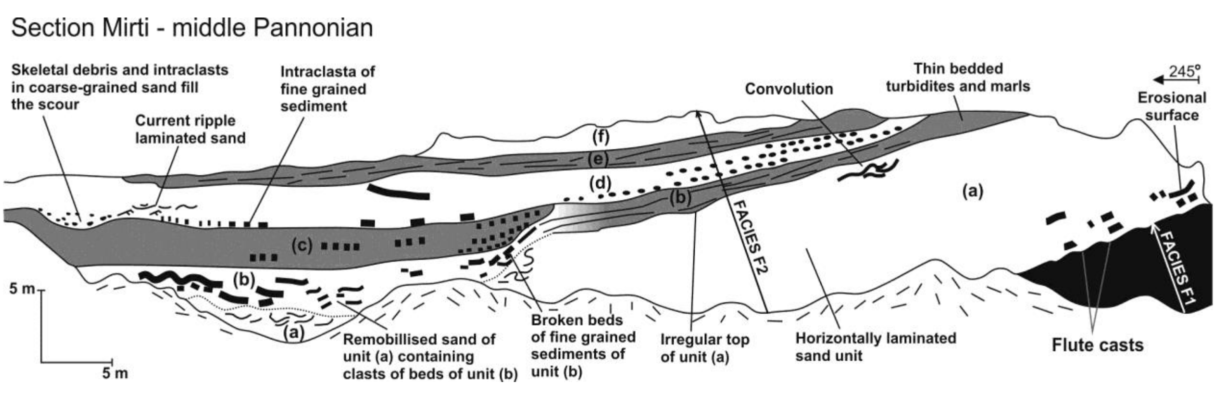


Fig. 19. Sketch of the outcrop of Late Pannonian deposits at Mirti locality displaying a vertical section of sediments of facies F2, and a small portion of the underlying facies F1 in the lower right corner. The orientation of the outcrop section is 65°–245°, which is approximately diagonal to the paleotransport directions shown by flutes (average = 95°) at the base of the sand body (a), and current ripples (SE) in thin turbidites of unit (c).

Facies F1

Marls of this interval form massive or bioturbated beds and may be intercalated with sands and silts. Sandy and silty beds are cm- to several dm-thick. Sands are fine-grained, well sorted showing either horizontal lamination with a gradual upward transition to thin sandy silts and overlaying marl, or vertical grading followed by gradual transition to marl. Less represented are current-ripple laminated sands followed by horizontally laminated sand. The mollusk association includes therein *Paradacna abichi* (Fig. 20), *P. lenzi*, and *Amygdalia czjzeki*.

Occasional intercalations of sands and minor silts, with sharp to erosional bases, overall grading and vertical sequences of structures are comparable to Tbde, Tae, Tde and Tcde turbiditic sequence of Bouma (1962). They record a distal, infrequent sediment delivery to the relevant part of the lake bottom. The mollusk assemblage in the marls represents the quiet brackish-lacustrine environment and the water depth beneath 50 m (Magyar, 1995). Such a depth suggests a quiet, uniform suspension settling of fine-grained material to the lake bottom, where these burrowing bivalves have lived.

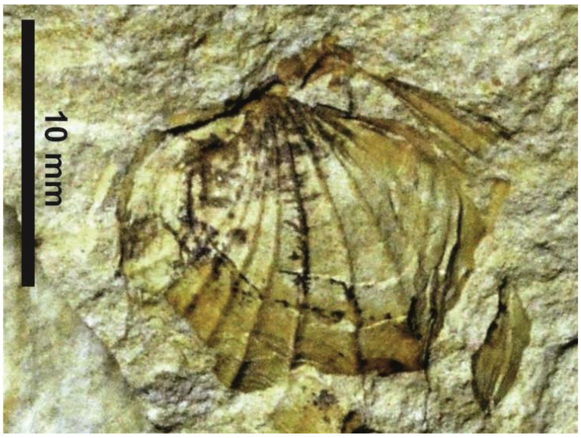


Fig. 20. *Paradacna abichi* from the lower part of the succession at Mirti. It indicates a deep brackish lake environment and Pannonian age (*abichi* beds) of F1 sediments.

Facies F2

The upper and main part of the succession consists of three thick sandy units separated by alternating sands and marls (Units a-f in Fig. 19).

Unit a is 10-m-thick. It consists of fine to medium sand characterized by horizontal lamination (Fig. 21A). Large scale convolutions, erosional surfaces as well as marl and laminated silt clasts occur within the sand body. The basal surface of the lower unit contains flute casts directed towards E-SE.

Unit b is about 1–2-m-thick. It consists of gently deformed, locally disrupted thin beds of sands, silty marls and marls. In the western part of the outcrop, the unit occupies a more than 20-m-wide depression showing a diffuse basal contact with highly deformed sands. Unit b is here represented by massive sand containing scattered angular clasts of thin marl and silt beds, which may be deformed (Fig. 21B).

Unit c is up to 2.6-m-thick and more than 25-m-wide in the outcrop section. The infill of the depression consists of an alternation of thin sands and marls (Fig. 21C). Some sands contain marl clasts. Current-ripple lamination in sands is directed towards the SE.

Unit d consists of up to 3.5-m-thick fine-grained sand. The erosional base of the unit truncates Units b and c, and includes a 1.2-m-deep and 5-m-wide scour in the western portion of the outcrop (Fig. 19, Fig. 21D). The scour is filled with coarse sand containing intraclasts of fine grained sediment, as well as mollusk debris. Other parts of the basal surface are floored by intraclasts of fine grained sediment.

Unit e comprises alternating thin-bedded sands and marls, while **Unit f** is represented by sand. Units e and f are not accessible for close inspection.

The deposition of **Unit a** probably started at a depth greater than 50 m, as implied by mollusks in the underlying Facies F1. Basal flute casts and crude horizontal lamination, together

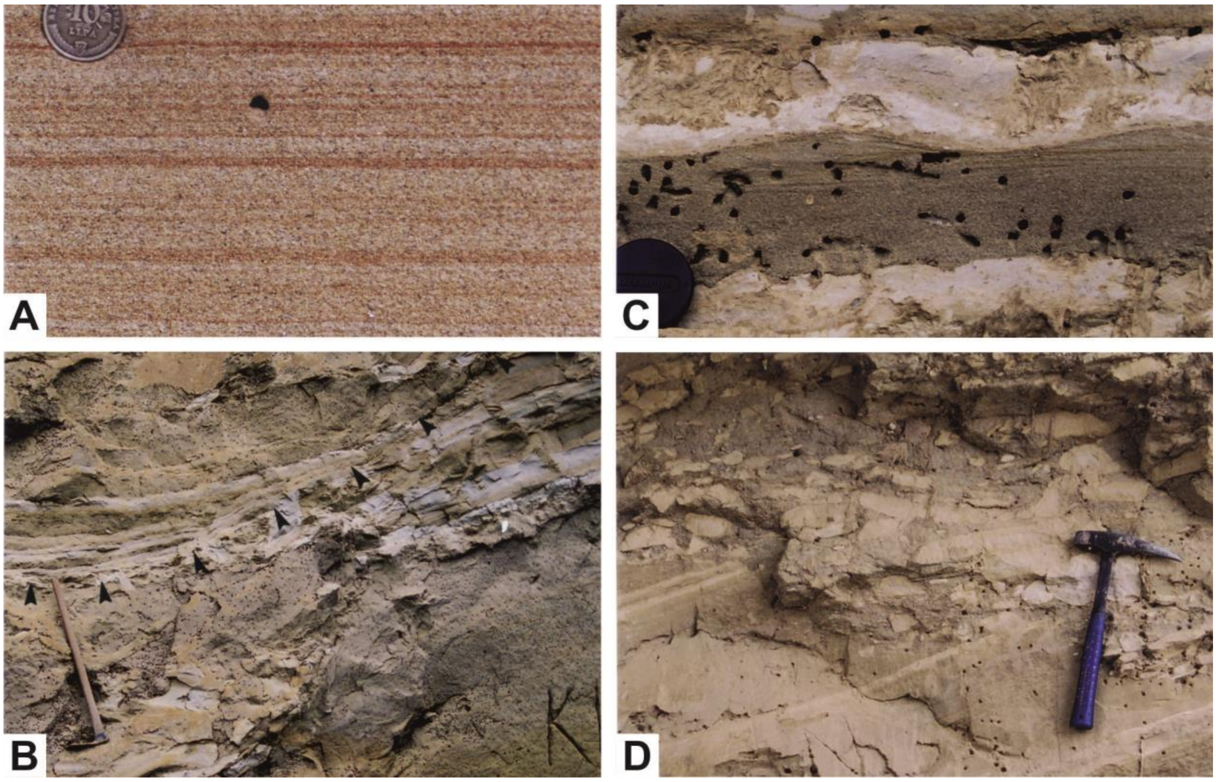


Fig. 21. Specific outcrop features of lacustrine late Pannonian delta slope facies at Mirti locality. A – Horizontally laminated sand in the lower unit (a) of facies F2. Coin is 2 cm in diameter. B – Partly deformed sand of unit (a) in the lower right is overlain by unit (b) consisting of thin-bedded turbidites including hemipelagic marls (upper right). In the lower left, the massive sand contains disrupted beds of silty marl and thin-bedded turbidites. The truncation surface (arrows) representing a slump scar (or erosional surface) is overlain by alternating thin-bedded turbidites and marls of unit (c). Hoe for scale is 1 m long. C – Alternation of sands (dark) and marls (light) of unit (c). Internal structures represent Bouma Tbcde sequences including hemipelagic marl. Current ripples migrated towards the SE. Lens cap is 5 cm in diameter. D – Erosionally truncated alternation of sands and thin marls of unit (c) in the lower part, and overlying basal portion of unit (d) showing intraclasts in a sand matrix. Hammer is 31 cm long.

with the presence of marl and silt intraclasts, reflect erosion by turbulent flow and deposition under upper-stage plane bed conditions. The great thickness of this sand suggests deposition by gradual aggradation from a quasi-steady turbidity flow sustained by a prolonged river flood-stage. Tentative depositional setting was the slope-base or the lowermost slope.

The succession of alternating marls and thin sands of the **Unit b** reflects the alternation of fine-grained background deposition and deposition from low-density turbidity currents. Laterally occurring massive sand, containing intraclasts in the western part, reflects sliding and sand flow. Internal structures in sand, the alternation of graded sand and marl, as well as the vertical association of these sediments suggest an alternation of turbidity-current deposition and slow, fine-grained lacustrine deposition. The depression was probably acting as a channel for the basin-ward sediment-transport, and was subsequently filled by thin-bedded turbidites.

The origins of **Units d**, **e**, and **f** are probably similar to comparable units occurring in the lower part of the exposure.

Conclusively, the sediments of **Facies F2** are related to fast, sustained, hyperpycnal flows, which scoured the bottom upslope. The sediment features indicate the deformation and sliding of different sediment types, liquefaction and flows of remobilized sand, as well as closely related scouring and channelling. These processes were occurring in close succession, thus indicating an unstable slope setting connected to the mouth of the river, very rich in sand.

Also their chute and ridge morphology indicates depositional dynamics described from recent submarine delta slopes (eg. Prior & Bornhold, 1989, 1990). The packages of alternating thin turbidites and fine-grained sediments may have been deposited either on interchute areas as overbank sediment or within chutes and slide scars. They have also been involved in sliding.

The slope was facing E-SE based on the directions of flute casts and current ripples. Sliding and deformation/liquefaction events were probably induced by seismic shocks.

POINT 5. HUM - Termination of the Lake Pannon through deltaic sand infill

Locality:	Hum Zabočki
WGS84 coordinates:	46.024894° N, 15.922667° E
Age:	Portaferrian / late Pannonian (Late Miocene–Pliocene)
Lithostratigraphy:	Hum Zabočki Formation

Introduction

Abandoned sandpit is located in the western area of Hum Zabočki, 1 km SE of Zabok, at the northern edge of the River Krapina valley (Fig. 22). About 100-m-thick succession, dominated by sand and silt, represents lacustrine deltaic environment. It belongs to the Hum Zabočki Formation and marks the topmost Pannonian interval in the region (Kovačić et al., 2004, 2009; Dedić et al., 2014). Its mollusk fauna allows correlation with the Portaferrian (late Pannonian) *Congeria rhomboidea* Zone. The whole succession dips 40° to the south and belongs to the northern limb of the Konjščina Syncline. The present description is based on data presented by Basch et al. (1995).

Depositional environment

Three facies associations (FA) are represented in the succession (Fig. 23): horizontally laminated silts and sands (FAA), cross laminated sands, horizontally laminated sands and massive silts (FAB), and trough cross laminated gravely sands and clayey silt (FAC).

FAA dominates the entire succession. In the lower part of the succession, well-sorted horizontally laminated fossil rich calcitic siltites prevail, while in the middle and upper part of the succession middle to well sorted fine-grained to medium-grained horizontally laminated quartz

Fig. 22. Outcrop of the abandoned sandpit in Hum Zabočki. White circle marks a geologist as scale.

sands dominate. Horizontally laminated silts and sands were deposited from suspension and represent mouth bar deposits. Cross laminated or trough cross laminated sands, which occur only sporadically, are the result of migration of 2D or 3D ripples. The position of cross laminae suggests transport direction to the south or southeast.

FAB appears in the lower part of the column. It represents only 2% of the succession and consists of two cycles. Both cycles are composed of cross laminated sand covered by horizontally laminated sand and massive silt. Sand is fine-grained and well sorted. The position of cross laminae suggests transport direction to the southwest. Silts are well sorted, dark colored and rich on brackish macro fauna and plant fragments. FAB represents sediments of crevasse splay environments, which formed within interdistributary bays of a delta during flood.

FAC appears in the middle part of the section and comprises only 1% of the succession. It consists of well sorted trough cross laminated course-grained or gravely sand with silt intraclasts. They represent distributary channel sediments. Clayey silts are massive and lie on top of the sand layer. Plenty of fragmented carbonized plant remains color them black. They are interpreted as sediments of an abandoned channel.

In conclusion, the succession is dominated by horizontally laminated sand and silt and represents a lacustrine delta environment, in particular the mouth-bar facies. Sporadically preserved cross-lamination and wave-ripples are result of reworking by coastal processes. The character of mouth-bars implies that delta was river dominated. The features of facies associations and their vertical succession evidence a mouth-bar delta type. Such deltas develop in relative deep-water basins, in front of vegetated, low gradient shores, fed from hinterland by a meandering river with well-developed natural levees.

Mollusk record

The endemic Lake Pannon mollusk fauna, dominated by melanopsid gastropods and dreissenid and lymnocardiinae bivalves is concentrated in the section to its 41-m-thick lower part. Two superposing assemblages are present therein. The lower one bears a highly diverse assemblage including 17 species, dominated by *Dreissena auricularis*. Associated are partly very frequent *Congeria rhomboidea* and *Congeria brandenburgi*. Such a composition points to calm brackisch lacustrine conditions and littoral paleodepths (Stevanović et al., 1989).

At a height of 24 m, immediately after the disappearance of *Congeria rhomboidea*, species richness decimates to 10 species. Assemblage therein is dominated by *Melanopsis decollata*, *Dreissena auricularis* and *Andrussoviconcha balatonica*, clearly reflecting decreased salinity values and a shallower littoral depth (Stevanović et al., 1989). As an apparent effect of delta progradation, this change correlates well with an increased sandy component in this interval.

The fossil-rich interval ends at height of 41 m, when mollusks virtually disappear from the succession. Nevertheless, occasional limnocardiinae bivalve remains recorded in that barren interval still suggests Pannonian age and persistence of brackish lacustrine shallow littoral deposition up to section's very top.

Congeria rhomboidea is an index fossil of the late Pannonian Portaferrian substage, providing a very clear biostratigraphic constraint for the succession. Yet, the assemblage composition with *Trigonipraxis triangulars* and *Andrussoviconcha balatonica* reminds strongly to older Transdanubian (middle Pannonian) fauna of Radmanest (W Romania) or Tihany (central Hungary) as recognized already by Basch et al. (1995). Because, the age difference (e.g., Geary et al., 2012) was unknown to former authors and paleontological documentation is missing in their study, a future taxonomic revision should clear the arisen stratigraphic controversy.

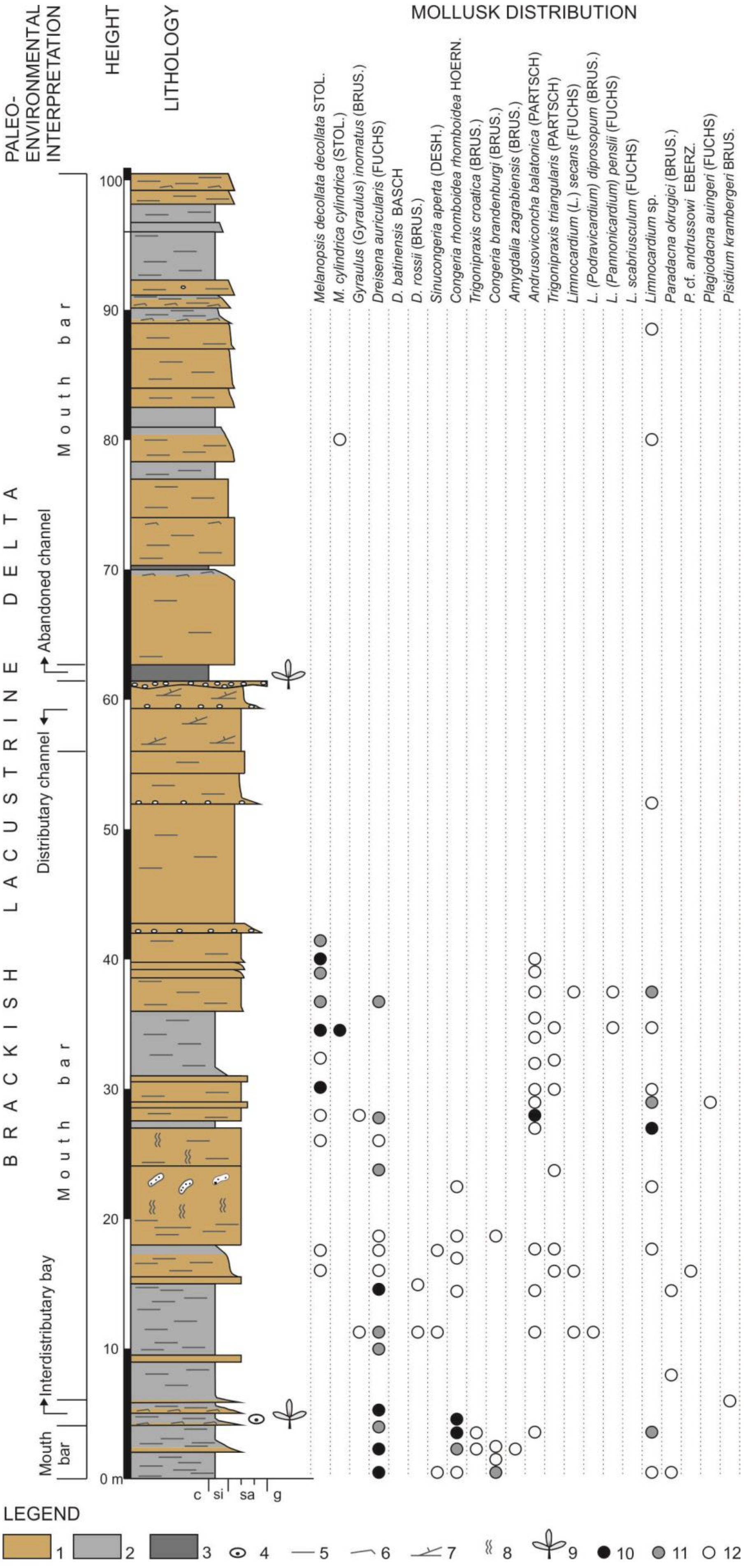


Fig. 23. Log and fossil macrofauna of the Late Pannonian deposits at Hum Zabočki locality (Hum Zabočki Formation). Legend: 1 – sand; 2 – silt; 3 – clayey silt; 4 – concretions; 5 – horizontal lamination; 6 – planar cross lamination; 7 – trough cross lamination; 8 – bioturbation; 9 – flora; 10 – frequent; 11 – rare; 12 – individual.

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PART 2 / EXCURSION 2

By Oleg Mandic, Karin Sant, Nevena Andrić, Nada Horvatinčić, Nikolina Ilijanić, Slobodan Miko, Nikola Markić, Anđelko Novosel, Liviu Matenco, Hazim Hrvatović
With contributions by Ursula B. Göhlich, Thomas A. Neubauer, Arjan de Leeuw, Wout Krijgsman

Dinarides lakes and basins – from 18 Ma to Present

1. Introduction: Dinarides lacustrine environments

The Dinarides area of Croatia and Bosnia and Herzegovina is an active fold and thrust belt positioned between the Mediterranean and the Pannonian Basin (Fig. 1). In the Neogene the region recorded an extended history of lacustrine deposition. Its early Neogene history is marked by the rise and fall of the Dinaride Lake System. After its disintegration in the Middle Miocene only three largest lake basins remained active – Lake Sarajevo, Livno, and Tomislavgrad. In the Quaternary, all lakes retreated in consequence of regional tectonic

Fig. 1. Distribution of Miocene lacustrine deposits attributed to the Dinaride Lake System (data from basic geological map M 1:100,000 of former Yugoslavia). Positions of excursion sites are indicated: 1 - Plitvice Lakes, 2 - Lake Vrana, 3 - Sutina, 4 - Tušnica, 5 - Mandek, 6 - Ostrožac, 7 - Cebara, 8 - Fatelj, 9 - Gračanica, 10 - Greben, 11 - Janjići, 12 - Lašva.

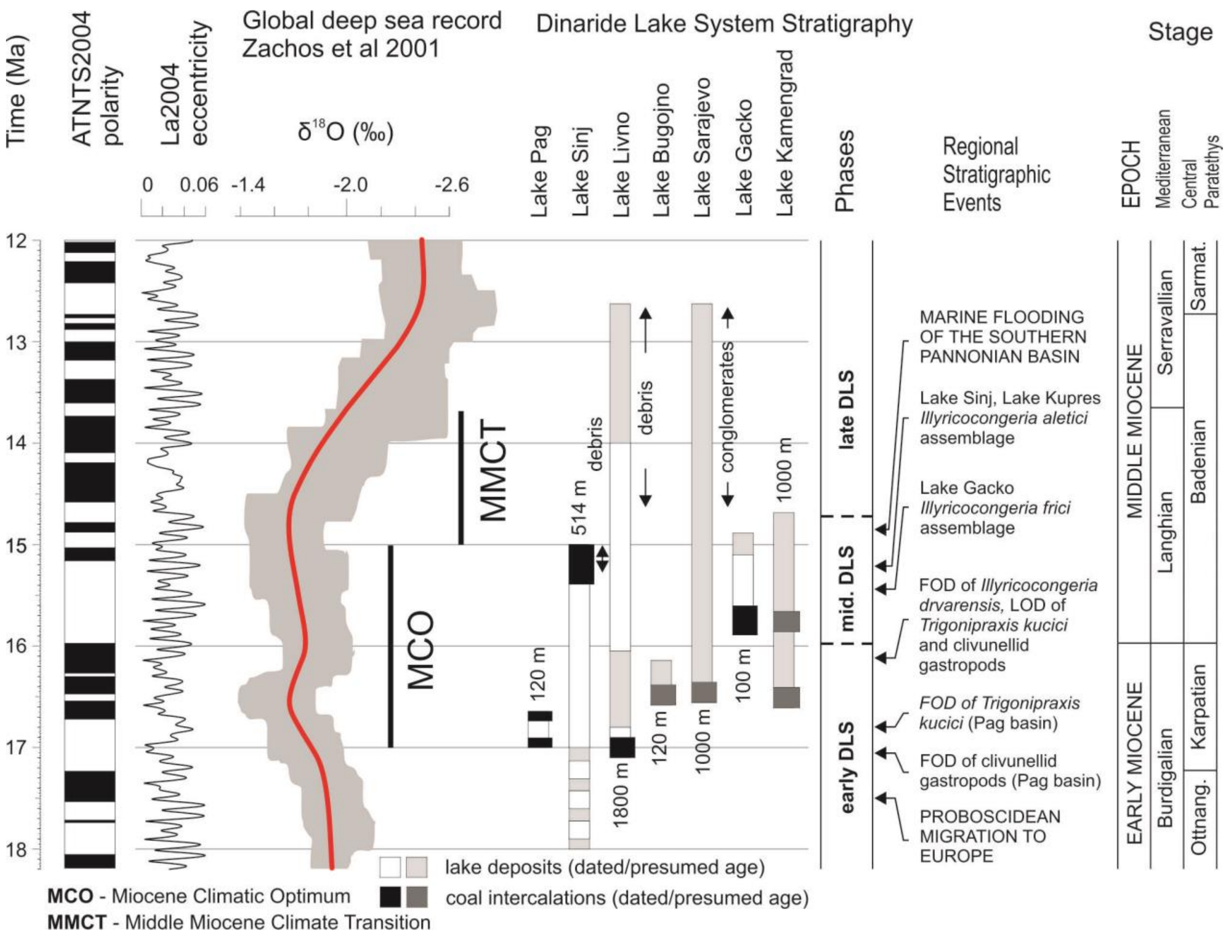


Fig. 2. MCO, MMCT and their stratigraphic correlation with DLS successions. Coal seams and detritic beds in the sections from the Dinaride intra-mountainous basins are indicated. The DLS stratigraphy is based on results from integrated Ar/Ar geochronology and magnetostratigraphy (modified after De Leeuw et al., 2011).

inversion and global climate deterioration. During the current Holocene intergacial period, the climate conditions facilitated return of lake environments. Except for a number of artificial lakes, two valuable natural examples are available with the Plitvice cascade lakes and the Lake Vrana. The latter represents the largest lake of Croatia.

During the period of substantial Miocene climatic changes, a series of long-living lakes occupied the intra-montane basins (Fig. 1 and 2) of the Dinaric Alps in Southeastern Europe (Harzhauser & Mandic, 2008, 2010; Jiménez-Moreno et al., 2008; De Leeuw et al., 2010, 2011, 2012; Mandic et al., 2011, 2012a). Settled on the western margin of the Dinaride–Anatolian Island landmass, they occupied a highly interesting palaeogeographic position sandwiched between the Paratethys and the proto-Mediterranean seas (Fig. 3) in an area known to be highly sensitive to climatic changes (Rögl, 1999; Harzhauser & Piller, 2007). The origin and disintegration of lacustrine settings were bound to the post-collisional tectonic evolution of the Dinaride fold and thrust belt (Fig. 4; Schmid et al., 2008). After the southwestwards back-stepping of wedge-top molasse basins in the Early Oligocene (Korbar, 2009), dextral strike-slip movement on the Periadriatic and mid-Hungarian sutures during the Late Oligocene were compensated in the Dinarides by tectonic wrenching (Hrvatović, 2006). Accommodating the extension from the back-arc rifting in the Pannonian basin, the longitudinal strike-slip faults become reactivated in the Early

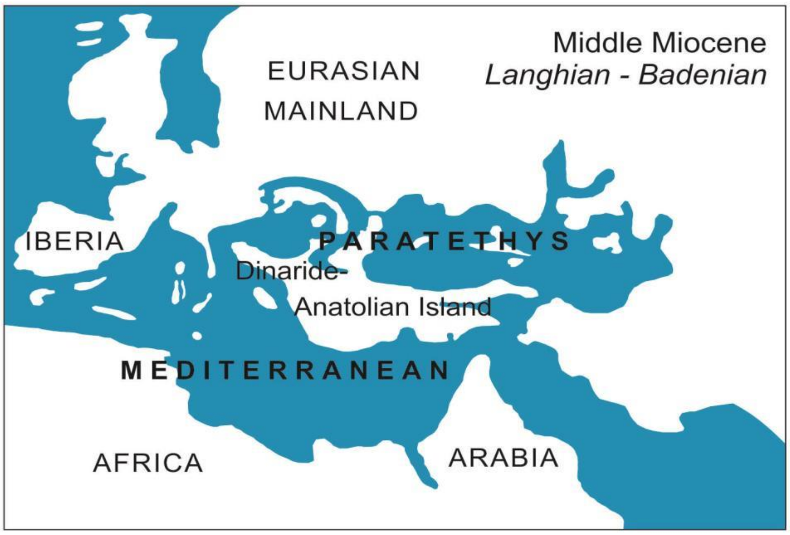


Fig. 3. Paleogeographic setting of the Dinaride-Anatolian Island during the early Middle Miocene (modified after Rögl, 1999).

Miocene allowing the subsidence and accumulation of large sediment piles (Fig. 2) in the intra-montane basins (Ilić & Neubauer, 2005; De Leeuw et al., 2012).

The Dinaride Lake System (DLS) formed in the early Miocene in today NW–SE trending intra-mountain basins between the slowly rising Dinarides mountain chains (De Leeuw et al., 2012). The comparatively low terrigenous input supported the diversification of lacustrine environments, including both deep- and shallow-water habitats. This habitat diversification sparked the spectacular Miocene radiation of the benthic fauna (Harzhauser & Mandic, 2008, 2010). Subsequent rifting in the Pannonian Basin System triggered the marine flooding of the northern DLS area and reduced its extension to the External Dinarides. Geographically, the deposits of the DLS cover parts of Croatia, Bosnia and Herzegovina, Montenegro, Serbia, Hungary and Slovenia (Fig. 1). During its maximum extent, the lake system covered an area of c. 75,000 km^2.

The long-living lakes left up to 2000-m-thick sedimentary successions distributed across the Dinaric Alps (Fig. 2). The current investigations provided a deep-time window to DLS in constructing the integrative Ar/Ar geochronologic and palaeomagnetic age model for its key basins (De Leeuw et al., 2012). Those results supported the establishment of a powerful bio-magnetostratigraphic tool allowing the stratigraphic correlations and a precise insight into the complex environmental history of that previously less-known region. In particular it could be demonstrated that the lakes recorded a suite of climatic parameters (Jiménez-Moreno et al., 2008, 2009; Mandic et al., 2009, 2011; Harzhauser et al., 2012). Moreover the lake level changes in Pag (Jiménez-Moreno et al., 2009) and Gacko (Mandic et al., 2011) basins were proven as cyclic and presumably driven by astronomical forces. The captured fluctuations therein provide actually a high-resolution archive that considering its length allows not only establishing relations between the global warming and its regional effects but also the weighting of the potential effect of MMCT (Holbourn et al., 2005; Lewis et al., 2008) and regional geodynamics to its disintegration.

In particular the early and the middle DLS stages (Fig. 2) coinciding with the MCO comprise partly vast coal deposits. Its late DLS stage is characterized in contrast by depositional hiatus or introduction of coarse clastic sedimentation. Yet, whereas in the northern DLS, thick successions of fluvial conglomerates are known from the Sarajevo Basin (Hrvatović, 2006), such conglomerates are missing in the southern DLS including the Tomislavgrad–Livno and Sinj ba sins (Fig. 2). There local debris flow deposits (sandstones and breccias) are recorded between ~15.2 and ~15.0 Ma in the Sinj Basin (Mandic et al., 2009; De Leeuw et al., 2010) and between 14.8 and ~13.0 Ma in the Tomislavgrad–Livno Basin (De Leeuw et al., 2011). In all three basins the coarse clastic deposition coincide with the terminal phase of the main DLS depositional sequence indicating synsedimentary tectonics and relief building as cause for basinal inversion terminating the lacustrine deposition in the late Middle Miocene.

The six intra-montane basins of the Dinarides will be visited to show the late syn- to post-orogenic sedimentation within the orogenic belt.

2. Tectonic setting of the Dinarides

Liviu Matenco, Arjan de Leeuw, Oleg Mandic

The Dinarides are located on the convergent plate boundary separating the Adriatic and Tisza-Dacia micro-plates in the Central part of the Mediterranean region (Fig. 4). The excursion will traverse the units of the Dinarides, derived from intense deformation of the Adriatic microplate during Late Jurassic - Eocene times, subsequently modified by Miocene extension and the latest Miocene - recent indentation of Adria. The term Adriatic microplate refers to the lithospheric plate that includes the present day undeformed areas of Istria and the Apulian carbonate platforms (Italy/Croatia/Montenegro) and is framed by the external thrust belts of Southern Alps, Dinarides and Apennines. This part of the Adriatic plate acted as a rigid indenter during its collisional interaction with the Alpine and Dinarides orogens to the north and east (Fig. 4), respectively. However, note that the term Adria is used for denoting the paleogeographical affiliation of structural entities that had originally formed part of a larger Adriatic (Channell and Horvath 1976) promontory or micro-continent but later became involved in its fringing folded belts (Dercourt et al., 1986).

The Adria-derived units that are presently located south of the Periadriatic Line and its eastern continuation (Fig. 4), i.e. south of the Tisza-Dacia and ALCAPA Mega-Unit, constitute the Southern Alps and all the non-ophiolitic tectonic units of the Dinarides. During the Triassic, these units were located SSW of the Neotethys Ocean, and thus they were derived from the northern passive margin of Adria that faced the Neotethys. This group of tectonic units includes (Fig. 4), the external Dinaridic platform (Dalmatian zone, Budva-Cukali Zone and High-Karst Unit), the internal Dinaridic platform (Pre-Karst and Bosnian Flysch Unit), the continental basement and Mesozoic cover which underlie the obducted Western Vardar Ophiolitic Unit in the East Bosnian - Durmitor, Drina-Ivanjica, Jadar - Kopaonik composite tectonic units (e.g., Schmid et al., 2008 and references therein). All these units structurally underlie remnants of the Western Vardar Ophiolitic units (Fig. 4) and are in a lower plate position with respect to the late Cretaceous - Paleogene subduction of the Sava Zone, which is the suture zone between the Dinarides in a lower plate position and the upper Tisza-Dacia Mega-Unit (Fig. 4).

Following the **Triassic** opening of the northern branch of the Neotethys (i.e. Vardar) ocean (e.g., Pamic et al., 1984), a number of major tectonic events are relevant for the understanding of the post-rifting structure and evolution of the Dinarides in the area crossed by the excursion (e.g., Schmid et al., 2008; Hrvatović and Pamić, 2005). The Late Jurassic deformation (170-150 Ma) is responsible for the obduction of the Western Vardar Ophiolitic unit. The obduction was associated with the formation of an ophiolitic mélange (or wildflysch). The late Early Cretaceous orogenic processes (125-100 Ma) are less precisely dated in the Dinarides, but participated at the formation of the composite units, which post-date the late Jurassic obduction of the ophiolitic unit.

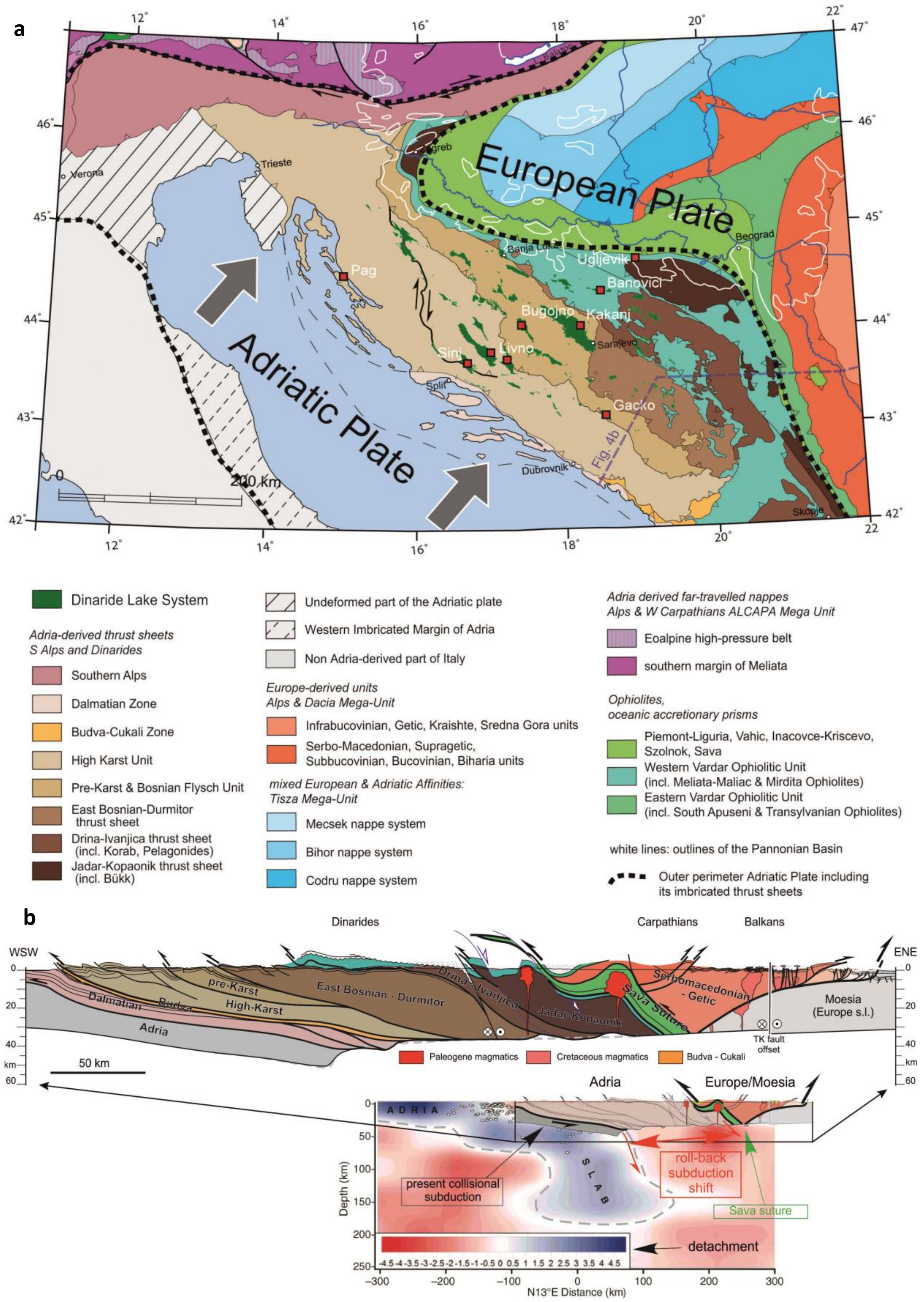


Fig. 4. **a**. Plate tectonic and geologic setting of the Dinarides and surrounding area, adapted from Schmid et al. (2008). The Neogene intra-montane basins filled by lacustrine deposits are marked green (see also Fig. 1), the sites evaluated by De Leeuw et al (2012) by dark red rectangles (see also Fig. 2). Main faults, major plate boundaries and the direction of movement of the Adriatic Plate are indicated. **b**. Simplified crosssection across the Dinarides and Balkans (modified after Matenco and Radivojevic, 2012; Schmid et al., 2008).

The **Maastrichtian - Paleogene** orogenic process essentially shaped the present-day Alps and Dinarides (Schmid et al., 2008; Ustaszewski et al., 2009). It was associated with a large magnitude of N-S convergence between Adria and Europe. This large scale crustal shortening in the Alps and Dinarides was associated with a differential N-ward displacement of the Adria plate, which must have been also accommodated in the Dinarides by some dextral strike-slip movements (Plate 1). These processes essentially terminated at the Eocene-Oligocene transition when the subducted Adriatic slab was detached from its continental lithosphere. A Middle Eocene phase of intense thrusting took place, as evidenced by the widespread associated flysch deposits (Tari, 2002, Korbar, 2009). Collision induced shortening continued in the Late Eocene and Oligocene and was associated with molasse sedimentation in the external parts of the Dinarides. Oligocene strike-slip faulting in response to movement on the Peri-Adriatic fault initiated transpressional depressions as precursors of the Neogene fresh-water basins (Hrvatović, 2006).

The **Neogene** tectonic events in the ALCADI realm are well constrained. The retreat of the subducted European lithospheric slab beneath the Carpathians and, possibly also below the Dinarides, facilitated the advance of the Tisza-Dacia Mega-Unit into the Pannonian embayment and controlled the collapse and development of the back-arc Pannonian Basin (i.e. Horvath et al., 2006; Matenco and Radivojevi, 2012). In the area of the Dinarides, this extension started apparently earlier (Oligocene) and lasted longer (Late Miocene) than in the classical extensional depocentres of the Pannonian basin (Matenco and Radivojevic, 2012, Toljic et al., 2013). In the Early to Middle Miocene, the north-eastern margin of the Dinarides was affected by profound extension in response to the rifting that initialized the Pannonian Basin (Tari, 2002). In or near the Dinarides this deformation was essentially asymmetric and resulted in the formation of extensional detachments aligned all along the northern margin of the Dinarides from Zagreb to SE-most Serbia (e.g., Ustaszewski et al., 2010; van Gelder et al., 2015) and they tend to reactivate by extension either the inherited Sava suture zone or the internal contacts of the Dinarides units. This extension resulted in subsidence in the Neogene basins below the base-level of the adjacent Paratethys: a Mediterranean sized epicontinental sea that covered large parts of south-eastern Europe at that time. In the more central and western parts of the Dinarides, this extensional phase reactivated some of the Oligocene transpressive structures and consequently triggered the development of a series of lacustrine intra-montane basins.

The **present** day-structure of the Dinarides is influenced by the indentation of Adria, a process that started during the latest Miocene and is still active (e.g., Pinter et al., 2005; Handy et al., 2010). This resulted in a large number of lower offset contractional structures distributed in the Dinarides and the adjacent part of the Pannonian Basin. At a larger scale a slab remnant is observed only in the SE part of the Dinarides, where its subduction is associated with intense seismicity and active shortening (Fig. 4b, e.g., Bennett et al., 2008).

3. Excursion Points

The current excursion will present a brief overview on the past and present fresh water lacustrine environments represented since the Early Miocene in the karst valleys and intra-mountainous basins of the Dinarides (the so-called Dinaride Lake System and its successors). Results from current and ongoing research about their geodynamic, depositional, environmental, and biotic histories will be first-hand presented by investigators in a three day bus excursion crossing the Dinarides in Croatia and in Bosnia-Herzegovina (Fig. 1).

The excursion starts with the World heritage site, the spectacular calcareous tufa cascades of the Plitvice lakes (P1), situated in the largest national park of Croatia hosting more than one million visitors per year. It continues with Lake Vrana (P2), located in a Dalmatian karst valley of the Adriatic coastal area, and represents the largest Croatian fresh water lake. Recent limnogeological drilling campaigns therein allowed reconstruction of the regional sea-level history in the late Quaternary. The end of the day will be spent in the Sinj Basin (P3), filled by coal bearing carbonate deposits of a long-living lake that existed there for about 3 myr during the Miocene Climate Optimum.

The second day will demonstrate the rise and fall of the long-lived lacustrine environments in the Livno and Tomislavgrad basins in Bosnia-Herzegovina. Beside different sediment types such as coal (P4), marl, carbonates, volcanic ashes (P5) and debrites (P6), the visit to the Mio-Pliocene proboscidean site Cebara (P7) will bring insights to the complex geodynamic history of these two classical karst valleys of the External Dinarides. A fossil site with excellently preserved 15 myr old endemic fresh water mollusks will be visited by the end of the day in the Kupres basin (P8).

The third day will start with a visit to the open cast mine Gračanica (P9) in the Bugojno basin where large-scale outcrops show transgressive open lake marls with slump structures grading over thick lignite measures, bearing large mammal remains. The rest of the day will be spent in the region of Kakanj in the Sarajevo Basin. This is the largest Dinaride lake basin. The asymmetric extensional basin formed in the hanging-wall of a large-scale top-NNE detachment and is associated with the exhumation of the Mid-Bosnian Schists Mountains in its footwall. The field stops will take you from the deep lake (P10) to alluvial plains (P11–12), and thereby illustrate the close connection between tectonics and sedimentation.

3.1. POINT 1. PLITVICE LAKES – Recent tufa sedimentation

Locality:	Plitvice Lakes [Plitvička jezera]
WGS84 coordinates:	44.880323° N, 15.618544° E
Age:	Recent

3.1.1. Environment, chronology and tufa sedimentation

Nada Horvatinčić

Introduction

The Plitvice Lakes, situated in the Dinaric karst in Central Croatia, consist of 16 lakes of different size, connected by streams and waterfalls (Fig. 5). The altitude of the area ranges from 505 m to 636 m asl, the climate is mountain-continental, the average air temperature is 9.1°C and the average yearly precipitation is 1558 mm for the period 1986–2010.

The lakes receive water from two main springs (Crna Rijeka and Bijela Rijeka springs) and two tributaries (Rječica and Plitvica Brooks) (Fig. 5a). The Plitvice Lakes feed the Korana River which issues from the lakes. The total distance from the springs to the Korana River is ~12 km. Lakes are divided into Upper and Lower Lakes by a large fault, which strikes northwest to south-

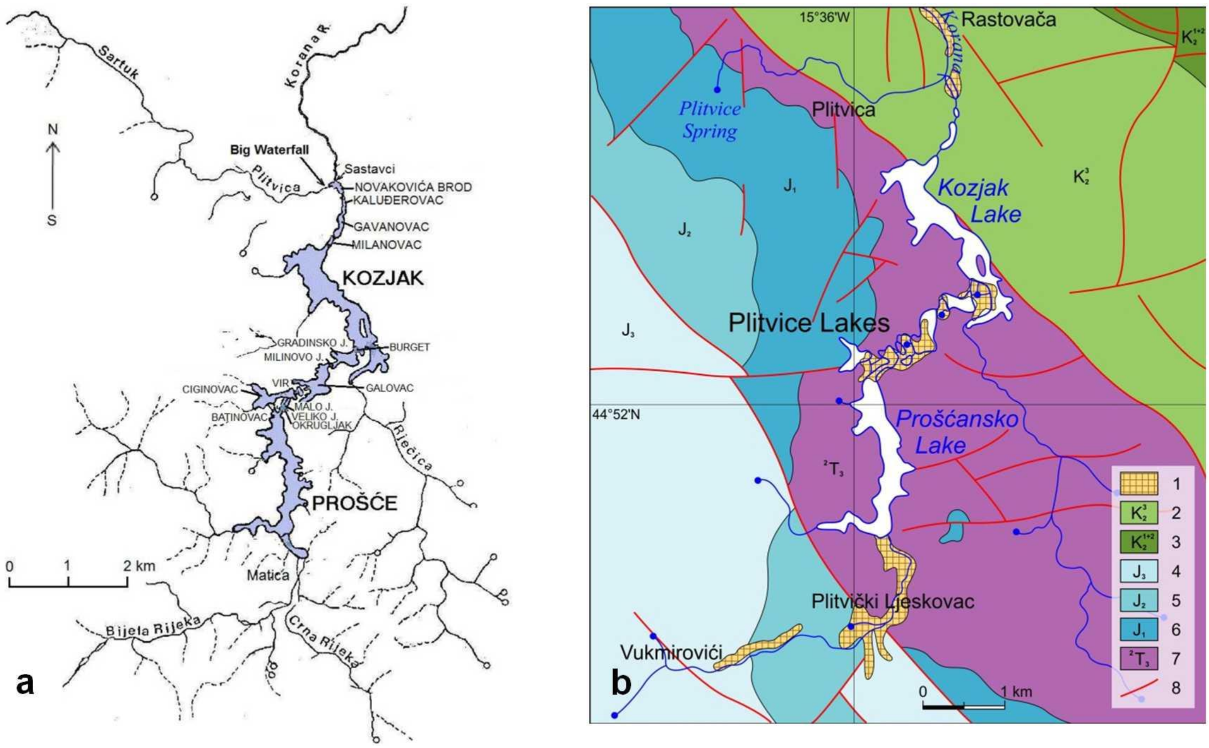


Fig. 5. a) Plitvice Lakes area from main springs (Crna and Bijela Rijeka) along 16 lakes to the outflow of the Korana River; b) Schematic geological map of the Plitvice Lakes area (simplified after Polšak et al., 1969); 1 – tufa, 2 – Upper Cretaceous rudist limestone, 3 – Upper Cretaceous limestone, marl and dolomite, 4 – Upper Jurassic dolomite and platy limestone, 5 Middle Jurassic limestone and dolomite, 6 Lower Jurassic limestone and dolomite, 7 Upper Triassic dolomite, 8 – fault.

east along the northeast edge of the Kozjak Lake (Fig. 5b). The lakes developed in the fluvial karstic river valley (palaeo-Korana River) which was dammed by tufa barriers. Twelve Upper Lakes developed in the open part of the river valley, mainly dolomite, and are surrounded by thick forests and interlinked by numerous waterfalls. Four Lower Lakes, smaller and shallower, developed in the karst canyon which was carved by paleo-river flow through limestone, presumably during last glacial period (Fig. 5b). The lakes and Korana River are characterized by intense calcium carbonate precipitation from the water forming tufa barriers and fine-grained lake sediments, mainly composed of authigenic calcite

The area is protected as a national park from 1949 and is included in the UNESCO World Heritage List. Human activities in the lake watersheds are relatively limited, although numerous tourists visit the area every year.

The Plitvice Lakes represent a unique phenomenon of karst hydrography, particularly because of tufa formation, a freshwater calcium carbonate which precipitates in presence of macrophites and microphites forming spectacular waterfalls and barriers. Although the area is protected as a national park, any pollution in global or local level can disturb very sensitive process of tufa formation. In order to understand the processes of tufa formation as well as to protect the area against any contamination, scientific research in the area of the National Park has been performed by various teams. Various projects include the study of tufa and lake sediment deposition, hydrogeology of the area, biological and environmental research, forest vegetation and forest management, inventory of various fauna species, monitoring of possible organic or inorganic pollutants and other topics. Regular monitoring of physico-chemical and bacteriological parameters in water have been performed by the staff of the Scientific Investigation Centre "Academician Ivo

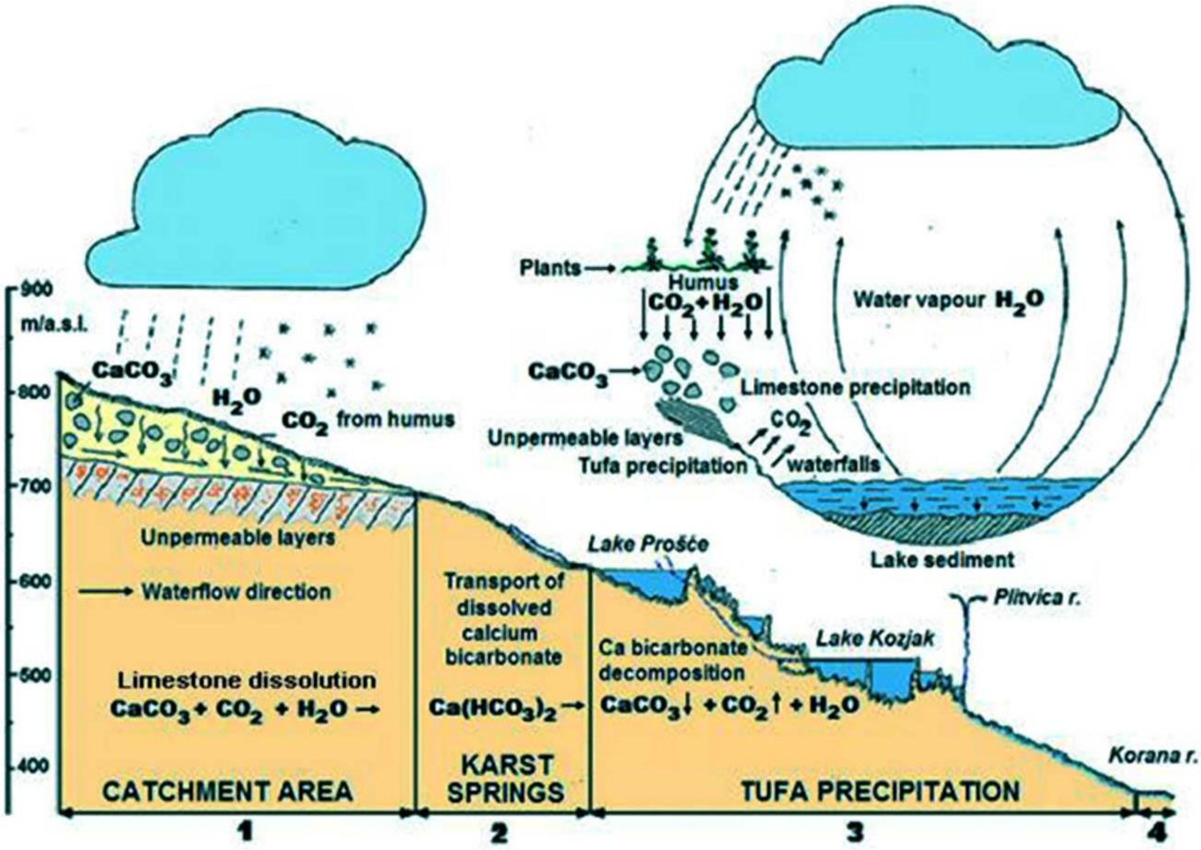


Fig. 6. Geochemical processes of tufa and lake sediment precipitation presented at the cross-section of the Plitvice Lakes.

Pevalek" located at the Plitvice Lakes since 2006.

Tufa and lake sediment formation

Tufa is a product of calcium carbonate precipitation at near ambient temperature and typically it contains the remains of micro and macrophytes and bacteria. Tufa is deposited in the surface water by a combination of physico-chemical and biological precipitation processes.

Geochemical process of tufa and lake sediment formation is presented at the cross-section of the Plitvice Lakes (Fig. 6). In the first step the rain water dissolves CO_2 produced by the decomposition of organic matter and by root respiration in the topsoil. Percolating water rich in CO_2 dissolves carbonate rocks and forms bicarbonate. When water containing calcium and bicarbonate ions emerges in the form of a karst spring, precipitation of calcium carbonate occurs either due to degassing of CO_2 from solution or by evaporation. Precipitation of carbonates in the form of lake sediment or tufa depends on the physico-chemical conditions of the water. It is enhanced by the photosynthetic activity of aquatic primary producers (algae, bacteria and plants) indicating that the interaction between atmosphere and biosphere determines the $CO_2 – HCO_3 – CaCO_3$ system.

Besides physico-chemical conditions the plants/biota have important role in the precipitation of the tufa. The biota remove CO_2, which increases the level of saturation of water, act as a convenient substrate for precipitation (Fig. 7a) and trap and bind calcite seed crystals within a biofilm which is a by-product of the microbial metabolic activity of diatoms, bacteria and/or cyanobacteria (Fig. 7b) (Chafetz et al., 1994, Golubić et al., 2008). Tufa formation is favoured where well-developed plants exist in streams and waterfalls resulting in different morphological forms (Fig. 7a). This process is very sensitive to physico-chemical or biological

Fig. 7. a) Presence of plants and percolation of water on cascades accelerates calcite precipitation in form of tufa barriers, b) SEM photograph of diatom aggregations on moss at the Plitvice Lakes.

changes in the water and also to seasonal fluctuation, e.g., temperature change.

Investigations of physico-chemical conditions of tufa precipitation from the freshwater at the Plitvice Lakes area were performed systematically in different seasons included three main springs feeding the Plitvice Lakes, lakes, streams and the Korana River which issued from the Plitvice Lakes, in total distance of ~12 km (Srdoč et al., 1985, Barešić et al., 2011). The lake waters are characterized by a high seasonal temperature variation of ~20°C, and the pH values of 7.3–7.6 in springs to 8.2–8.6 in lakes area increasing downstream. CO_2 concentration decreases rapidly in spring area, while concentration of bicarbonates as a main component of dissolved inorganic carbon steadily decreases downstream from 5.2 to 3.5 $mmolL^{-1}$. In the area of the lakes where the process of calcite precipitation is very intensive, the waters are oversaturated, the saturation index (Isat) of $CaCO_3$ ranges from 4 to 10.

The whole karstic environment of Plitvice Lakes, comprising water, soil and air, is very sensitive to any kind of pollution. Although the Plitvice Lakes area is protected as the national park and is scarcely populated, some contamination by local settlements, tourism activities and traffic is possible. Comprehensive study of possible anthropogenic and environmental change influence on Plivice Lakes area has been performed on the recent lake sediments (precipitated in last 100–150 yr). Lake sediments consist mostly of calcite (70–85% in big lakes, 90–95% in small lakes) with very small amount of dolomite, quartz, and low fraction of organic matter (2–8%). Both, calcite and organic matter are mainly authigenic (>90%), which is demonstrated by the $\delta^{13}C$ analyses of the sediments.

Anthropogenic influence on ^{14}C activity in recent lake sediment, interpreted as a delayed and damped response to bomb-produced ^{14}C in the atmosphere was observed in Prošće, Kozjak, Gradinsko and Kaluđerovac lakes (Horvatinčić et al., 2008). For the small lakes, the increase of $\delta^{13}C$ in the last two decades and at least part of the increase of $\delta\ ^{14}C$ is probably due to an increase in primary productivity that enhanced biologically-induced calcite precipitation with accompanying changes in the carbon isotopic composition of carbonate sediments. This corresponds with the global temperature increase.

Trace element analyses showed no significant difference among the trace element concentration in the top segment of all cores, corresponding to last 50 years when higher anthropogenic influence can be expected. Analyses of lake sediment show no significant contamination caused by anthropogenic influence

(Horvatinčić et al., 2006).

Moreover, the lakes are located in mostly deciduous forest, and huge amount of leaves are transported into the lakes every year. Additionally, some preliminary measurements of dissolved organic carbon (DOC) in water in this area showed that increase of DOC can disturb or even stop the process of tufa precipitation (Srdoč et al., 1985; Barešić et al., 2011). In last decades the process of eutrophication in the Plitvice Lakes has been observed in the form of intense plant growth in some lakes, tufa barriers and water streams. This process is attributed to influx of nutrients into lakes and streams from natural and anthropogenic sources resulting in deterioration of water quality.

Geochronology

Results of ^{14}C dating of active tufa deposits show that they are younger than 8000 years BP and formed during the Holocene period, i.e., after the last deglaciation. Outcrops of old tufa deposits found at three locations in the Park area were dated by $^{230}Th/^{234}U$ dating method (Srdoč et al., 1994; Horvatinčić et al., 2000). These results showed that most of old tufa samples clustered around interglacial marine ^{18}O stage 5, and then interglacial stages 7 and 9. ^{14}C and $^{230}Th/^{234}U$ ages of tufa in the Plitvice Lakes area demonstrate that the formation of tufa barriers was stimulated by changing climate, e.g., during interglacial periods with warm and humid conditions (Horvatinčić et al., 2003).

Sediment cores from lakes Prošće and Kozjak, of total length up to 12 m from the bottom of the lake to the bedrock, were extracted in 1983. This enabled numerous analyses that have contributed to the further understanding of lake geochronology (Srdoč et al., 1986). Seismic profiling of lakes, geochemical and sedimentological analyses, dating of lake sediment and organic detritus, measurement of stable isotope ratios ($^{13}C/^{12}C$ and $^{18}O/^{16}O$), and analyses of pollen and diatoms were performed.

^{14}C measurements showed that the sedimentation in Lake Prošće began about 7000 years ago, and at Lake Kozjak 6500 years ago. Due to very small variations in $\delta^{18}O$ it can be concluded that climatic conditions during the deposition of sediment in Holocene were stable. ^{14}C age of Lake Prošće sediment was compared with those from two peat cores adjacent

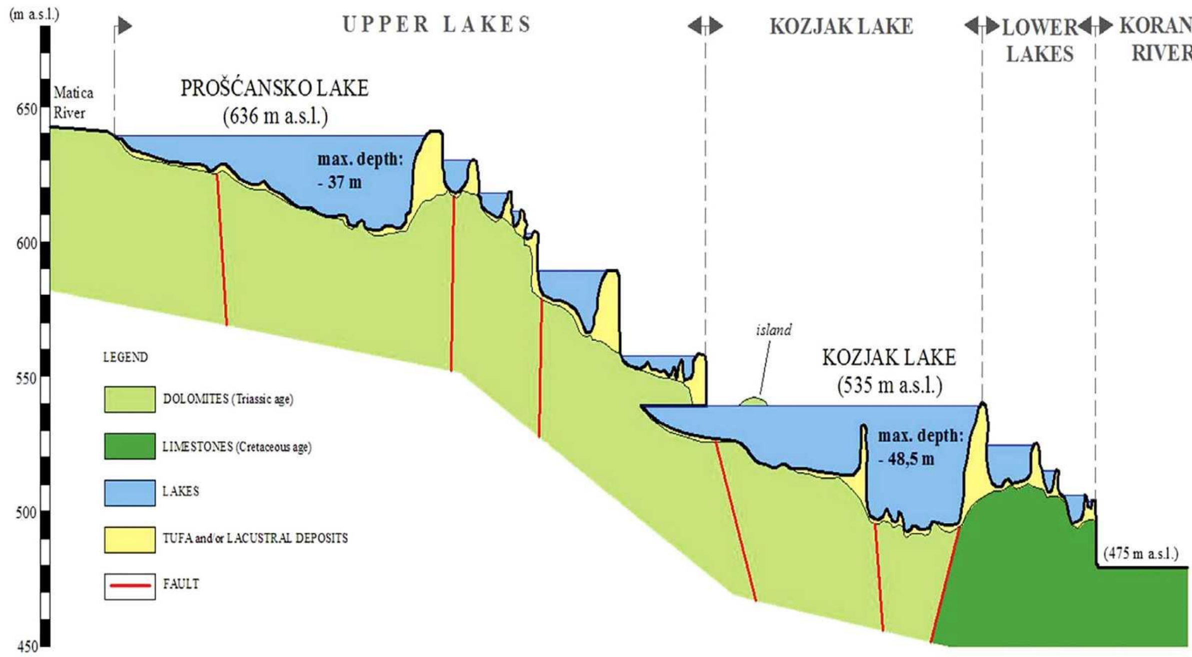


Fig. 8. Schematic hydrogeological cross-section of the Plitvice Lakes water resource system (Biondić et al., 2010).

to this lake (Srdoč et al., 1985). Good correlation of data obtained by ^{14}C dating of active tufa, lake sediments and peat deposit confirms that the formation of Plitvice Lakes, i.e., the beginning of growth of recent tufa barriers, coincided with global warming during the Holocene.

3.1.2. Geology and hydrogeology of the Plitvice Lakes

Nikola Markić, Anđelko Novosel, Oleg Mandic

The territory of the Plitvice Lakes National park and surrounding area is part of the External Dinarides marked by stable carbonate-platform deposition in the Mesozoic (Fig. 5). Current geomorphological features of the area resulted from its complex regional tectonic and climatic history. The tectonic processes, which formed the neighboring mountain ranges, such as Velebit, Velika and Mala Kapela, and Lička Plješivica, defined the current distribution of different porosity complexes in the area. Today's relief appearance, marked by an intensive regional karstification, was highly affected through extreme climate conditions in the Pleistocene.

The present region dominantly consists of Upper Triassic to Upper Cretaceous carbonate

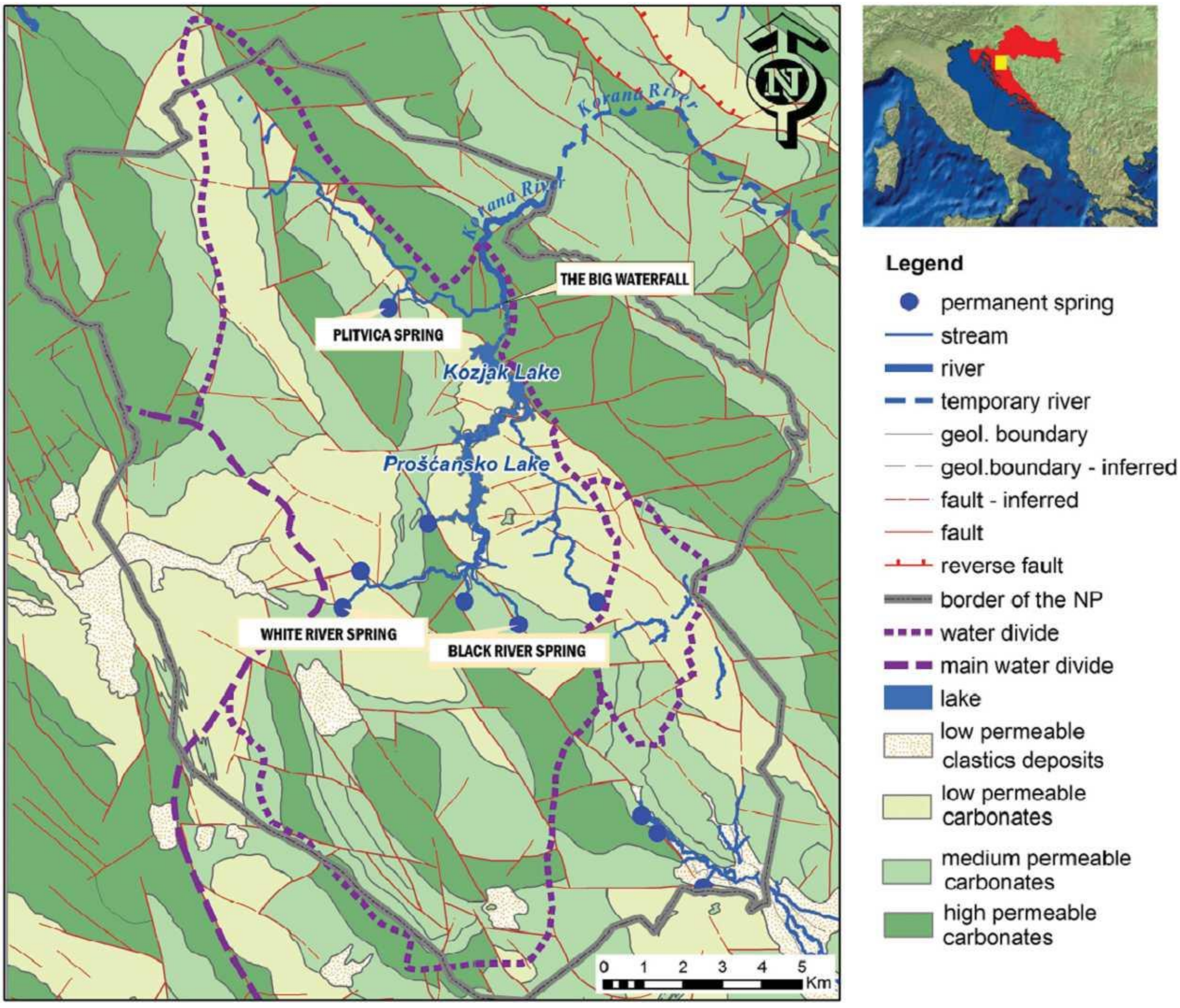


Fig. 9. Schematic hydrogeological map of the Plitvice Lakes catchment area (Biondić et al., 2010).

rocks (Fig. 5b). These limestones and dolomites show numerous varieties visible in relief differences. Besides, their composition controls the water capture on the surface. In the area of the national park, the karstification particularly influenced the Jurassic limestone, therefore strongly contrasting the appearance of resistant, low porous Upper Triassic dolomite. In addition, the canyon incisions are restricted to the porous Cretaceous limestone, whereas the hydrogeological features of the dolomite rocks gained the lake creation.

Quaternary rocks comprise the tufa barriers of the Plitvice Lakes together with the deluvial and alluvial gravel, sand and clay deposits in depressions and river valleys. The carbonate-dominated lithology strongly influences the chemical composition of the subterranean karst-water, communicating with the surface by permanent in- and outflow processes. Such chemistry facilitated the settlement of plants controlling the origin and growth of calcareous tufa barriers in the lake water.

The poorly permeable Triassic dolomite, essential for the emergence and formation of the so-called Upper Lakes, represents the oldest carbonate complex in the region (Fig. 5 and 9). In particular, it enabled the surface water accumulation from today's Lake Prošćan [Prošćansko jezero], through Ciginovac, Galovac and Gradin [Gradinsko jezero] lakes up to the largest Lake Kozjak (Fig. 5a and 8). The dolomite, that emerged by tectonic forces, acts as a barrier to the water-discharge from the Mt. Mala Kapela northeastern slopes, representing itself a large limestone complex.

The aquatorium of Upper Lakes is fed by the rivers Bijela Rijeka and Crna Rijeka (Fig. 9), by the streams from existing subterranean water accumulations, by the superficial water of melted snow, and finally by the numerous small permanent springs. After the groundwater discharge, the flow takes place up to the longitudinal fault zone on the north-eastern margin of Lake Kozjak without any losses. After this line, a gradual water-escape from the system occasionally results in complete desiccation of the Korana River, about 1-km-downstream from the Plitvice Lakes.

Almost the entire Plitvice Lakes catchment area is located within the National Park territory. Positioned close to the border of the Adriatic Sea catchment, the Plitvice Lakes still belong to the Black Sea catchment area.

3.2. POINT 2. LAKE VRANA – Holocene climate archive

Nikolina Ilijanić, Slobodan Miko

Locality:	Lake Vrana [Vransko jezero]
WGS84 coordinates:	43.849984° N, 15.629439° E
Age:	Recent

Fig. 10. Panorama photograph of the Lake Vrana (green) from viewpoint Kamenjak (290 m asl); note the Adriatic Sea water front (blue) in the back behind the land barrier.

Introduction

Lake Vrana (Fig. 10 and 11) is the largest Croatian freshwater lake, with a surface area of 30.5 km^2, but of very shallow depth (1.5–2 m in average). It extends 13.6 km in the NW-SE direction along the Eastern Adriatic coast, central Mediterranean. This is a crypto-depression in the immediate vicinity of the sea communicating with it through a thin strip of karstified limestone and through the artificial canal Prosika built in the 18th century (salinity ranges between 0.7–1.2‰). For that reason, the lake water becomes saline in extremely dry periods, when the salinity increases several times in relation to the average concentrations (Rubinić & Katalinić, 2014), endangering the lake ecosystem protected as a nature park (declared in 1999). Promoted by the potential of the undisturbed sedimentary sequence from the lake bottom to identify past changes in and around the lake and characterize depositional environment, coring campaigns were carried out in 2012 and 2015. The sedimentary record of the Lake Vrana coupled with Pirovac Bay allowed obtaining a long and continuous sequence that covers the Late Pleistocene–Holocene and gives evidence for Holocene climate change in central Mediterranean and Adriatic sea level rise.

Lake Vrana is a karst polje filled with water (Fig. 11). Since it is the lowest point of the Ravni Kotari region, it collects surface waters of almost half of the area. It has a large orographic catchment of 490 km^2. The lake is supplied by surface waters-channels from Vrana polje, supplied by discharge from freshwater and brackish

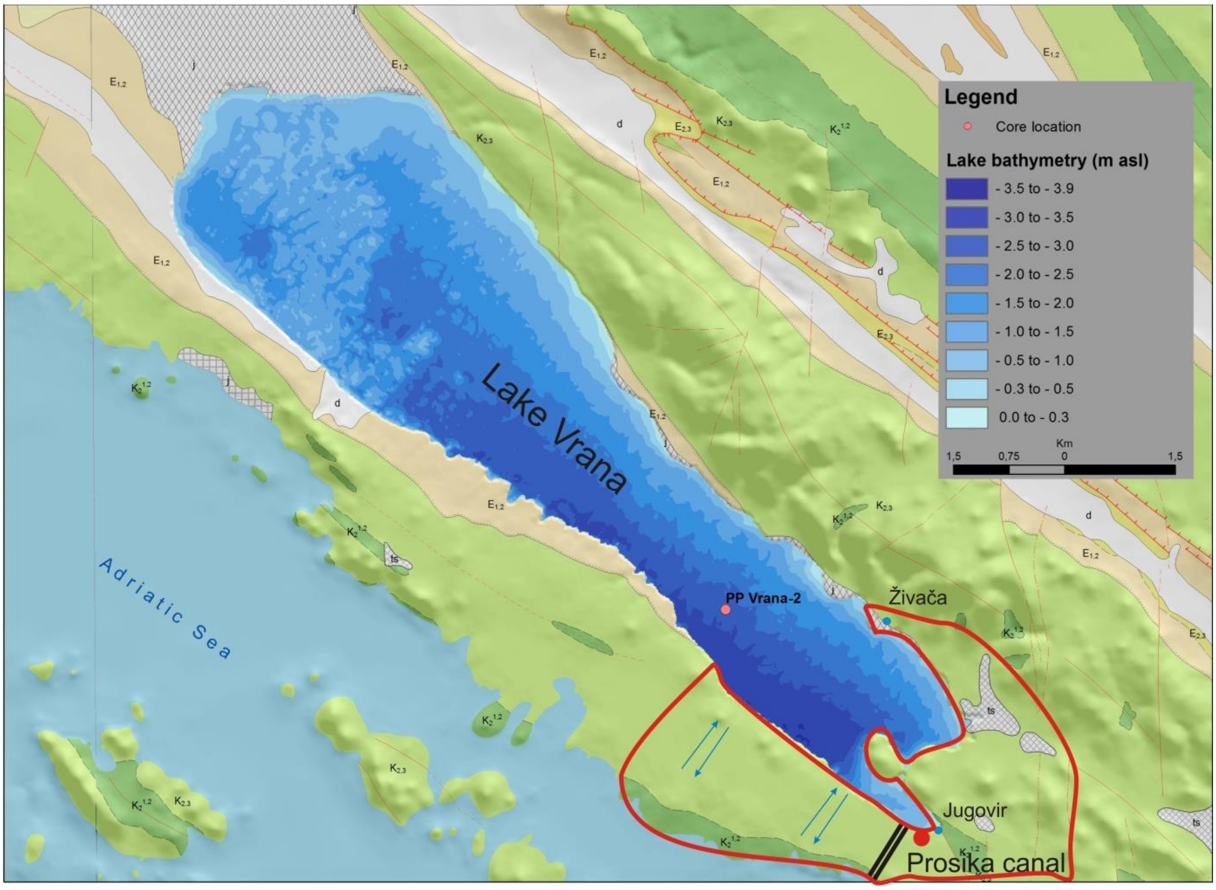


Fig. 11. Bathymetry of the Lake Vrana (Rubinić, 2014) and geological map of the area. Legend: K21,2-limestones and dolomites, K23-rudist limestones, E1,2-foraminifera limestones, E2,3-flisch, ts-terra rossa, j-lake sediments. Red line is boundary of sea water intrusion (Fritz, 1983). PP Vrana-2: 11 m long sediment core (Ilijanić, 2014).

springs along Vrana polje and around the lake. There isn't a strong continuous inflow, so water regime is directly dependent on the rainfall. Influence of the sea water was determined through the karstified limestone ridge (800 to 2500 m wide) in the SW part and through artificial canal Prosika built in the 18th century (length of ~1 km). Also, there are brackish springs in SW part (Kutijin stan, Vrbica) and SE part of the Vrana polje (Ošac, Modro jezero, Kotlić, Begovača, Mali Stabanj), spring Jugovir in the SW part of the lake near canal Prosika and Živača in the SE part of the lake, which prove a strong connection of the sea and lake through the underground (Fritz, 1983). According to previous studies made by Fritz (1983), the thickness of lacustrine sediments is uniform throughout the lake. Detailed sediment composition is determined in the cores from the central part of the lake, where the construction of a barrier was planned to produce two independent water reservoirs – the SE part under marine influence and the NW part as a pure freshwater reservoir (Fritz, 1976). The maximum thickness of unconsolidated sediments is 29 m. They superpose the Eocene flysch deposits. Based on the exploration well constructed on the NW shoreline, the lake sediment thickness proportionally increases to the terrain slope. The direction of the surface water flow in the Quaternary was the same as today. Fritz (1984) correlated the complete Lake Vrana infill with the Holocene. He linked the existence of the lake to the present sea level preventing its waters from running out into the sea through the karstified carbonate ridge around Prosika.

The wider area of Lake Vrana and Vrana polje is composed of Cretaceous (rudist) and Eocene (foraminifera) limestones, Cretaceous dolomites and Eocene flysch, mainly marls. The Cretaceous and Paleogene (Eocene) rocks are covered with Quaternary sediments (Fig. 11). The latter are predominantly lake sediments covering the most of the Vrana polje and continuing laterally under the lake. Recent paleolimnological research (Ilijanić, 2014) showed that only the upper 1/3 of total 29 m lake sediments (approx. 10 m) belong to the Holocene.

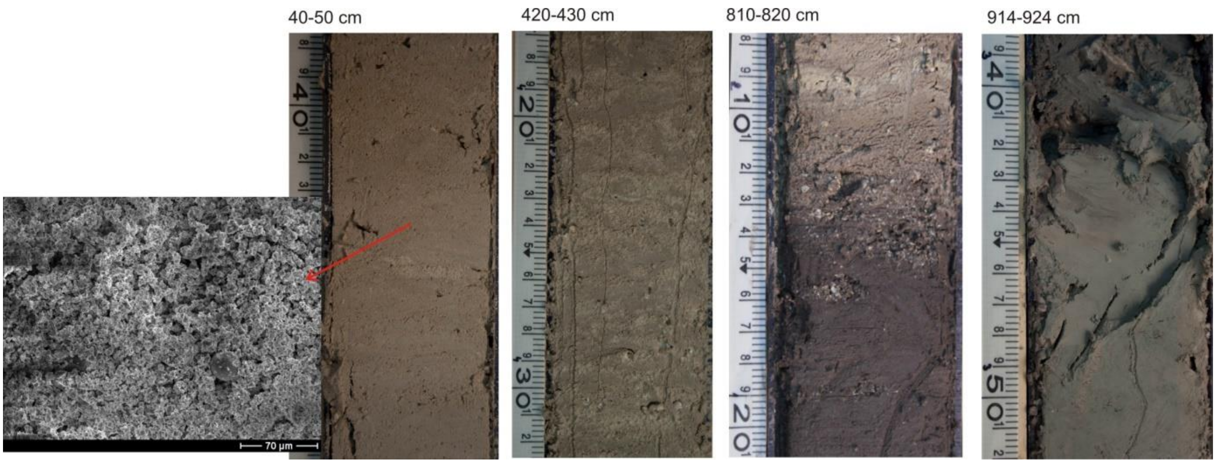


Fig. 12. Core photograph of sedimentary facies: 40–50 cm homogenous carbonate mud (lake marl) – SEM image; 420–430 cm banded carbonate silts and muds; 810–820 cm transition from light grey to dark grey sediment; 914–924 cm clayey greenish-grey sediment.

Paleoenvironmental history

One 11-m-long sediment core was drilled in 2012 (Fig. 12). Clay minerals below 8.1-m-depth show composition of flysch or loess sediments from the catchment, dominated by smectite, while upper sediments contain small amounts of clay minerals, which are presented by hydroxyl-interlayered vermiculite, kaolinite and illite, and they originate from the terra rossa of the surrounding soils. Based on the succession captured by the core, we carried out a paleoenvironmental reconstruction of Lake Vrana at centennial resolution (Fig. 13):

11.0–8.6 m. – The oldest, still undated part of the core indicates a period of pond or wetland deposition characterized by carbonates bearing an increased amount of siliciclastic material. Clasts with diameters of 0.5–1 cm suggest the presence of high-energy inflow linked with erosion processes.

8.6–8.1 m. – Transitional phase to the lake is characterized by formation of dark organic rich sediment, which is evident in the interval from 8.6 to 8.1 m.

9.1–6.1 ka BP. – The lake as we know it today was formed at around 9.1 ka BP (8.1 m depth), when the sea level rose and the water from the lake could no longer run through the karstified underground in an approximately 1-km-long zone on the SE part of the lake. Lake sediments are characterized by high amounts of carbonates.

6.1–3.8 ka BP. – After **6.1** ka BP siliciclastic detritus gradually increases due to human settlement in the catchment accompanied by deforestation, increasing soil erosion and input of the siliciclastic material. Also, the pollen analysis showed assemblage of typical Mediterranean holm-oak vegetation from 6.1 ka BP onwards. The marine influence on Lake Vrana sediments is likely visible after 6.1 ka BP, by increased proportions of magnesium (Mg) and strontium (Sr) and the presence of aragonite.

3.8–0.0 ka BP. – The present lake water conditions (alternating seasonal changes in the salinity, freshwater-brackish) were established at 3.8 ka BP. Deposition of homogenous carbonate mud (lake marl) started at 3 ka BP. Parts of the lake sediments are influenced by sea intrusion so that lake freshwater partly lies on more saline pore-water in the lake sediments.

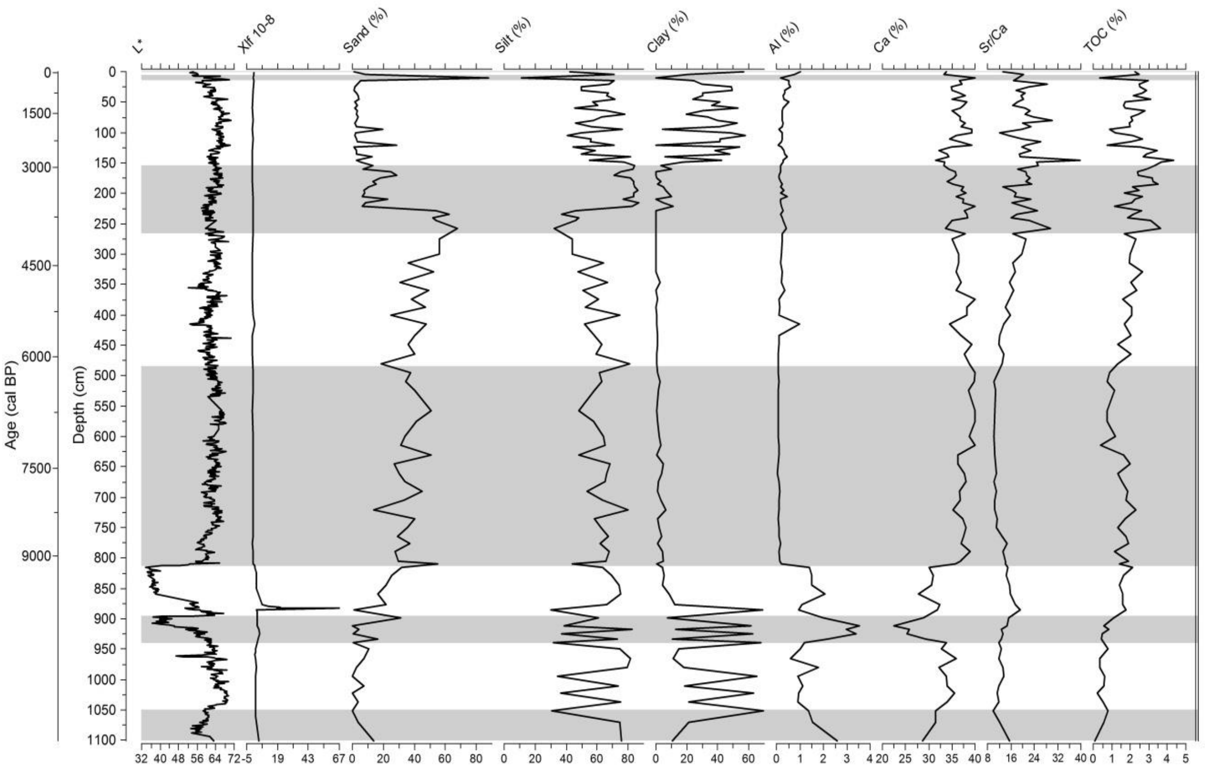


Fig. 13. Paleoenvironmental reconstruction through the Holocene of the sediment core (PP Vrana-2) from Lake Vrana based on geochemical and sedimentological proxies.

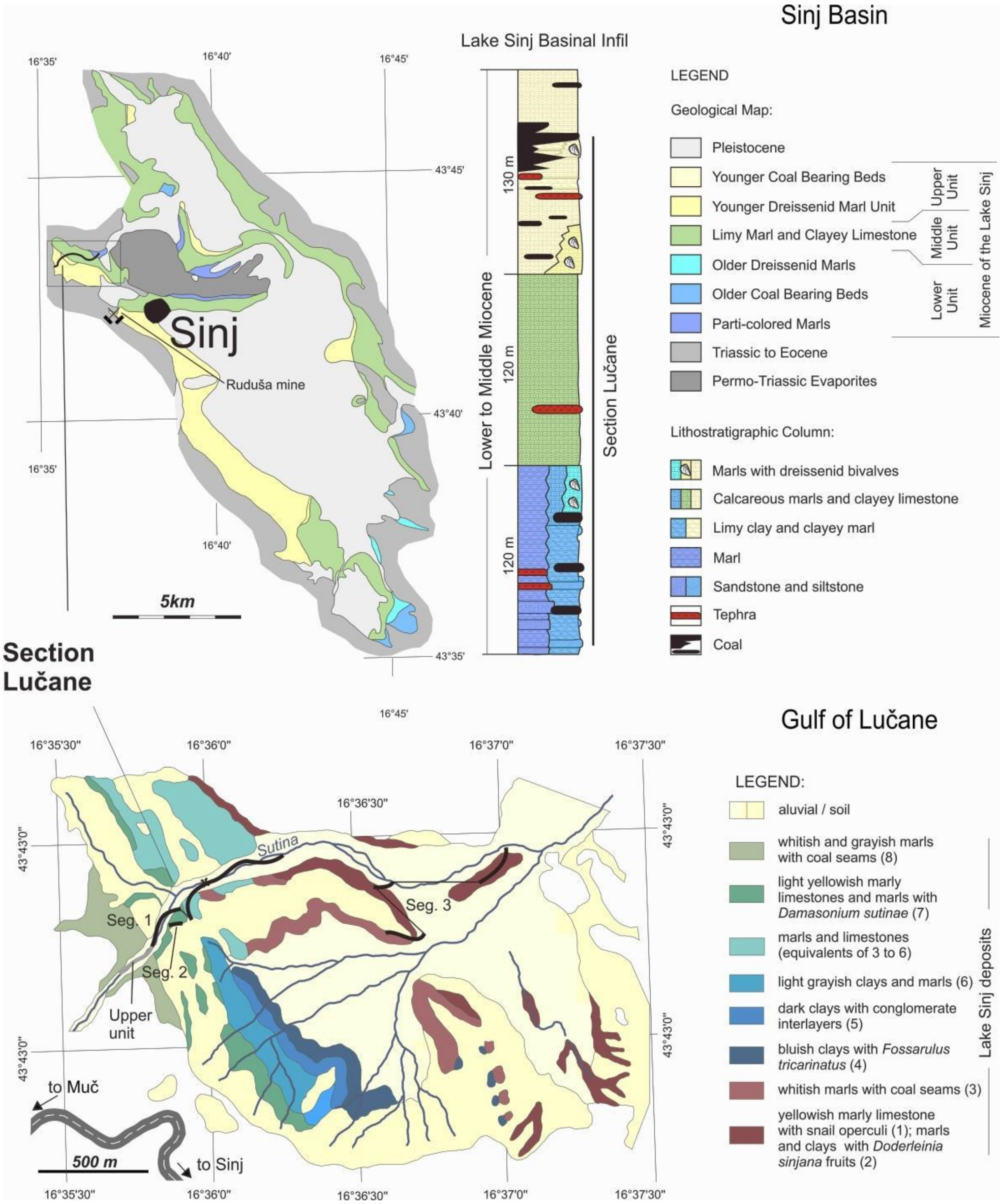


Fig. 14. Geological map of the Sinj basin with schematic lithological section through its infill (above) accompanied by detail geological map of the Lučane embayment (below) (modified after De Leeuw et al., 2010).

3.3. Lake Sinj – 18–15 Ma continuous freshwater lake succession[1]

The Sinj Basin (Fig. 14), with a surface area of ~140 km^2, is located in the hinterland of Split in SE Croatia. Its sigmoidal plan-view shape suggests an origin as a strike-slip basin, although

[1] The present chapter is based on Mandic et al. (2012b).

the shape can as well be an artefact of post-depositional wrench-fault tectonics related to the formation of the South Adriatic strike-slip basin. The basin formed in a karst environment. Whereas the pre-Neogene basement is dominated by Mesozoic platform carbonates along the basin margins, extensive Permian evaporite deposits with a direct sedimentary contact with the basal lake sediments occur beneath the basin. Doming of those evaporites decreased subsidence rates within the basin. The presence of steep hinterland topography is pinpointed by massive breccia intercalations into marginal lake deposits.

The basin-fill succession consists of freshwater lacustrine limestones and marls, more than 500 m thick, with the lignite intercalations and large mammal remains in the uppermost part marking the ultimate shallowing of the basin. The late depositional phase is characterized by a cyclic architecture attributed to orbitally-forced regional climatic fluctuations. Based on the main range of $\delta^{18}O$ values between -2 and -6 typical for freshwater settings, Harzhauser et al. (2012) interpret Lake Sinj as a pure freshwater system. The lake existence duration is estimated at about 3 Ma, between ~18 and ~15 Ma BP, correlating

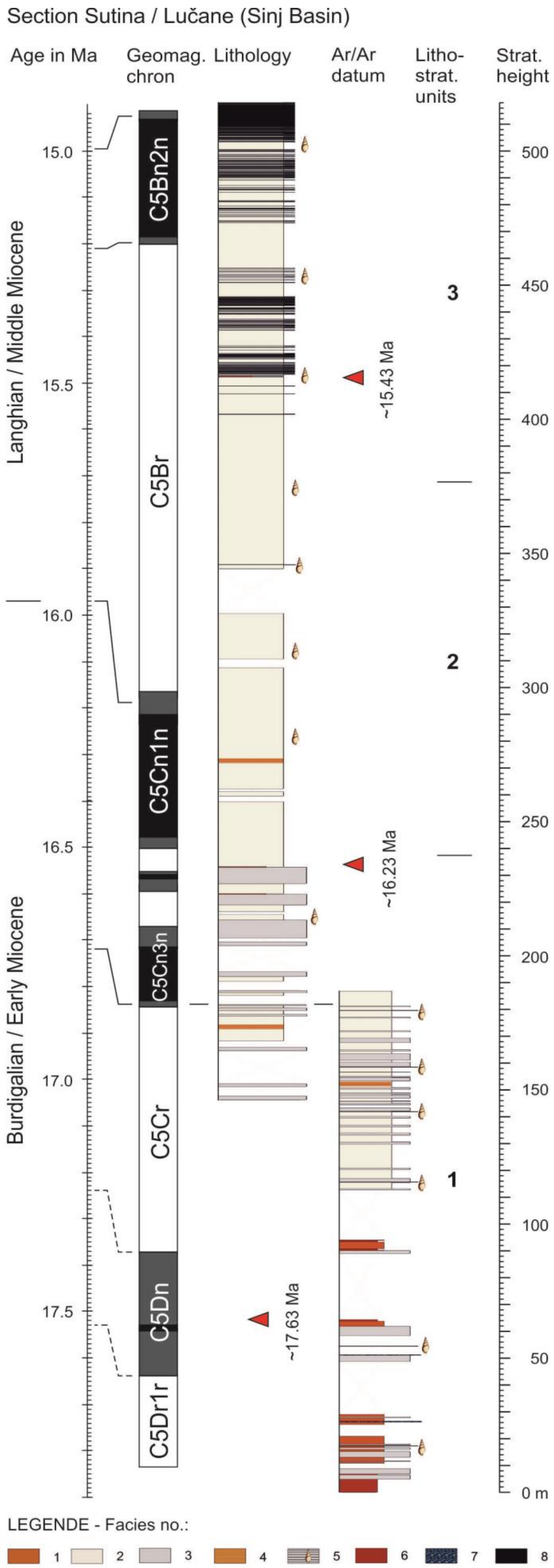


Fig. 15. Age model based of Ar/Ar geochronology and magnetostratigraphic results by De Leeuw et al. (2010) and facies distribution in the Lučane section by Vranjković (2011). Legend: 1 – micrite, 2 – biomicrite, 3 – calcisiltite, 4 – laminated micrite, 5 – shell accumulation, 6 – tephra, 7 – breccia and conglomerate, 8 – coal.

largely with the Miocene Climatic Optimum (De Leeuw et al., 2010). This ancient lacustrine basin is well known since the Darwin time for its strictly endemic mollusc fauna, serving as a textbook example of adaptive fauna radiation (Neubauer et al., 2011).

3.3.1. POINT 3. SUTINA – Paleoenvironments of the lacustrine carbonate ramp

Locality:	Sutina Brook / Lučane
WGS84 coordinates:	43.723310° N, 16.594943° E
Age:	Burdigalian-Langhian (Early–Middle Miocene)

Lučane section is exposed along the Sutina Creek W of Sinj. Located at the western margin of the Sinj basin it allows the study of the complete infill succession (Fig. 14 and 15). Already described by Kerner (1905) it was currently a subject of multiproxy investigation campaign providing new data on stratigraphy, depositional history, palaeobiology, and palaeoclimatology (Jiménez-Moreno et al., 2008; Mandic et al., 2009; De Leeuw et al., 2010; Neubauer et al., 2011). It comprises two partially overlapping sections, representing together a continuous, around 500-m-thick record of lacustrine deposits. Magnetostratigraphic pattern together with facies correspondence prove their precise correlation. The uppermost beds include coal seam intercalations, whereas the basal and the middle part of the infill show exclusively carbonate rocks. The whole succession is intercalated occasionally by volcanic ash layers. Magnetostratigraphic study together with Ar/Ar dating of ash layer provided precise age model for the section proving its continuous sedimentation within a 3 myr period from the latest Early to the earliest Middle Miocene (Burdigalian to Langhian) (De Leeuw et al., 2010).

Sedimentological analysis and petrography made it possible to distinguish nine main facies types in the Sutina succession (Vranjković, 2011). Five facies are carbonate in origin in addition to the coal, breccia and tephra facies: **Micrite**. – Consists of very fine-grained lime mudstones. The deposition of the fine-grained components of lacustrine carbonates is dominantly induced by the photosynthetic activity of macrophytes and microphytes. It belongs to deeper and protected lake parts (Fig. 16a). **Biomicrite**. – Mudstones and wackestones containing degraded, and/or carbonized plant remains, plant encrustations, most commonly related to the stems of the submerged Charophytes and fruits and stems of *Damasonium* plant. Rooted submerged macrophytes indicate a vegetated littoral environment of the carbonate lake (Fig. 16b). **Calcisiltite**. – Accumulation out of sediment-laden density currents (hyperpycnal flow; underflow) following expanded floods (Fig. 16c). **Laminated micrite**. – Alternation of thin micritic laminae, and micrite to microsparite laminae containing Charophytes plant encrustations (Fig. 16e). **Coquina**. – The association of gastropods, bivalves, ostracods, plant encrustations and predominantly oxidized macrophyte remains suggests a calm, very shallow freshwater environment of a carbonate lake interrupted by higher energy events probably related to storms and earthquakes. **Tephra**. – Pyroclastic fall of volcanic ash derived from distant eruptions (Fig. 16d). **Breccia**. – Olistoliths and debris flow deposits transported basinwards by gravity processes at the margin of the lake. **Coal**. – Deposition of allochthonous phytoclasts took place in small delta topset at the mouth of a creek draining a vegetated marsh while 4-m-thick coal seam was accumulated in a swamp–marsh complex.

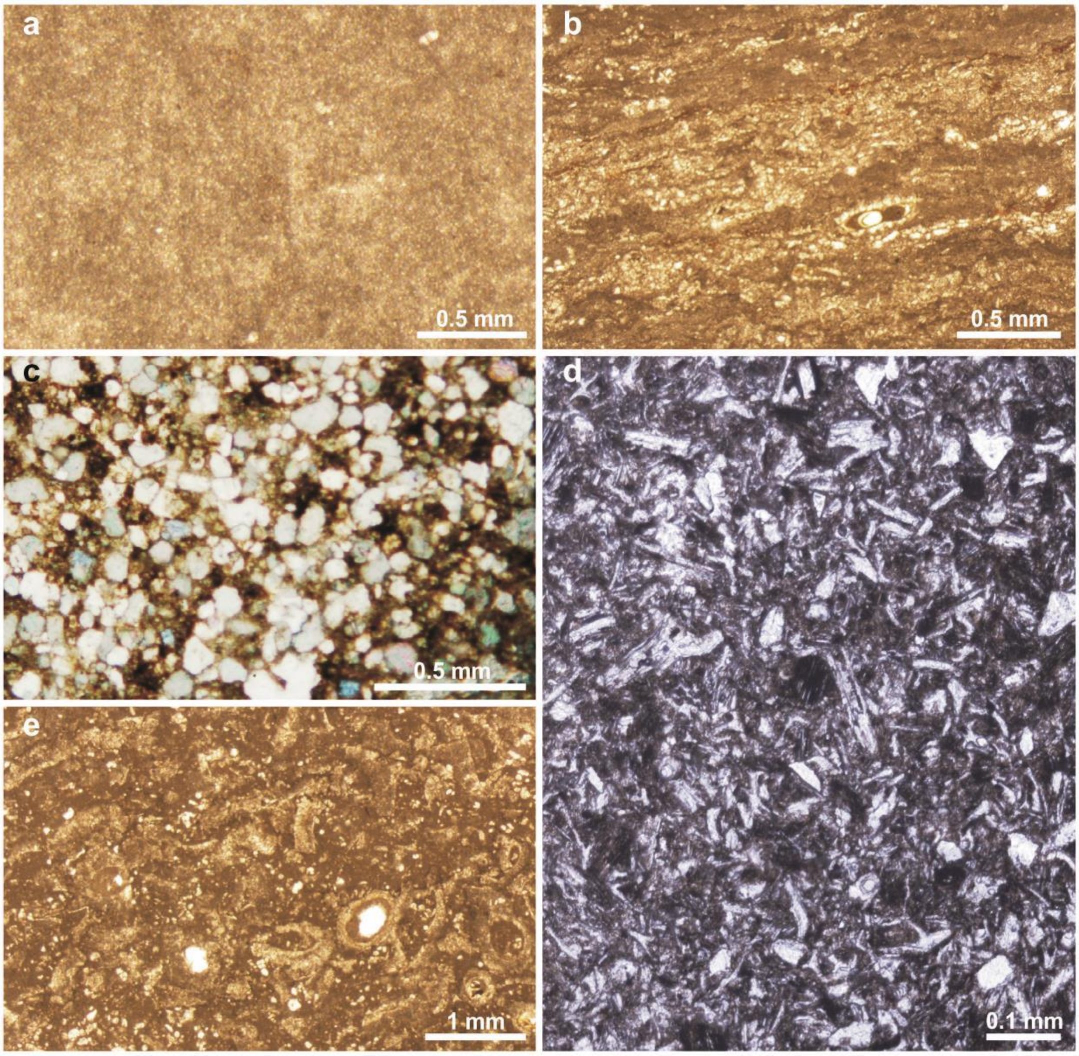


Fig. 16. Microfacies types recognized at Ostrožac section by Vranjković (2011): a – micrite, b – laminated micrite with completely preserved, compacted characean remains, c – calcisiltite made of idiomorphic, rhomboedral calcite crystals, d – diagenetically alternated vitroclastic tuff, e – biomicrite with characean remains.

The ordinance of those facies types in the section proves a continuous record of a shallowing upward sequence for the Sinj basin infill. The sequence starts with basinal micrites and ends with a 4-m-thick peaty coal. Hence the dominant limestone deposition marks the lower and the middle part of the succession. Those limestones are usually light, thin to medium bedded, and commonly soft and porous. The $CaCO_3$ content varies between 82% and 99%, and it primarily refers to the calcite. Depositional environment changes in the uppermost part of the succession due to gradual shallowing of the lake and generally more humid climate (Jiménez-Moreno et al., 2008). The changing conditions resulted into cyclic appearance of coal seams alternating with limestone. That alternation was triggered by a short-term, orbitally forced cyclic fluctuation of humid and dry periods. That phase, characterized by stable hard-water lake conditions, witnessed a strong diversification of the ecosystem followed by a significant morphospace increase in melanopsid and hydrobiid snails (Neubauer et al., 2011).

The paleoenvironmental analysis combining sedimentology, microfacies analysis, coal petrology and palaeoecology of mollusks and plant remains by Mandic et al. (2009), inferred a variety of environments for that part of the section including (1) littoral below the fair weather wave base, (2) littoral above the fair weather wave base, (3) infralittoral with vegetated areas dominated by aquatic, perennial plants, (4) low supralittoral to upper infralittoral with starfruit meadows, (5) areas covered by cyanobacterial mats, (6) carbonate marshes, (7) peripheral swamps, (8) stream catchments areas and vegetated marches, which were (9) more or (10) less frequently flooded. The latter environment was inhabited by large land mammals related to elephants and rhinoceroses.

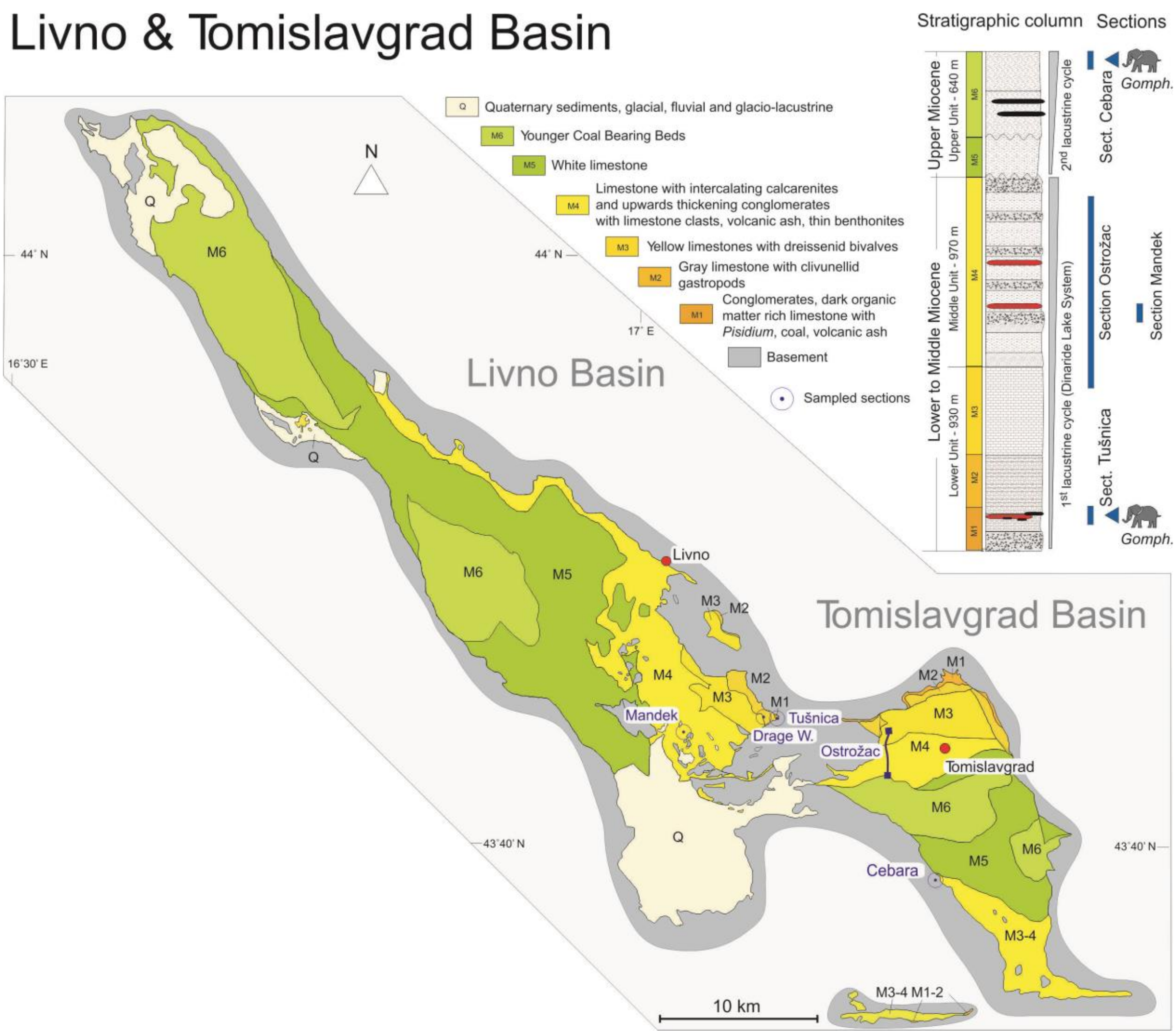


Fig. 17. Generalized stratigraphic column and geological map of Livno and Tomislavgrad Basins with indicated positions of excursion sites (modified after De Leeuw et al., 2011).

3.4. Lake Livno-Tomislavgrad – the second largest Dinarides basin[2]

Oleg Mandic, Urulsa B. Göhlich, Arjan de Leeuw, Hazim Hrvatović

The Livno and Tomislavgrad (=Duvno) basins (Fig. 17) are located in the SW Bosnia and Herzegovina. They represent two different, tectonically-disconnected karst poljes developed at

[2] The present chapter is based on Mandic et al. (2012b and 2013).

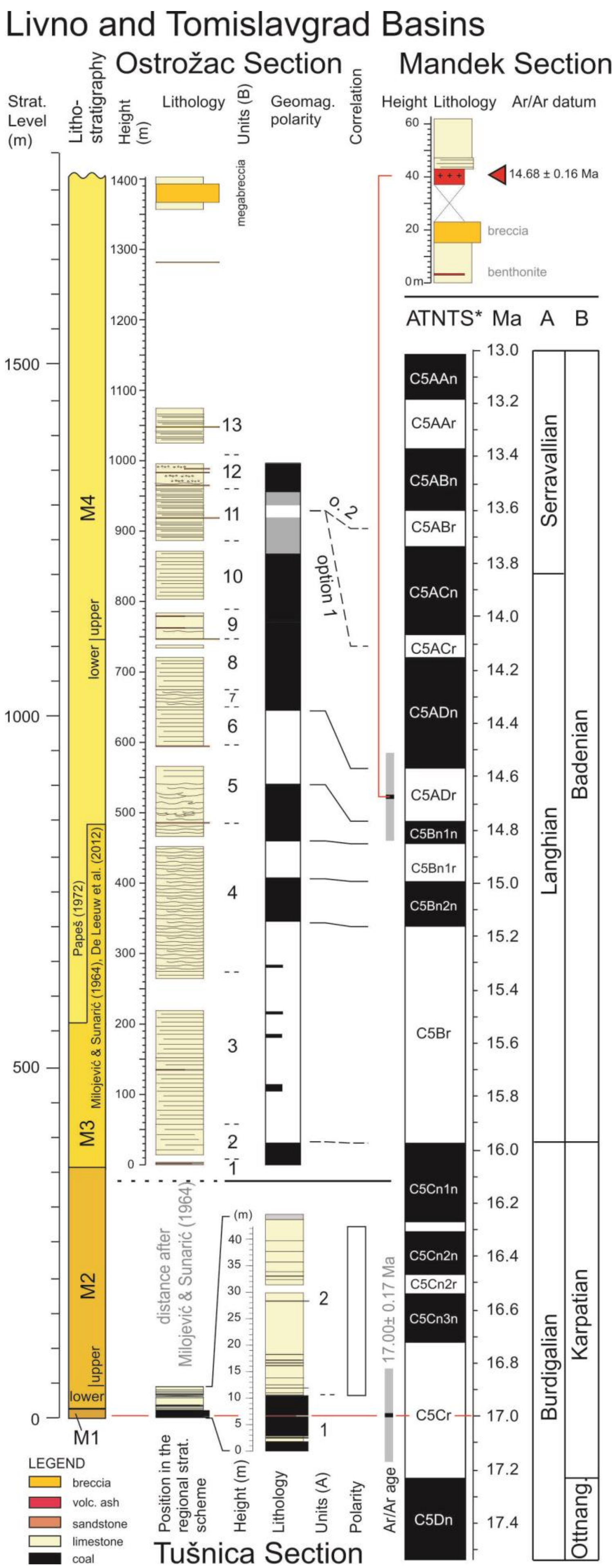


Fig. 18. Lithostratigraphy and lithology (see text for explanation) of three sections (Tušnica, Mandek and Ostrožac) representing the main (DLS related) cycle of the basinal infill in Livno and Tomislavgrad Basins accompanied by magnetostratigraphic and geochronologic results by De Leeuw et al. (2011). ATNTS. Astronomically Tuned Neogene Time Scale by Lourens

about 1000 m a.s.l. During the DLS deposition, they formed a single basin with an area of about 590 km^2, the second largest intramontane basin in the Dinarides after the Sarajevo-Zenica Basin.

The basin-fill succession is more than 2000 m thick, comprising two depositional sequences bounded by an angular unconformity. The lower sequence is ~1700 m thick, composed of Early to Middle Miocene freshwater deposits that commence with ~10-m-thick coal bed bearing elephant remains and pass upwards into a monotonous, limestone-dominated lacustrine succession. At a stratigraphic height of ~850 m the first intercalation of margin-derived debris-flow deposits occurs. The successive coarse-clastic intercalations are thickening and coarsening upwards, including up to 10-m-thick volcaniclastic beds. The succession culminates in megabreccia bed, ~26 m thick, near the top, which suggests strongly that active tectonics was the main cause for the cessation of deposition in the large original basin.

The basin subsequently became split into two parts and the second cycle of sedimentation followed above an angular unconformity overlain by lacustrine claystones passing upwards into lignite-dominated deposits. The Holocene witnessed an expansion of peat deposition. The Livno Basin, with an area of 410 km^2, is the largest karst peatland basin of the Dinarides.

3.4.1. POINT 4. TUŠNICA – The lake formation – brown coal and open lake limestone

Locality: Tušnica
WGS84 coordinates: 43.741771° N, 17.086560° E
Age: 17.0 Ma (late Burdigalian, Early Miocene)

The 45-m-thick Tušnica section is located in the Drage opencast coalmine situated at the foot of the Tušnica Mountain near the eastern boundary of the Livno Basin (Fig. 17, 18 and 19). It was logged along the SSE–NNW striking wall of the quarry in 2007.

The lower 10.5 m of the section are dominated by coal subdivided in three seams. The lower two seams are separated by a ~1-m-thick organic material rich sandy limestone interval with lymnaeid snails and plant remains. A volcanic ash bed separates the middle and the upper coal seam (Fig. 19a). The ash layer is ~20 cm thick, laterally continuous, grayish-whitish in color, and consists of sandy and silty clay with dark mica flakes. The transition from coal to ash and vice versa is very sharp. A transitional zone with clayey and coaly interlayers starts above the upper coal seam. It is followed by dominantly dark brown and grayish well bedded limestones (Fig. 19b) rich in organic matter that dominate the remaining 30 m of the section. These beds belong to interval M2 (Milojević & Sunarić, 1964) and contain scattered fish and plant remains.

In the main coal seam, remains of *Gomphoterium angustidens* were found and Malez & Slišković (1976) therefore considered it to be of Middle Miocene age. The same level was, in contrast, thought to pertain to the upper part of the Early Miocene based on its pollen content (Pantić, 1961). ^{40}Ar/^{39}Ar measurements reveal that the Tušnica volcanic ash, found in between the coal seams at the base of the basin infill, is 17.0 ± 0.17 Ma old (De Leeuw et al., 2011). Milojević & Sunarić (1964) described coal seams and organic matter rich limestone beds of Tušnica type from the abandoned Vučipolje coal mine at 1 km lateral distance from the base of the Ostrožac section. They apparently belong to the same coal bed disturbed tectonically due to rise of the Tušnica mountain block.

Fig. 19. Outcrops in the Tušnica open cast coal mine. a – coal interval intercalated with the Ar/Ar dated white ash layer showing remain of an old underground work, b – open lake profundal limestone series in top of the coal.

The coals exposed in the Tušnica and Vučipolje testify of swamp conditions during the initial phase of basin formation. Coal formation is terminated when the basin floods and a long-lived lake establishes itself. As the lake deepened suboxic bottom conditions developed, as indicated by the organic matter rich limestones of the Tušnica mine and overlying clivunellid limestones (Unit M2). Although the clivunellid bearing interval M2 is in general badly exposed in the Livno as well as the Tomislavgrad basin, fragments crop out at Drage West site located about 300 m W of the main entrance to the Tušnica coalmine (N43°44’29.0’’ E17°04’55.6’’).

The little quarry displays there light and dark brownish bedded limestones with endemic deep water gastropod *Clivunella katzeri*, small dreissenid bivalves and plant remains such as *Taxodium*-related *Glyptostrobus europaeus* and pertains to the upper part of interval M2. The clivunellid limestone interval is about 300 m thick (Milojević & Sunarić, 1964) and reaches up to the base of the Ostrožac section (De Leeuw et al., 2011).

3.4.2. POINT 5. MANDEK – Massive Middle Miocene volcanic ash fall

Locality: Mandek
WGS84 coordinates: 43. 730639° N, 17. 022426° E
Age: Middle Langhian (Middle Miocene)

The Mandek section is located 10 km south of Livno, just E of the Mandek village, on the shore of artificial lake Mandek (Fig. 17, 18 and 20) and belongs to stratigraphic unit M4. The section was logged from North to South along the gulley of the Vojvodinac brook which runs normal to the bedding. The outcrop was already mentioned by Luburić (1963).

The section starts with about 15 m of lacustrine limestone starting by 30 cm thick bentonitic tephra layer. A prominent 8-m-thick breccia horizon follows, topped by about 14 m interval of presumable lacustrine limestone completely covered by vegetation. About 6-m-thick coarse grained volcanic ash, weakly lithified and whitish in colour follows on top. Finally upsection

Fig. 20. Artificial Lake Mandek section: a – (from left to right) above the lake, a thick breccia interval (grayish brown) forms a step in the landscape, the superposing lacustrine deposits (orange) bear in its lower part thick ash fall layer (small whitish area), b – thick bentonite succession representing the diagenetically alternated volcanic ash fall sediments (whitish gray) overlain by a lacustrine marl (orange).

the ash grades into lacustrine carbonates, dominated by fine-bedded limestone.

Ash horizons of the Lake Mandek section are both indicated on the geological map by Papeš (1972). A sample of the 6-m-thick main ash layer was collected in a small pit (Fig. 20b) about 100 m E of the gulley. The lowermost tephra analyzed by Luburić (1963) represent vitroclastic volcanic ash composed mostly by volcanic glass (~80%) calcite (~18.5%) quartz (~1%) and biotiote (~0.5%). The glass particles are elongated, angulated and filled by gas inclusions. It is well sorted fine sand to silt.

Absence of larger grains, together with angular grain shape point to their transport from larger distance. That coincides with the fact that no Miocene volcanic rocks have been detected in radius of at least 100 km. The extreme depth of the main ash horizon however provides mystery about the transportation of such a sediment quantity from the long distance.

$^{40}Ar/^{39}Ar$ dating on feldspar crystals found in the main tephra bed of Mandek delivered an age of 14.68 ± 0.16 Ma providing its correlation with the middle Langhian of the standard geological scale and lower Badenian of the Central Paratethys scale (Middle Miocene). Considering its association with the mega-breccia beds this datum allows the dating of important tectonic event for the Dinarides. This event marks the start of the disintegration of the Dinaride Lake System due to extensive relief building and exhumation and was recorded throughout the Dinarides such as Zenica–Sarajevo basin where massive fluvial conglomerates marks the corresponding event (Hrvatović, 2006). Event coincides with the initial marine flooding of the southern Pannonian Basin (Ćorić et al., 2009; Mandic et al., 2012) and could reflect the compensation of the extensional tectonics therein (De Leeuw et al., 2012). Indeed the new magnetostratigraphic and geochronologic data could prove the complete cessation of lacustrine sedimentation synchronous with these movements for the smaller Dinaride basins such are Gacko (Mandic et al., 2011) or Sinj Basin (De Leeuw et al., 2010).

3.4.3. POINT 6. OSTROŽAC – Megabreccia – end of the main lacustrine cycle

Locality:	Ostražac
WGS84 coordinates:	43.709919° N, 17.182881° E
Age:	Late Langhian (Middle Miocene)

The 1700-m-thick Ostrožac section (Fig. 17, 18 and 21) is situated near the NW margin of the Tomislavgrad basin. It follows the Ostrožac brook, running down the eastern slope of the Tušnica Mountain, for about 2 km. The brook strikes N–S, subnormal to the bedding that is ~150°/30° in the stratigraphically lower part of the section and ~170°/55° in the upper part of the section. The base (N43°43’40.5’’ E17°10’59.6’’) is located about 150 m N of the place where the path to Eminovo Selo meets the road to the abandoned Vučipolje coal mine. The top (N43°43’40.5’’ E17°10’59.6’’) reaches the village of Josanica where a large megabreccia crops out just north of a large curve in the main road to Tomislavgrad. The section comprises 13 lithostratigraphic units ordered below from the base to the top.

Unit **1** (8.2 m) is made by light colored lacustrine limestones intercalated by clay layers and volcanic ash beds. These already pertain to stratigraphic interval M3. The well bedded limestone, light beige, gray, yellowish or brownish in color, is dominantly fine-grained, although some coarser-grained intervals are present as well. The beds are around 10 cm thick.

The intercalations are at maximum 20 cm thick and are predominantly found in the lower part of the unit. Unit **2** (49.6 m) is an interval of brownish limestone with roots of water plants (Fig. 21a) follows. The limestone is somewhat softer than before. Unit **3** (215.9 m) comprise thick interval of planar bedded limestones (Fig. 21b) with a bed thickness of 5–20 cm. In this interval, plant remains disappear completely. A single bentonite layer appears in its middle part

Unit **4** (211.2 m) shows ripple bedded limestones (Fig. 21c, d) with only few plain bedded intervals. The ripples are commonly about 1 cm thick and there is about 10 cm of distance between consecutive crests. Some intercalations of plant remains occur in association with horizons of coarser grained limestone. Unit **5** (111.2 m) starts with an about 5-cm-thick calcarenite layer situated within laminated limestones with plant-stems preserved on its bedding plains. Ripple and trough cross beds characterize this unit. Slump and channel structures occur in combination with more calcarenite intercalations. These are red or brownish in colour and consist of badly sorted, angular lithoclasts. Unit **6** (54.0 m) is dominated by bedded limestone (Fig. 21e), Unit **7** (24.4 m) by ripple bedded limestone, whereas Unit **8** (72.2 m) represents a thinning upward succession of bedded limestone.

Unit **9** (42.0 m) dominantly composed of alternating cross-bedded and massive limestones starts with the initial breccia layer of the Ostrožac succession. The breccia is about 2 m thick and consists of angular, badly sorted carbonate lithoclasts from basement rocks. Two, up to 0.5 thick, volcanic ash layers occur in this unit as well. Both the tephra and breccia beds are laterally continuous and can be traced for at least several 100 m. The breccia thickens in westward direction. Unit **10** (97.2 m) of thick bedded limestones is followed by Unit **11** comprising the thin bedded limestone with intercalated calcarenite layers (Fig. 21f) and inversely graded breccias (Fig. 21g). Unit **12** (48.3 m) displays a unique carbonate facies with frequent micro-breccia intercalations and ooid intervals.

Finally the Unit **13** (394.9 m) representing the topmost interval is badly exposed due to valley infill through artificial lake. It consists of marly limestones with recurrent breccia intercalations. The topmost breccia (Fig. 21h) is a 26.3-m-thick megabed with limestone blocks of up to 2 m in diameter. More marly limestones follow up to the discordant contact (Milojević & Sunarić, 1964; Papeš, 1975) with the deposits of the younger lacustrine cycle. The measured thicknesses and the succession of lithologic units correspond very well with data presented by Milojević & Sunarić (1964).

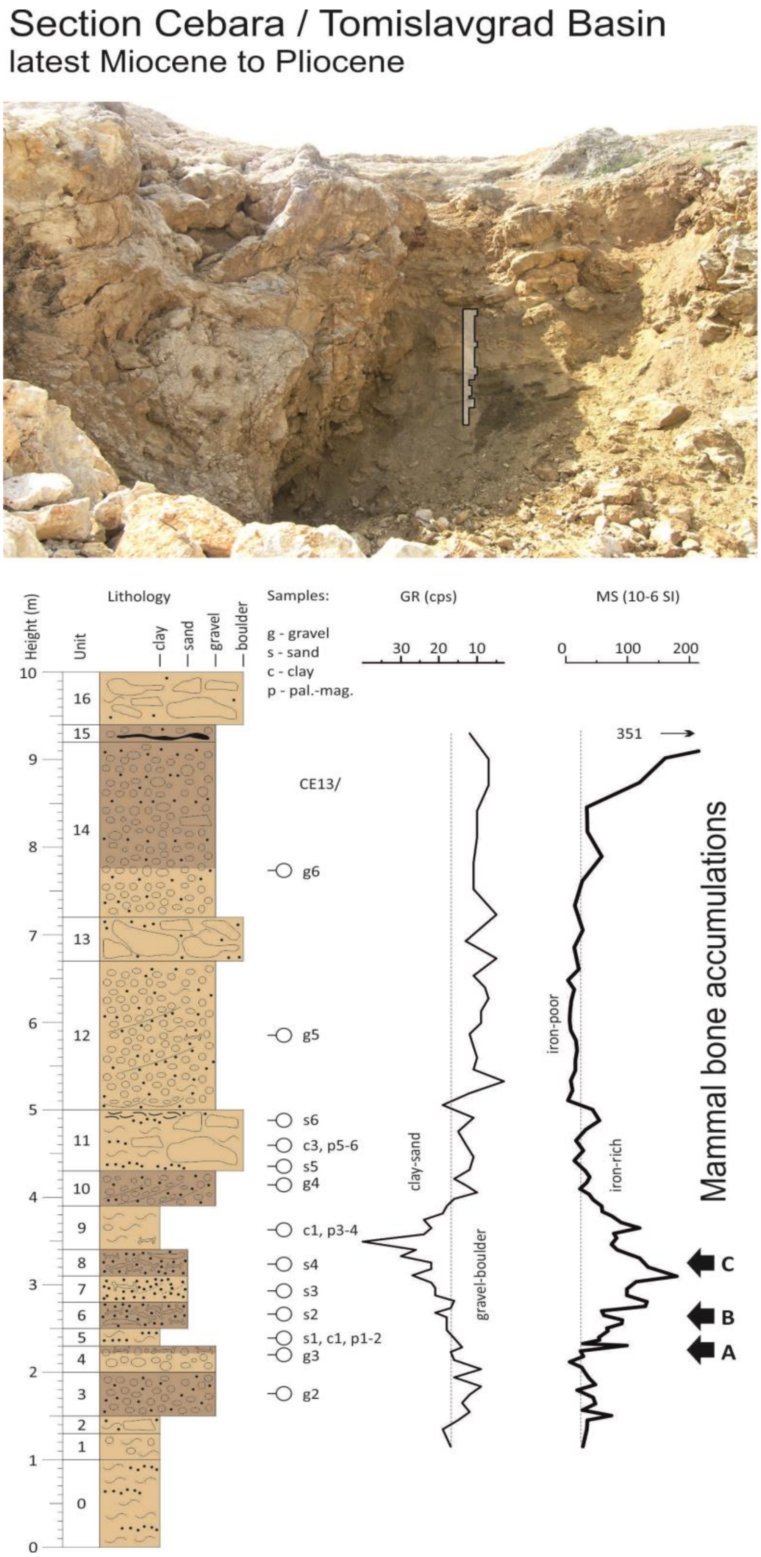
The strata exposed in the lower part of the Ostrožac section are indicative of predominantly shallow water conditions. The rippled structure of these limestone beds points out that they accumulated in the shallow littoral zone. The calcarenites and breccias that characterize interval M4 are badly sorted, which implies short transport. We interpret them as debris-flows indicative of local seismic activity in conjunction with uplift of the basin margins from which the material originates. The coarsening upwards sequence, which these calcarenites and breccias built, preludes the end of the first lacustrine phase.

The angular discordance on top of the Unit 13, representing the boundary between the first and second lacustrine cycle results from the tectonic activity at the end of the first lacustrine phase. This interpretation is in line with that of Milojević & Sunarić (1964) and Papeš (1975), who also suggested that uplift of the Tušnica Mountain began during deposition of Unit M_4. This event divided the Livno–Tomislavgrad basin in two portions, providing independent depositional settings to the subsequent, Late Miocene lakes.

Fig. 21. Photographs with detail view to sedimentary facies of the Ostrožac section: a – subaquatic plant root remains, b – well bedded limestone, c- Ripple bedded limestone, d – trough cross-bedded limestone, e – bedded limestone of the unit 10, f – calcarenite intercalation, g–h – Breccia of the unit 11 (compare with Fig. 18).

3.4.4. POINT 7. CEBARA – The final act – large terrestrial mammals in karst-sinkholes

Locality: Cebara
WGS84 coordinates: 43.650897° N, 17.216894° E
Age: Latest Miocene–Pliocene



New late Neogene proboscidean site Cebara (Fig. 17 and 22) has been currently discovered by local fossil collector Vinko Ljubas south of Tomislavgrad in Bosnia and Herzegovina. It is located in one ~40 m deep, ~20 m high and ~17 m wide incision of the escarpment at the southwestern margin of Duvanjsko polje, a typical Dinaride karst polje. The latter represents a ~240 km² large and NW-SE striking intra-mountainous basin that was initiated in the early Miocene (~17 Ma) as the eastern part of the Livno-Tomislavgrad basin. The two sedimentary cycles accumulated more than 2500 m of coal bearing lacustrine deposits until the latest Miocene (~6 Ma) therein (Fig. 17).

The posterior wall of distally narrowing incision shows coarsening upward succession of clays, fluvial gravels and block-breccia including up to 5 m diameter boulders developed through reoccur-

Fig. 22. Photograph and log of the Cebara section S Tomislavgrad. Clastic sediments of various grain sizes fill in a cavern in the Cretaceous limestone rocks (log position is indicated on photograph). The cavern passes upwards into a sinkhole. The log shows the lithological column, sample positions and gamma ray (GR) and magnetic susceptibility (MS) measurements. The latter show increasing

ring cave roof collapses (Fig. 22). Upward the incision is unroofed passing into a ~35-m-wide and ~10-m-deep funnel-shaped doline. The logged succession (Fig. 22) is 10 m thick with the base covered by debris and top not reachable at present outcrop conditions. It comprises two units of equal thickness. The lower one is characterized by deposition of brownish clay that can include sand lenses and/or laterally grade to block-breccia. Beyond that up to 1 m thick sand, gravel and boulder intercalations are present. The upper unit is composed of two conglomerate packages both topped by cave-in breccia. The lower gravel shows through- and cross-bedding and at its base operculi accumulations of freshwater snail *Bythinia* occur supporting the inference of riverine and/or lacustrine origin of the sediment.

The bone bed interval is about 1.5 m thick (Fig. 22) and marks the middle part of the lower unit. The bones, tusks and teeth oriented horizontally to the bedding plane, are disarticulated and concentrated in three 10 to 30 cm thick horizons. The lower one appears on top of one 30-cm-thick gravel bed, the other two mark lower and upper part of one 90-cm-thick sandy layer. Strongly increased magnetic susceptibility values (>100 x 10^{-6} SI) detects the black color of the bones and matrix sediments as containing iron-bearing minerals. The inspection of up to now available fossil remains allows their tentative classification with *Anancus arvernensis*, representing a gomphothere proboscidean characterized by two oversized straightened tusks in the upper jaw and a body-size of today's elephant (Fig. 23).

This European gomphothere was a browser with the peak distribution in the late Plio-

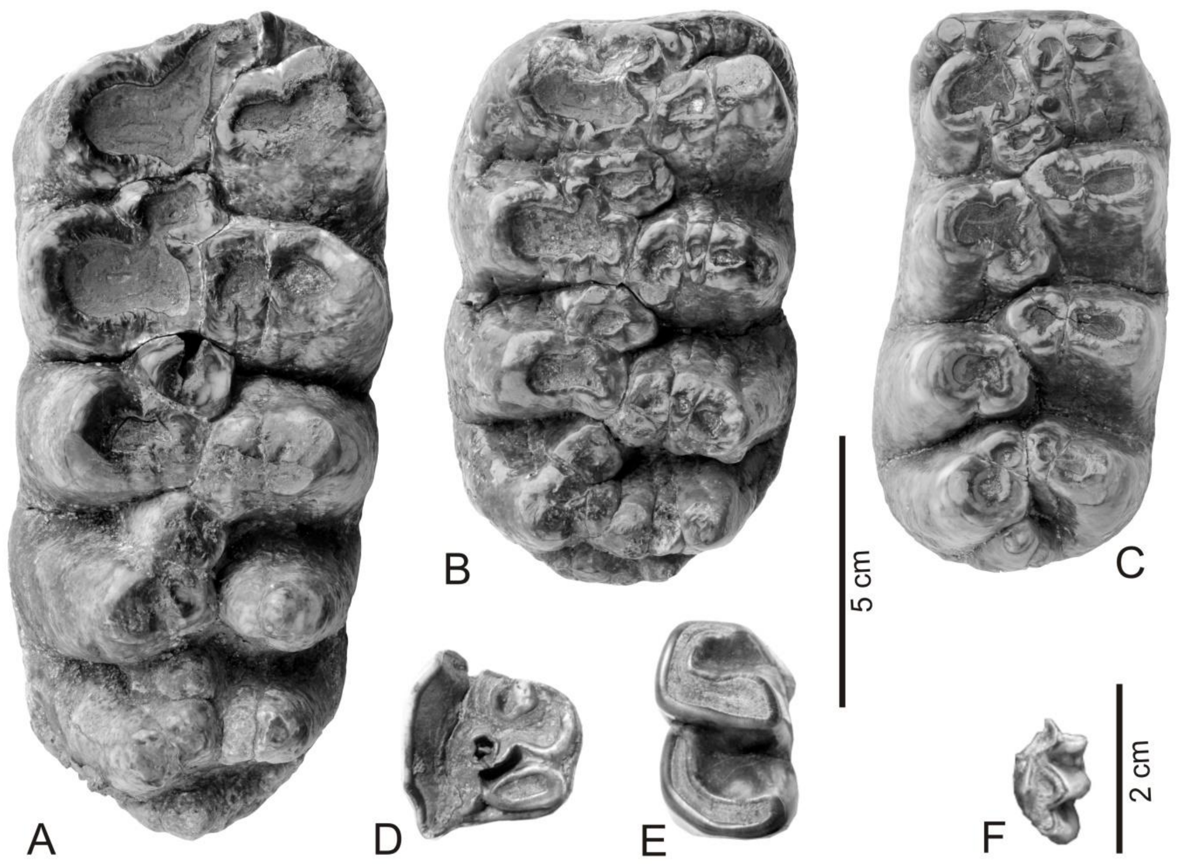
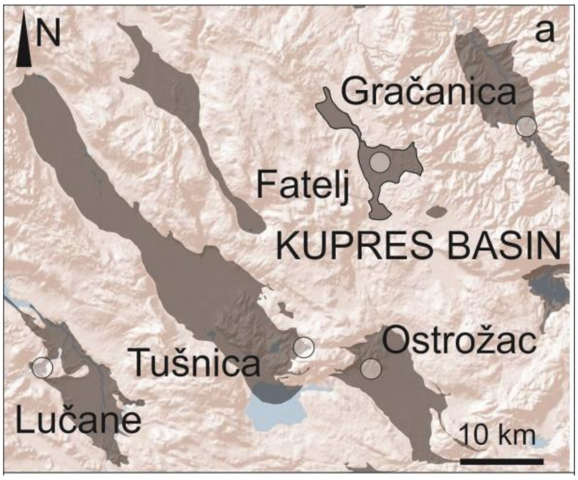


Fig. 23. Selection of mammalian fossils and taxa from the Late Miocene/(Early Pliocene) of Cebara, Bosnia-Hercegovina: A–C – molars of *Anancus arvernensis*, A – left M3 sup., B – left M1 sup., C – left m1 inf. D–E – cheek teeth of Rhinocerotidae indet., D – P2 sup. sin., E – p/m inf., F – m3 inf. of a Bovidae indet. All material is stored in the Croatian Academy of Sciences and Arts, Zagreb.

cene, and the stratigraphic range from the latest Miocene MN 11 to the early Pleistocene MN 17. Its extinction correlates with the decimation of the wood cover in Europe during the early Ice Age period. Although widely distributed in the Pliocene of SE Europe from Slovenia through Croatia, Serbia, Romania, Bulgaria, to Greece this is the first finding from the southern Bosnia and Herzegovina and the High Karst Dinarides up to now.

Although the stratigraphic data does not allow a precise inference of the age yet, the lithostratigraphic evidence supports the correlation with the Pliocene in a phase post-dating the Miocene long-lived lake conditions.

The studied site with 920 m a.s.l. represents probably the topographic highest known proboscidean locality. In particular, their mass occurrence in several fossiliferous layers indicates the presence of a well settled gomphothere population in the study area over many generations. This is the most striking feature of the new locality because the gomphotheres, considering their huge size preferred rather low-land settings rich in wood vegetation than the mountainous regions. Yet, the presence of former habitats in the Dinaride High Karst during the deposition of investigated succession is well supported by tectonic reconstructions placing the main mountain elevation phase into the Pliocene–Pleistocene transition interval.



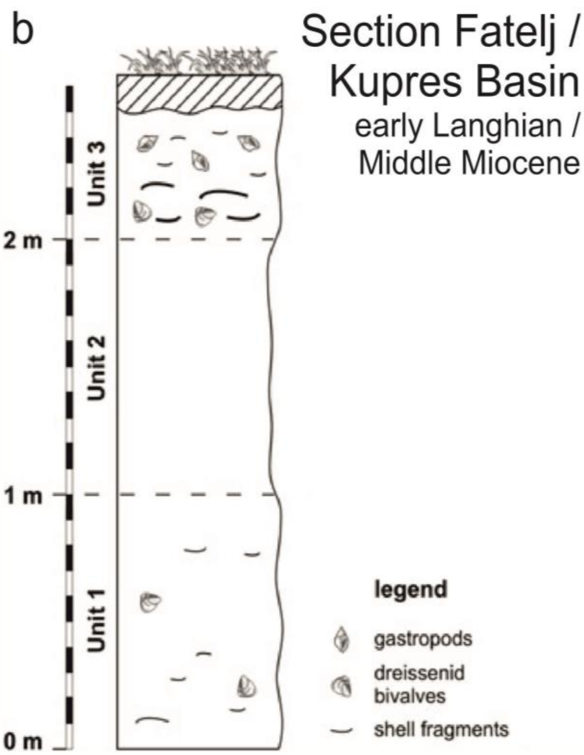


Fig. 24. Overview on the early Langhian (Middle Miocene) Fatelj section: a – map shows the regional setting of the Kupres Basin with indicated positions of the Fatelj section and other localities described in the present guide book (see also Fig. 1), b – log shows the mollusk distribution in the lacustrine marl and limestone at Fatelj.

3.5. Lake Kupres – the highest Dinarides intra-mountain basin[3]

Oleg Mandic, Thomas A. Neubauer, Hazim Hrvatović

The Kupres basin is an about 95 km² large, NW-SE striking karst plane (polje) in southern Bosnia and Herzegovina (Fig. 24). It is the highest plane in that part of the Dinarides comprising the

[3] The present chapter is based on Neubauer et al. (2013).

water shed between the Adriatic and Black seas fluvial systems. The basement represents the northern margin of the External Dinarides and consists predominantly of Mesozoic marine platform carbonates (Hrvatović, 2006). The basin was presumably initiated during the Early Miocene, reflecting the extensional tectonic regime originating from back arc rifting of the Pannonian basin (Ilić & Neubauer, 2005). The sedimentary thickness of the lacustrine, predominantly carbonate deposits is unknown because the lack of intercalated coal deposits did not favor explorational drillings (Đerković, 1964). They are exposed on an area of only about 23 km², yet with possible extension below the Pleistocene–Holocene cover of up to 80 km² (Papeš, 1972, 1975; Vujnović, 1981; Vujnović et al., 1975).

3.5.1. POINT 8. FATELJ – Miocene endemic mollusks from a carbonate oversaturated lake

Locality:	Fatelj
WGS84 coordinates:	43.971637° N, 17.235321° E
Age:	Early Langhian (Middle Miocene)

The investigated locality (1140 m a.s.l.) is placed at the NW slope of a small hill termed Fatelj (Fig. 24). It was artificially outcropped at a distance of about 5 m on the west side of a small path leading to the main road (Bugojno-Livno). The path leaves the road about 3.8 km S of Kupres and heads to the WNW along the northern side of the Fatelj hill. The site is distanced about 1 km from the road close to the bank of the rivulet Mrtvica.

The section is about 3 m long and comprises three lithological units delimited by transitional boundaries (Fig. 24). The beds are dipping with 15° to the NNE (015°). Unit 1 is about 1 m thick and made up by greenish clayey marl with small to medium sized dreissenid bivalves and gastropods floating in the sediment. Additionally, fish bone remains are frequent. Aragonite shells are largely leached. The about 1-m-thick Unit 2 is lithologically similar to the previous unit but barren of macrofossils. Unit 3 is about 0.5 m thick and comprises beige to whitish-grey marls with large dreissenid shells in its lower part grading into the gastropod dominated upper part of the unit. It is a moderately dense shell accumulation with horizontally oriented bivalve shells and non-oriented gastropod shells in the upper part. The aragonite preservation is moderate to excellent. At about 2.5 m, Unit 3 grades into an about 30-cm-thick soil horizon rich in gastropods that are reworked from the underlying horizon.

The mollusk fauna (Fig. 25) is outstandingly preserved, bearing 18 species. The assemblage is strongly dominated by melanopsid and hydrobiid gastropods present each by seven species. One third of the occurring taxa are restricted to the Kupres basin, the others indicate faunistic relations to Sinj, Drniš, and Džepi basins. The stratigraphic ranges of the species imply a depositional age of 15.5 ± 0.2 Ma (earliest Middle Miocene; Langhian).

The alternation of sculptural features relates with the environmental change. Phases of hydrological isolation, indicated by carbonate dominated lithology, coincide with a high frequency of sculptured types within the gastropods. Phases of increased aridity led to high evaporation, a lowered lake level and enhanced carbonate production which seem to have promoted strongly calcified shells.

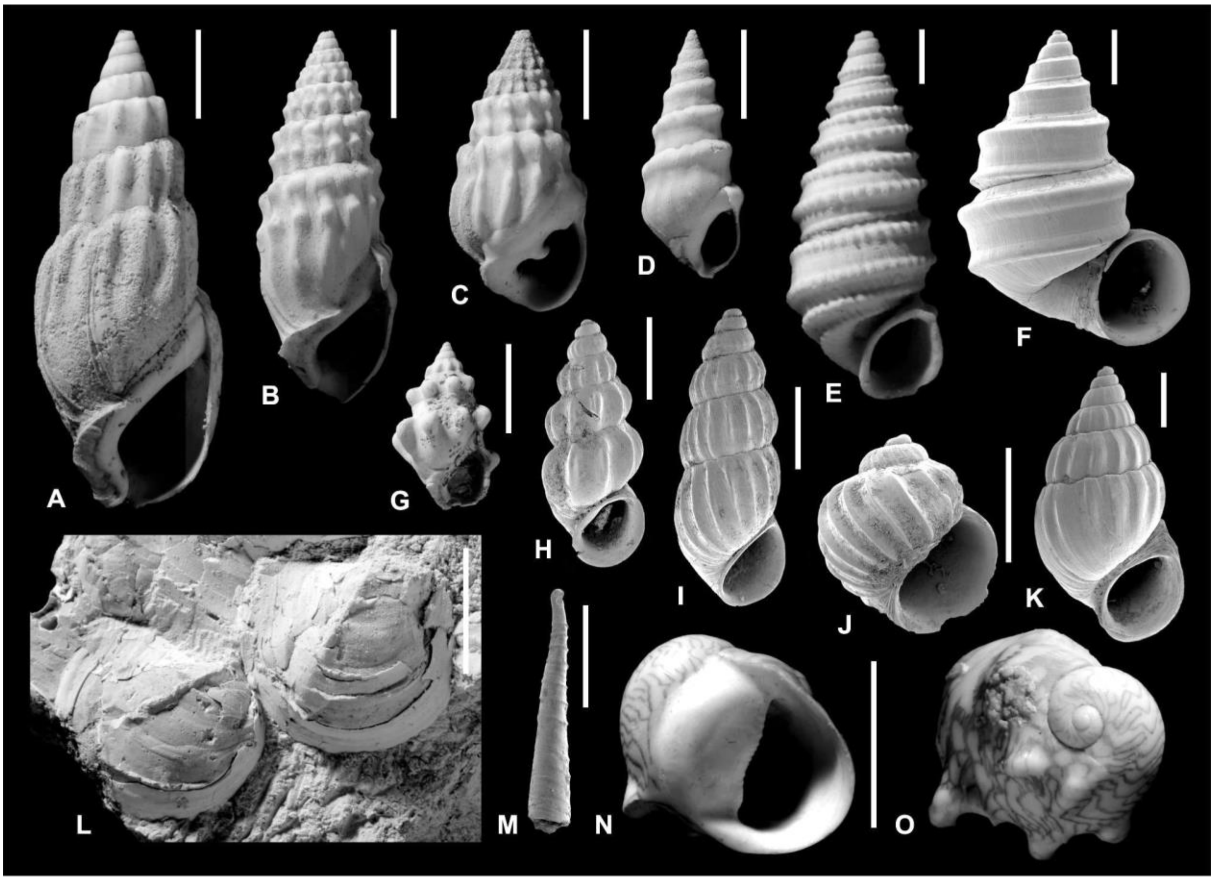


Fig. 25. Gastropods dominate the mollusk assemblage at Fatelj, comprising diverse melanopsids (A – *Melanopsis cvijici*, B – *M. lyrata*, C – *M. medinae,* D – *M. fateljensis,* G – *M. geniculata*) and hydrobiids (E – *Pseudodianella haueri*, F – *Marticia hidalgoi*, H – *Cyclothyrella tryoniopsis*, I – *Prososthenia diaphoros*, K – *P. undocostata*, J – *Bania obliquaecostata*), accompanied by few planorbids (M – *Orygoceras dentaliforme*) and neritids (N–O – *Theodoxus imbricatus*) species. Bivalves are species-poor but abundant in certain levels, represented by only one dreissenid species (L – *Illyricocongeria aletici*). The latter is an early Langhian marker fossil. Scale bars: 10 mm (L), 5 mm (A–G, N–O), and 1 mm (E-F, H–K, M).

3.6. Lake Bugojno – three lacustrine cycles

Oleg Mandic, Ursula B. Göhlich, Wout Krijgsman, Arjan de Leeuw, Hazim Hrvatović

Bugojno Basin is situated in Western Bosnia and Herzegovina, between Donji Vakuf and Gornji Vakuf (Fig. 26). With a total surface of 125 km^2, it belongs to larger intra-mountain basins of the Dinarides. In its central part, it accommodates the Vrbas River. The latter is flowing in the NNW direction and belongs to the Black Sea catchment area. Mean elevation of the Vrbas alluvial plane is about 620 m asl, the mountain peaks are about 2 km high in the SW and 1.5 km in the NE. The elongated basin shows a Dinaride strike and a total length of 28 km; the lacustrine deposits extend for about 22 km. It is 9 to 1.4 km wide, drop-shaped in outline pointed to the SSE (Čičić, 1976).

The basin stretches along the Ruduša Nappe dominated by Upper Triassic platform carbonates (dolomites and limestone) representing the NE margin of the External Dinarides. By its NE part, the basin extends into the Bosnian Schists Mountains, which is a Miocene exhumed core complex dominated by Paleozoic schists and sandstones. Accompanied are in the present area Permian limestones with gastro-

Fig. 26. Geological map showing the Neogene to Quaternary infill of the Bugojno intra-mountain basin (after Čičić, 1976). White ring indicates the position of the Gračanica mine.

pod *Belerophon* sp., Early Triassic shale and sandstones, and Middle Triassic volcanogenic sedimentary series. The Vrbas fault, largely covered by lacustrine deposits, disjoins the Ruduša Nappe from the core complex and stretches for several hundred kilometers to the NW up to Banja Luka region (Hrvatović, 2006).

Infill of the Bugojno Basin (Fig. 26) is about 900-m-thick and comprises three lacustrine depositional cycles (from base to top: ~250 m / ~300 m / ~300 m) covered by up to 100 m alluvial sands (Čičić, 1976). The basal zone of the first cycle (50 m) comprises conglomerates, sandy and gravel bearing clay, intercalated by lenses with marl and limestones. Main coal seam (35 m) follows intercalated by clay and marl, bearing large mammal remains. Finally, 150-m-thick succession of marl and sandy to marly limestone with sphaeriid and dreissenid bivalve remains closes the interval. The second cycle starts with a 5-m-thick coal seam intercalated by clay and marl. It is overlain by a series of clay and sandstones. The upper cycle starts finally with a 40-m-thick interval with large scale lignite lenses in clay, grading upward into a 250-m-thick interval made by gray clay.

The general structure of the basin is a syncline with the limbs dipping by 5°-30° toward the basin axis. It is apparently asymmetric with oldest deposits concentrated at the southern and southwestern margin of the basin. To the north and northeast, ever younger cycles become transgressive to the basement, pointing to a gradual shift of the depositional center in that direction (Čičić, 1976).

In general the lower and middle cycle are considered as Miocene, the upper one as Pliocene in age. This stratigraphic correlation is ambiguous, because the only relevant fossil remains in the basin are restricted to the lower lacustrine cycle. There, the large mammals identified *as Prodeinotherium bavaricum* and *Deinotherium giganteum* point to the latest Early or Middle Miocene age (Malez and Slišković, 1976). Their presence in the basal layers of the Bugojno Basin defines ~17.5 Ma (=European Proboscidean Datum) as maximum possible age of the Bugojno Basin formation (Pálfy et al., 2007).

3.6.1. P9. GRAČANICA – Swamp lignite and profundal open-lake marl

Locality: Gračanica open-cast coal-mine / Gornji Vakuf
WGS84 coordinates: 43.997662° N, 17.518516° E
Age: Burdigalian–Langhian (Early–Middle Miocene)

The coal mine is located near the Village Gračanica about 10 km SSE from the center of Bugojno, northeast of the main road to Gornji Vakuf-Uskopje (Fig. 26). The exploitation started 1939 in an underground work. Today it is a large opencast mine area providing good outcrop conditions for investigation of vertical and lateral facies changes in transgressive lacustrine successions. Besides, the pit is well known for its mammal remains occasionally found in the lower part of the coal interval (Fig. 27). Muftić & Behlilović (1966) carried out a detailed exploration study in the mine. The coal mine exposes the lower lacustrine deposition cycle of Čičić (1976). It superposes the Upper Triassic dolomite basement rocks with the transgressive contact exposed in the northern part of the mine area. The very top of the lacustrine succession in the Gračanica area is marked by the first occurrence of *Illyricocongeria frici* astronomically dated in Gacko Basin to 15.5 Ma (Mandic et al., 2011).

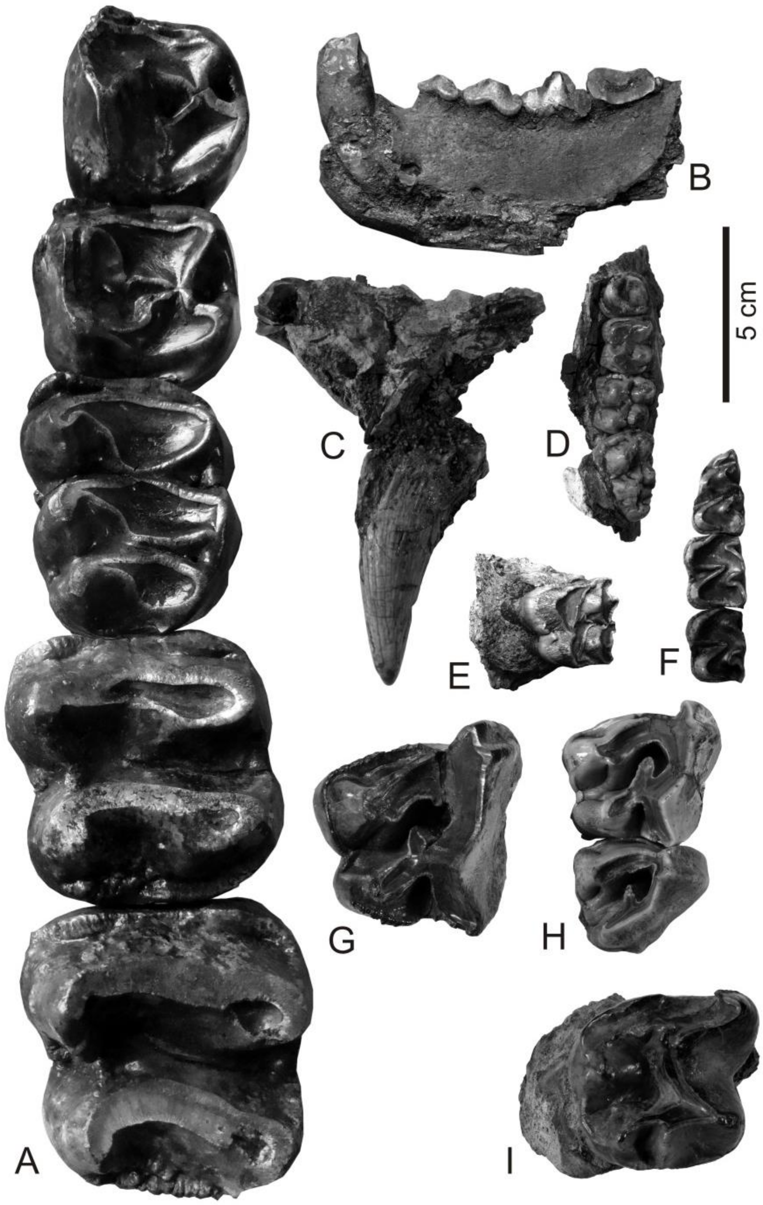


Fig. 27. Selection of mammalian fossils and taxa from the Miocene of Gračanica, Bugojno, Bosnia-Hercegovina: A – *Prodeinotherium* sp., maxillary toothrow P3–M3 (SNSM–BSPG, Munich), B – Carnivora mandible with dentition (c, p2–m1), C – suoid *Bunolistriodon* sp. maxillary canine, D – suoid *Bunolistriodon* sp. maxillary toothrow P4–M3, E – Palaeomerycidae indet. Upper molar (M2/3), F – three-toed horse *Anchitherium* sp., premolars (p2–p4), G – rhino *Brachypotherium* sp., upper molar (M2), H – Rhinocerotidae indet., upper molars (M2–M3), I – Chalicotheriidae indet., upper molar (M2/3). All material (except A) is stored in Natural History Museum Vienna, Austria.

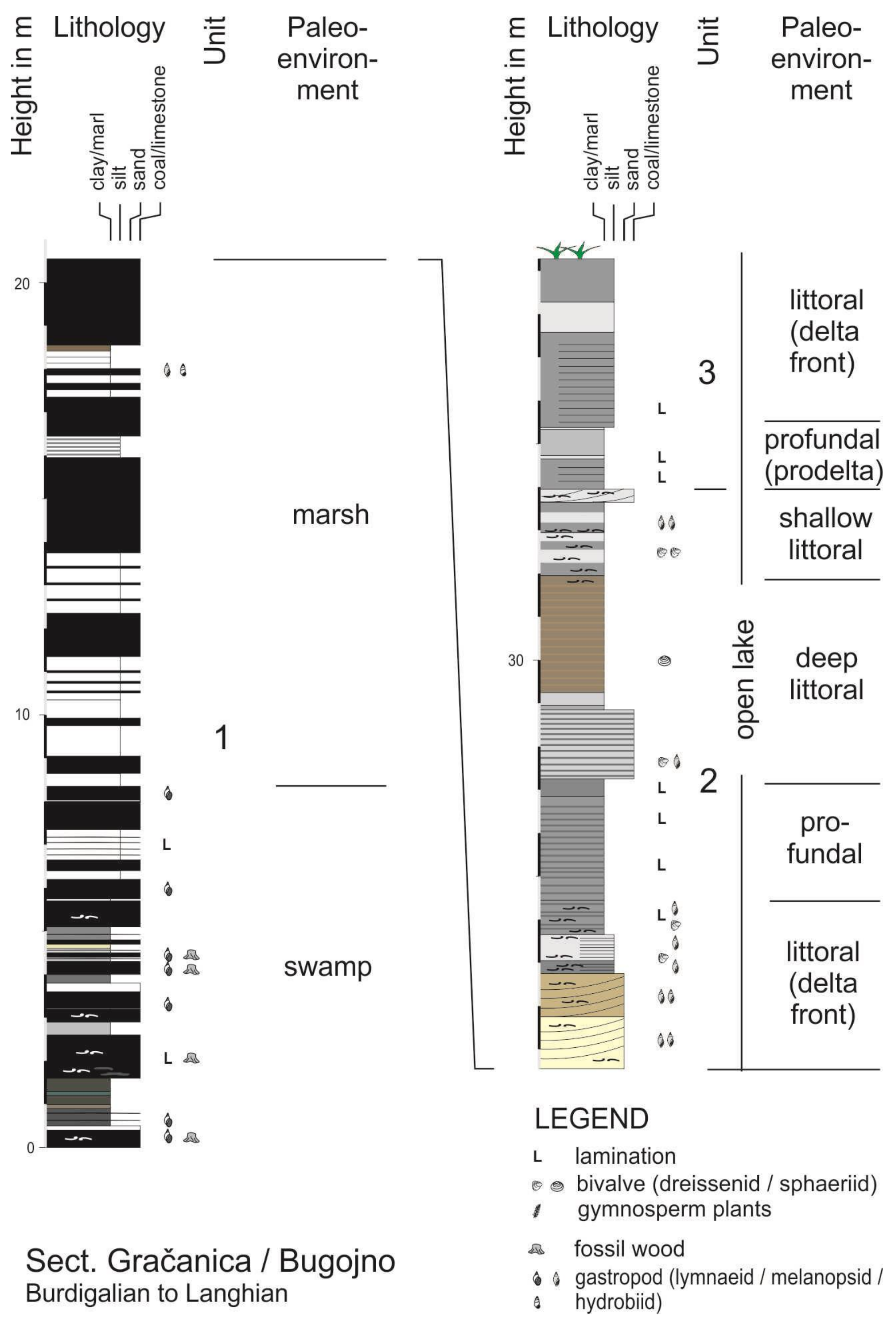


Fig. 28. Section Gračanica from the open-cast coal-mine S Bugojno. The facies succession reflects a gradual deepening of depositional environments, culminating at 35-m-height with installation of open lake profundal setting.

The succession originally logged in 2008 is 40 m thick (Fig. 28). The lower half is represented by coal deposits exploited by the mine company. The upper part of the succession is dominated by marly sediment, representing the open lake environment. The beds are dipping by 10° to 15° to the south (~180°).

The initial 5 m of the coal interval shows terrestrial influence, bearing common three trunks and intercalations of colored clay. Also, the lymnaeid snails are very frequent pointing there to very shallow, swamp-related subaquatic environment. The lymnaeids are present for the next 4 m, after the last trunk occurrence.

The following 9-m-thick interval is barren of fossils. Its lower part is made by whitish silty marl intercalated by up to 1-m-thick coal seams. The upper 4 m are dominated by coal. The overlaying 1-m-thick whitish marl, alternating with coal, shows the first occurrence of melanopsids and hydrobiids and marks the first shift of depositional settings into the open-lake littoral conditions. Indeed, after a short retreat marked by the last coal seam (2 m), the cross-bedded sand (2 m) rich in melanopsids introduces transition into the open lake conditions persisting later on up to the section's top.

The lower part of the lacustrine interval (13 m) represents a single transgression-regression cycle. The fossil-rich littoral sand and marl (3.5 m) grade upward into laminated and banded dark marl (3 m) marking the initiation of profundal depositional settings. The deepening trend stops with one contorted bed proving the start of the synsedimentary seismic activity in the area. Immediate shallowing trend is marked by the re-appearance of gastropods and dreissenid bivalves in banded limestone (1.5 m) and marl (3 m). The final 2 m of the cycle shows mollusks accumulated in shell-beds and in cross-bedded sands indicating the re-establishment of shallow littoral settings.

The top interval of the section (5 m) shows renewed transgression-regression trend. It is a coarsening upward succession from clay to silt barren od macro-fossils and intensively laminated for the initial 2 m. The latter indicates a short-term reoccurrence of profundal settings. The increasing importance of silt component towards the top points clearly to the shallowing upwards trend.

3.7. Lake Sarajevo – Sarajevo-Zenica Basin

Nevena Andrić, Karin Sant, Oleg Mandic, Liviu Matenco, Hazim Hrvatović

Introduction

The Sarajevo-Zenica Basin (Fig. 29) is the largest intra-mountainous basin of the Dinaride Lake System (DLS, Krstić et al., 2001, 2003; Harzhauser et al., 2008). The basin was formed nearby the inherited nappe contact between the pre-Karst and East Bosnian – Durmitor units, the so-called Busovača Fault, on the northern flank of the Mid-Bosnian Schist Mountains. Its present-day Neogene basin infill covers an area over 1500 km^2. The basin margins are the Mid-Bosnian Schist Mountains to the south-west, and Cretaceous limestones of the Bosnian Flysch to the north-east. Because of infrastructure and mining activities, the basin bears plenty of interesting outcrops, which have been studied in many local and regional studies (e.g., Hrvatović, 2006 and references therein). Recently, an intensive field study was performed to unravel the interplay between tectonics, sedimentation and climate in this basin (Andrić et al., 2015; Sant et al., 2015).

Stratigraphy and sedimentology

The deposition in the Sarajevo-Zenica basin during Oligocene–Miocene times was predominantly controlled by the tectonically induced changes affecting the accommodation space geometry and source area. The basin infill can be divided into three main depositional cycles, which are most likely related to three distinct tectonic phases (Fig. 30, Andrić et al., in prep). The ages were estimated by pollen analysis (Pantić et al., 1966). The lacustrine fossil as-

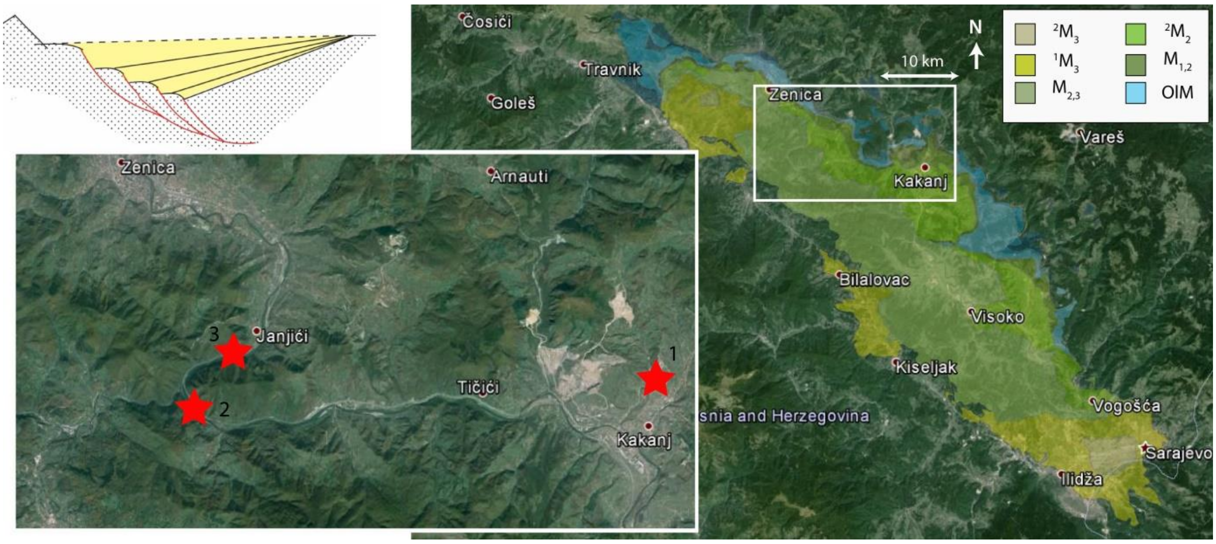


Fig. 29. Overview of the basin with main geological units in map view, a zoom in on the area with indicated excursion stops, and a schematic cross-section of an asymmetric basin. Map after Milojević (1964).

semblage is very poor in diversity and number of individuals and includes some endemic mollusk species, ostracods, characea, plant fragments and pollen

The first, Oligocene–Early Miocene depositional cycle started with red alluvial clastics deposited over Bosnian Flysch. This was followed by carbonate deposits with coal sequence (i.e., Košćan coal seam) interbedded with alluvial sediments (Milojević, 1964). The general regression resulted in deposition of red alluvial clastics which are locally overlain by porous bituminous limestones (Muftić, 1965). Fauna includes the mollusks *Lymnaea* sp. and *Helix*? sp. (Milojević, 1964).

The new transgressional cycle (i.e., second, Early–Middle Miocene depositional cycle) starts with a relatively quiet environment with deposition of lacustrine carbonates, coals (i.e., nine coal seams) intercalated with shaly sandstones and mudstones (Milojević, 1964; Muftić, 1965). Gradually, they are replaced by siltstones, sandstones and conglomerates. The first appearance of Mid-Bosnian Schist Mts. clasts marks the shift from 'transitional' unit $^2M_2$ to the Lašva unit $M_{2,3}$. The cycle is completed by (coarse) clastic deltaic facies followed by alluvial and fluvial conglomerates. The most common fossils are mollusks *Lymnaea* sp., *Fossarulus* sp. and *Unio* sp. (Milojević, 1964), and the mammal *Prodeinotherium bavaricum* (found in the Kakanj coal mine; Milojković, 1929).

The third, post-Middle Miocene, depositional cycle is very poorly exposed, and is composed of shales, coals and limestones that indicate a gradual drowning of a swamp environment and the creation of perennial lake (Milojević, 1964). These deposits are locally overlain by the Orlac conglomerates, and by the 'Pliocene' alluvial sediments that were deposited over a larger area transgressing over the Mid-Bosnian Schist Mountains (Milojević, 1964).

Tectonic evolution and dating

The Oligocene–Early Miocene depositional cycle was associated with NE-SW oriented thrusts showing a dominantly SW transport direction. The basin formed as a wedge top basin in the footwall of the coeval thrusts which were active

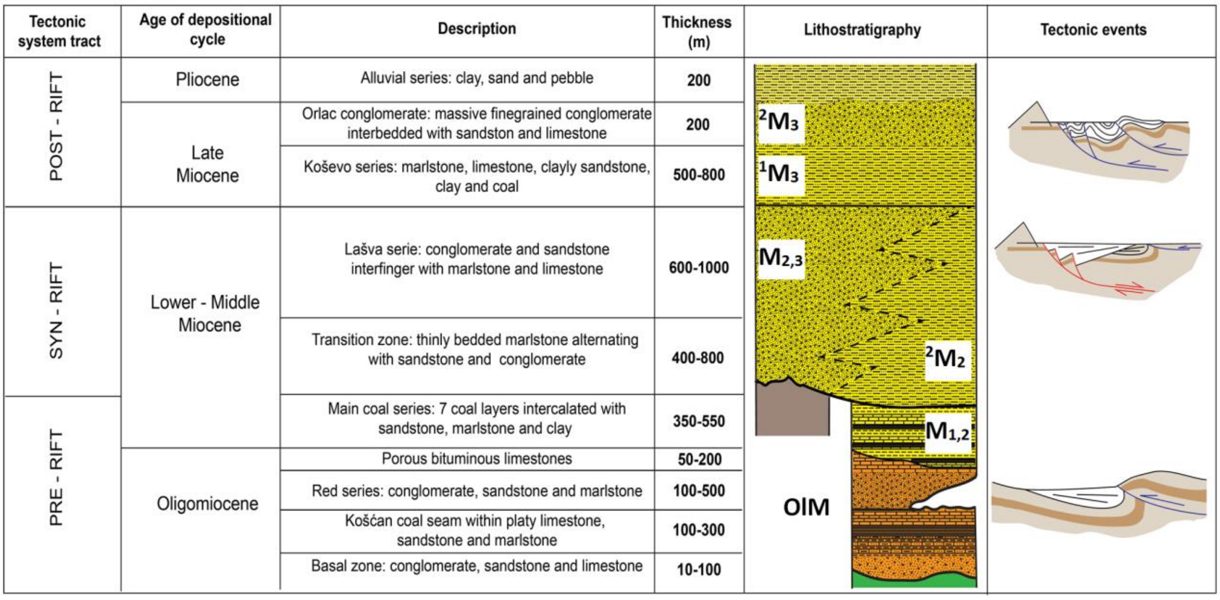


Fig. 30. Generalized basin infill of the Sarajevo-Zenica Basin, and interpreted tectonic phases. Modified after Milojević (1964) and Andrić et al. (in prep).

during the final collisional stage in the Dinarides (Andrić et al., in prep).

The subsequent Early–Middle Miocene extension resulted in the deposition of new tectono-sedimentary cycle. The deposition is driven by a system of NE-dipping normal faults which gradually exhumed Mid-Bosnian Schist Mountains along the south-western margin creating the asymmetric basin geometry. This is evidenced by the NE-ward pinching alluvial clastic wedges aligned along the south-western basin margin. The main source area for the alluvial-deltaic clastics were the Mid-Bosnian Schist Mountains. The overall fill is organized in one coarsening-upward low-order depositional cycle. The temporal and spatial migration of the normal faults in the footwall direction (i.e., SW-wards) progressively enlarges the basin and lead to a retrogradational depositional trend. The proximal facies are being buried by distal facies during subsidence created by the following normal faulting event. There are three subsequent normal faulting events, where each was associated with deposition of transgressive-regressive higher-order cycles with a SW-ward younging trend. The cycles are bounded by sub-areal unconformities and maximal regressive surfaces in the proximal and distal part of the basin, respectively. Internally, the cycles reflect the evolution of each major fault event. After the Middle Miocene, the basin was inverted (Andrić et al., in prep).

A detailed magnetostratigraphic study was performed on a composite section of the fine-grained basin infill of $M_{1,2}$ – $M_{2,3}$. The preliminary results suggest that deposition took place between ~18 and 15 Ma, which is similar to the Sinj and Livno basin (De Leeuw et al., 2010). The 'deepest', most quiet lake phase existed around 17 Ma. The major extensional rifting phase started between 16 and 15 Ma, which might be similar to the erosive phase in the Livno Basin. No clear sign of climatic forcing was found in the sections (Sant et al., 2015).

3.7.1. POINT 10. GREBEN – Deep lake organic rich limestone

Locality: Greben / Kakanj
WGS84 coordinates: 44.140301°N, 18.120600° E
Age: Burdigalian (Early Miocene)

The fine-grained carbonate rocks of the Greben section (Fig. 31) are representative for the low energy, lacustrine environment that existed during the beginning of the 'second cycle', after deposition of the main coal seam. The section is dominated by mudstones and marlstones. It bears rare remains of gymnosperm plants (Fig. 32), fishes and mollusks (spaeriid bivalves). The lowermost 8 m of partial section 1 are most bioturbated. Upwards in the section more silts and clays appear.

Characteristic lithological features are a high amount of organic matter and the internally banded limestones with regular and irregular

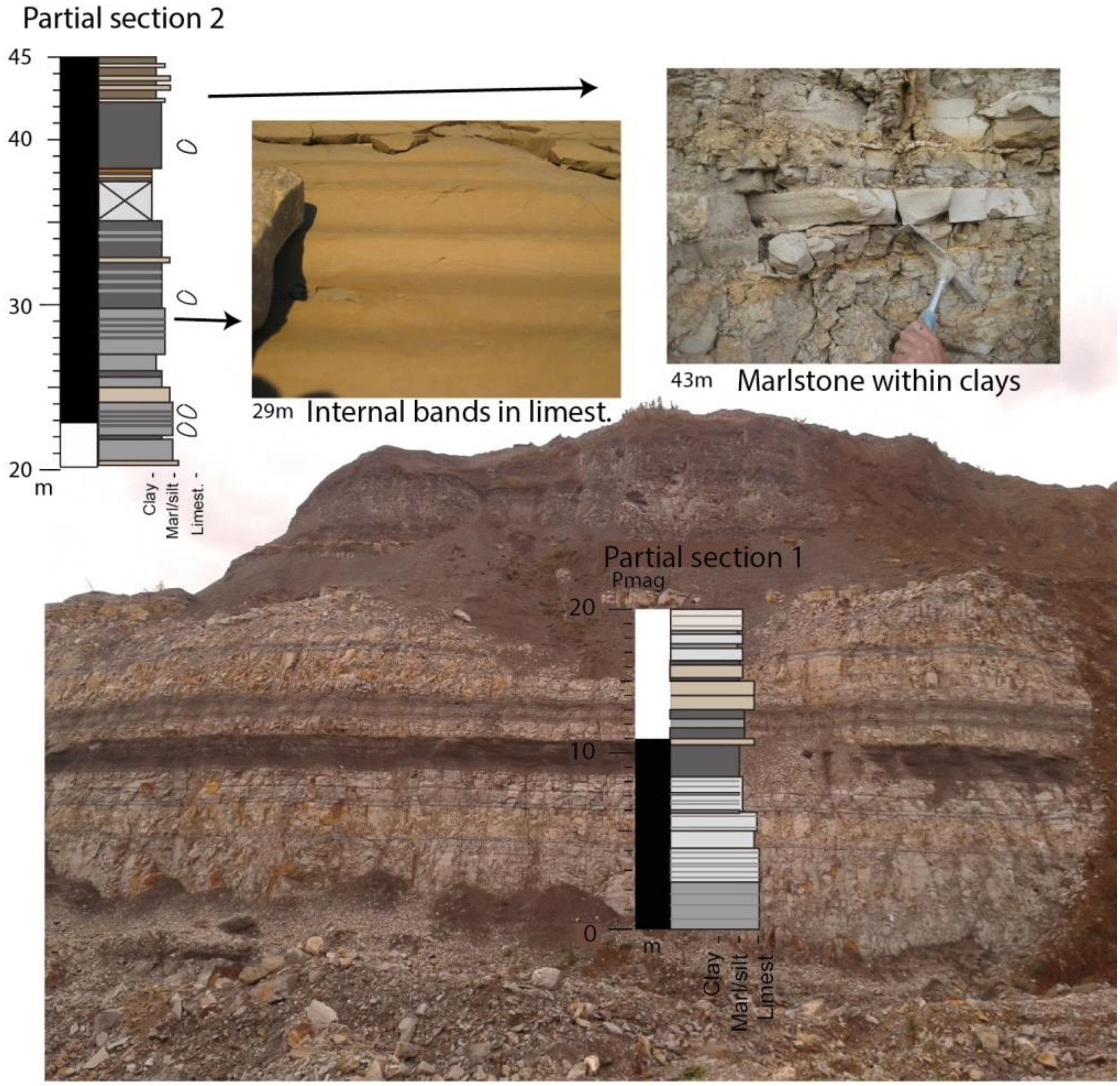


Fig. 31. Overview of the Greben section with lithology and magnetostratigraphy. Ostracod-rich layers are marked in partial section 2.

Fig. 32. *Taxodium*-related gymnosperm plant *Glyptostrobus europaeus* found in the Greben section.

alternations of dark and lighter grey bands (1–5 cm thickness). Micro-analyses revealed that bioturbations are concentrated in the lighter colored bands. Moreover, hematite/pyrite spots are concentrated around the bioturbated parts. This suggests that the lighter colored parts were well-oxygenized, whereas the darker parts were (almost) anoxic. In the lowermost part of the section almost no quartz particles are visible in thin sections, while in the upper part (>20 m) some more quartz particles are visible. They are too small to determine the source area. In general, the facies of the Greben section indicate calm lacustrine conditions with almost no external sediment input.

Magnetostratigraphy and biostratigraphy

The magnetostratigraphic study yielded straightforward magnetic directions with two reversals. A correlation of this pattern to the Global Polarity Time Scale (Hilgen et al., 2012) was not yet possible due to a lack of tie points. When we follow the preliminary age correlation of the whole basin infill, the age of the Greben section is between 17.5 and 16.5 Ma. This partly overlaps with the Middle Miocene Climatic Optimum and might correlate with the similar open lake profundal facies from the Livno-Tomislavgrad basin Ar/Ar dated to ~17 Ma (De Leeuw et al., 2011).

From the corresponding interval near Zenica (referred there as 90-m-thick marl overlaying the topmost coal seam), Kochansky-Devidé & Slišković (1972) reported the presence of *Clivunella* sp. The latter deep-water gastropod is a marker fossil for the uppermost Lower Miocene in the Dinaride Lake System (~16.7 and 16.0 Ma; De Leeuw et al., 2011). Its presence in present interval stays in accordance with the previous inference.

3.7.2. POINT 11. JANJIĆI – Lacustrine delta deposits of the "transitional unit"

Locality:	Janjića Vrh / Janjići
WGS84 coordinates:	44.148444° N, 17.951676° E
Age:	Middle Miocene
Formation:	"Transitional unit" ($^2M_2$)

The road-cut on the left bank of the Bosna river exposes an over 100-m-thick Early to Middle Miocene fill of the Sarajevo-Zenica basin (i.e., Transitional unit $^2M_2$ sensu Milojević, 1964). The section represents an excellent example of a prograding river dominated delta into a lacustrine environment (Figs. 29, 30, 33a and 34).

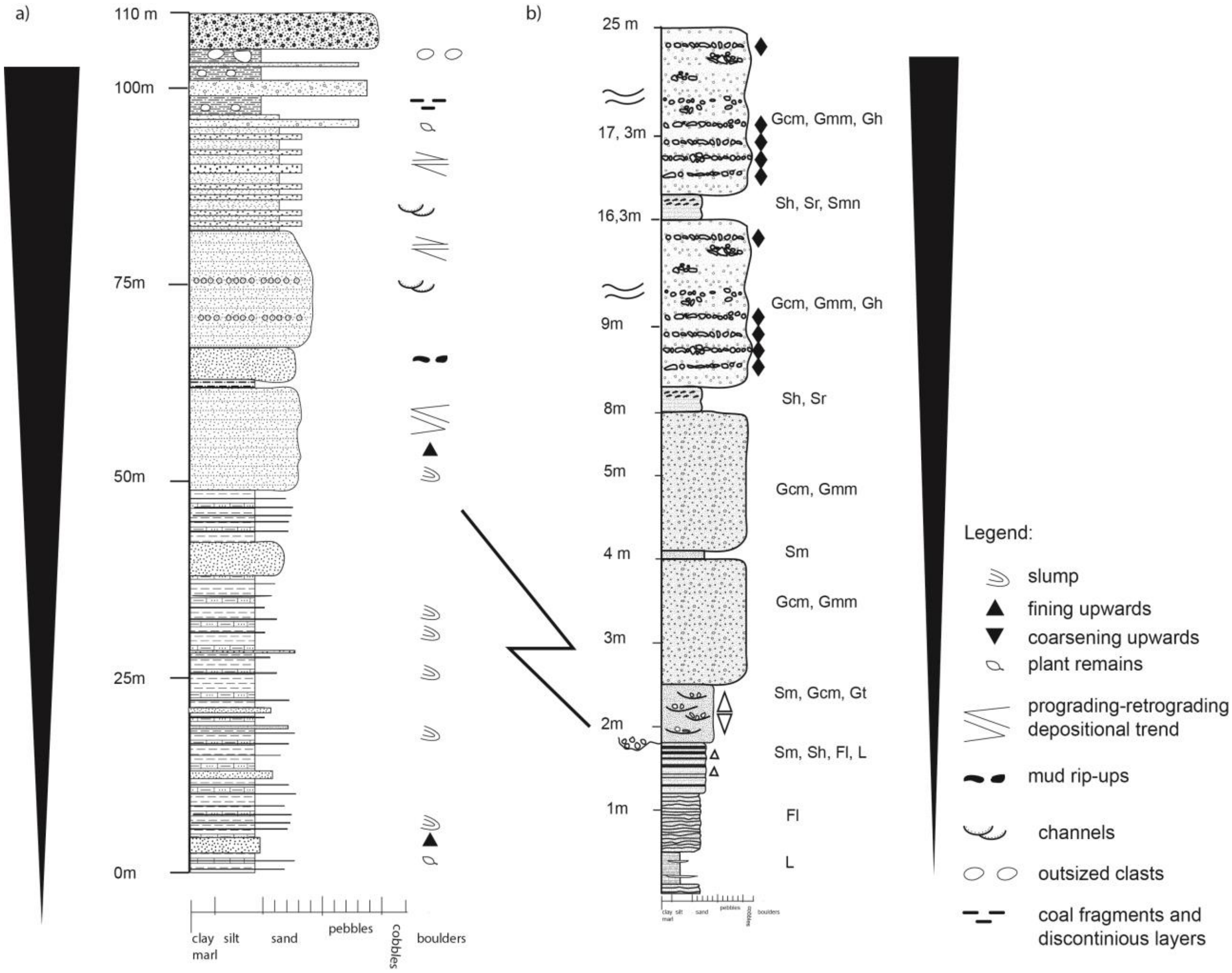


Fig. 33. Sedimentary logs of Janjića Vrh section (a) and Lašva section (b). The thick black line represents diachronous progradation of river dominated delta into lake environment.

Description and interpretation

The succession starts with laminated calcareous mudstones intercalated with laminas to thin layers/lenses of siltstones and sandstones (Fig. 33a). The mudstones contain dispersed organic matter and traces of ostracods; the latter is suggestive for deposition by fallout from the "background" suspension in a lacustrine environment. The thin intercalations originated from dilute turbidity currents feeding the terminal lobe in the prodelta environment. Further on in the section, the number of turbiditic layers increases. The sheet-like to lenticular high- and low-density turbidites often intercalated with slumps and massflow deposits (cohesionless and cohesive debris flows, Fig. 33a, 34). The turbidites usually contain a bipartite geometry with lower part made of granula to medium sandstones (Ta, Tb) capped by fine-grained sandstones, siltstones and mudstones (Tc, Td, Te). The debris flow conglomerates mainly comprise of granula to cobble size sub-angular to sub-rounded clasts. Most clasts are metariolites, quarzites, various schists and carbonates sourced from the Mid-Bosnian Schist Mountains.

The increased in high frequency of gravity deposits, especially slumps in the lower part of the section imply steeper gradients and slope instability which might be triggered by the activity of normal faults. The numerous plant remains,

Fig. 34. The migration of the channels in the turbidite sequence of the Janjića Vrh section.

coal fragments, immature clasts (angular, derived from Mid-Bosnian Schist Mountains) and coarsening upwards suggest an increase of land derived material prograding into the deeper water environment

This section is a good example of gradually forced regression in a river-dominated deltaic succession. It is characterized by a conformable shift of facies from lacustrine and prodelta deposits to the overlaying delta front sediments. The forced regression occurred during a stage of base level fall induced by a decrease in accommodation space creation rate as a response to cessation of the normal fault activity. The sediment supply exceeded accommodation space which caused bypass of terrigenous material in a shallow water setting and deposition in more distal setting as seen in the final depositional packages of Janjića Vrh log (Fig. 1; Andrić et al., 2015).

3.7.2. POINT 12. LAŠVA – Lacustrine delta deposits of the Lašva Formation

Locality:	Lašva
WGS84 coordinates:	44.133401° N, 17.937542° E
Age:	Middle Miocene
Formation:	Lašva Formation ($M_{2,3}$)

The impressive Lašva section is located nearby the confluence of the Lašva and Bosna rivers (Fig. 29, 33b and 35). It shows 25 m of coarse-grained alluvial-deltaic sediments of the Lower to Middle Miocene (i.e., Lašva unit sensu Milojević, 1964). This is an example of the rapid transition from floodplain deposits into braided channels of the braid-delta plain and delta front (Fig. 33b). Most likely, it represents a more proximal equivalent to the Janjića vrh section.

Description and interpretation

The succession starts with floodplain deposits represented by the alternation of (dark) grey parallel laminated siltstone and organic rich claystone pairs intercalated with thin beds of red fine-grained sandstones or isolated granula to coarse sand channels. These deposits engulfed beige to yellow mudstone with traces of ostracods. Deposition is associated with ostracods indicating suspension settling in shallow lacustrine/lagoon environment. Further on, the amalgamation of the channels and channel/floodplain sediments ratio increases up in the section creating an overall coarsening-upwards trend (Fig. 33b). The amalgamated packages are partly eroded and overlain by more proximal alluvial deposits supplying the prograding delta front. The upper part of the

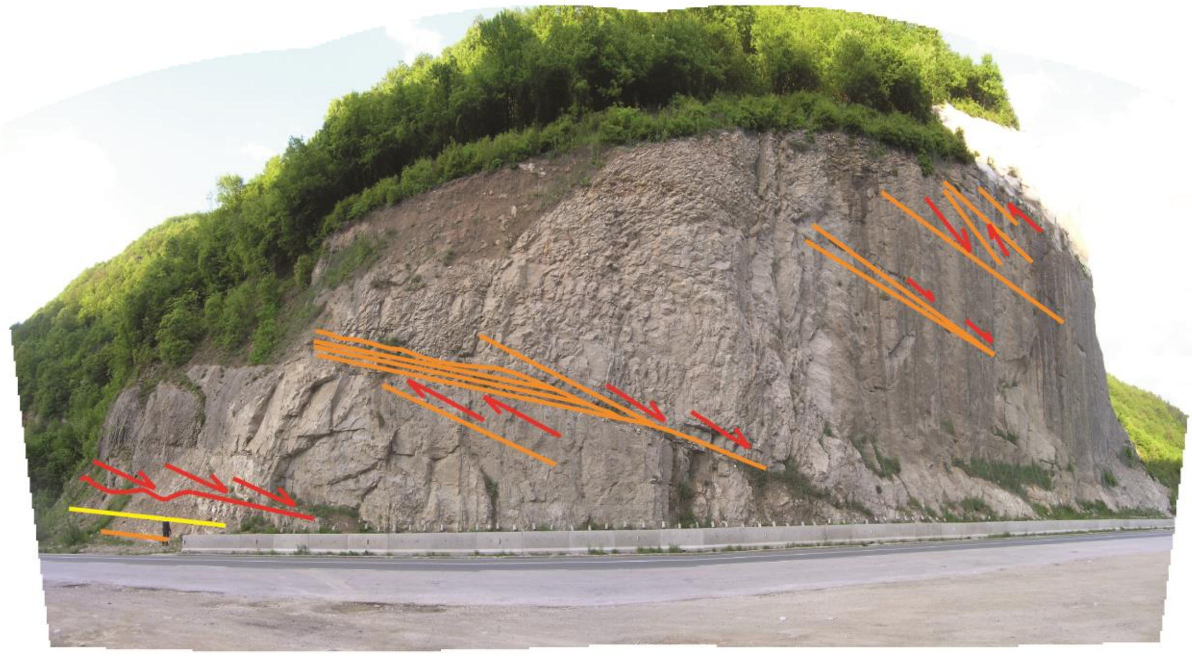


Fig. 35. High-frequency prograding-retrograding depositional trends in the Lašva section resulting from rapid changes in sedimentation rates and/or accommodation space formed in the overall prograding style in the delta front setting (orange lines). The red wavy line represents the surface of forced regression, the yellow line marks the maximum flooding surface, orange lines delineate bedding planes (Andrić et al., in prep.).

section is dominated by matrix-to clast-supported pebble to cobble conglomerates. The clasts are sub-angular to sub-rounded, poorly sorted, and predominantly sourced from the Mid-Bosnian Schist Mountains. Up to 5-m-thick conglomeratic packages are sealed by thin parallel- to ripple-laminated fine sandstone-siltstone couplets. This “bipartite” geometry most likely represents the higher-order progradational-retrogradational cycles on the river mouth (Fig. 35).

The shallow water lacustrine carbonates with ostracods dividing floodplain deposits mark the maximum flooding surface formed during rapid increase of accommodation space most probably during a period of highest displacement rate along the normal fault. The overlying facies associations typically display progradational stacking patterns and coarsening upwards trends accompanied by low rates of aggradation. The erosion of delta plain deposits and abrupt shift to the alluvial fan deposits attest for the force regressive surface at the mouth of the river dominated delta (Andrić et al., 2015).

Andrić et al. (in prep) concluded that both the Janjića Vrh and Lašva section represent regressive system tracts deposited during the final stage of normal fault activity. The exhumation of normal fault footwalls increased the profile of the source area and produced bed-load dominated rivers carrying coarse grained material into the basin further away from the source filling up the basin. Hereby a diachronous basal progradation surface (force regressive surface) was created, which is younger in a distal direction (Sweet et al., 2003, Ramaekers & Catuneanu, 2004). The over-filled nature of the basin during this period was caused by the predominance of sediment supply rates resulting from the exhumation of the footwall over rates of accommodation space creation (e.g., Carroll & Bohacs, 1999; Withjack et al., 2002).

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