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Alluvial-lacustrine-marine complex of Mount Medvednica: the early syn-rift deposition and palaeogeography (Early to Middle Miocene, North Croatian Basin)

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Original scientific paper

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Abstract

Mt. Medvednica belongs to the western part of the Neogene rift-type North Croatian Basin that occupies the south-western Pannonian Basin System. The Lower to Middle Miocene continental to marine sedimentary complex was studied on Mt. Medvednica in order to interpret the early syn-rift depositional environment and reconstruct palaeogeography of the North Croatian Basin. Based on facies analysis, deposits are grouped into 16 facies based on their lithological characteristics. Six of the facies belong to the alluvial environment that is characterized by coarse-grained bedload siliciclastics. Nine facies are of lacustrine origin. They comprise: a) limestone of shallow lake carbonate bench with silty coal of vegetated marsh, b) deep lake and prodelta marl with sand and conglomerate intercalations deposited by gravity flows, and c) coarse-grained Gilbert-type delta conglomerate. The lacustrine deposits compose a transgressive-regressive sequence. The studied succession ends by facies of calcareous silt intercalated by conglomerates. These deposits belong to the marine offshore to prodelta as the consequence of establishment of the connection to the sea. The deposition was strongly controlled by allogenic factors, such as synsedimentary tectonics, climate, eustatic sea level changes and explosive volcanic activity. The alluvial deposits of Mt. Medvednica are the oldest syn-rift deposits and belong to the large alluvial plain that probably covered the entire North Croatian Basin in the Ottnangian and the Karpatian. These deposits are overlain by the lower Badenian lacustrine deposits, but the question of the existence of one large or several small lakes in the early Badenian North Croatian Basin remains open.

Keywords:
alluvial deposits; lacustrine deposits; marine deposits; syn-rift; North Croatian Basin

1. Introduction

Continental rifting is a complicated geotectonic process that strongly affects the Earth's crust. It is generated by the mantle uplift that results in the attenuation and extension of the crust and formation of a sedimentary basin. The first phase of basin development is characterized by the tectonic thinning of the crust and isostatic subsidence (syn-rift), while the second phase is marked by the cessation of rifting, and subsidence caused by the cooling of the lithosphere (post-rift). The syn-rift phase of the newly forming basin evolution is characterized by a specific depositional sequence. Due to the extensional tectonics mostly characterized by normal faulting, the subsided area is represented by half-grabens that are usually filled by alluvial deposits as a result of erosion of uplifted blocks (**Surlyk, 1978, 1989; Allen and Allen, 1990; Nøttvedt et al., 1995; Gawthorpe and Leeder, 2000; Brune et al., 2023**). The continuation of the tectonic subsidence may generate shift from the alluvial to the lacustrine environment, and the establishment of the connection to the sea later on. The syn-rift deposition is usually accompanied with volcanic activity. One such continental rifting process formed the central European Neogene Pannonian Basin System (PBS) which has had a complex geological history (**Stegena et al., 1975; Horváth and Royden, 1981; Royden, 1988; Cloetingh et al., 2005; Matenco and Radivojević, 2012**) (see **Figure 1**). The PBS is surrounded by orogenic mountain chains of the Alps, Carpathians and Dinarides, and palaeogeographically belongs to the area of Central Paratethys. During the Miocene, connection of the Central Paratethys with the open sea was established and ceased several times. The specific nature of Central Paratethys evolution and the occurrences of endemic faunas have necessitated the establishment of regional Neogene stages (**Steininger and Rögl, 1979; Baldi, 1980; Rögl and Steininger, 1984; Popov et al., 2004; Piller et al., 2007; Kováč et al., 2017**).

The south-western marginal zone of PBS is represented by the North Croatian Basin (NCB) characterized by

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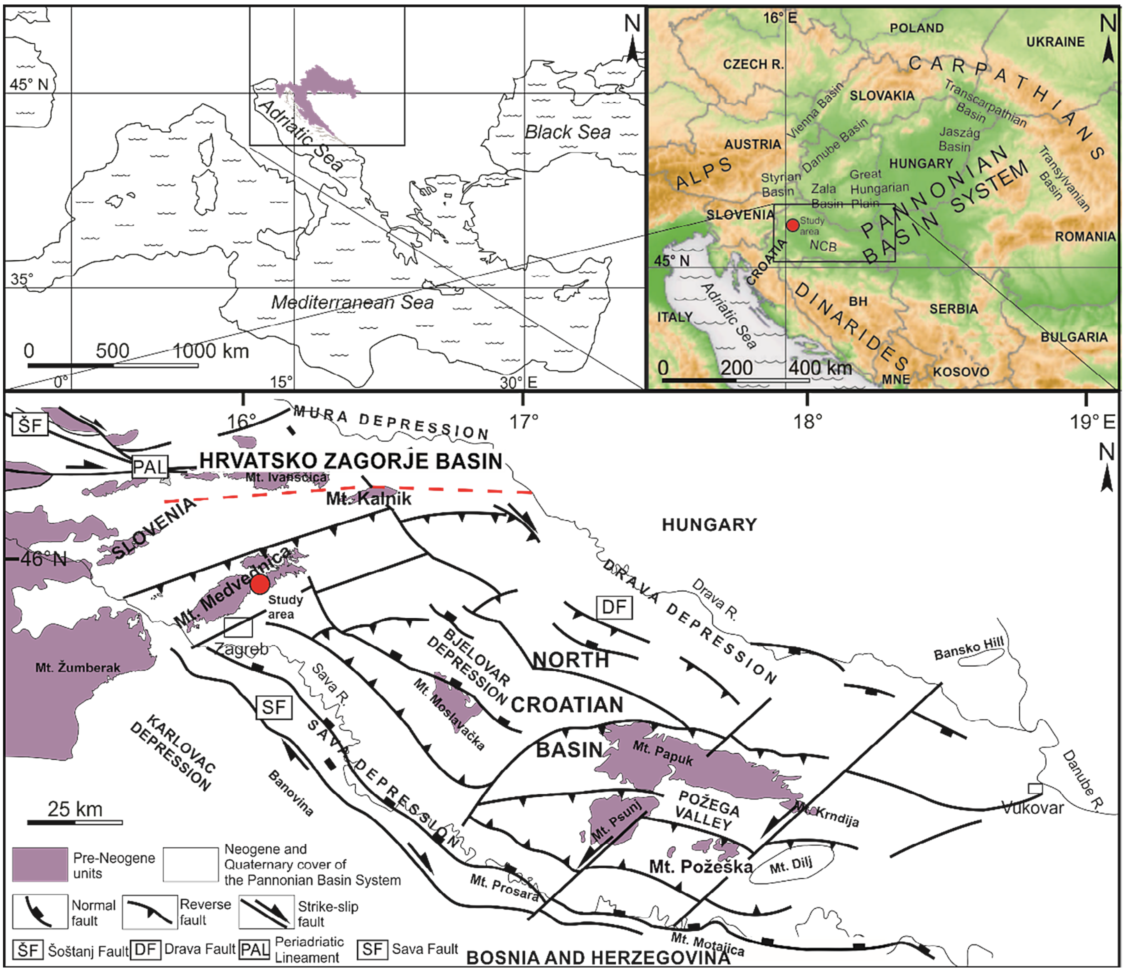

Figure 1: Location map. The North Croatian Basin belongs to the south-western zone of the Pannonian Basin System, that occupies most of northern Croatia. The main faults are modified after **Márton et al. (2002)**, **Ustaszewski et al. (2014)** and **Rukavina et al. (2023)**.

specific evolution, particularly concerning the syn-rift phase (see **Figure 1**). After the long-lasting emersion, the rifting processes commenced in the late Early Miocene when a large alluvial plain with a saline lake was formed, that was controlled by the semi-arid climate. More north-western, the Central Paratethys Sea evolved contemporaneously (**Avanić et al., 2021**). Successive tectonic subsidence of the NCB, together with the climate change towards humid conditions, generated a lacustrine depositional system that was substituted by a marine environment in the Middle Miocene. The continental to the marine sedimentation was followed by increasing explosive volcanic activity that resulted in pyroclastic accumulations within the alluvial, lacustrine and marine deposits (**Mutić, 1969, 1980, 1981; Mandic et al., 2012; Brlek et al., 2020; Marković et al., 2021; Trinajstić et al., 2023**). A similar continental sequence occurred in the Slovenj Gradec Basin in Slovenia (**Ivančič et al., 2018a, 2018b**) indicating a unique tectono-sedimentary development of the south-western PBS. The continental deposition was also spread in the neighbouring Dinarides in the Early and Middle Miocene (**de Leeuw et al., 2012; Andrić et al., 2017**).

The syn-rift sedimentary complex is developed on many uplifted rocky massifs in NCB, but has been sedimentologicaly studied in detail only on Mt. Požeška, Mt. Papuk and Mt. Kalnik (**Pavelić and Kovačić, 1998; Pavelić et al., 1998, 2001, 2022b**). As the complex is well developed on Mt. Medvednica, data and results based on sedimentological study can contribute to a better knowledge of the regional development of the NCB in its syn-rift phase (see **Figure 1**). In order to reconstruct the evolution of the Lower to the Middle Miocene continental deposits on Mt. Medvednica, ten sections were measured and their facies were analysed.

2. Geological setting

Mt. Medvednica is an uplifted rocky massif characterized by a complex lithological composition and structure. The mountain belongs to two independently evolved geotectonic units, the older Inner Dinarides and the younger Pannonian Basin System (**Herak, 1986; Royden, 1988; Šikić, 1995; Schmid et al., 2008; Kováč et al., 2017, 2018b**). The Dinaridic core of Mt. Medvednica is composed of different types of metamorphic,

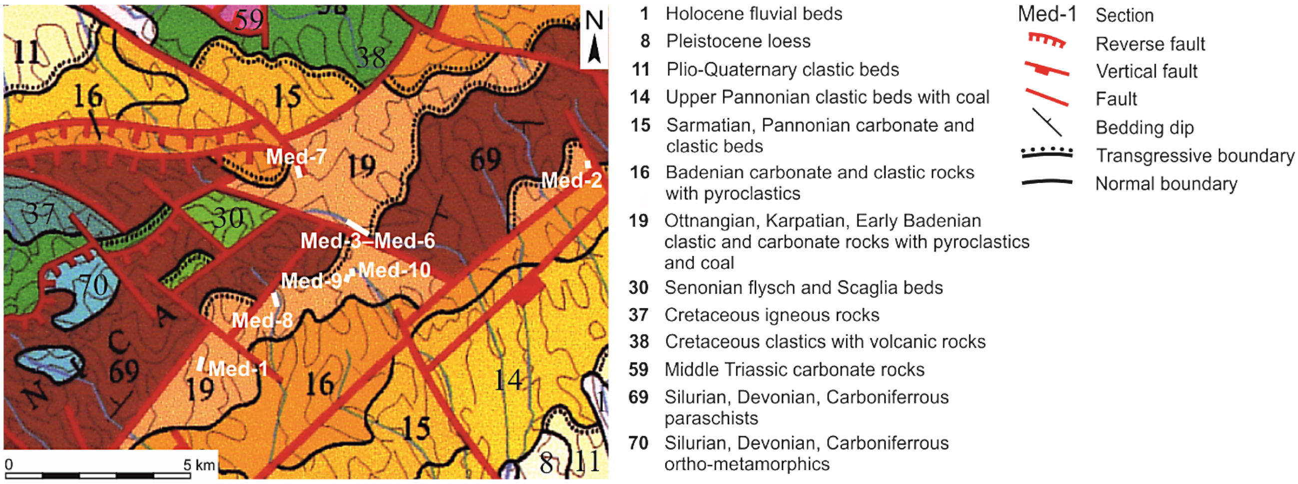

Figure 2: A simplified geological map of the central part of Mt. Medvednica (after **HGI, 2009**) with study localities.

sedimentary, and magmatic rocks of Paleozoic, Mesozoic and Paleogene age (see **Figure 2**). They are strongly deformed due to polyphasic extensional to compressional long-lasting geotectonic processes related to evolution of the Western Tethys Ocean realm and the orogenic uplifting of the Dinarides (**Gorjanović-Kramberger, 1908; Šikić et al., 1979; Basch, 1983; Pamić, 1987; Šikić, 1995; Belak and Tibljaš, 1998; Halamić et al., 1998, 1999; Pamić and Tomljenović, 1998; Slovenec and Lugović, 2009; Belak et al., 2023**). The core is surrounded by the Neogene and Quaternary deposits that are the result of the NCB evolution. The oldest Neogene deposits crop out in the central area of the Mt. Medvednica (see **Figure 2**). They are of continental origin, and are Early (Ottnangian, Karpatian) to Middle Miocene (early Badenian) in age (see **Figure 3**). The continental deposition reflects the early syn-rift phase of the NCB evolution. The deposition commenced in the alluvial environment (Daranovci formation, according to lithostratigraphy established on Mt. Požeška, **Pavelić et al., 2022a**) that shifted to the lacustrine environment (Glavnica formation, **Hajek-Tadesse et al., 2022**). Contemporaneously with the lacustrine deposition, the Central Paratethys Sea affected the area of Mt. Medvednica (**Premec Fućek et al., 2022; Trinajstić et al., 2023**). Due to the opening of the connection to the sea and transgression in the middle Badenian, the lacustrine environment was replaced by a marine environment in the late syn-rift phase (**Ćorić et al., 2009; Bošnjak et al., 2017; Pezelj and Drobnjak, 2019**) (Vejalnica formation, **Avanić et al., 2022**), while the uplifted pre-Neogene basement was flooded in places (**Brlek et al., 2016**). This Early to Middle Miocene continental to marine complex is characterized by various types of siliciclastic and carbonate deposits, while pyroclastic layers occur within the lacustrine and marine deposits (**Mutić 1969; Marković et al., 2021; Trinajstić et al., 2023**). The post-rift phase (late Badenian – Quaternary) is characterized by marine carbonates and siliciclastics with occurrences of pyroclastics, that are overain by marls and siliciclastics of the brackish Lake Pannon (**Šikić et al., 1979; Basch, 1983; Vrsaljko et al., 2005, 2006; Kovačić et al., 2004; Kovačić and Grizelj, 2006; Bakrač et al., 2012; Galović and Young, 2012; Grizelj**

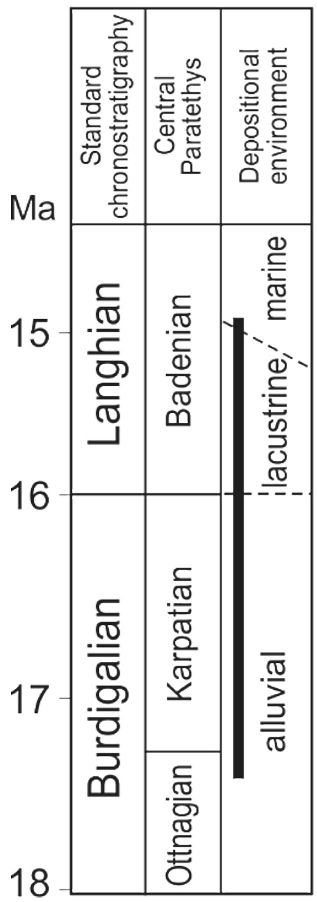

Figure 3: The stratigraphic and depositional scheme of Mount Medvednica in the Early and Middle Miocene. Standard chronostratigraphy derived from **Hilgen et al. (2012)**. Compilation of Central Paratethys stages is adopted from **Piller et al. (2007)**, and **Pavelić and Kovačić (2018)**. The tentative stratigraphic position of studied deposits on Mount Medvednica is represented by the black bar.

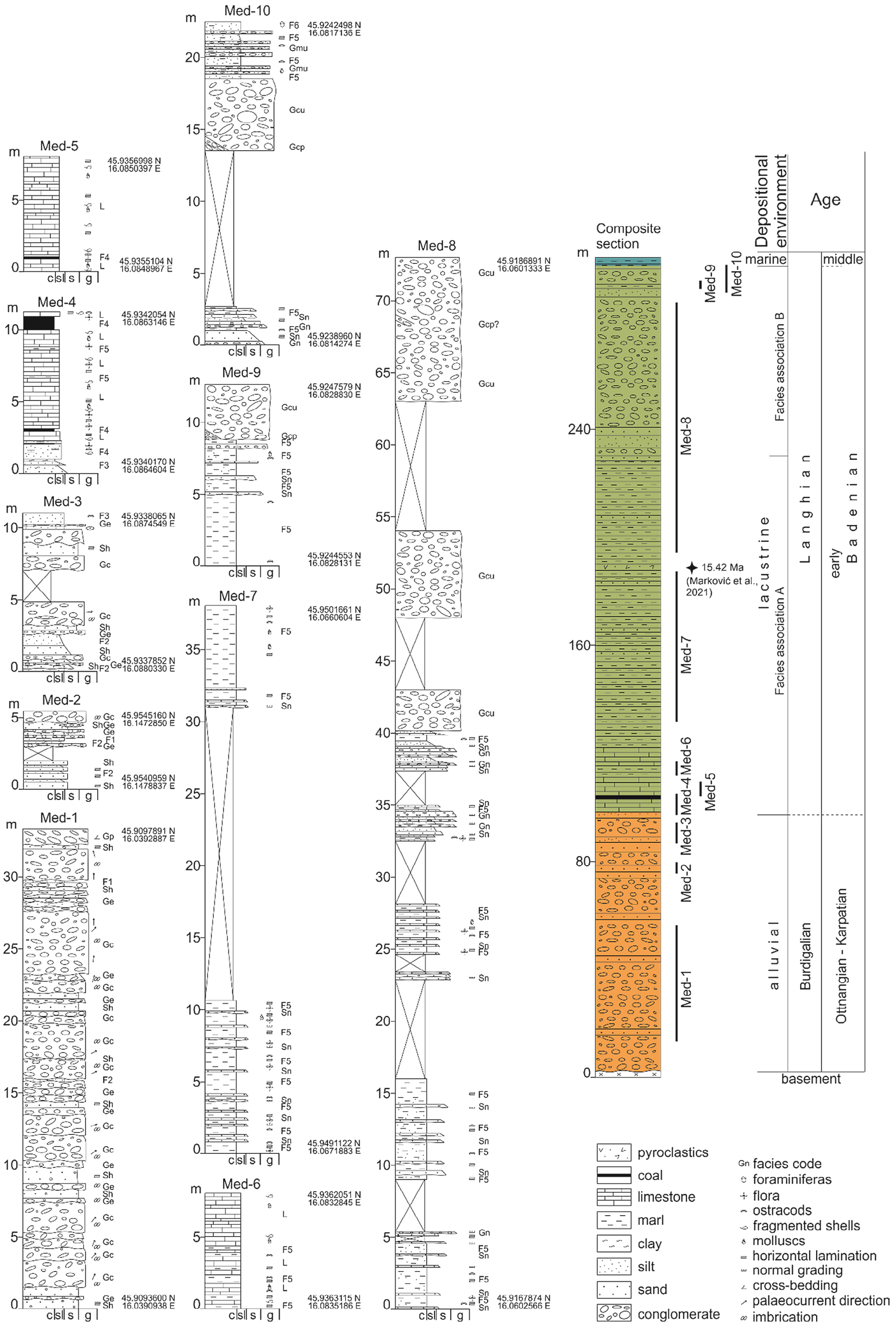

Figure 4: Stratigraphic sections at Mount Medvednica (Med-1 – Med-10). The composite section shows the stratigraphic relation of the measured sections, the depositional environments of beds, and the tentative age. The asterisk shows 40Ar/39Ar age obtained from volcanic glass from the lacustrine tuff (**Marković et al., 2021**).

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Table 1: Facies description and interpretation.

Facies	Code	Section	Description	Interpretation	References for interpretation
Alluvial					
Horizontally bedded conglomerate, clast-supported	Gc	Med-1–Med-3	Beds few tens of cm thick form amalgamated units up to 400 cm thick. Low-angle cross-bedding in places. Lower bedding surfaces erosional. Rounded to sub-rounded pebbles and cobbles. Some boulders up to 35 cm long in the base of beds. Imbrication $a_{(t)}$ $b_{(i)}$. Fine grained conglomerate and coarse grained sandstone as matrix. Medium sorted. Brownish colour. **Figure 5a, b, c**.	Longitudinal bar; channel lag	**Rust, 1972; Ramos & Sopeña, 1983; Nemec & Postma, 1993**
Planar cross-bedded conglomerate	Gp	Med-1	Form a unit 150 cm thick. Well-developed planar cross-bedding. Cross-beds 10-30 cm thick. Lower bedding surface of the unit erosional. Rounded pebbles and cobbles. Coarse grained sandstone as matrix. Brownish colour. **Figure 5b**.	Transverse bar	**Smith, 1970, 1974; Miall, 1978a; Steel & Thompson, 1983**
Lense-like conglomerate	Ge	Med-1–Med-3	Lenses up to 6 m long, and up to 50 cm thick. Concave-up erosion surfaces. Clast-supported. Well-rounded to semi-angular mostly pebbles and rare cobbles. Fine grained conglomerate and coarse grained sandstone as matrix. Imbrication $a_{(t)}$ $b_{(i)}$ in places. Brownish colour. **Figure 5d**.	Shallow channel	**Rust, 1972; Steel & Thompson, 1983**
Horizontally laminated sandstone	Sh	Med-1–Med-3	Forms units between 5 and 110 cm thick. Horizontal laminae up to few mm thick. Fine to coarse grained, gravelly in places. Poorly to very well sorted. Brownish colour. **Figure 5b, c**.	Traction in the upper flow regime on bar or in shallow channel	**Rust, 1972, 1978; Miall, 1978a**
Structureless silt	F1	Med-1, Med-2	Form units 6 to 180 cm thick. Well sorted. Yellowish-brown colour.	Flood plain; abandoned channel	**Miall, 1996**
Modified silt	F2	Med-1–Med-3	Forms structureless units 3 to 50 cm thick. Sandy or clayey in places. Fe-oxide concretions. Poorly sorted. Bluish to reddish colour.	Flood plain palaeosol	**Walker & al., 1978; Tandon & Friend, 1989**
Lacustrine					
Structureless conglomerate, matrix-supported	Gmu	Med-10	Forms units between 5 and 30 cm in thickness. Lower bedding surfaces irregular and non-erosive. Rounded to well rounded pebbles to cobbles up to 16 cm in diameter. Sandy silt as matrix. Very poorly sorted.	Cohessive debris flow in proximal prodelta	**Lowe, 1982; Nemec & Steel, 1984, 1988; Massari & Colella, 1988; Nemec, 1990; Postma, 1990; Dasgupta, 2003**
Structureless conglomerate, clast-supported	Gcu	Med-8–Med-10	Forms probably a chaotic unit 34 m thick. Composed of pebbles, cobbles and boulders up to 120 cm long. Scarce fine grained gravel as matrix. Very poorly sorted. **Figure 6a, b, c, d**.	Cohessionless debris flow in coarse-grained delta	**Lowe, 1982; Nemec & Steel, 1984, 1988; Massari & Colella, 1988; Nemec, 1990; Postma, 1990; Surlyk & Noe-Nygaard, 2001; Dasgupta, 2003; Gierlowski-Kordesch, 2010**
Cross-bedded conglomerate	Gcp	Med-9, Med-10	Thickness of cross-beds between 5 and 10 cm. Composed of rounded to sub-rounded pebbles, cobbles and boulders up to 40 cm long. Clast-supported. Larger clasts in basal parts of cross-beds. Scarce fine grained gravel and sand as matrix. **Figure 6c**.	Avalanching in Gilbert-type fan delta	**Postma, 1990; Postma & Cruickshank, 1988; Kazanci, 1990; Prior & Bornhold, 1990**
Normally graded conglomerate	Gn	Med-8, Med-10	Horizontally bedding. Bed thickness between 10 and 40 cm. Erosive lower bedding surfaces. Fine to coarse grained with pebbles up to 3 cm in diameter. Coarse grained sand as matrix, more accumulated in upper parts of beds.	Gravelly high-concenrated turbidity currents; proximal prodelta	**Lowe, 1982; Marzo & Anadon, 1988; Prior & Bornhold, 1988; Surlyk & Noe-Nygaard, 2001; Dasgupta, 2003; Gierlowski-Kordesch, 2010**

Table 1: Continued

Facies	Code	Section	Description	Interpretation	References for interpretation
Normally graded sand	Sn	Med-7–Med-10	Horizontal beds and units between 1 and 50 cm thick. Slightly erosive lower bedding surfaces. Medium to fine grained, coarse grained and gravelly in places. Millimetre scale horizontal lamination in lower parts of units. Silty in uppermost parts of beds or units. Well to very well sorted. Tiny fragments of carbonized plant remains.	Sandy high-concenrated turbidity currents; hyperpycnal flow; distal prodelta	**Lowe, 1976; Marzo & Anadon, 1988; Prior & Bornhold, 1988; Kneller & Branney, 1995; Dasgupta, 2003; Kostic & Parker, 2003; Gierlowski-Kordesch, 2010; Andrews & Hartly, 2015**
Sandy to clayey silt	F3	Med-3, Med-4	Form units 25-90 cm thick. Base of the units sandy, tops clayey. Medium sorted. Fresh water ostracods, fragments of plant roots, and Fe-oxide concretions on places.	Very shallow lake, temporarely emersion	**Pavelić, 1998; Andrews & Hartly, 2015; Frisch et al., 2019**
Silty coal	F4	Med-4, Med-5	Horizontal beds or units 1 to 125 cm thick. Thinner coal beds intercalated with mm scale laminae of silt and clay. Rare freshwater bivalves and gastropods. **Figure 6g**.	Vegetated marsh	**Cabrera and Saez, 1987; Alonso-Zarza & Calvo, 2000; Mandic et al., 2009; Vranjković et al., 2024**
Horizontally laminated marl	F5	Med-4, Med-6–Med-10	Form units between few and 550 cm in thickness. Silty on places. Horizontal lamination of mm scale, varve-like. Some horizons of units non-laminated. Grey colour in general. Fresh-water bivalves, gastropods, ostracods, characeans and fragments of carbonized terrestrial plant remains. **Figure 6d, e, f**.	Deep lake	**Murphy & Wilkinson, 1980; Treese & Wilkinson, 1982; Pavelić, 1998; Platt & Wright, 1992**
Horizontally laminated limestone	L	Med-4–Med-6	Horizontally bedded, bed thickness varies between 1 and 25 cm. Horizontal lamination of mm scale. Non-laminated beds include fragments and whole bivalves and gastropods. Characheans and carbonized terrestrial plant remains. **Figure 6g**.	Carbonate bench of shallow lake	**Murphy & Wilkinson, 1980; Platt & Wright, 1992; Pavelić, 1998; Alonso-Zarza & Calvo, 2000; Della Porta, 2015; Wright, 2020; Vranjković et al., 2024**
Marine					
Calcareous silt	F6	Med-10	Forms a 135 cm thick unit at the top of succession. Structureless, calcareous, includes Gmu intercalations. Tiny fragments of carbonized plant remains. Rare foraminiferas.	Marine offshore, proximal prodelta	**Hunter et al., 1979; Bourgeois, 1980; Pavelić, 1998; Schwarz, 2012**

et al., 2017; Sremac et al., 2018; Brlek et al., 2018). The lake was infilled at the Miocene/Pliocene boundary, when an alluvial plane formed (**Kovačić, 2004**). The post-rift compressional events caused basin inversion and strong uplifting of tectonic blocks that resulted in the modern structural pattern of the Mt. Medvednica characterized by different types of deformations, such as inclined beds, and numerous folds and faults, including overturned tectonic structures (**Šikić et al., 1977; Basch, 1983; Tomljenović and Csontos, 2001**) (see **Figure 2**). These tectonic processes generated counterclockwise rotation of structural blocks of Mt. Medvednica (**Márton et al., 2002**).

3. Methods

The field work comprised detailed facies analysis and measurements. In order to interpret the depositional mechanism of siliciclastic deposits, clast-size was measured, their roundness and sorting was described, and clast/matrix ratio was estimated. The character of bedding surfaces was determined, while the geometry of sedimentary bodies was measured at large outcrops. Furthermore, the general colour of sediments was defined. The fossil content in limestones and fine-grained deposits was specified that enabled palaeoecological reconstruction of depositional environments. The dip direction of $a_{(t)}$ $b_{(i)}$ imbricated, mostly platy pebble-cobble sized fragments was measured in order to reconstruct palaeoflow directions and estimate the location of the main depocentre in NCB during the time of sedimentation.

4. Results with interpretation

On Mt. Medvedica ten sections (Med-1 – Med 10, see **Figure 4**) were measured. Sections are located in the central area of the mountain (see **Figure 1**). The total thickness of the sections is 220.5 m. However, some portions of sections were covered by soil and vegetation that represents stratigraphic gaps, so the thickness of measured deposits is 188 m. According to their lithological characteristics, the deposits are divided into 16 lithofacies that generally belong to three depositional environments: alluvial, lacustrine and marine. Their stratigraphic relation suggests the alluvial deposits are overlain by the lacustrine deposits that are covered by marine deposits. Therefore, the superposition defines the alluvial deposits as the oldest, followed by the lacustrine deposits, and marine deposits on top as the youngest. The measured thicknesses indicate prevailing of the lacustrine deposits (108 m) over the alluvial deposits (45.5 m), while the marine deposits occur only at the top of the general sequence as a sole unit of 1 m thickness. The main lithological characteristics, position in the sequence and interpretation of the facies are presented in **Table 1**.

4.1. Description and interpretation of facies

The main characteristics of alluvial deposits are a domination of coarse-grained over fine-grained siliciclastics, notable variations in grain size, rapid lateral and vertical facies alternations, erosive lower bedding surfaces, rare occurrences of reddish beds, and lack of fossils. The alluvial deposits are well illustrated in three geological sections (Med-1 – Med-3) where they are grouped into six facies. Various types of conglomerate prevail (Gc, Gp and Ge), while sandstone (Sh) and silt (F1 and F2) occur rarely (see **Figures 4** and **5, Table 1**).

Lacustrine deposits are more organized, and are characterised by the prevailing carbonates. Silt and limestone with silty coal intercalations represent the base of the sedimentary complex, that is overlain by a relatively thick horizon of marl intercalated with sand. The lacustrine succession ends by various types of conglomerates which comprise the largest fragments in the entire sequence that indicates a fining- to coarsening-upwards cycle (except its top). The limestone, marl and silt are rich in freshwater bivalves, gastropods, ostracods, characeans, and carbonized terrestrial plant remnants (**Pavelić, 1998**, and references therein). The lacustrine deposits are illustrated in eight sections (Med-3 – Med-10), where they are divided into nine facies (Gmu, Gcu, Gcp, Gn, Sn, F3, F4, F5 and L) (see **Figures 4** and **6, Table 1**).

Marine deposits are located at the top of the entire sequence (Med-10, F6) (see **Table 1**) where they are represented by calcareous silt with a foraminifera association (**Pavelić, 1998**, and references therein). That association palaeocologically distinguishes these deposits from similar lacustrine deposits (F3 and F5).

The composition of macroscopically studied conglomerates is heterogenous. Most common fragments are limestones, arenites, diabase, basalt, tuffite, metagreywackes, schists, marble, and others. These pebbles, cobbles and boulders are comparable with various types of pre-Neogene basement rocks of Mt. Medvednica and its neighbouring compositions that indicates local provenance and relatively short transport of the material (**Pavelić, 1998**, and references therein).

4.2. Palaeotransport

Palaeoflow directions are reconstructed by measurements of the dip direction imbricated, fragments in facies Gc.

A total of 217 fragment orientations were measured - 192 in the section Med-1, and 25 in the section Med-2 (see **Figure 7**). In the measured sections, a wide dispersion of palaeoflow orientation data was recorded. The results indicate a general palaeoflow direction towards the north to north-east (see **Figure 7**). However, palaeomagnetic data indicates a post-depositional counterclockwise rotation of Mt. Medvednica tectonic blocks

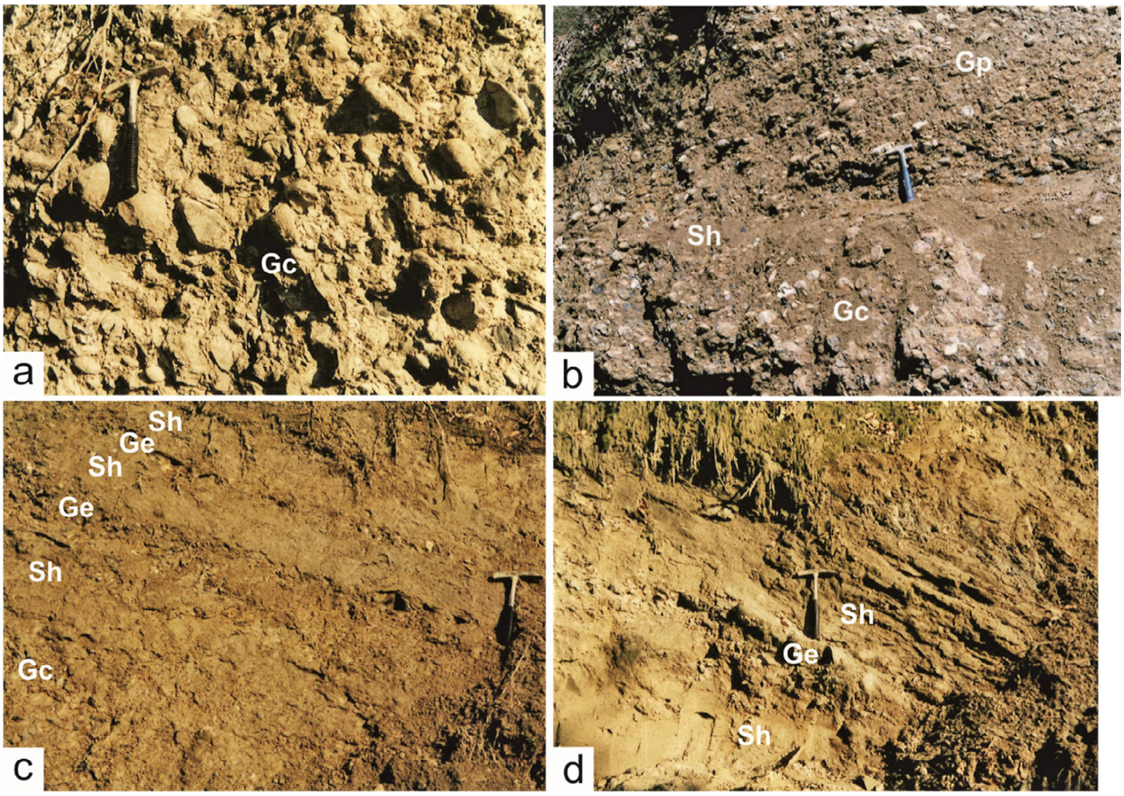

Figure 5: Alluvial facies. a) Horizontally bedded conglomerate, clast-supported (Gc) with imbricated fragments representing longitudinal bar. Hammer is 31 cm long. Section Med-1. b) Horizontally bedded conglomerate, clast-supported (Gc) in the lower part of photo (longitudinal bar), that is overlain by planar cross-bedded conglomerate (Gp) of transverse bar. 60 cm left from hammer is a lense of horizontally laminated sandstone (Sh) as sandy cover of the bar. Reddish colour of deposits is visible. Hammer is 31 cm long. Section Med-1. c) Intercalation of lense-like conglomerate (Ge) of shallow channels and horizontally laminated sandstone cover (Sh) in the upper part of photo. Horizontally bedded conglomerate, clast-supported (Gc) of longitudinal bar in the lower part. Hammer is 31 cm long. Section Med-1. d) Channel lense-like conglomerate (Ge) in the upper right part of photo. The conglomerate is covered by well developed horizontally laminated sandstone (Sh). Hammer is 31 cm long. Section Med-1.

by about 30°, as is the characteristic probably of the entire NCB (**Jamičić 1995; Márton et al., 1999, 2002, 2006**). It means that the real palaeotransport directions might be generally towards the north-east.

5. Discussion

5.1. Facies association of alluvial deposits

The alluvial deposits comprise six facies that encompass a facies association with the prevailing of various types of conglomerates (**Figure 4**, Med-1 – Med-3). Horizontally bedded conglomerates (Gc) are interpreted as longitudinal bars and channel lag, planar cross-bedded conglomerates (Gp) belong to a transverse bar, while lense-like conglomerates represent shallow channels (Ge). The scarce occurrence of horizontally laminated sandstones (Sh) is interpreted as traction deposits on bars or in shallow channels, flood plain or abandoned channel silt (F1) and floodplain silt (F2) modified by pedogenetic processes.

The prevalence of conglomeratic facies and bedload deposition, the thickness of deposits, the lack of fossils, soil forming, and the type of dispersion of the palaeotransport indicates the characteristics of a well developed gravelly braided river (**Williams and Rust, 1969; Smith, 1974; Miall, 1978a; Ramos and Sopeña, 1983; Steel and Thompson, 1983**). The interpreted facies association suggests a large supply of coarse-grained material that is indicated by the prevailing facies. Most of the material is accumulated in longitudinal bars by vertical aggradation during river floods. The bars also grew by lateral aggradation in periods of waning flow. Multiple repetition of growing of the longitudinal bars probably caused the braiding of flows that is a characteristic of shallow braided river systems (**Miall, 1996**). The conglomeratic unit interpreted as the transverse bar reflects a lower water and sediment discharge than longitudinal bars (**Hein and Walker, 1977**; **Ramos and Sopeña, 1983**). Flood plain reddish paleosol (F2) and lack of traces of vegetation indicate semi-arid conditions (**Walker et al., 1978; Tandon and Friend, 1989; Miall, 1996**). The significant prevalence of the gravelly bars over the flood plain deposits indicates the braided river deposition on the upper alluvial plain (**Vos, 1975**).

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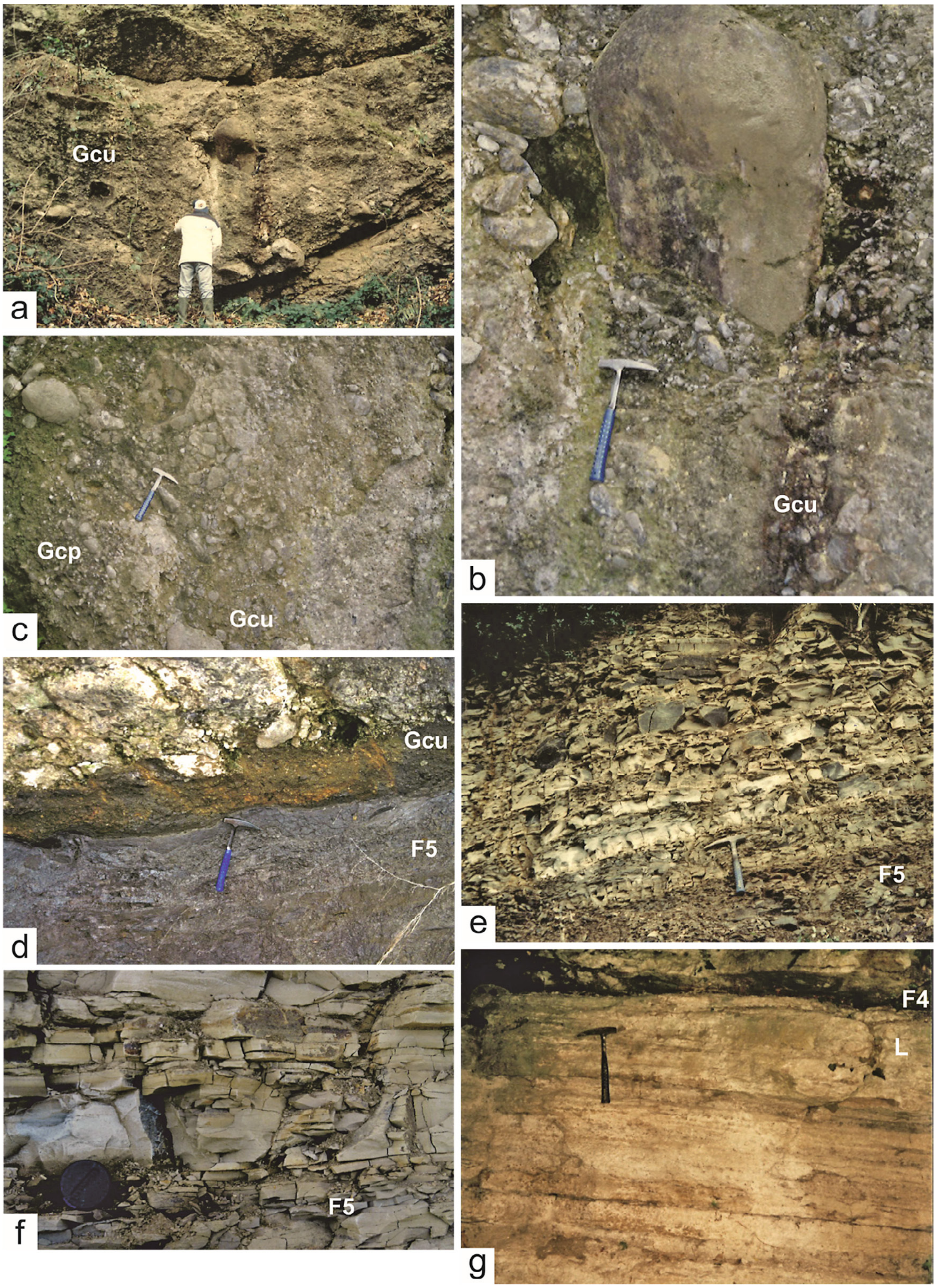

Figure 6: Lacustrine facies. a) Structureless conglomerate, clast-supported (Gcu) showing fragments of various size deposited by cohesionless debris flow in lacustrine coarse-grained delta. Section Med-8. b) Structureless conglomerate, clast-supported (Gcu) with block 50 cm long. Hammer is 31 cm long. Section Med-8. c) Cross-bedded conglomerate (Gcp) of Gilbert-type coarse-grained delta overlain by structureless conglomerate, clast-supported (Gcu). Hammer is 31 cm long. Section Med-10. d) Sharp and erosive contact between deep basinal horizontally laminated marl (F5) and structureless conglomerate, clast-supported (Gcu) indicates forced regression in the late episode of the lacustrine deposition. Hammer is 31 cm long. Section Med-10. e) Horizontally laminated marl (F5) forms units up to 550 cm thick. Hammer is 31 cm long. Section Med-8. f) Well developed horizontal lamination in F5. The camera lense cap is 5.5 cm in diameter. Section Med-7. g) Horizontally laminated limestone (L) of shallow lake carbonate bench. Silty coal bed (F4) in the upper part of photo as result of forming of vegetated marsh due to the lake level fall. Hammer is 31 cm long. Section Med-5.

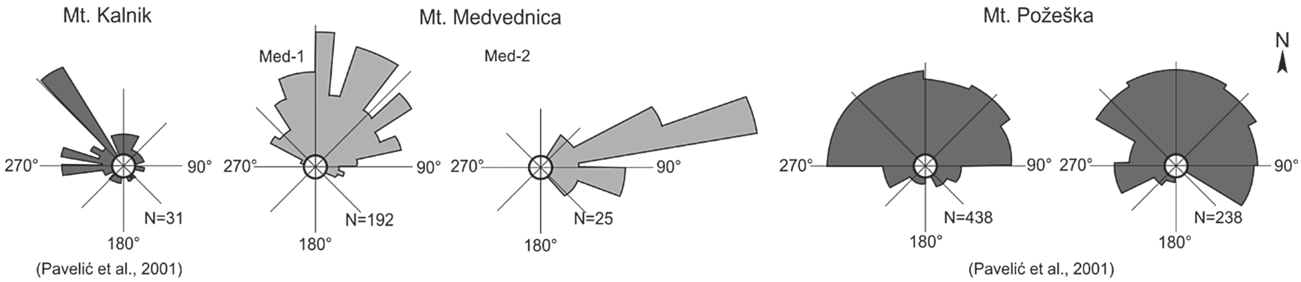

Figure 7: Correlation of palaeoflow directions of alluvial deposits on Mount Medvednica with Mount Požeška (**Pavelić and Kovačić, 1998**) and Mount Kalnik (**Pavelić et al., 2001**) based on rose diagrams. On Mount Medvednica the dip of imbrication in horizontally bedded conglomerate, clast-supported (Gc) shows palaeoflows towards the north to north-east. The counterclockwise correction of about 30° is not taken into account.

5.2. Facies associations of lacustrine and marine deposits

The lacustrine deposits can be divided in two facies associations (A and B) in a clear superposition succession that exhibits a transgressive-regressive sequence (except its topmost part).

Facies association A, that directly overlays alluvial deposits, is composed mostly of fine grained sediments and limestones. So, sandy to clayey silt (F3) belongs to the association, that is interpreted as the very shallow lake deposit, together with silty coal (F4) of vegetated marsh, horizontally laminated limestone (L) of the shallow lake carbonate bench, and horizontally laminated marl (F5) deposited in deep lake. This facies association represents the lower portion of the lacustrine succession (see **Figure 4**). The vertical tendency of the Facies association A shows an alternation of the deposits that indicate a deepening of the lake. There is sandy to clayey silt (F3) of the very shallow lake in the base, that is overlain by the intercalation of the vegetated marsh silty coal (F4) and shallow lake carbonate bench limestone (L). The generally shallow lake deposits are overlain by the deep lake intercalation of the prevailing horizontally laminated marl (F5) and normally graded sand (Sn) deposited by turbidity currents or hyperpycnal flows in distal prodelta.

Facies association B belongs to the upper portion of the lacustrine succession (see **Figure 4**). The association, that is interpreted as the proximal coarse-grained delta, is mostly composed of coarse-grained deposits, while finer varieties occur sporadically. The coarse-grained sediments are represented by conglomerates as the result of different types of gravity flows. Clast-supported structureless conglomerate (Gcu) prevails in the Facies association B occupying the uppermost portion of the lacustrine succession, and is associated with a cross-bedded conglomerate (Gcp) of the Gilbert-type fan delta. Those types of conglomerates overlay the intercalation of the deep lake horizontally laminated marl (F5) with the prodelta matrix-supported structureless conglomerate (Gmu), normally graded conglomerate (Gn) and normally graded sand (Sn). The uppermost portion of the lacustrine succession is characterized by the repeated occurrence of the deep lake horizontally laminated marl (F5) intercalated by the prodelta matrix-supported conglomerate (Gmu). The lacustrine deposits are overlain by marine offshore calcareous silt (F6) with intercalations of the matrix-supported structureless conglomerate (Gmu) that indicates a proximal prodelta.

Ecological characteristics of flora and fauna in fine-grained deposits and limestones indicate a freshwater lacustrine environment (**Pavelić 1998**, and references therein). Shallow water limestones (L) and deep lake marls (F5) reflect the lake with prevailing carbonate deposition, so the lake can be compared with the facies distribution in modern marly lakes (**Murphy and Wilkinson, 1980; Platt and Wright, 1991**).

The Facies association A indicates the initial episode of the forming of the lake when the lake water flooded deposits of the previous river flood plain (F2 and Ge). The silt (F3) of the very shallow lake was the first lacustrine deposit that was soon overlayed by carbonates as a consequence of the discontinuation of the terrestrial supply, and the evolution of the shallow lake carbonate bench (L). The initial episode was followed by the lake bottom colonization of fresh water flora and fauna, such as characeans, bivalves, gastropods and ostracods. The terrestrial vegetation was flourishing that resulted in the development of marsh, while the accumulation of the organic matter formed coal beds. The successive lake level rise resulted in the deposition of marl (F5). The frequent carbonized terrestrial plant fragments in the marl indicate a climate change into more humid conditions. The deepening ended with the formation of a stable lacustrine environment characterized by the prevalent deposition of marl that was temporarily interrupted by the deposition of sand (Sn) by gravity flows (**Kneller and Branney, 1995**) or hyperpycnal flows that were emanating from delta channels during periods of fluvial flooding on land (**Dasgupta, 2003; Kostic and Parker, 2003; Yang et al., 2017**).

The transition from the carbonate bench to the marly deep lake may indicate specific allogenic controls on the lacustrine deposition. The development of the carbonate bench might reflect its distal position from the river mouth, or it was the result of a quick tectonic subsidence at the active margin of the basin, when clastic material accumulates in traps in the proximity of the source area (**Blair and Bilodeau, 1988; Heller and Paola, 1992**). The vertical transition from the shallow into the deep lake indicates prevailing of the subsidence rate over the sedimentation rate, which is an important characteristic of lakes in rift tectonic settings (**Platt and Wright, 1991**). The deepening of the lake might also be forced by increased water budget as the consequence of climate change towards humid conditions, which is documented by frequent occurrences of the terrestrial vegetation in lacustrine deposits. However, there is also a possibility of indirect eustatic influence on the lake level that might have played a role (cf. **Steininger et al., 1989; Dam and Surlyk, 1993**) because the lake formed in the period of the eustatic sea level rise (**Kováč et al., 2007, 2018a; Piller et al., 2007**). It is likely that two or even three allogenic controls, acting simultaneously, caused the deepening of the lake system: 1) the rift tectonics, 2) the humid climate and 3) the indirect eustatic influence.

The Facies association B, with the coarsest conglomerates (Gcu and Gcp) in its upper portion, is interpreted as to belong to the coarse-grained delta, and represents the late episode of the lake evolution. The delta, in which such depositional mechanisms operate, may indicate some characteristics of the lake coast. The planar cross-bedded conglomerates (Gcp) as the result of avalanching indicate the existence of a relatively steep slope, while boulders up to 40 cm long suggest proximity of the source area. Such a coarse-grained delta can be compared with the Gilbert-type fan delta of the type A (after the classification by **Postma, 1990**), where the conglomerates represent the delta front. Resedimentation is a common process in a delta of that type, so it could have caused the accumulation of the clast-supported structureless conglomerates (Gcu) by cohesionless debris flow (**Postma and Cruickshank, 1988; Prior and Bornhold, 1989, 1990; Gobo et al., 2014, 2015; Gruszka and Zieliński, 2021**). Resedimentation processes in a coarse-grained delta on a steep slope commonly occur during progradation of the clastic system (**Massari and Colella, 1988**). The progradation might reflect the forced regression generated by abrupt lake level fall in the period of tectonic quiescence (**Blair and Bilodeau, 1988; Gawthorpe and Colella, 1990; Heller and Paola, 1992**). The interpretation is supported by the sharp contact between the deep lake marl (F5) and overlying conglomerates (Gcu) (see **Figure 6d**).

The initial episode of lake formation was related to the active basin margin. The margin might have affected the lake in its late episode, too, as indicated by the Gilbert-type fan delta, the specific depositional environment which commonly forms along an unstable basin margin (**Massari and Colella, 1988**). Such an isolated coarse-grained delta can be related to transverse faults in extensional basins (**Reading and Richards, 1994**), like it was in the NCB.

The occurrence of fine-grained deposits (F5) at the top of the lacustrine sequence indicates repeated deepening of the lake where its basinal part was reached by cohesive debris flow (Gmu) in the zone of the lacustrine proximal prodelta. The deepening is interpreted as the consequence of reactivation of tectonics that generated the basin subsidence (after **Blair and Bilodeau, 1988; Heller and Paola, 1992**).

The topmost portion of the sequence represented by the offshore marine calcareous silt (F6) indicates termination of the lacustrine phase, and the onset of the marine phase. The lack of any traces of emersion and the beginning of the marine deposition with no transgressive deposits indicates the continuity of deposition from the lake into the sea. Intercalations of conglomerate (Gmu) within marine silts suggest the coarse-grained delta still affected the marine basin.

5.3. Palaeogeographic implications of alluvial deposits

Rifts are usually characterized by normal faulting along the active margin of the extensional basin. There, the source is mostly represented by uplifted footwall blocks where the fault scarp is directed perpendicular to the braided system general flow (**Miall, 1978b; Gawthorpe and Leeder, 2000; Leeder, 2011; Chen et al., 2020**). That indicates the north-eastern facing footwall block acted as the water and sediment source of the gravelly braided river on Mt. Medvednica. As its deposits belong to the upper alluvial plain, the source block and the proximal river area was probably located relatively close to the study area, i.e. more towards the south-west. The interpretation is supported by the composition of the river material that reflects the Mt. Medvednica pre-Neogene rocks, but is also comparable with rock formations found in boreholes south-eastern from Mt. Medvednica (**Pavelić, 1998,** and references therein). Moreover, the partial palaeotransport towards Mt. Medvednica (see **Figure 7**) suggests the mountain was probably represented by just a small uplifted massif that might have acted as the minor source in the Early Miocene, probably as a remnant of a mostly eroded footwall crest (see **Figure 8**). This palaeogeographic reconstruction is not comparable with the modern north-east – south-west elongation of Mt. Medvednica. That indicates the area of the modern Mt. Medvednica was characterized by a different structural and geomorphologic pattern in the Early Miocene, that was later deformed by a few tectonic phases, and accompanying erosion (**Pavelić, 2001; Tomljenović and Csontos, 2001; Márton et al., 2002**).

The palaeoflow directions on Mt. Medvednica are comparable with palaeoflow directions yielded on Mt. Kalnik and Mt. Požeška (see **Figures 1** and **7**), enabling better palaeogeographic reconstruction of the rift North Croatian Basin in the Early Miocene. At all three locali-

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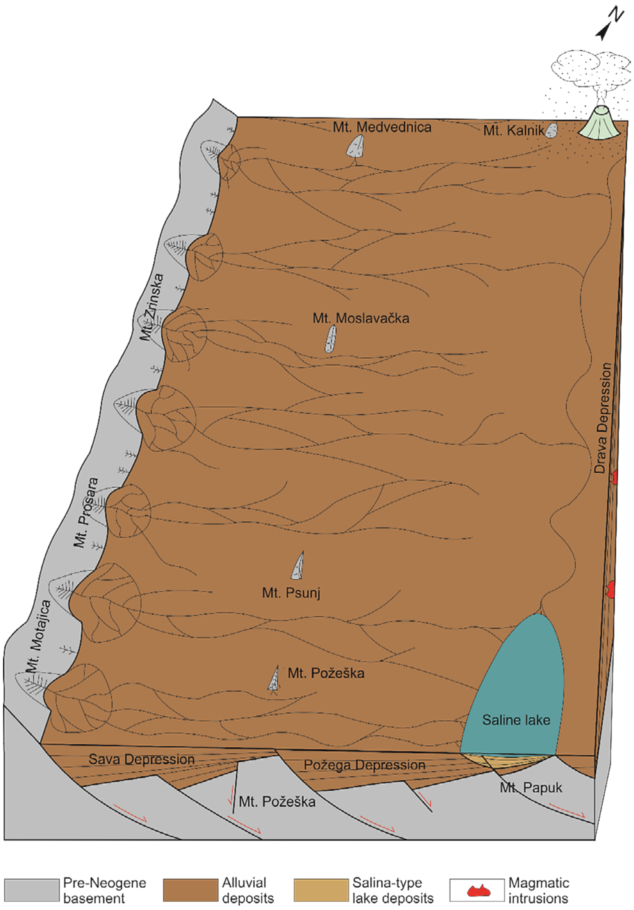

Figure 8: Palaeogeographic reconstruction of the late Early Miocene North Croatian Basin. Extensional tectonics characterized by successive normal faulting and the backstepping propagation towards the south-west (i.e. towards the Dinarides) generated development of the large alluvial plain that covered almost the whole NCB. Material, as the result of erosion of uplifted footwall blocks, was transported by rivers towards the north-east, i.e. towards the Drava Depression as the main depocentre. A saline lake evolved in the area of Mount Papuk. The post-depositional CCW rotation of tectonic blocks in the NCB indicates that the Drava Depression was elongated probably in the direction NW-SE in the early syn-rift phase of the basin evolution.

ties, alluvial deposits are the oldest syn-rift sedimentary accumulations, and belong to the Early Miocene. Such deposits occur on the other mountains in NCB, such as Mt. Žumberak, the Banovina region, Mt. Moslavačka, Mt. Psunj and Mt. Papuk, but have not been studied in detail there (**Šikić et al., 1977; Šparica et al., 1984; Jamičić and Brkić, 1987; Jamičić, 1989; Crnko, 2014; Šikić, 2014a, 2014b**) (see **Figure 1**). They have also been registered in the subsurface where they are covered by younger deposits (**Pavelić, 1998; Lučić et al., 2001; Saftić et al., 2003; Malvić, 2012; Bigunac, 2022; Rukavina et al., 2023**) indicating the existence of a large Early Miocene alluvial plain in the NCB (see **Figure 8**). The palaeogeographic reconstruction is supported by more facts. The occurrence of coarse-grained alluvial deposits close to the top of Mt. Psunj (**Jamičić et al., 1987**) suggests that the pre-Neogene basement of Mt. Psunj was almost completely covered by similar clastics of the alluvial plain. Moreover, the highest peaks of Mt. Požega are composed of the alluvial deposits (**Šparica et al., 1980, 1984**) indicating that the mountain was not uplifted in the time of the alluvial deposition, i.e. the pre-Neogene basement was mostly covered by the alluvial plain while the source of material was located more south-western, and probably represented by the now uplifted magmatic and metamorphic core of Mt. Motajica in north Bosnia (**Pavelić and Kovačić, 1998**) (see **Figure 1**).

The palaeoflow directions on Mt. Kalnik, Mt. Medvednica and Mt. Požeška are dispersed generally between the north (Mt. Kalnik) and north-east (Mt. Medvednica and Mt. Požeška) (after the corrections of the flow direction due to the postdepositional CCW rotation of 30°), i.e towards the Drava Depression as the oldest and deepest tectonic elongated zone where the rifting processes commenced (**Pavelić, 2001; Rukavina et al., 2023**). Contemporaneously, in the area of Mt. Papuk (see **Figure 2**) a hydrologically closed lake evolved (saline lake, **Šćavničar et al., 1983; Pavelić et al., 2022b**), towards which rivers flowed from the source located in the south-west (**Pavelić et al., 2016, 2022b**). These palaeoflow directions indicate the prevalence of a transverse drainage system on the alluvial plain that probably formed due to successive normal faulting and the backstepping propagation (*sensu* **Heward, 1978**) of the main extensional fault towards the south-west, i.e. towards the Dinarides (see **Figure 8**), as was indicated on Mt. Požeška (**Pavelić and Kovačić, 1999**). Such palaeogeographic reconstruction reflects the typical tectono-sedimentary evolution of the normal fault array in early syn-rift geotectonic settings (**Gawthorpe and Leeder, 2000; Barrett et al., 2020**).

5.4. Correlation of lacustrine deposition

There is a significant lithological difference among the lacustrine deposits in the NCB. While on Mt. Kalnik, Mt. Medvednica and Mt. Požeška they are characterized by a relatively high content of carbonates (marl, limestone and calcareous siltstone) (**Kochansky-Devidé and Slišković, 1978; Pavelić et al., 2000, 2001, 2003; Mandic et al., 2019; Hajek-Tadesse et al., 2022**), on Mt. Papuk the deposits are characterized by the prevalence of siliciclastics (siltstone and sandstone) (**Pavelić et al., 1998, 2022b**). The prevalance of marl and limestone indicates the evolution of a carbonate lake (**Murphy and Wilkinson, 1980**). It is especially emphasized on Mt. Medvednica and Mt. Požeška by its distribution of facies, where limestone represents the lacustrine littoral, while marl reflects deposition in deep lake. Siliciclastics that prevail on Mt. Papuk indicate the lake was affected by a strong terrestrial input, i.e. the lake developed in proximity of the river mouth (**Pavelić et al., 1998, 2022b**).

The correlation of the late episode of the lacustrine environments in NCB indicates some similarities but also differences. The late episode of the lake development on Mt. Medvednica is characterized by the forced regression that generated shallowing and development of the coarse-grained Gilbert-type delta due to tectonic activity. The upper portion of the lacustrine deposits on Mt. Kalnik is more often composed of sandstone beds intercalating with marl, indicating a coarsening-upwards sequence, and shallowing of the lake (**Pavelić et al., 2001**). However, on Mt. Papuk and Mt. Požeška the relatively deep lake remained till its gradual transition into the marine nevironment. The depositional dissimilarity can be interpreted as a consequence of differential tectonics that affected NCB in the early Badenian, as is a common characteristic of the syn-rift phase of the basin evolution (**Gawthorpe and Leeder, 2000**). The end of the lacustrine phase is characterized by a short-lived deepening of the lake before forming of the marine offshore, i.e. a marine prodelta (see **Figure 4**).

5.5. One large or several small lakes?

Concerning the lacustrine deposition in NCB, there are two general opinions on the palaeogeography of the lacustrine phase: some authors favour development of one large lake that flooded the most area of NCB (**Pavelić, 2001; Pavelić and Kovačić, 2018**) while another group support the development of a system of smaller lakes centered on syn-rift depocenters (**Kochansky-Devidé and Slišković, 1978; Saftić et al., 2003; Mandic et al., 2019**). There is also the interpretation on „connected lakes" in NCB, without a detailed explanation (**Šikić, 2014b**). The answer to this question should be reached by looking into the depositional characteristics, stratigraphic relationships, and characteristics of geological boundaries of the Lower to Middle Miocene alluvial-lacustrine-marine complex with the pre-Neogene basement on the surface. The main regularity of the complex is as follows: alluvial deposits unconformably cover the pre-Neogene basement, while they are overlain by lacustrine deposits, that are finally covered by marine deposits. Such a stratigraphic relation was documented at almost all localities in NCB where the complex occurs on the surface: Mt. Medvednica (**Basch, 1981**), Mt. Moslavačka (**Crnko and Vragović, 2014**), Mt. Papuk (**Jamičić and Brkić, 1987; Pavelić et al., 1998**), Mt. Požeška (**Šparica et al., 1980, 1984; Pavelić, 1998**) and the Banovina region (**Šikić, 2014b**) (see **Figure 1**). On Mt. Kalnik the relation between lacustrine deposits with overlaying marine deposits is not known. However, the most important fact is that the first Neogene marine deposits overlay lacustrine deposits at almost all the localities, while the unconformable contact between the pre-Neogene basement and the marine deposits is quite uncommon, such as on Mt. Medvednica and Mt. Papuk (**Brlek et al., 2016; Kovačić et al., 2015**). If several lakes existed, that unconformable contact should occur on many places on the surface because the strong Badenian marine transgression, that formed the relatively large Central Paratethyan Sea, had to affect the land among lakes. So, it supports the opinion that one large lake existed. However, fossils of *Prodeinotherium bavaricum* (Proboscidea, Mammalia) were found in lacustrine deposits on Mt. Moslavačka (**Krizmanić, 1995**) that complicates the palaeogeographic reconstruction. The occurrence of the terrestrial mammal in the central NCB suggests the area of Mt. Moslavačka was partly a land at that time, i.e. the land might separate smaller lakes. Another explanation can be related to the possible lake level fall due to the temporary climate change into more arid conditions. In such climatic circumstances, the lake surface should shrink enabling the migration of mammals from the south (i.e. the land of the Dinarides) towards the north-west. So, the question on one large or several small lakes in the early Badenian remains open.

Additionally, the relation of the lake/lakes with the sea in NCB is also not clear. Based on rich marine fossil associations and radiometric dating, the early Badenian marine deposition coeval with the lacustrine deposition was indicated on Mt. Požeška (**Brlek et al., 2020**) and on Mt. Medvednica (**Premec Fućek et al., 2023; Trinajstić et al., 2023**). That suggests that some probably narrow and elongated sea bays reached the south-western Central Paratethys marginal area, that were separated from the lake/lakes probably by syn-rift tectonically induced geomorphological barriers. However, the palaeogeographic position of the marine connection towards the early Badenian Central Paratethys Sea, that was located western to north-western from NCB (**Sant et al., 2017; Kováč et al., 2018**), is still questionable and requires additional study. The lacustrine environment finally turned into a marine environment, probably due to the eustatic sea level rise in the middle Badenian (**Kováč et al., 2007, 2018a; Pavelić, 2001, 2005; Hajek-Tadesse et al., 2009; Sant et al., 2017, 2019; Pavelić and Kovačić, 2018**), that might be forced by the syn-rift tectonic subsidence.

6. Conclusions

1. The early syn-rift continental deposits on Mt. Medvednica were accumulated in a braided river and overlying lacustrine environments in the late Early Miocene (Ottnangian, Karpatian) and the Middle Miocene (early Badenian).

2. The braided river deposits are represented mostly by coarse-grained material that was transported towards the north-east, i.e. towards the Drava Depression as the main depocenter.

3. The lacustrine deposits represent a transgressive-regressive sequence composed mostly of limestone and

marl of the lake initial phase, while the late episode of the lake evolution is characterized by a coarse-grained Gilbert-type delta progradation. The lake evolution ends by short-lived deepening.

4. Contemporaneously with the lacustrine deposition, the Central Paratethys Sea affected the area of Mt. Medvednica.

5. The lake gradually shifted to the sea in the Middle Miocene (middle Badenian).

6. The deposition was strongly controlled by extensional syn-sedimentary tectonics and the climate change from semi-arid towards a more humid. The eustatic sea level changes also had allogenic controls on the deposition.

7. The braided river evolved on the large alluvial plain that covered probably the entire North Croatian Basin.

8. The question on one large or several small lakes in the early Badenian North Croatian Basin remains open.

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SAŽETAK

Aluvijalno-jezersko-marinski kompleks na Medvednici: rano sin-riftno taloženje i paleogeografija (rani do srednji miocen, Sjevernohrvatski bazen)

Gora Medvednica pripada zapadnomu dijelu neogenskoga riftnog Sjevernohrvatskog bazena, koji zauzima jugozapadni dio Panonskoga bazenskog sustava. Donjomiocenski do srednjomiocenski kontinentalno-marinski taložni kompleks istražen je na području Medvednice, s ciljem interpretacije sin-riftnoga taložnog okoliša i paleogeografske rekonstrukcije ranoga Sjevernohrvatskoga bazena. Analizom facijesa, na temelju litoloških karakteristika sedimenti su svrstani u 16 facijesa. Aluvijalnome taložnom okolišu pripada šest facijesa, koji su krupnozrnasti i rezultat su odlaganja vučnim mehanizmima. Jezerskog je postanka devet facijesa. Uključuju vapnenac plitkoga jezera tipa "bench" sa siltnim ugljenom vegetirane močvare, lapor s proslojcima pijeska i konglomerata odlaganih gravitacijskim tokovima u dubokome jezeru i prodelti te konglomerat krupnozrnaste delte tipa Gilbert. Ovi jezerski talozi formiraju transgresivno-regresivnu sekvenciju. Cijeli slijed završava facijesom marinskoga vapnenačkog silta s proslojcima konglomerata, koji pripada pučinskome taložnom okolišu, odnosno prodelti, uslijed uspostave veze s morem. Taloženje je bilo pod snažnim utjecajem alogenih čimbenika, kao što su sinsedimentacijska tektonika, klima, eustatske promjene razine mora i eksplozivna vulkanska aktivnost. Taložni je kompleks rezultat procesa riftanja koji su formirali Sjevernohrvatski bazen i odražavaju njegovu ranu sin-riftnu fazu. Aluvijalne naslage Medvednice su najstariji sin-riftni talozi i pripadaju prostranoj aluvijalnoj ravnici koja je zauzimala vjerojatno cijeli Sjevernohrvatski bazen u otnangu i karpatu. Prekriveni su donjobadenskima jezerskim naslagama, no pitanje o razvoju jednoga velikog jezera ili više manjih ostaje otvoreno.

Ključne riječi:
aluvijalne naslage, jezerske naslage, marinske naslage, sin-rift, Sjevernohrvatski bazen

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Authors' contribution

Davor Pavelić (Professor) conducted field work, provided the facies analysis, interpretation of depositional environment and palaeogeographic reconstruction. **Marijan Kovačić** (2) (Professor) conducted field work, and interpreted the composition of deposits and provenance. **Davor Vrsaljko** (3) (Dr.) conducted field work and supervised macrofossil study. **Radovan Avanić** (4) (Dr.) was responsible for planning, field work and depositional environment interpretation.