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Middle Miocene (Upper Badenian/Sarmatian) Palaeoecology and Evolution of the Environments in the Area of Medvednica Mt. (North Croatia)

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Abstract

In the area of Medvednica Mt., the Upper Badenian and Sarmatian deposits are divided into four facies associations: (A) deposits of a small carbonate platform represented by breccia, conglomerates, biocalcirudites, biocalcarenites and biocalclutites; (B) open-sea deposits composed of marls with intercalations of clay; (C) nearshore deposits of reduced salinity composed of conglomerates, sandstones, biocalcarenites, biocalcirudites and biocalclutites, and (D) lagoonal deposits represented by spongitic calclutites with clay, marl and sand intercalations. Deposits of these facies associations contain numerous and very diverse fossil species with very different palaeoecological characteristics, from shallow- and deeper-water normal marine to shallow- and deeper-water environment of reduced salinity, even of fresh-water.

The transition from Late Badenian to Sarmatian deposition was characterized by three different unconformities and one conformity. Unconformities are located between different lithologies reflecting an amount of uplifting and erosion at the end of the Badenian. The occurrence of an angular unconformity suggests the influence of local tectonics.

The Middle Miocene deposition shows different local variations but generally fits with the evolution of Central Paratethys and the Pannonian Basin System.

1. INTRODUCTION

The Middle Miocene (Upper Badenian and Sarmatian) deposits cover a large area of north Croatia, and their lithological and stratigraphic characteristics have been studied both at the surface and in the subsurface. Their general evolutionary characteristics have been primarily based on their palaeoecological indications from the fossil fauna. In that sense, Upper Badenian sediments are characterized as marine while the Sarmatian sediments are characterized as brackish or of reduced salinity (KOCHANSKY-DEVIDE, 1944; ŠIKIĆ, 1967; ŠIKIĆ et al., 1979; BAJRAKTAREVIĆ, 1980; KOCHANSKY-DEVIDE & BAJRAKTAREVIĆ, 1981;BASCH, 1983; AVANIĆ et al., 1995; VRSALJKO et al., 1995a, b, 2005; VRSALJKO, 1999; AVANIĆ et al., 2003; PAVELIĆ et al., 2003).

The Upper Badenian and Sarmatian deposits at several localities on Medvednica Mt. illustrate specific types of sedimentation (Fig. 3). These were developed in various lithologies reflecting evolution of different environments in a relatively small area, dominated by carbonates in the Late Badenian, and siliciclastics in the Sarmatian. Additionally, the transition from the Late Badenian to the Sarmatian resulted in different types of boundary between these deposits characterized by unconformities and a conformity (Figs. 5 & 6).

Evolution of the environment may have been controlled by specifics such as characteristics of the pre-Neogene basement, erosion intensity, water energy and local tectonics. However, since the basin evolution indicates a transgressive–regressive succession in the Late Badenian and a new transgression in the Sarmatian, typical for Central Paratethys and the Pannonian Basin System, important regional external controls on sedimentation should be taken into account, including the opening and closing of an oceanic connection, climate and regional tectonic events (RÖGL & STEININGER, 1984; KOVAČ et al., 1997; HARDENBOL et al., 1998; PAVELIĆ, 2001; PAVELIĆ et al., 2003; VRSALJKO et al., 2005).

2. GEOLOGICAL SETTING

Miocene deposits of the investigated area belong palaeogeographically to the south-western margins of Central Paratethys (Figs. 1 & 2), and geotectonically to the Pannonian Basin System (PAVELIĆ, 2001).

Miocene deposits on the Medvednica Mt. disconformably overlie Mesozoic basement, and contacts with Palaeozoic/Mesozoic basement are tectonic–erosional (ŠIKIĆ et al., 1979; BASCH, 1983; AVANIĆ et al., 2003). Triassic dolomites and limestones occur in the SW part, while the central and NE parts of Medvednica

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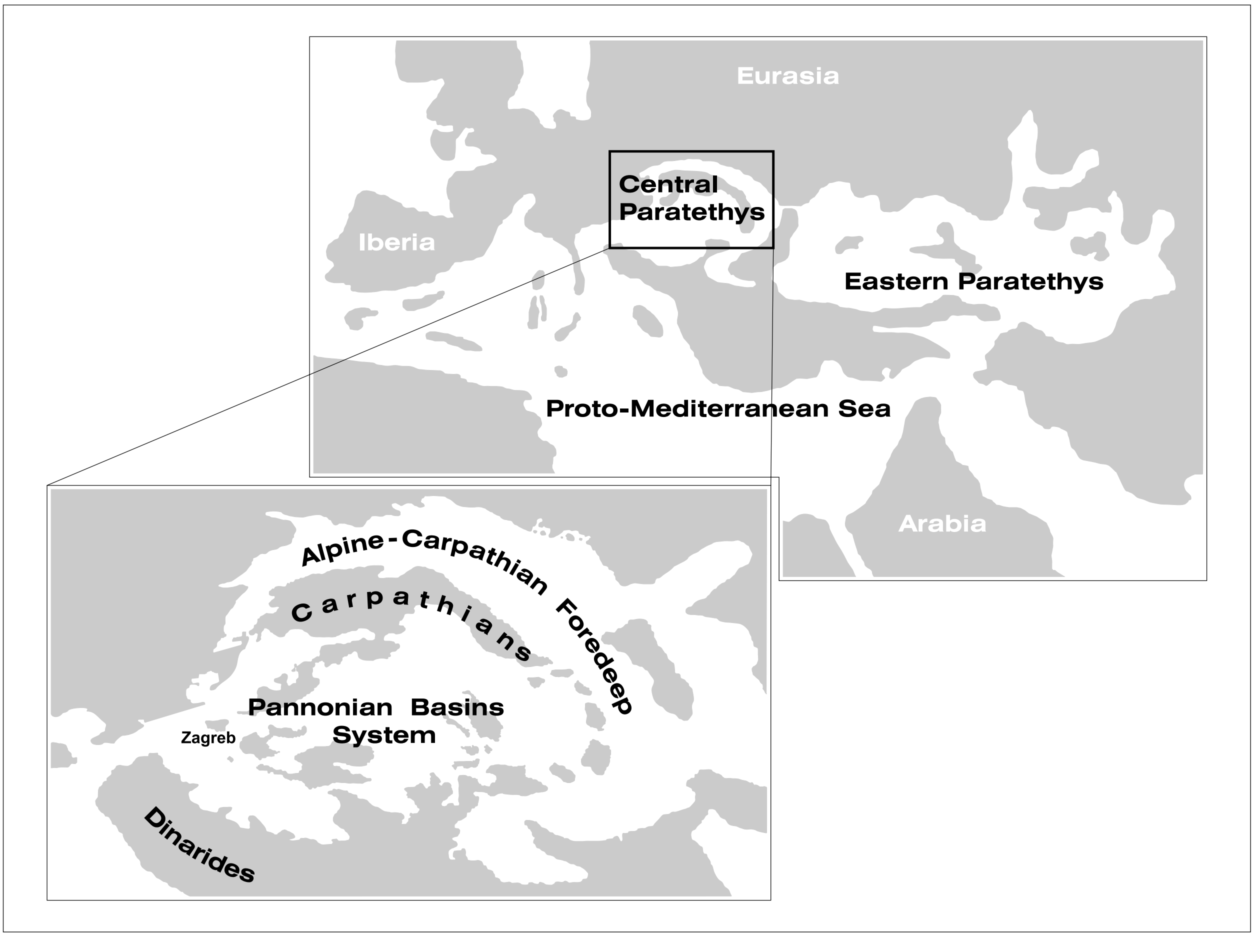

Fig. 1 Palaeogeographic map of Central Paratethys: Middle Miocene (after RÖGL, 1998).

Mt. are dominated by Cretaceous deposits (magmatic–sedimentary complex).

Miocene deposits of the investigated area were divided into three parts by KOCHANSKY-DEVIDE (1944): (1) SW part called the "Dolje development", (2) a middle part, the "Čučerje development", and (3) the north-eastern part called the "Zelina development". Within the "Doljanski envelopment", the first Miocene sediments are fine-grained deposits and biogenic limestones of Badenian age transgressive over the Mesozoic basement. This succession also occurs in the northern-eastern part of Medvednica Mt., known as the "Zelina development". In the central part of Medvednica Mt. ("Čučerje development"), the first Miocene sediments were Lower Miocene (Ottnangian) freshwater sediments followed by marine (Karpatian) deposits, which are partly equivalent to the "Rzehakia layers". These sediments were succeeded by the Badenian coarse-grained sediments, tuffitic marls and fine-grained deep marine deposits, which can be compared with isochronous Miocene deposits of the Vienna Basin (Central Paratethys), known as "Schlier".

Upper Badenian deposits are approximately 30 to 70 m thick on the slopes of Medvednica Mt., and the maximum thickness of the Sarmatian deposits is 50 m (after BASCH, 1983).

3. DESCRIPTION AND INTERPRETATION OF FACIES

Four sections were studied on the slopes of Medvednica Mt. – Podsusedsko Dolje, Gornje Vrapče, Krvarić and Donje Orešje (Figs. 2, 3 & 5). The studied deposits belong to the Upper Badenian and Sarmatian, and their total thickness is 80 m. Based on their lithological characteristics and faunal content (Tables 1 & 2), these sediments were grouped into four facies associations suggesting different palaeoecological conditions (Figs. 5 & 6).

3.1. Facies association A: deposits of a small carbonate platform

Deposits of this facies association (Fig. 4) were studied in the Gornje Vrapče, Krvarić and Donje Orešje columns (Fig. 5), consisting of breccia, conglomerates, biocalcirudites, biocalcarenites and biocalclutites.

Breccia and conglomerates are composed mostly of fragments of Upper Triassic dolomites and Upper Cretaceous limestones reflecting the composition of the basement. The siliciclastic content is very low.

Biocalcirudites, biocalcarenites and biocalclutites are almost structureless, but cross-bedding can be seen

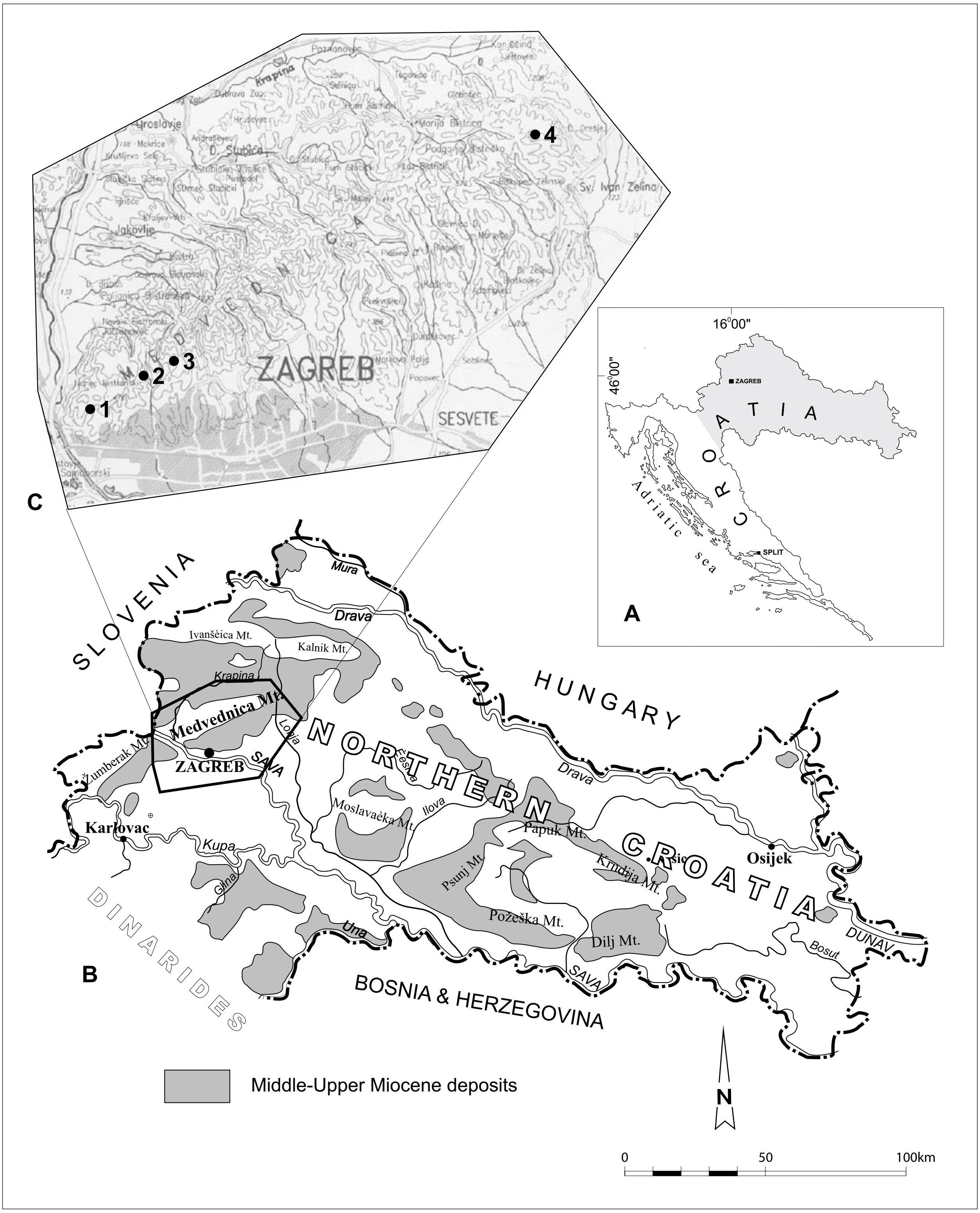

Fig. 2 Study area: (A) Croatia; (B) Northern Croatia; (C) Medvednica Mt.: location of geological columns (1 – Podsusedsko Dolje, 2 – Gornje Vrapče, 3 – Krvarić, 4 – Donje Orešje).

sporadically. These deposits consist mostly of fragments or whole skeletons of shallow marine organisms: algae *Lithotamnion* sp. which dominate, large molluscs (*Ostrea* sp., *Lucinoma borealis*, *Pecten* sp., *Isocardia cor*, *Panopea menardi*, *Conus* sp., *Chlamys elegans* and many cardiids), bryozoans, serpulids, echinoids, foraminifera of *Ammonia viennensis–Elphidium crispum* zone: *Lobatula lobatula*, *C. pseudungerianus*, *Elphidium fichtelianum*, *E. crispum* and *Ammonia viennensis*, and ostracods: *Cytheretta tenuipunctata dentata* and *Senesia* cf. *philippii*. These organisms document fully marine conditions during Late Badenian time.

SPECIES	Facies association
MOLLUSCA	
Lucinoma borealis (LINNÉ)	A, B, D
Palliolum zoellikoferi (BITTNER)	B, D
Isocardia cor (LINNÉ)	A, D
Panopea menardii DESHAYES	A
Chlamys elegans (ANDRZ.)	A, B
Glycymeris cor (PARTSCH)	A, B
Corbula gibba (OLIVI)	D
Callista chione (DEFRANCE)	D
Ostrea sp.	A
Natica sp.	D
Venus sp.	B
FORAMINIFERA	
Ammonia viennensis (d'ORBIGNY)	A
Bolivina dilatata REUSS	D
Bulimina elongata d'ORBIGNY	D
Praeglobobulimina pyrula (d'ORBIGNY)	B, D
Globocassidulina oblonga (REUSS)	B, D
Lobatula lobatula (WALKER & JACOB)	A
Cibicidoides pseudoungerianus (CUSHMAN)	A
Elphidium crispum (LINNÉ)	A
E. fichtelianum (d'ORBIGNY)	A
Uvigerina semiornata d'ORBIGNY	B, D
U. venusta FRANZENAU	B, D
Pavonitina styriaca SCHUBERT	B, D
Heterolepa dutemplei (d'ORBIGNY)	B, D
Globigerina diplostoma REUSS	B
G. bulloides d'ORBIGNY	B, D
Orbulina universa d'ORBIGNY	B
Velapertina indigena (LUCZKOWSKA)	B
Pappina neudorfensis (TOULA)	D
Globorotalia scitula (BRADY)	D
Orbulina suturalis BRÖNNIMANN	D
Reophax sp.	B, D
Alveolophragmium crassum (REUSS)	B, D
Spirorutilus carinatus (d'ORBIGNY)	D
OSTRACODA	
Aurila angulata (REUSS)	D
Callistocythere canaliculata (REUSS)	D
Cnestocythere lamellicosta TRIEBEL	D
Hermanites haidingeri (REUSS)	D
Loxoconcha punctatella (REUSS)	D
L. hastata (REUSS)	D
Xestoleberis glabrescens (REUSS)	D
Senesia cf. *philippii* (REUSS)	A
Cytheretta tenuipunctata dentata BRETENSKA	D, A
OTHERS	
Algae (*Lithotamnion* sp.)	A, B
Hydrozoa	A, B
Bryozoa	A, B
Echinoids	A, B, D
Ostracodes	A, B, D
Fishes	A, B, D
Terrestrial flora	A, B, D

Table 1 The important fossil association of the Late Badenian on Medvednica Mt.

SPECIES	Facies association
MOLLUSCA	
Ervilia dissita (EICHWALD)	C
Musculus sarmaticus GATUEV	C
Modiolus sp.	C
Mactra sp.	C
Gibbula sp.	C
Irus sp.	C
Cerithium sp.	C
Cardium vindobonense (PARTSCH)	C
C. gleichenbergense (PAPP)	C
Planorbidae sp. nov.?	D
FORAMINIFERA	
Elphidium hauerinum (d'ORBIGNY)	C
E. reginum (d'ORBIGNY)	C
E. josephinum (d'ORBIGNY)	C
Rosalina obtusa d'ORBIGNY	C
Articulina problema BOGDANOWICZ	C
Sinoloculina volhynica (DIDKOWSKIY)	C
Sinzowella novorossica (KARRER & SINZOW)	C
Porosononion granosum (d'ORBIGNY)	D
OSTRACODA	
Candona cf. *oblonga* (SARS)	D
Aurila merita (ZALANYI)	*D*
A. mehesi (ZALANYI)	*D*
Loxoconcha kochi (MEHES)	*D*
Darwinula cylindrica STRAUB	*D*
Pseudocandona fertilis TRIEBEL	*D*
OTHERS	
Characea; *Chalmasia moreleti* POKORNY	D
Fishes	D, C
Spongia	D, C
Serpulids	D, C
Algae	D, C
Terrestrial flora	D, C

Table 2 The important fossil association of the Sarmatian on Medvednica Mt.

The occurrence of coarse-grained sediments, i.e. breccia and conglomerates overlying the basement, and their petrographic composition, indicate erosion and reworking of the basement material during the early marine transgression, and deposition within high-energy shallow-water environments (Fig. 6).

Biocalcirudites, biocalcarenites and biocalclutites suggest lower energy conditions compared to those of the breccia and conglomerates. Their faunal association documents favourable palaeoecological conditions for the expansion of organisms in a shallow-marine environment formed over a carbonate basement. These organisms were reworked by strong currents as indicated by the grain-size of sediments and fragmentation of skeletons. Additionally, cross-bedding suggests deposition by traction currents generated by tides or waves.

The sedimentary environment was probably that of an isolated small carbonate platform formed over the previous land highs protected from terrestrial influence. On this platform algal banks were developed, colonized by a shallow-water fauna which was penecontemporaneously reworked and resedimented by strong currents within the same environment.

3.2. Facies association B: open sea deposits

These deposits were studied at the Donje Orešje locality (Fig. 7). They overlie sediments of a small carbonate platform (Figs. 5 & 6). The association is represented by marls with several intercalations of clay (Fig. 5). The bed thicknesses vary between 3 and 15 cm.

Marls are massive and strongly bioturbated, comprising a rich association of foraminifera of the *Bulimina–Bolivina* zone: *Pavonitina styriaca*, *Reophax* sp., *Cribrostomoides columbiensis*, *Alveolophragmium*

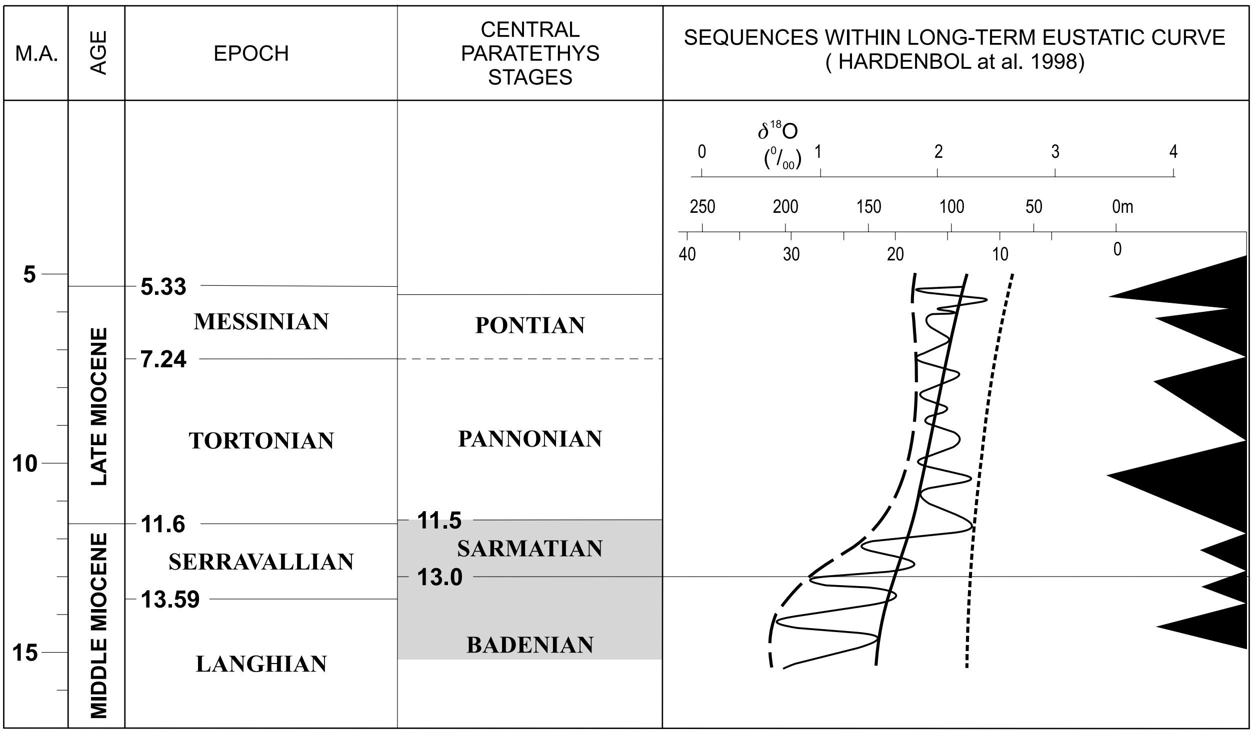

Fig. 3 Stratigraphic scheme (modified after RÖGL, 1998; HARDENBOL et al., 1998).

Fig. 4 Facies association A: deposits of a small carbonate platform; Krvarić locality.

crassum, *Uvigerina semiornata*, *U. venusta*, *Heterolepa dutemplei* and *Astrorhyzidae*, and predominating planktonic species *Globigerina diplostoma*, *G. bulloides*, *Orbulina universa* and *Velapertina indigena* (Tables 1 & 2). Some molluscs occur sporadically, such as *Lucinoma borealis*, *Palliolum zoelikoferi*, *Glycymeris cor*, *Nassa* sp., *Venus* sp., *Chlamys* sp. and *Cardium* sp. Fragments of echinoids and bryozoans are rare. This foraminiferal association indicates deposition from the neritic to the basinal area (about 100 m depth, according to SPEZZAFERRI et al., 2005; HOHENEGGER, 2005). In the uppermost part of this facies association agglutinated forms of foraminifera are absent, excluding *Pavonitina styriaca*. The clay intercalations may be explained as a consequence of a temporary but strong terrestrial influence. The whole aforementioned faunal association suggests an open sea environment and deposition of marls and clays during the Late Badenian.

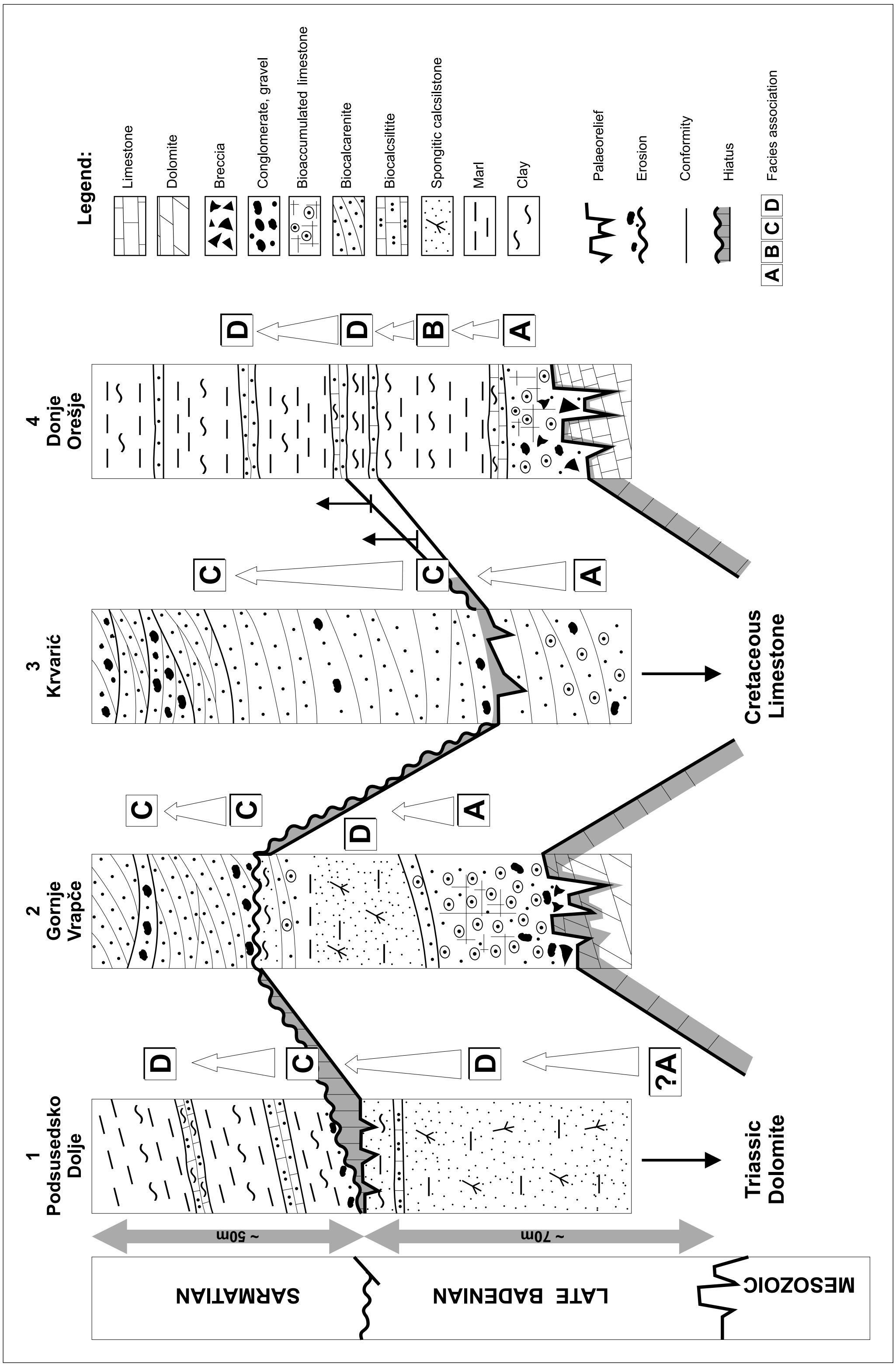

Fig. 5 Stratigraphic columns: 1 – Podsusedsko Dolje, 2 – Gornje Vrapče, 3 – Krvarić, 4 – Donje Orešje.

3.3. Facies association C: nearshore deposits of reduced salinity

Deposits of this association (Fig. 8) were studied in the Podsusedsko Dolje, Gornje Vrapče and Krvarić localities (Fig. 5). Facies association C is composed of conglomerates and sandstones, and biocalcarenites, biocalcirudites and biocalclutites (Figs. 5 & 6).

Conglomerates and sandstones occur in the lowest part of Facies association C. Pebbles average 3 cm in diameter. Cobbles up to 15 cm in diameter are uncommon. Sandstones are coarse-grained and include some fine-grained pebbles. The composition of fragments is very different to older deposits, reflecting the composition of the basement. Fragments of the Upper Badenian marls up to 30 cm long are also frequent and are found

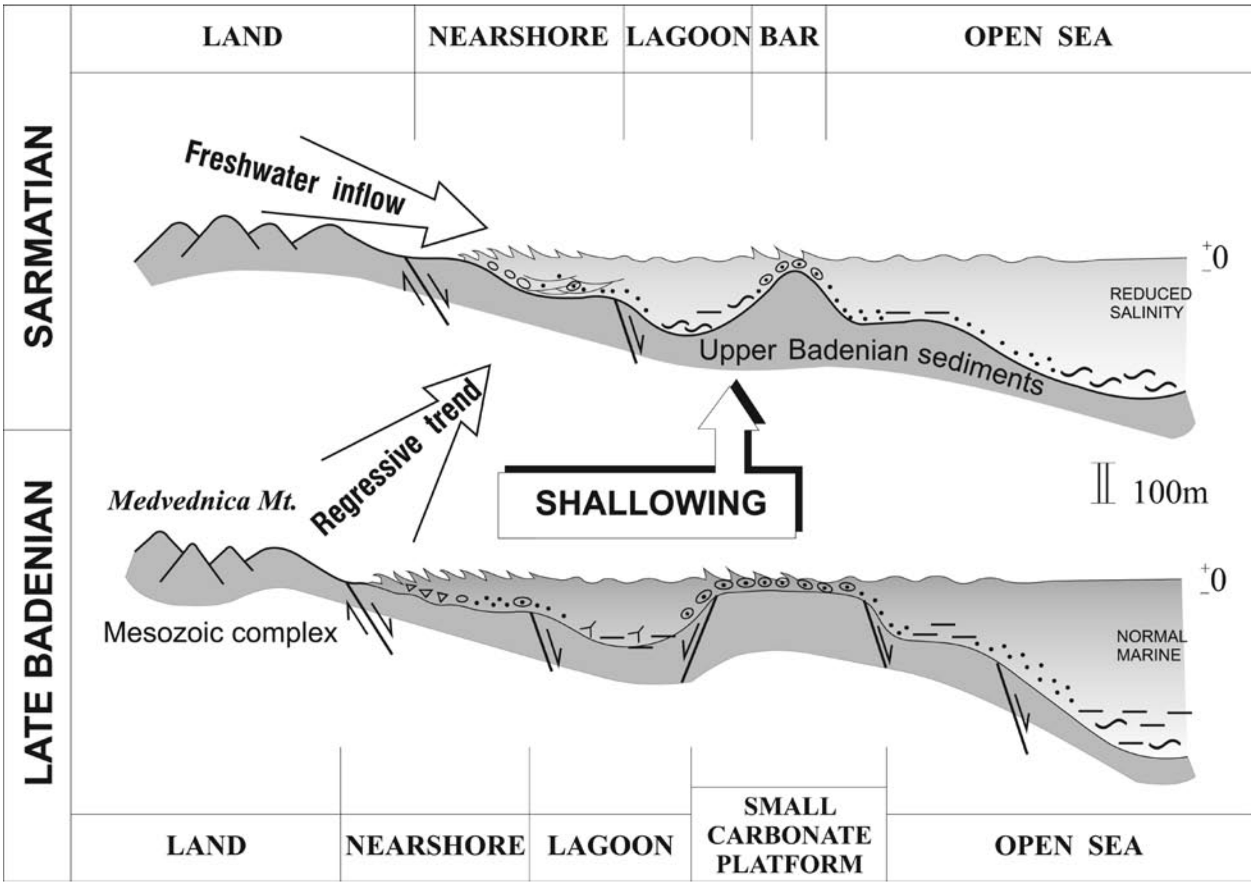

Fig. 6 Evolution of the environments; Badenian–Sarmatian deposits (idealized profile).

Fig. 7 Facies association B: open sea deposits; Donje Orešje locality.

in the lower part of the facies association. The sorting is poor.

Biocalcarenites, biocalcrudites and biocalclutites predominate in this facies association. They are horizontal to cross-bedded. The composition is characterized by a high content of molluscs, foraminifera and ostracods. The most frequent molluscs are *Cerithium* sp., *Gibbula* sp., *Mactra* sp., *Irus* sp., *Modiolus* sp., *Ervilia dissita*, *Cardium vindobonense*, *C. gleichenbergense* and *Musculus sarmaticus*. The foraminiferal association is represented by species of the *Elphidium reginum* zone: *Elphidium reginum*, *E. josephinum*, *Sin-*

Fig. 8 Facies association C: nearshore deposits; Krvarić locality.

zowella novorossica and *Rosalina obtusa.* Ostracods are *Aurila* sp. and *Cytheridea* sp. Fragments of alga occur sporadically – *Chalmasia moreletti* and characean girogonias. This fossil association indicates deposition in a shallow marine environment of reduced salinity.

Except for the Sarmatian fossils, this facies association often includes resedimented fragments of Upper Badenian algae and foraminifera. Oncoids, ooids and vadoids also occur.

Conglomerates in the lower part of the facies association indicate high-energy environments, while their structural and petrographic composition suggests strong terrestrial input and deposition in shallow water. The occurrence of the Upper Badenian fragments indicates erosion of those sediments on the land.

Biocalcarenites and biocalcrudites were probably deposited by traction currents in a shallow-water environment. Biocalclutites indicate low-energy sedimentation. Palaeoecological characteristics of the fauna additionally indicate shallow-water deposition in an environment of reduced salinity. Imperforate foraminifera *Articulina problema*, *Sinoloculina volhynica* and *Sinzowella novorossica* and encrusting foraminifera *Sinzowella caespitosa* indicate the existence of small reefs or biostromes, while ooids (oncoids, vadoids) suggest low currents and the existence of sandy bars (FRIEBE, 1994).

Strong inflow of fresh water very probably reduced the salinity of this environment. Such ecological conditions generated the development of specific organisms. Currents and oxic conditions enabled the expansion of life on the bottom on which epiphytic organisms evolved, including molluscs, foraminifera and ostracods. Most of these organisms lived as vagile benthos which was very active on the bottom. At the same time, nubecularians built up small reefs. Species of ervilias, mactras, iruses and cardiums lived on the muddy–sandy bottom feeding from the substratum. Most of the gastropods from the family Ceritidae, and some miliolid foraminifera existed in proximity to the fresh water inflow.

3.4. Facies association D: lagoonal deposits

Based on their different lithology and palaeoecology, lagoonal deposits (Fig. 9) are divided into two groups: spongitic calclutites (Podsusedsko Dolje and Gornje Vrapče localities), and clay, marl and sand intercalations (Podsusedsko Dolje, Gornje Vrapče and Donje Orešje) (Fig. 5).

Spongitic calclutites are horizontally bedded and intensively bioturbated with bed thicknesses between 0.1–1.5 m. Calclutites are characterized by a high content of biogenic remnants, such as the stone cores of monaxonid and triaxonid sponges, skeletons of crabs and fish, serpulids, echinoids, and an association of molluscs and foraminifera. Some fragments of algae as well as small coal clasts also occur.

The *Spirorutilus–Praeglobobulimina–Heterolepa* foraminiferal association in spongitic calclutites is characterized by benthic species *Semivulvulina deperdita*, *Spirorutilus carinatus*, *Pavonitina styriaca*, *Bolivina dilatata*, *Bulimina elongata*, *Uvigerina brunnensis*, *U. venusta*, *Pappina neuderfensis* and *Heterolepa dutemplei.* Planktonic species are very rare, but include *Globorotalia scitula*, *Globigerina bulloides* and *Orbulina suturalis*. The most frequent molluscs are *Lucinoma borealis*, *Isocardia cor*, *Palliolum zoelikoferi*, *Corbula*

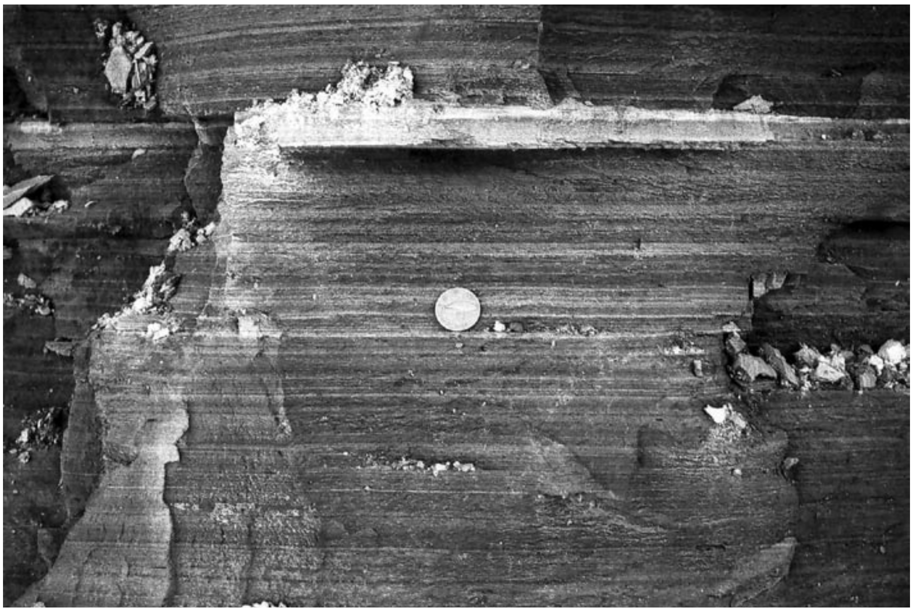

Fig. 9 Facies association D: lagoonal deposits; Gornje Vrapče locality.

gibba, *Callista chione* and *Natica* sp. The most common ostracod species include *Aurila angulata*, *Callistocythere canaliculata*, *Cnestocythere lamellicostata*, *Hermanites haidingeri*, *Loxoconcha punctatella*, *L. hastata* and *Xestoleberis glabrescens*. This fossil association documents a fully marine environment and deposition in the Late Badenian (VRSALJKO et al., 1995a; HAJEK-TADESSE, 2006).

The grain-size of the calclutites indicates deposition from suspension while the lack of coarse-grained intercalations suggests an environment protected from stronger intrabasinal influence. Benthic organisms indicate deposition on the marine bottom up to 70 m depth. The absence of strong current indicators and the rare occurrence of planktonic foraminifera can be explained as a consequence of the restricted connection with the open sea, i.e. sedimentation in a lagoon or bay.

The bottom of the lagoon was muddy–silty and most of the benthic organisms lived burrowed in the substratum. Some gastropods such as *Natica* sp. were carnivorous. There were also coprophags (serpulids, echinoids and some molluscs). A restricted marine connection enabled conditions needed for the existence of a greater quantity of planktonic foraminifera.

Clays and marls are horizontally bedded and almost laminated. Sometimes these sediments are massive. Sands occur as thin intercalations within this group of sediments. A rich fossil association is found in the marls (Table 2). An *Elphidium–Protelphidium–Porosononion* foraminiferal association is an important palaeoecological characteristic of the marls. This association is very similar to the one described in Facies association C. The most common species are *Elphidium josephinum*, *E. hauerinum*, *E. macellum*, and *Porosononion granosum*. There are also some ostracods, remnants of fish skeletons, molluscs and a terrestrial flora. Molluscs *Ervilia* sp., *Mactra* sp. and *Cardium* sp. also occur in both Facies associations C and D, but are of smaller dimensions in the Facies association D. Ostracod species *Aurila merita*, *A. mehesi*, *Loxoconcha kochi* infer reduced salinity, while *Candona* cf. *oblonga*, *Darwinula cylindrica* and *Pseudocandona fertilis* are fresh-water species. The whole fossil association documents generally reduced salinity within Sarmatian environments. Some fresh-water ostracods may reflect stratification of the water, similar to the recent Black Sea. Characean girogonias and gastropods *Planorbidae* occur sporadically.

Clays and marls settled out from suspension while thin sandy intercalations may represent turbidites deposited from weak gravity flows. The lack of planktonic foraminifera suggests a restricted connection with the open sea (ŠIKIĆ, 1967; KOCHANSKY-DEVIDE & BAJRAKTAREVIĆ, 1981; VRSALJKO et al., 1995a). This facies association and its palaeoecological characteristics indicate deposition in a lagoon or bay, which had an input of fine-grained terrestrial material.

The foraminiferal association is strongly reduced in the number of constituent species and diversity compared to that of the Late Badenian. This can be explained by the formation of an environment of reduced salinity (Tables 1 & 2), and is supported by the observed increase in the number of ostracods and the occurrence of fresh-water species.

4. CHARACTERISTICS OF THE BADENIAN–SARMATIAN BOUNDARY

The transition from the Late Badenian to the Sarmatian is very variable in the relatively small studied area of Mt. Medvednica. It is characterized by three types of unconformities, and a conformity.

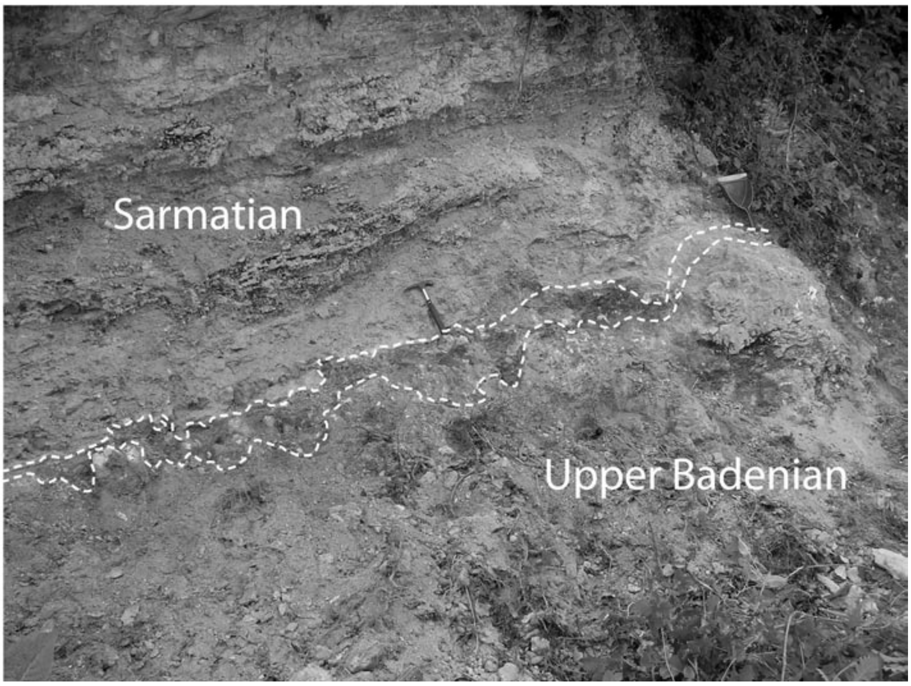

Fig. 10 The Badenian–Sarmatian boundary; Krvarić locality.

The Gornje Vrapče locality was characterized by very strong erosion of the Upper Badenian deposits and their resedimentation in the beginning of the Sarmatian (Figs. 5 & 6). The unconformity is very clear, marked by desiccation cracks in the uppermost Badenian deposits and reworked fragments of marls with Upper Badenian fauna within transgressive Sarmatian deposits.

The Krvarić locality is very specific (Fig. 5). The lithology of the Upper Badenian and Sarmatian sediments is similar and represented by biocalcarenites that partly hides the unconformity. The hiatus is recognizable by the occurrence of a thin irregular clay–bauxite interbed which documents short-lived emersion before the onset of the Sarmatian transgression (Fig. 10).

In the Podsusedsko Dolje locality (Figs. 5 & 11) a typical angular disconformity between the Upper Badenian and Sarmatian is found. The dip of the Sarmatian deposits is ca. 10° less than the dip of the Upper Badenian sediments. The Sarmatian succession begins with conglomerates and sandstones which represent a transgressive lag. It is overlain by fine-grained sediments deposited in a lagoon of reduced salinity.

The boundary between the Upper Badenian and Sarmatian sediments in the Donje Orešje locality is characterized by its conformity (Fig. 5). The sedimentation style is similar in the Late Badenian to the Sarmatian. The transition is characterized by a gradual change of palaeoecological characteristics from a normal marine to reduced salinity fauna. This conformable transition indicates sedimentation in the deeper part of the basin which was not significantly affected by the sea-level fall at the end of the Badenian.

5. EVOLUTION OF THE ENVIRONMENTS

The onset of Late Badenian deposition is characterized by transgression and formation of a normal marine environment. This transgression was very probably a consequence of the opening of a connection between Central Paratehys and the Indo–Pacific Ocean due to eustatic sea-level rise (STEININGER et al., 1978; RÖGL & STEININGER, 1984; KOVAČ et al., 1997; HARDENBOL et al., 1998; RÖGL, 1998). Pre-existing land could have been formed due to fault-block rotation and uplifting in the Early Badenian, representing the end of the syn-rift phase (PAVELIĆ, 2001; PAVELIĆ et al., 2003). This uplift enabled strong erosion of all syn-rift deposits and the occurrence of pre-Neogene basement on the surface, including Upper Triassic dolomites and Upper Cretaceous limestones. These rocks provided favourable conditions for the evolution of small carbonate platforms on which different shallow-water organisms started to develop. Algal banks with *Lithotamnion* sp. predominated, but ecological conditions also supported the expansion of many different shallow-water organisms, such as bivalves, gastropods, bryozoans, echinoids, foraminifera etc. These carbonate platforms were protected from terrestrial influence. However, strong currents generated by tides or waves caused reworking of material on the bottom and resedimentation. Similar interpretations have been made for deposits from central Medvednica Mt., eastern Croatia and the Styrian Basin, supporting the ideas that in SW Central Paratethys, several small carbonate platforms existed in the beginning of the Late Badenian (SCHMID et al., 2001; AVANIĆ et al., 2003; PAVELIĆ et al., 2003; VRSALJKO, 2003; VRSALJKO et al., 2005).

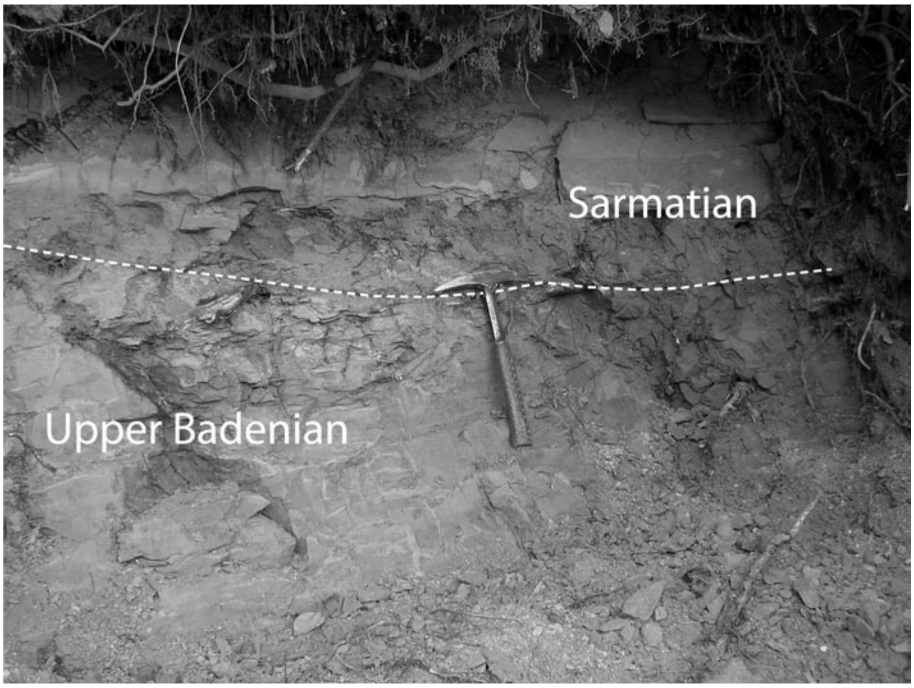

Fig. 11 The Badenian–Sarmatian boundary; Podsusedsko Dolje locality.

A continuation of sea-level rise generated deepening and the evolution of two different environments with fine-grained deposition. In NE Medvednica Mt. (Donje Orešje locality; Fig. 2) open marine environments were formed, characterized by the deposition of marls on the steep slope reaching depths of 100 m or more. Open marine conditions enabled the evolution of numerous and diverse planktonic foraminifera. In contrast, in SW Medvednica Mt. (Podsusedsko Dolje and Gornje Vrapče localities; Fig. 2) ca. 70 m deep lagoon or bay formed in the shallow sea. This environment was partly protected from the open sea, and enabled the existence primarily of benthic organisms, while the number and diversity of planktonic organisms was restricted (Tables 1 & 2). This difference in two contemporaneous environments could be explained by palinspastic reconstruction. The position of the Podsusedsko Dolje and Gornje Vrapče localities was close to the Dinarides, i.e. to the land which may have surrounded the lagoon or bay (Figs. 1 & 2). The Donje Orešje locality was more distal from the land, i.e. closer to the central part of Central Paratethys, and there the influence of the open sea was more important (Figs. 1 & 2). Upper Badenian deposition in the central part of Medvednica Mt. also occurred in an open marine environment, which supports this palinspastic reconstruction (AVANIĆ et al., 2003).

The end of the Badenian was characterized by sea-level fall causing shallowing. It has been explained by the beginning of the isolation of Central Paratethys from the Ocean (PAPP & SENEŠ, 1974; SENEŠ, 1974; RÖGL & STEININGER, 1984; KOVAČ et al., 1997; RÖGL, 1998; VRSALJKO, 1999, 2003; PAVELIĆ, 2001; PAVELIĆ et al., 2003; VRSALJKO et al., 2005). In north-eastern Medvednica Mt., shallowing of the open sea did not have a significant influence on sedimentation, suggesting that it was deep enough to maintain relatively similar deposition. In its SW part, shallowing caused emergence and the formation of small islands, i.e. an archipelago, and was followed by a new transgression in the Sarmatian. This emergence indicates external controls on deposition. In the Gornje Vrapče locality the unconformity between the Upper Badenian and Sarmatian deposits was marked by strong erosion and resedimentation of lagoonal marl fragments up to 30 cm long, together with the first transgressive deposits. Sarmatian sediments indicate significant sea-level fall that exposed relatively deep-water Upper Badenian deposits on the surface. At the Krvarić locality, the unconformity is marked by a thin clay–bauxite interbed between shallow-water deposits, suggesting weaker erosion, and insignificant sea-level fall at the end of the Late Badenian (Figs. 5 & 10). The unconformity which occurs at the Podsusedsko Dolje locality may be used for interpretation of this differential shallowing. Since this unconformity is of an angular type, it was very probably caused by uplift due to tectonics (Figs. 5 & 11). Strong uplift which primarily caused the exposure of relatively deep, lagoonal deposits on the surface, additionally resulted in the inclination of the Upper Badenian beds. Upper Badenian sedimentation belongs to the post-rift phase, which is generally characterized by subsidence due to cooling of the lithosphere, but local tectonics may also be expected in its earliest part (KOVAČ et al., 1997; PAVELIĆ, 2001; PAVELIĆ et al., 2003). So, it can be summarized that local tectonics in the earliest post-rift phase probably controlled sedimentation in that area of Medvednica Mt. (AVANIĆ et al., 2003).

The onset of Sarmatian deposition was a result of the beginning of a transgression (ŠIKIĆ et al., 1979;

BASCH, 1983; VRSALJKO et al., 1995a, b; VRSALJKO, 1999). The connection of Central Paratethys with the Ocean was restricted, but a change of climate to more humid one, could generate sea-level rise (PIKIJA et al., 1989; FRIEBE, 1994). Erosion of terrestrial material and its resedimentation was an important characteristic during that transgression. After shallow-water deposition, continued sea-level rise formed an environment approximately 100 m deep characterized by dramatically different ecological conditions. Due to the restricted connection with the sea, salinity was reduced, resulting in the occurrence of new species, particularly benthic organisms: foraminifera, molluscs, ostracods and characeans (RÖGL & STEININGER, 1984).

6. CONCLUSIONS

On the slopes of Medvednica Mt., the Late Badenian was characterized by formation of fully marine conditions, and the development of small carbonate platforms over pre-existing land due to the marine transgression. The sea-level rise caused deepening and evolution of the open sea environment in its NE part, and a lagoon or bay in its SW part. The formation of the lagoon or bay may be a consequence of the proximity of the Dinarides which represented land at that time, while an open sea environment developed closer to the central part of Central Paratethys. Deposition was strongly controlled by eustacy, and was mostly protected from terrestrial influence.

At the end of the Late Badenian, local tectonics generated differential uplifting, shallowing and exposure of the Upper Badenian deposits on the surface in the SW part of Mt. Medvednica, while in its NE part sedimentation continued into the Sarmatian. The Late Badenian represents the onset of the post-rift phase, generally characterized by thermal subsidence, but tectonics still controlled sedimentation locally (RÖGL & STEININGER, 1984; PAVELIĆ, 2001; PAVELIĆ et al., 2003).

The beginning of the Sarmatian was characterized by a new transgression, erosion and resedimentation of the Upper Badenian deposits, and formation of a relatively deep-water environment of reduced salinity. Such a specific environment, influenced by the input of fine-grained terrestrial material enabled development of species of different palaeoecological characteristics.

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