

# Badenian Ostracoda from the Pokupsko area (Banovina, Croatia)

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(Manuscript received May 14, 2010; accepted in revised form April 14, 2011)

**Abstract:** In this paper we present the results of the investigations on the Badenian (Middle Miocene) ostracods from the Pokupsko area. For the first time the presence of Badenian aged sediments in Croatia can be supported by the occurrence of ostracod biozonal markers. Four Badenian ostracod zones are established: Lower Badenian Biozone NO7 *Acanthocythereis hystrix*–*Bythocypris lucida*, Middle Badenian Biozone NO8 *Eocytheropteron inflatum*–*Olimfalunia spinulosa*, and the two Upper Badenian Biozones NO9 *Neomonoceratina laskarevi*–*Miocyprideis sarmatica elongata* and NO10 *Carinocythereis carinata*–*Phlyctenophora farkasi*. On the basis of the generally accepted paleoecology of selected genera, we identified the following ostracod faunas: shallow-water marine, shallow-water brackish-marine, shallow-water reef, and deep-water marine. The paleontological and trace element analyses suggest that the Pokupsko ostracod fauna lived in shallow (50 m deep), warm, and limpid waters, connected to a deeper sea and occasionally exposed to freshwater inflows.

**Key words:** Miocene, Badenian, North Croatian Basin, Ostracoda, biostratigraphy, paleoecology, trace elements.

## Introduction

The present study focuses on the Badenian Ostracoda from the surroundings of Pokupsko, north Croatia. The investigated area is part of the Banovina region, central Croatia, bordered by the rivers Sava, Una, and Kupa. During the Middle Miocene, the investigated area of Banovina was located at the south-western margin of the North Croatian Basin (NCB further on), which represented the south-western margin of the Pannonian Basin system and the Central Paratethys Sea (Fig. 1).

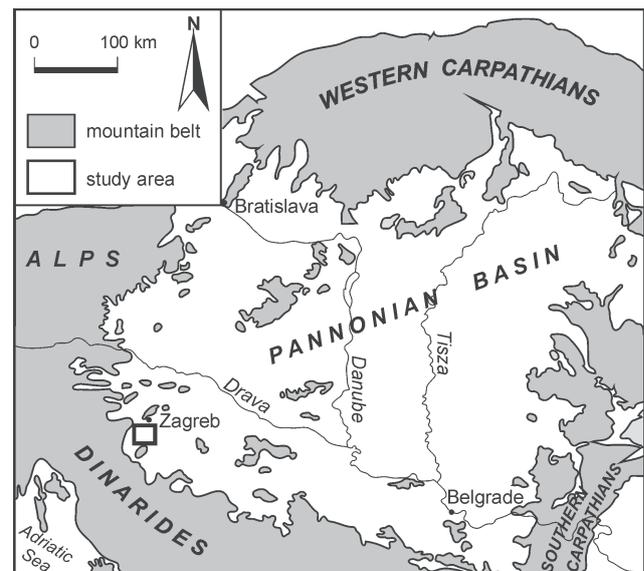
The Central Paratethys extended from Bavaria to the Carpathian mountain chain (Steininger & Rögl 1979, 1984; Rögl & Steininger 1983, 1984; Rögl 1998, 1999). It was part of an intercontinental bioprovince that, began to evolve in the Oligocene, and was formed due to collision of the European (Tisa-Moesia) and African Plates (Horváth & Royden 1981; Kováč et al. 1998). During the Miocene, connections of the Central Paratethys with the Mediterranean and the Indo-Pacific Ocean were repeatedly established and interrupted (Steininger et al. 1988; Rögl 1996). Such unstable connections resulted in sea-level oscillations (Haq 1991), different depositional modes and paleoecological conditions, thus resulting in the development of different ostracod faunas.

The formation of the NCB was associated with a passive continental rifting. A syn-rift phase began during the Oligocene and lasted until the Middle Badenian. The post-rift phase lasted from the Middle Badenian to the Pliocene (Pavelić 2001).

In the Central Paratethys, a threefold subdivision of the Badenian (16.3–12.7 Ma) is generally accepted (Papp et al. 1978; Harzhauser & Piller 2007). The Early Badenian (Langhian) sea-level rise and transgression are related to the global sea-level cycle TB 2.3 (Haq et al. 1988). In the NCB,

the Early Badenian deepening event resulted in deposition of marls and gravelly calcarenites in the offshore areas (Pavelić et al. 1998).

The second Badenian cycle corresponds to the global cycle TB 2.4. (Haq et al. 1988). It was followed by a regression and the lowstand Ser2 of Hardenbol et al. (1998). During the Late Badenian, the transgression flooded even the tips of the exposed blocks that had formed isolated islands during the Early Badenian. Marine sedimentation was initiated by the deposition of gravels, which are overlain by coralline algal beds.



**Fig. 1.** Geographical setting of the Pannonian Basin system with marked position of the investigated area.

Finally, the renewed flooding belongs to the Late Badenian Langhian/Serravallian cycle TB 2.5 (*sensu* Haq et al. 1988). Further deepening in the area of the NCB resulted in the deposition of marls.

Generally, the Early Badenian transgressions were controlled by both, tectonics (induced mainly by the back-arc basin rifting) and eustacy, followed by forced regression. The Late Badenian transgression and regression were dominantly controlled by sea-level changes within the Central Paratethys realm (Pavelić et al. 1998; Bakrač et al. 2010).

The results presented in this paper are exclusively based on paleontological and geochemical analyses of the ostracod fauna. The richness and diversity of the ostracod fauna in the investigated area is the consequence of important changes in the Badenian Paratethys, which had a positive effect on marine organisms. The enrichment of marine fauna was the consequence of open seaways between the Mediterranean Sea/Indo-Pacific and the Pannonian basin complex during the Badenian (Rögl 1998; Popov et al. 2004; Harzhauser & Piller 2007).

In addition to identification of the ostracod fauna, this study focuses on (1) paleoenvironmental reconstructions; (2) Badenian ostracod-based biozonation, recognized for the first time in Croatia after the Miocene Paratethys Biozonation of Jiříček (1983) and Jiříček & Říha (1990); and (3), comparison of the investigated ostracod fauna with coeval faunas from other parts of the Central Paratethys and Tethys.

In our analysis of the ostracod fauna, we included all the available samples; some of them were recently recovered from logged outcrops and cores, others were already preserved at the Croatian Geological Survey.

### Geological settings

The available literature on the Miocene deposits of the investigated area of Banovina is relatively sparse. The first geological map of the Glinsko Pokuplje area, along with a short discussion, was published by Štúr (1863). Tietze (1871) investigated the stratigraphy of the older deposits, whereas Šuklje (1914) suggested the existence of Tortonian, Sarmatian, and freshwater Pliocene *Conger* beds in the environs of Pokupsko.

Takšić (unpublished 1951) described geological and mining relationships in the environs of Abes, and reported on the shaft in Stipan. Kochansky-Devide & Slišković (1978) concluded that the deposits of Banovina are of the Middle Miocene, probably Late Helvetian (Karpatian) age. This conclusion is based on determinations of the *Conger* species and comparison with similar deposits on Mt Medvednica, as well as on the fact that the freshwater deposits are overlain by *Leitha* Limestone.

Jurišić Polšak (1979) determined the Lower Sarmatian mollusc fauna of Glinsko Pokuplje. In an unpublished report related to the geological map of the Vrginmost-Topusko-Viduševac area, Šikić K. & Šikić L. (1960) described the Dugo Selo and Stipan coal-bearing deposits.

Geological investigations associated with mapping of the Karlovac sheet, Basic Geological Map of former Yugoslavia 1:100,000, were carried out from 1974 to 1976, and all the

field and laboratory reports are stored at the Croatian Geological Survey. The micropaleontological report on the Cretaceous and Tertiary samples of the Karlovac sheet (Šikić 1974 unpubl.) concluded that the oldest Neogene deposits are represented by freshwater sediments immediately underlying Tortonian deposits with poorly preserved ostracods of reputed Helvetian age. According to the same author, the marine Tortonian deposits start with the *Spiroplectamina carinata* (*Spirorutilus carinatus*) Biozone. Later, Pikija (1984; unpubl. report) concluded that the Badenian deposits transgressively and unconformably overlie the older deposits, the latter ranging from the Triassic dolomites to basal breccias, Paleogene clastites, tuffs and tuffites.

During the investigations on the thickness and spatial distribution of subsurface coal-bearing deposits in the village of Stipan, Vrginmost-Lasinja area (Lukšić 1985, unpubl.), Miknić (1985, unpubl.) micropaleontologically analysed 16 cores and confirmed the presence of Badenian strata for two of them.

Bajraktarević (1983) analysed foraminiferal fauna and nannoplankton from Glinsko Pokupje (localities Čremušnica, Babin potok, and Ilovačak) and had assigned the Badenian age to the deposits (*Spiroplectamina carinata* Zone).

In a paper on the Neogene ostracod assemblages of Yugoslavia, Sokač & Krstić (1987) described the Šljivovac locality as one with a rich and well-preserved freshwater ostracod fauna. In her Master's thesis, Hajek-Tadesse (unpublished, 2000) described the ostracod fauna from Pokupsko.

### Study sites and methods

#### Study sites

The investigated area is situated near the village of Pokupsko, Banovina region, south of the Kupa River in Croatia (Fig. 2).

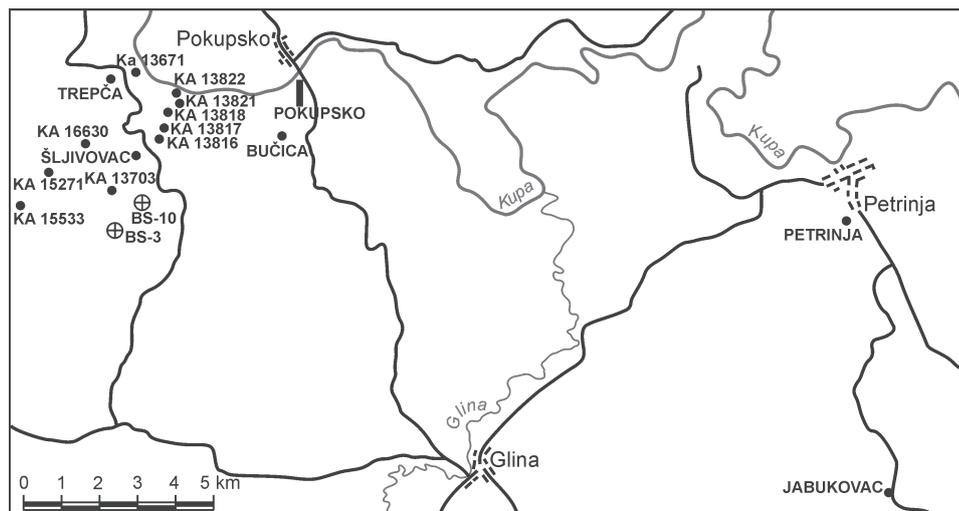
In addition to the Pokupsko outcrops, two cores at the Stipan locality (BS-3 and BS-10) and ten samples acquired during the 1974 Basic Geological mapping, Karlovac sheet, have been available for this study. We have also analysed five previously collected samples from the area; these samples are available at the Department of Geology, Croatian Geological Survey.

#### Pokupsko

The bulk of the samples has been collected at the Pokupsko outcrop near the Kupa River, along the unpaved road running parallel to the Kupa fluvial terrace, one kilometer southwest from Pokupsko. The outcrop extends 15 m in width and it is 5 to 6 meters thick. It consists of yellowish, poorly cemented sandstones, alternating laterally with yellowish-white sandy marls. The outcrop is very friable, and the bedding cannot be observed.

#### Stipan

The samples labelled Stipan well (BS), previously recovered near the Stipan village between Vrginmost and Lasinja were assigned to the Badenian age (Lukšić 1985, unpubl.).



**Fig. 2.** Location map: study area with marked position of Pokupsko outcrops (I); two wells Stipan (BS-3⊕); and sampling points (KA13671 ●).

The BS-3/84 well is situated in the Minići village, in an area known as Ostrožin. The sediment core is composed of sandy-limy Badenian deposits, whose thickness reaches up to 96.0 m; coal intercalations occur near the bottom of the core. Micropaleontological samples were collected from the intervals 42.00–42.10 m and 59.90–60.00 m. In the first 42.00–42.10 m interval, the Badenian deposits are fine-grained, and sandy-limy. In the second interval (59.90–60.00 m), the deposits are marly-sandy.

The BS-10/84 well is situated in a ditch 200 m south of the Šljivovac village, and it penetrated through 93 meters of Badenian deposits. The analysed samples were collected from sandy fossiliferous marls (interval 66.00–66.10 m).

Based on Lukšić's (1985, unpubl.) results it is obvious that the Badenian deposits in the Stipan wells and the surrounding area are stratigraphically younger than the coal-bearing series, and/or unconformably overlie the older bedrock composed of Cretaceous flysh-like facies and the volcanogenic-sedimentary complex.

The Lower Badenian deposits consist of decimeter-thick interbedded *Leitha* Limestone, calcareous sandstones, and light-yellow massive *Nullipore* Limestone, composed of *Lithothamnium* lumps. The upper parts of the Badenian are composed of marls with varying amounts of carbonate component, so that transitions from marls to calcareous marls to marly limestones can be observed. Marls are sandy and fossiliferous, and sporadically they contain tuffitic intercalations. The most remarkable Badenian lithologic member is the grey to light-yellow bedded to massive organogenous *Leitha* Limestone, which is often accompanied by limestones with abundant macrofossil shells. The peaks of all major neighbouring hills are composed of the same type of sediment, because the underlying sandy-marly parts are more easily eroded.

#### *Samples from mapping of the Karlovac Sheet*

During the 1974 geological mapping of the Karlovac sheet, sections Sjeniĉak and Ćremušnica were sampled for micropaleontological analyses. Ten samples were collected

and these have contributed to the completion of the sampling net in the investigated area. According to the field-note data, the samples have been collected from various sediments. Samples KA/13816, 13817, 13818 and 13821 were collected from sandy-clayey sediments; 13822, 16630, and 15533 were collected from marly-sandy and sandy sediments; 15271 was collected from sandy sediments; and 13703 and 13671 from clays.

#### *Samples from the micropaleontological collection*

The five samples found in the micropaleontological collection of the Department of Geology were found among the stored Neogene material labelled Jabukovac, Šljivovac, Petrinja, Trepĉa and Buĉica. Since the above samples do not have any additional marks, it was impossible to pinpoint precise locations as well as additional information on accompanying fauna, sediment type, and the environment in which they were found.

#### *Methods*

The collected field samples were disaggregated by soaking in a hydrogen peroxide solution for 24 hours, followed by washing through sieves (0.5; 0.25; 0.125; 0.063 mm) and drying. Some of the samples needed extra cleaning and these were re-soaked in hydrogen peroxide and treated ultrasonically for approximately 20 seconds. A hundred grams of each dried residue were observed under a stereomicroscope. Ostracods and other fossil remains (foraminifers and gastropods) were hand-picked, counted and determined. Ostracods were qualitatively, not selectively picked in order to preserve the relative composition of the thanatocoenosis.

The stored material was subjected to an additional cleaning process in an ultrasound dish after additional cleaning the material was picked again.

For the geochemical analyses of trace elements, the available amount of shells (about 50 mg) was weighed into 30 ml glass test tubes for one-time use, and 3 mg of concentrated HCl p.a. was added. The solutions were then analysed in the

Croatian Geological Survey by a simultaneous ICP atomic emission spectroscope Jobin-Yvon JY-50P. Concentrations of Mg, Ca, Mn, and Sr were determined; small sample and dilution prevented determination of other elements. The accuracy of the analyses was checked by the parallel analysis of the International Geological Standard Soil Samples GXR-5, GXR-6, and SJS-1, verified by USGS. The data were statistically analysed using the statistical package STATISTICA.

Photographs were made with the SEM at the Ina Naftapljin, Zagreb. All ostracod specimens are stored in the repository of the Croatian Geological Survey.

In this paper we essentially followed the ostracod classification of Morkhoven (1963), Hartmann & Puri (1974) and Horne et al. (2002).

## Paleontological and geochemical analyses

### Ostracods

The Badenian ostracod fauna from 17 localities (22 samples) analysed from the vicinity of Pokupsko is interesting due to its diversity and richness (Table 1; Figs. 3, 4). We have determined a total of 45 genera and 64 species. Samples were grouped according to differences or similarities of the ostracod fauna at one locality and by correlation between different localities.

In addition to the presence of zonal markers for the Ostracod Biozone for the Badenian (Jiriček 1983; Jiriček & Řiha 1990), we attempted to define the attribution of samples to a particular zone, out of the four Badenian ostracod zones recognized so far. However, the ostracod zonations should be treated with caution, because some new results in ostracod research have increased the stratigraphic range of several species (Zorn 2003, 2004; Gross 2006).

#### Pokupsko

The Pokupsko locality contains the majority of the species determined in this paper. Due to poor bedding conditions, the samples in the field were not taken continuously. Following the analysis of the ostracod fauna, and based on the differences observed in quantitative and qualitative representation of genera and species (differences in colour) and on sedimentological determinations, the eleven samples were classified into two groups, labelled Pokupsko I and Pokupsko II.

In Pokupsko I group, the representatives of the tribe Aurlinae are the most abundant, especially the species *Aurila angulata*, *A. cicatricosa*, *A. haueri*, *A. punctata*, *Senesia trigonella*, *S. cinctella*, *Pokornyella deformis*; also abundant are the following species: *Tenedocythere sulcatopunctata*, *Pachycaudites ungeri*, *Heliocythere vejhonsis*, *Costa edwardsi*, *C. reticulata*, *C. punctatissima*, *Carinocythereis carinata*, *Occultocythereis bituberculata*, *Grinioneis haindigeri*, *Henryhowella asperrima*, *Pterygocythereis calcarata*, *Olimfalunia plicatula*, *O. spinulosa*, *Olimfalunia* sp. and *Cytheridea* sp.

Less abundant are the following species: *Cytherella compressa*, *Bairdoppilata* sp., *Callistocythere* aff. *canaliculata*, *Echinocythereis scabra*, *Cnestocythere lamellicostata*, *Lox-*

*corniculum hastatum*, *L. punctatella*, *Neomonoceratina* sp. and *Xestoleberis* cf. *X. glabrescens*.

The Pokupsko II group contains all of the above mentioned species from Pokupsko I, and in addition it contains an increasing number of deeper water species: *Krithe* sp., *Parakrithe dactylomorpha* and *Eucythere* sp. The genus *Semicytherura* is also abundantly represented, with *Semicytherura alata*, *S. acuticostata*, *S. cf. S. alifera*, *Semicytherura* sp. as well as *Eucytherura textilis*, *Hemicytherura* sp., *Cytheretta tenuipunctata dentata*, *Flexus triebeli* and a few remains of *Ruggieria* cf. *R. micheliniana*, species which occurred only in the Pokupsko II group.

Also, in contrast to the Pokupsko I group, ostracods in the Pokupsko II group are preserved mostly in adult stage and with closed valves. The age of both groups, Pokupsko I and Pokupsko II, is Late Badenian.

#### The Stipan wells

Two cores have been studied: BS-3 with two intervals and BS-10 with one interval.

BS-3 (42.00–42.10 m). The most abundant species within this interval are *Olimfalunia plicatula*, *Olimfalunia* sp., *Cytheridea* sp. and *C. acuminata*; less abundant are *Cytherella compressa*, *Aurila angulata*, *Senesia cinctella*, *Callistocythere* aff. *canaliculata* and *Cnestocythere lamellicostata*, whereas *Costa edwardsi*, *Loxocorniculum hastatum* and *Bosquetina dentata* are present with only a few specimens. Of particular significance is the recovery of *Cytherelloidea sissinghi*, which represents its first finding within the Paratethys realm.

BS-3 (59.90–60.00 m). This interval contains a rich and diverse ostracod fauna. Of particular interest is the finding of *Ruggieria* ex gr. *carinata* and *Cytherelloidea sissinghi*, forms that are not frequent in Paratethys. Their findings in the investigated area represents an additional proof of transgressive events in the Badenian and migration of ostracods from the Tethys to Paratethys. Also, abundant are the representatives of the family Cyprididae, indicative of deeper water environment, such as *Paracypris polita* and *Phlyctenophora affinis*, as well as *Henryhowella asperrima* and *Pterygocythereis calcarata*. Similarly to the preceding interval of the same well, the species *Olimfalunia plicatula*, *O. spinulosa*, *Olimfalunia* sp., *Cytheridea* sp., *Cytherella compressa* are also abundant, whereas the following are less numerous: *Callistocythere* aff. *canaliculata*, *Costa edwardsi*, *Loxocorniculum hastatum*, *L. punctatella*, *Xestoleberis* cf. *X. glabrescens*, *Bosquetina dentata* and *Bythocythere* cf. *B. neerlandica*.

The sample from this interval differs in its faunal content from the upper interval of the same well, being more similar to the fauna from the well BS-10 (60.00–60.10 m).

BS-10 (60.00–60.10 m). The ostracod assemblage from this sample is one of the most interesting in the whole area investigated. It is dominated by valves of adult individuals, 80 % of which are very well preserved.

The finding of the key species *Acanthocythereis hystrix* is important for the age determination, and it supports an earlier attribution to the older part of the Badenian (unpublished Miknić 1985). In addition to that species, the sample contains important representatives of the family Cyprididae, as

**Table 1:** Distribution of the ostracod species within the samples of the Pokupsko area.

Ostracod species	POKUPSKO		STIPAN		KARLOVAC (KA)										TREPČA	BUČICA	JABUKOVAC	ŠLJIVOVAC	PETRINJA
	I	II	BS-3 BS-10		13671	13703	13816	13817	13818	13821	13822	15271	15533	16630					
<i>Cytherella compressa</i> (Münster, 1830)	•	•	•	•								•							
<i>Cytherella inaequalis</i> Moyes, 1965					•							•							
<i>Cytherella beyrichi</i> (Reuss, 1851)																			
<i>Cytherelloidea sissinghi</i> Szczechura, 1988			•	•	•														
<i>Bairdoppilata</i> sp.	•	•											•						
<i>Paranesidea</i> sp.												•							
<i>Bythocypris</i> sp.	•	•																	
<i>Phlyctenophora affinis</i> (Schneider, 1958)	•	•		•	•	•					•	•						•	
<i>Paracypris</i> cf. <i>P. polita</i> Sars, 1866						•					•						•		
<i>Callistocythere</i> aff. <i>canaliculata</i> (Reuss, 1850)	•	•	•	•			•										•	•	
<i>Cnestocythere lamellicosta</i> Triebel, 1950	•	•	•					•									•		
<i>Neomonoceratina</i> sp.	•	•																	
<i>Aurila angulata</i> (Reuss, 1850)	•	•	•					•				•					•	•	
<i>Aurila cicatricosa</i> (Reuss, 1850)	•	•					•				•								
<i>Aurila haueri</i> (Reuss, 1850)	•	•	•				•	•				•				•	•		
<i>Aurila punctata</i> (Münster, 1830)	•	•																	
<i>Senesia trigonella</i> (Reuss, 1850)	•	•						•											
<i>Senesia cinctella</i> (Reuss, 1850)	•	•	•					•			•								
<i>Pokornyella deformis deformis</i> (Reuss, 1850)	•	•																•	
<i>Echinocythereis scabra</i> (Münster, 1830)	•	•									•								
<i>Urocythereis</i> sp.	•	•																	
<i>Bosquetina dentata</i> (Müller, 1894)					•						•						•		
<i>Senesia</i> sp.	•	•					•												
<i>Elofsonella</i> sp.	•	•																	
<i>Tenedocythere sulcatopunctata</i> (Reuss, 1850)	•	•																•	
<i>Tenedocythere</i> cf. <i>T. salebrosa</i> (Uliczny, 1972)	•	•																	
<i>Tenedocythere</i> sp.	•	•																	
<i>Ruggieria</i> ex gr. <i>carinata</i> Moyes, 1965				•	•		•	•	•			•	•						
<i>Ruggieria</i> cf. <i>R. micheliniana</i> (Bosquet, 1852)				•															
<i>Pachycaudites ungeri</i> (Reuss, 1850)	•	•																	
<i>Helicythere vejhonensis</i> (Prochazka, 1893)	•	•																	
<i>Occultocythereis bituberculata</i> (Reuss, 1850)	•	•																	
<i>Costa edwardsi</i> (Roemer, 1838)	•	•		•	•		•	•	•	•	•	•	•	•	•	•	•	•	
<i>Costa reticulata</i> (Reuss, 1850)	•	•																	
<i>Costa punctatissima</i> Ruggieri, 1961	•	•																	
<i>Carinocythereis carinata</i> (Roemer, 1838)	•	•									•								
<i>Olimfalumia plicatula</i> (Reuss, 1850)	•	•	•	•	•				•	•							•	•	
<i>Olimfalumia spinulosa</i> (Reuss, 1850)	•	•	•	•				•									•		
<i>Olimfalumia</i> sp.				•				•											
<i>Grinioneis haidingeri</i> (Reuss, 1850)	•	•							•					•				•	
<i>Henryhowella asperrima</i> (Reuss, 1850)	•	•			•							•						•	
<i>Pterygocythereis calcarata</i> (Bosquet, 1852)	•	•			•	•					•		•					•	
<i>Acanthocythereis histrix</i> (Reuss, 1850)					•									•					
<i>Cytheretta tenuipunctata dentata</i> Brestenska, 1978	•	•																	
<i>Flexus triebeli</i> Ruggieri, 1962	•	•		•									•	•					
<i>Cytheridea</i> sp.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
<i>Cytheridea acuminata</i> Bosquet, 1852				•		•					•							•	
<i>Miocyprideis</i> sp.								•											
<i>Eucythere</i> sp.	•	•																	
<i>Kritha</i> sp.	•	•																	
<i>Parakritha dactylomorpha</i> Ruggieri, 1962	•	•						•											
<i>Hemicytherura</i> sp.		•																	
<i>Paracytheridea</i> sp.																	•		
<i>Pontocythere</i> cf. <i>P. curvata</i> (Bosquet, 1852)								•	•							•	•	•	
<i>Eucytherura textilis</i> Ruggieri, 1962	•	•																	
<i>Semicytherura alata</i> (Lienenklaus, 1894)	•	•																	
<i>Semicytherura acuticostata</i> (Sars, 1866)	•	•																	
<i>Semicytherura</i> cf. <i>S. alifera</i> Ruggieri, 1959	•	•																	
<i>Semicytherura</i> sp.		•																	
<i>Eocytheropteron inflatum</i> (Schneider, 1949)								•											
<i>Loxconcha punctatella</i> (Reuss, 1850)	•	•	•							•	•								
<i>Loxocorniculum hastatum</i> (Reuss, 1850)	•	•	•						•										
<i>Bythocythere</i> cf. <i>B. neerlandica</i> Kuiper, 1918																			
<i>Xestoleberis glabrescens</i> (Reuss, 1850)	•	•	•	•													•	•	

well as *Ruggieria* ex gr. *carinata*, *Cytherella inaequalis*, *Cytherelloidea sissinghi*, *Henryhowella asperrima*, *Pterygocythereis calcarata*, *Bythocythere* cf. *B. neerlandica*, *Olimfalunia plicatula*, *Cytheridea* sp., *Flexus triebeli*, *Costa edwardsi* and *Xestoleberis* cf. *X. glabrescens*.

According to the results obtained from the three intervals in two cores, we argue that the rich and well preserved ostracod fauna from the Stipan cores is interesting for several reasons. In the BS-3 well, a continuous transition from the upper part of the Lower Badenian into the lower part of the Middle Badenian may be discerned based on foraminifers (unpublished Miknić 1985), and a comparison of ostracod fauna from the well BS-3 59.90–60.00 m interval with the BS-10 60.00–60.10 m interval can be carried out.

The recovery of the biostratigraphic marker-species *Acanthocythereis hystrix* in the sample BS-10 (60.00–60.10 m) is extremely important, as it proves the Early Badenian age of the sample. The occurrence of typical representatives of a deeper water environment, such as: *Acanthocythereis hystrix*, *Henryhowella asperrima*, *Bythocythere* cf. *B. neerlandica* and *Paracypris polita* suggests deepening of the basin; *Cytherelloidea sissinghi* and *Ruggieria* ex gr. *carinata*, which have previously not been recorded from the Badenian deposits of the Central Paratethys, indicate migration of ostracod faunas from the Tethys into this region. The data about the reverse migration of the ostracod fauna, namely from the Paratethys to Tethys (Szczechura & Abd-Elshafy 1988) also support these considerations.

#### *Samples collected during mapping of the Karlovac sheet*

Ten samples collected during the geological mapping of the Karlovac sheet are classified into six groups according to the similarity of the ostracod fauna observed.

Karlovac I (KA 16630, 15533). This group is distinguished from the other groups by the presence of the index species *Acanthocythereis hystrix*, indicating the Early Badenian age. Other abundant species include *Ruggieria* ex gr. *carinata*, *Pterygocythereis calcarata*, *Henryhowella asperrima*, *Flexus triebeli*, *Cytheridea* sp., and less numerous *Grinioneis haidingeri*, *Aurila haueri*, *Costa edwardsi* and *Bairdoppilata* sp.

Karlovac II (KA 13703). The recovery of *Eocytheropteron inflatum* in sample KA 13703 has been decisive in separating this sample into a different group. In addition to *Eocytheropteron inflatum*, this group is characterized by a mixed shallow-water/deep-water ostracod fauna. The abundant ostracod fauna includes *Ruggieria* ex gr. *carinata*, *Phlyctenophora affinis*, *Paracypris polita*, *Olimfalunia spinulosa*, *Olimfalunia* sp., *Cytheridea* sp., *Pontocythere* cf. *P. curvata* and, less numerous, *Aurila cicatricosa*, *Bosquetina dentata* and *Senesia* sp.

Karlovac III (KA 13817, KA 13816). In the third group, the most numerous species are shallow-water representatives of the genus *Aurila*, with *A. angulata*, *A. cicatricosa*, *A. haueri*, *A. punctata*, *Senesia trigonella*, *S. cinctella*, as well as the species *Costa edwardsi*, *C. reticulata*, *Cytheridea* sp., *Pontocythere* cf. *P. curvata*, *Callistocythere* aff. *canaliculata*, *Cnestocythere lamellicostata*, *Phlyctenophora affinis*, *Grinioneis haidingeri*, *Pterygocythereis calcarata*, *Olim-*

*falunia plicatula*, *O. spinulosa* and *Olimfalunia* sp. Similar to the above-mentioned groups, this group also contains *Ruggieria* ex gr. *carinata*, and the age of the sample is determined as Middle Badenian; this age was also documented by foraminifers (unpublished Šikić L. 1974).

Karlovac IV (KA 13818, KA 13821). The fourth group has been based on findings of *Miocyprideis* sp. in two samples. The dominant species are *Cytheridea* sp., *Costa edwardsi* and *C. reticulata*, but *Olimfalunia plicatula*, *Carinocythereis carinata*, *Senesia cinctella* and *A. cicatricosa* are also present, though less numerous. Specimens of the genera *Costa* and *Olimfalunia* show environmentally cued polymorphous changes (Peypouquet et al. 1988) on their valves. The Late Badenian age of the sample has been determined based on the ostracod fauna. According to the foraminiferal assemblage, the “Upper Tortonian” *Ammonia beccarii* Zone was determined (unpublished Šikić L. 1974).

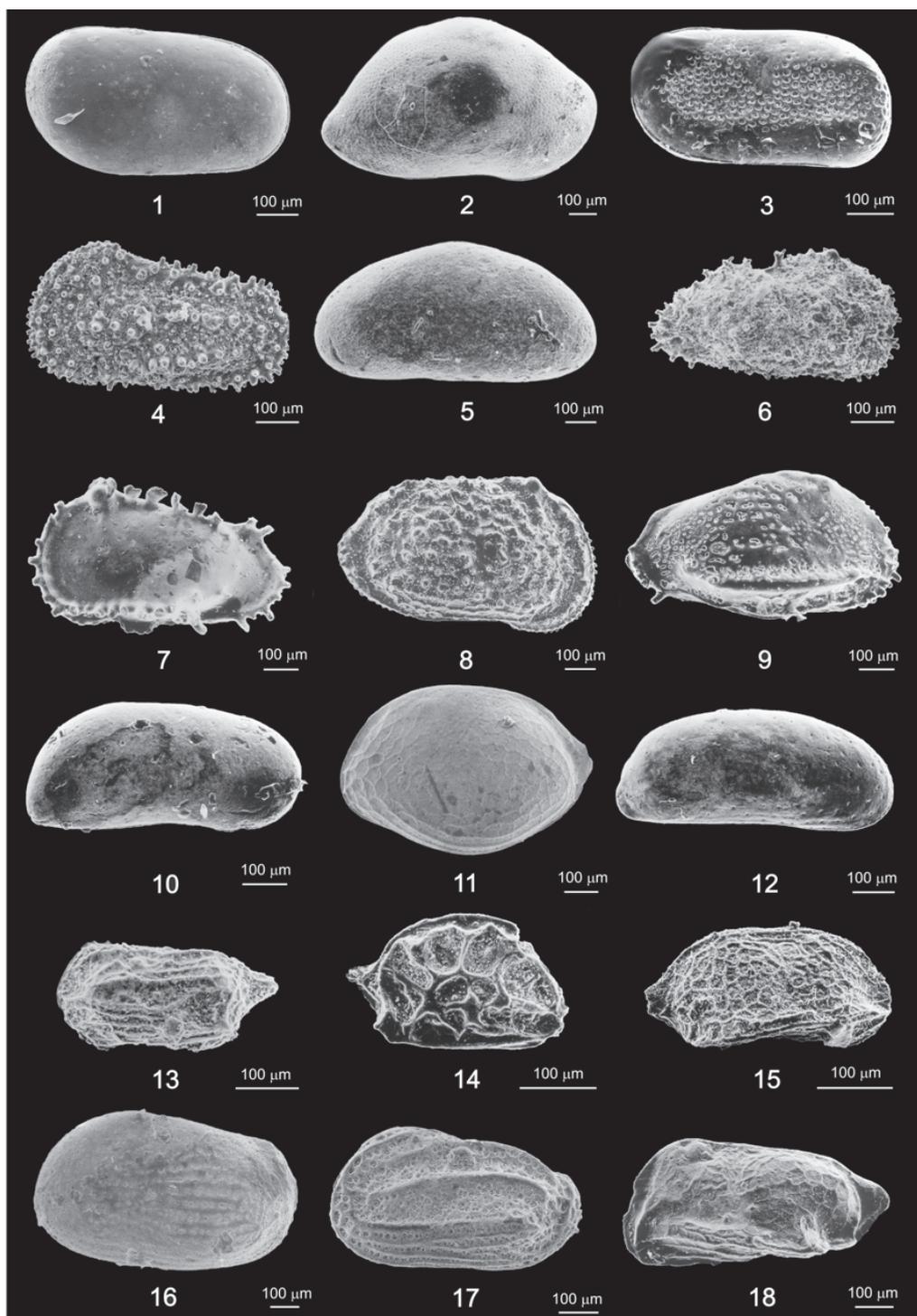
Karlovac V (KA 15271). The dominant species in this group are *Cytherella compressa*, *Cytherella inaequalis*, *Paranesidea* sp., *Phlyctenophora affinis* and *Aurila angulata*. Contrary to previous groups, this group is impoverished with respect to both the number of species and the number of specimens. On the basis of the ostracod fauna and foraminifers (unpublished Šikić L. 1974), the Late Badenian age of that sample has been determined.

Karlovac VI (KA 13822, KA 13671). This group has been identified based on the shallow-water fauna, which, in contrast to the KA III group, is not dominated by the genus *Aurila*. This group is characterized by *Phlyctenophora affinis*, *Costa edwardsi*, *C. reticulata*, *Cytheridea* sp., *C. acuminata* and less abundant deeper water species *Paracypris polita*, *Bosquetina dentata*, *Echinocythereis scabra* and *Pterygocythereis calcarata*. The age of the sample is Late Badenian.

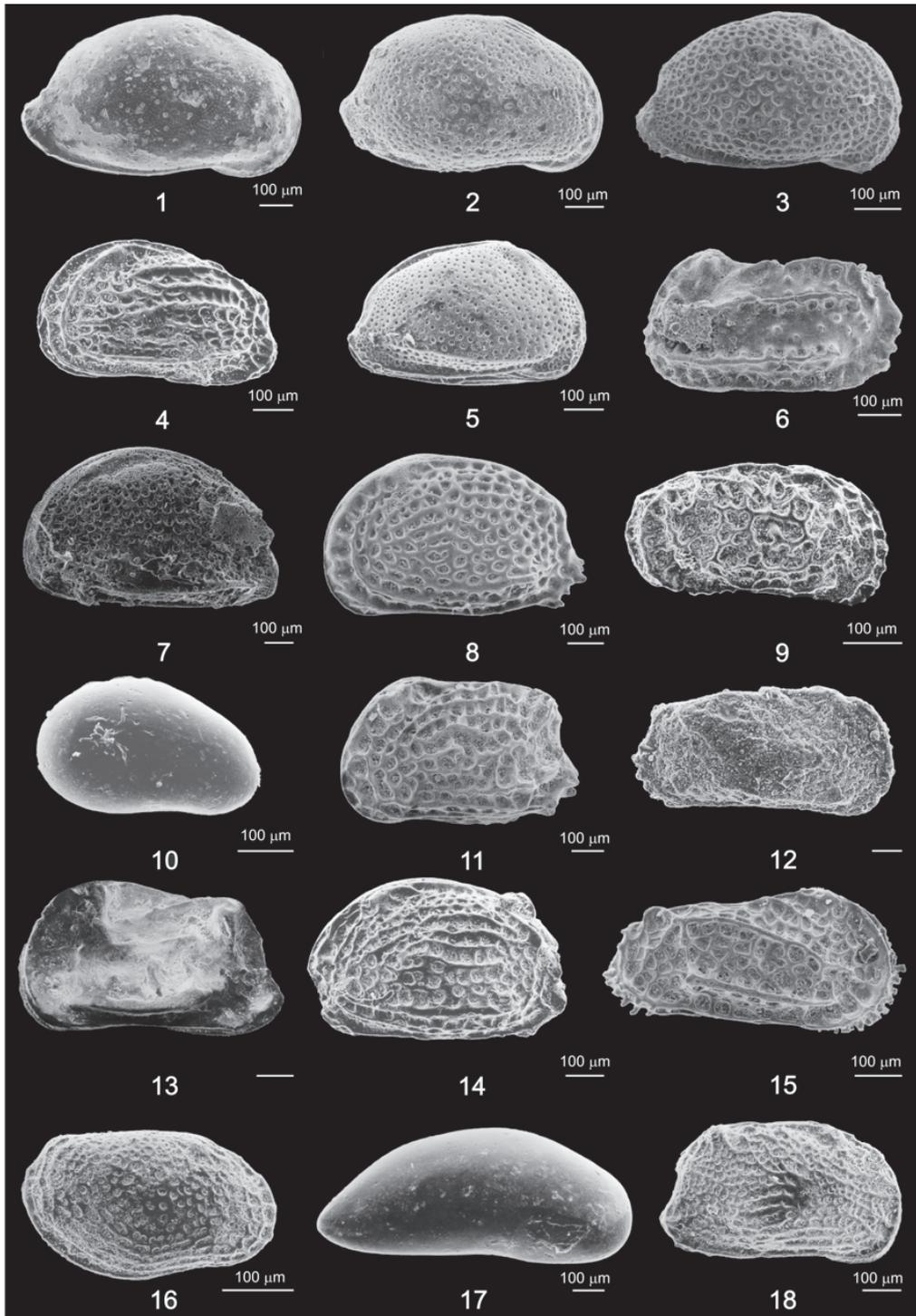
The ostracod fauna in the samples collected during mapping yields some important information on Badenian deposits in the investigated area. The key species *Acanthocythereis hystrix* in the first group and *Eocytheropteron inflatum* in the third group define the age of these deposits as Early and Middle Badenian. The common characteristic of the first three groups is the presence of the “new-entry” species *Ruggieria* ex gr. *carinata*, whereas the presence of the genus *Miocyprideis* in the fourth group indicates global paleoecological changes in the Paratethys realm during the transition from Middle to Late Badenian.

#### *Šljivovac*

Although the Šljivovac locality is situated close to Stipan, its faunal content is more similar to the ostracod fauna from the B-3 well (59.90–60.00 m interval), except for the species *Parakriithe dactylomorpha*, *Pontocythere* cf. *P. curvata*, *Paracytheridea* sp. and *Cytherella beyrichi*, which were found only in that sample. In the Šljivovac sample, the most abundant species are *Henryhowella asperrima*, *Pterygocythereis calcarata*, *Cytheridea* sp., *Costa edwardsi*, *Olimfalunia plicatula* and *Callistocythere* aff. *canaliculata*. Of particular importance is findings of the “new-entry” species *Cytherelloidea sissinghi*, which prior to this study has not been identified in the Paratethys realm. The environmentally cued polymorphous



**Fig. 3.** SEM microphotographs of selected ostracods. **1** — *Cytherella compressa* (Münster), sample Pokupsko I, right valve, external view. **2** — *Bairdoppilata* sp., sample Pokupsko I, right valve, external view. **3** — *Cytherelloidea sissinghi* Szczechura, sample Stipan (BS-10), right valve, external view. **4** — *Henryhowella asperrima* (Reuss), sample Stipan (BS-10), left valve, external view. **5** — *Bythocypris* sp., sample Pokupsko II, left valve, external view. **6** — *Acanthocythereis hystrix* (Reuss), sample Stipan (BS-10), right valve, external view. **7** — *Pterygocythereis calcarata* (Bosquet), sample Pokupsko I, left valve, external view. **8** — *Echinocythereis scabra* (Münster), sample Pokupsko I, right valve, external view. **9** — *Ruggieria* ex gr. *carinata* Moyes, sample Stipan (BS-10), right valve, external view. **10** — *Krithe* sp., sample Pokupsko II, right valve, external view. **11** — *Eocytheropteron inflatum* (Schneider), sample KA 13703, left valve, external view. **12** — *Pontocythere curvata* (Bosquet), sample KA 13816, right valve, external view. **13** — *Semicytherura acuticostata* (Sars), sample Pokupsko I, left valve, external view. **14** — *Hemicytherura* sp., sample Pokupsko II, right valve, external view. **15** — *Semicytherura* sp., sample Pokupsko II, right valve, external view. **16** — *Cytheretta tenuipunctata dentata* Brestenska, sample Pokupsko I, left valve, external view. **17** — *Flexus triebeli* (Ruggieri), sample Pokupsko I, left valve, external view. **18** — *Semicytherura alata* (Lienenklaus), sample Pokupsko II, left valve, external view.



**Fig. 4.** SEM microphotographs of selected ostracods. **1** — *Aurila haueri* (Reuss), sample Pokupsko I, right valve, external view. **2** — *Pokornyella deformis* (Reuss), sample Pokupsko I, right valve, external view. **3** — *Aurila punctata* (Münster), sample Pokupsko I, right valve, external view. **4** — *Elofsonella* sp., sample Pokupsko II, left valve, external view. **5** — *Aurila angulata* (Reuss), sample Bučica, right valve, external view. **6** — *Carinocythereis carinata* (Roemer), sample Pokupsko II, left valve, external view. **7** — *Senesia* sp. sample KA 13703, left valve, external view. **8** — *Tenedocythere sulcatopunctata* (Reuss) sample Pokupsko I, left valve, external view. **9** — *Callistocythere* aff. *canaliculata* (Reuss), sample KA 13816, right valve, external view. **10** — *Xestoleberis glabrescens* (Reuss) sample Pokupsko II, left valve, external view. **11** — *Tenedocythere* cf. *T. salebrosa* Uliczny, sample Pokupsko I, left valve, external view. **12** — *Ruggieria* cf. *R. micheliniana* (Bosquet), sample Pokupsko II, right valve, external view. **13** — *Pachicaudites ungeri* (Reuss), sample Pokupsko II, left valve, external view. **14** — *Tenedocythere* sp. sample Pokupsko I, left valve, external view. **15** — *Costa edwardsi* (Roemer), sample Bučica, left valve, external view. **16** — *Loxococoncha punctatella* (Reuss), sample KA 13818, right valve, external view. **17** — *Phlyctenophora affinis* (Schneider), sample KA 13671, right valve, external view. **18** — *Heliocythere vejhonensis* Prochazka, sample Pokupsko I, right valve, external view.

changes (Peypouquet et al. 1988) have been observed on valve surfaces of *Costa* and *Olimfalunia*. The Middle Badenian age of this sample has been determined on the basis of the ostracod fauna and Sokač's observations (pers. comm.).

#### *Trepča and Bučica*

The faunas from the two samples are very similar. They are both dominated by *Callistocythere* aff. *canaliculata*, *Cnestocythere lamellicosta*, *Aurila angulata*, *A. haueri*, *Costa edwardsi*, *Olimfalunia plicatula* and *O. spinulosa*. In addition to the species mentioned in the Trepča sample, less numerous are *Senesia* sp. and *Bosquetina dentata*, absent in the Bučica sample, which contains, instead, *Cytheridea* sp. According to the analysis of the ostracod fauna and comparison with fauna from other localities, the Late Badenian age has been determined.

#### *Jabukovac and Petrinja*

The main characteristic of the two localities is the predominance of adult specimens of *Pontocythere* cf. *P. curvata*. Other species common to both localities include *Xestoleberis* cf. *X. glabrescens* and *Olimfalunia plicatula*. In addition, the Jabukovac locality contains *Cytherella compressa*, *C. inaequalis* and *Paracypris polita*.

The Petrinja sample contains a richer fauna than the above described. In addition to the above species it also includes *Bairdoppilata* sp., *Phlyctenophora affinis*, *Callistocythere* aff. *canaliculata*, *Aurila angulata*, *Pokornyyella deformis*, *Tenedocythere sulcatopunctata*, *Costa edwardsi*, *Grinioneis haidingeri*, *Olimfalunia plicatula* and *Cytheridea acuminata*. The Late Badenian age of this sample has been determined on the basis of the ostracod fauna.

#### *Trace element analyses of the Upper Badenian ostracod valves*

Ostracods are organisms sensitive to environmental changes that control their occurrence, distribution, and reproduction (Barbieri et al. 1999; Holmes & Chivas 2002). Ostracod valves are made of Ca and Mg-carbonates, but other chemical elements, including Sr, K, Na, Mn, Fe, and Ba, may also be present.

Chivas et al. (1983) were among the first who showed that certain geochemical parameters of ostracod valves yielded more detailed information on the environment in which the fauna lived. The analysis of concentrations and ratios of Ca, Mg, Sr, and Mn in ostracod valves from the vicinity of Pokupsko (all samples studied come from the sixth biofacies, thus being Late Badenian in age) enabled us to do the paleoenvironmental reconstruction. Generically determined valves were separated for geochemical analyses. According to Barbieri et al. (1999), this is acceptable since species of the same genus, or even phylogenetically related genera, have similar Sr and Mg concentrations.

The selected genera inhabited both shallow-water (*Aurila*, *Cytheridea*, *Tenedocythere*) and deep-water environments (*Cytherella*, *Bairdoppilata*).

The concentrations of elements vary in different deposits, depending on regional features, differences in mineralogy, and ratio between inorganic and organic components. Chivas et al. (1983) argued that the amount of Mg in ostracod valves depends on the temperature and concentration of  $Mg^{2+}$  in water, whereas the Sr content depends directly on the concentration of  $Sr^{2+}$  in water. In sea water, the concentration of Mg and Sr increases with the increasing salinity and decreases with the decreasing temperature, whereas the higher Mn concentrations are due to increased influx of terrigenous material (Prasada 1996). The ratio of Sr/Ca and Mg/Ca concentrations in ostracod valves remains unchanged if the water, temperature and salinity remain constant. If the value of Mg/Ca ratio varies, and the Sr/Ca ratio remains constant, the water temperature varies and salinity is constant. Finally, if both the Sr/Ca and Mg/Ca ratios vary, changes in salinity and insignificant changes in water temperature are expected.

Dweyer et al. (1995) were among the first to postulate a connection between the variations in Mg/Ca ratio in valves of the deep-water genus *Krithe* and the water depth in which the genus lived. The authors concluded that the lower Mg/Ca values in valves correspond to lower water-temperature, and higher values correspond to higher temperatures.

In both organic and inorganic aragonite, the Sr/Ca ratio often increases with the lowered temperature (Prasada 1996), whereas the rather stable Sr/Ca values are indicative of an equalized temperature.

Certain conclusions can be drawn from the above mentioned data and the results obtained by geochemical analyses shown in Table 2 and Fig. 5a-c.

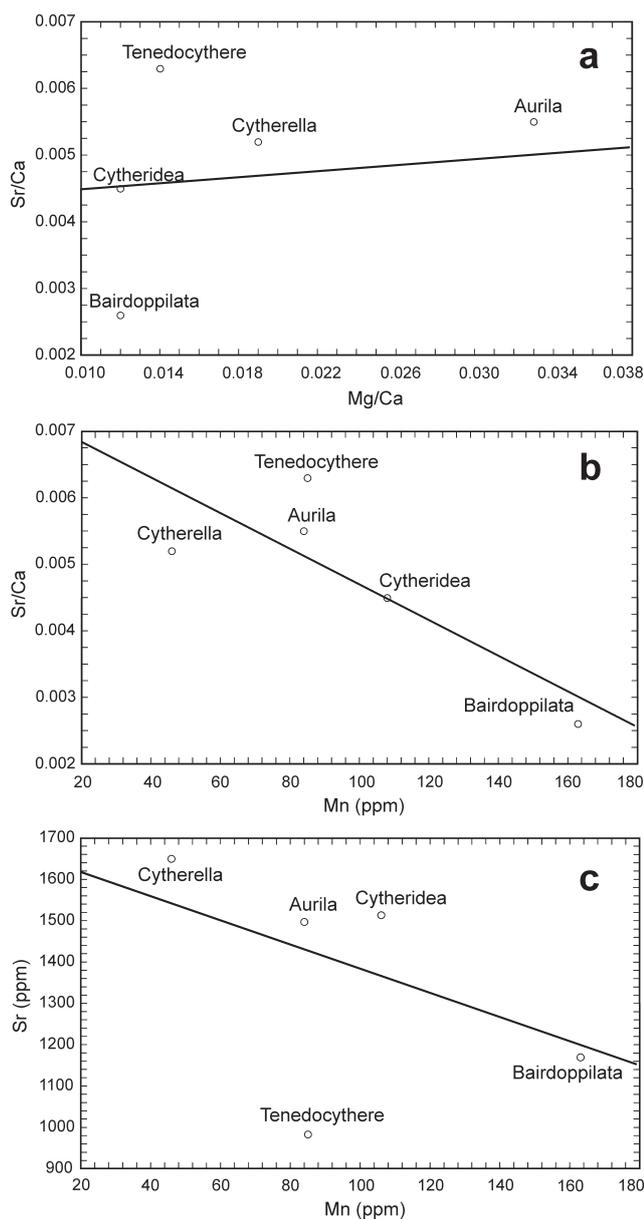
The greatest deviations from the group of analysed genera in the first two diagrams (Fig. 5a,b) is found in the genus *Bairdoppilata*. The low Mg/Ca and Sr/Ca ratios, as well as the increased concentrations of Mn (163 ppm), distinguish this genus from the group of other genera. This may be explained through the interpretation of different micro-environments.

It is known, that the genus *Bairdoppilata* inhabits both very shallow and deep marine environments. According to the geochemical analyses of the Pokupsko sample, we suggest a shallow-water environment with considerable influx of terrigenous material, and so close to lower salinity freshwater sources enriched in Mn as indicated by the lower values of the Mg/Ca and Sr/Ca ratios.

As shown in Fig. 5b,c, the genus *Bairdoppilata* is joined by the genus *Tenedocythere*, in its deviation from the group of shallow-water marine forms. The lowest Sr concentrations (985 ppm) in the valves of this genus, as well as the low Mg concentration, indicate the change in water salinity. Because we are dealing with a marine environment, such deviations

**Table 2:** Obtained results of trace element analyses for selected ostracod genera from the Pokupsko area.

	Mg ppm	Mn ppm	Sr ppm	Mg/Ca	Sr/Ca
<i>Aurila</i>	9214	84	1497	0.033	0.0055
<i>Cytherella</i>	5942	46	1650	0.019	0.0052
<i>Bairdoppilata</i>	5327	163	1170	0.012	0.0026
<i>Cytheridea</i>	3868	108	1512	0.012	0.0045
<i>Tenedocythere</i>	2935	85	983	0.014	0.0063



**Fig. 5.** a — Mg/Ca versus Sr/Ca plot in the valves of analysed genera. b — Sr/Ca versus Mn concentration plot in the valves of analysed genera. c — Sr concentration versus Mn concentration plot in the valves of analysed genera.

may be explained by decreased magnesium and strontium values as a consequence of crystal growth (Prasada 1996).

The other three analysed genera do not show considerable deviations regarding the concentrations of elements, the exception being genus *Cytherella*, in which the lowest Mn concentration (46 ppm) and the highest Sr concentration (1650 ppm) have been determined. The deviations in Mn and Sr concentrations may be explained in two ways, either as an adaptability to greater depths, or life in a protected marine shallow-water environment, devoid of freshwater influx. The decision, on which hypothesis should be accepted can be reached only after analysis of the whole ostracod assemblage in which *Cytherella* has been found.

Taking into consideration all the above-mentioned data, the environment during life of the selected genera corresponded to the model of an open/half-closed lagoon with periodical freshwater influx, presented in the paleoenvironment reconstruction section of this paper.

## Discussion

### Correlation of samples based on analysed fauna

The studied ostracod faunas were collected in a relatively small investigated area on the basis of common characteristics, namely key species, facies indicative species and common biocoenoses. Accordingly, we were able to classify 25 samples into 14 groups; groups were classified into six biofacies. These biofacies do not necessarily represent biostratigraphic units; sometimes, they are identified exclusively according to the paleoecological diversity of the constituent fauna (Fig. 6.).

**First biofacies.** It includes the Stipan BS-10 (60.00–60.10 m) fauna, and its temporal and faunistic equivalent, KA I (15533, 16630); these two groups share three important characteristics.

Both groups contain the key species *Acanthocythereis hystrix*, which determines the attribution of the samples to the homonym biozone of the Lower Badenian Biozone (NO7) *Acanthocythereis hystrix-Bythocypris lucida* (Jiříček 1983; Jiříček & Řiha 1990).

Also, both groups contain a mixed deeper and shallow-water fauna. Among the deeper water forms, the most abundant are *Henryhowella asperrima*, *Pterygocythereis calcarata* and *Bythocythere neerlandica*, whereas the shallower environment is characterized by four genera, namely *Olimfalunia*, *Cytheridea*, *Flexus* and *Costa*.

The findings of the so-called “new-entry” species *Ruggieria ex gr. carinata* and *Cytherelloidea sissinghi* imply, the transgressive changes occurring during the Early Badenian, and the migration of ostracod species from southern parts of the Mediterranean, indicating the establishment of the Tethys-Paratethys connection.

The **second biofacies** continuously succeeds the first biofacies. It includes samples from the Stipan BS-3 well (59.60–60.00 m) and the Šljivovac locality. Like the first facies described above, it contains a mixed fauna of deeper water ostracods such as *Henryhowella asperrima*, *Pterygocythereis calcarata*, *Bosquetina* sp., *Paracypris polita*, *Phlyctenophora affinis* and *Bythocythere neerlandica* and shallow-water forms, dominated by genus *Olimfalunia* with several species of the *Olimfalunia-Cytheridea-Callistocythere-Costa* association. Due to the abundance of genus *Olimfalunia* and continuous sedimentation that is clearly observed in the Stipan well samples, it is possible to assign the samples from this biofacies to the Middle Badenian ostracod Biozone (NO8), *Eocytheropteron inflatum-Olimfalunia spinulosa* (Jiříček 1983; Jiříček & Řiha 1990).

Both samples contain the species *Ruggieria ex gr. carinata* and *Cytherelloidea sissinghi*.

The **third biofacies** continuously overlies the second biofacies. The samples of this biofacies BS-3 (42.00–42.10 m) and

Stages	Ostracod Zonation of the Central Paratethys (Jiriček & Říha 1990)	Local biofacies	Samples	
BADENIAN	UPPER	sixth biofacies	PETRINJA JABUKOVAC KARLOVAC KA VI (15271) KARLOVAC KA V (13822, 13671) POKUPSKO I, II BUČICA TREPČA	
			fifth biofacies	KARLOVAC KA IV (13818, 13821)
	MIDDLE	fourth biofacies	KARLOVAC KA III (13703)	
		third biofacies	STIPAN BS-3 (42.00–42.10 m) KARLOVAC KA II (13817, 13816)	
		second biofacies	STIPAN BS-3 (59.90–60.00 m) ŠLJIVOVAC	
	LOWER	first biofacies	STIPAN BS-10 (60.00–60.10 m) KARLOVAC KA I (15533, 16630)	
		NO10 <i>Carinocythereis carinata</i> – <i>Phlyctenophora farkasi</i>		
		NO9 <i>Neomonoceratina laskarevi</i> – <i>Miocyprideis sarmatica elongata</i>		
		NO8 <i>Eocytheropteron inflatum</i> – <i>Olimfalunia spinulosa</i>		
		NO7 <i>Acanthocythereis hystrix</i> – <i>Bythocypris lucida</i>		

Fig. 6. Ostracod biozonation of the Badenian samples from the Pokupsko area.

KA (13817, 13816) are distinguished from the previous facies on the basis of paleoecological differences. The biofacies is characterized by shallow-water ostracod assemblages, that dominate over the less numerous deeper water forms. The most abundant form is genus *Olimfalunia* (with three species), associated with genera *Aurila*, *Costa* and *Cytheridea*. On the basis of the predominance of the *Olimfalunia* genus, this biofacies is assigned to the Middle Badenian ostracod Biozone (NO8) *Eocytheropteron inflatum*–*Falunia spinulosa* (Jiriček 1983; Jiriček & Říha 1990).

The two samples of this biofacies differ in two details. In sample BS-3 we found the species *Cytherelloidea sissinghi*, which is missing in the KA II group, whereas in KA II we found *Ruggieria ex gr. carinata*, which is not present in the BS-3 sample. In this level we notice the last occurrence of the new-entry species *Cytherelloidea sissinghi*.

**Fourth biofacies.** Samples from the KA III group (13703). The recovery of well preserved and numerous adult

specimens of *Eocytheropteron inflatum* (which is found only in this sample) is important biostratigraphical information. It is well known as the key species of the Middle Badenian Biozone in the Paratethys (Jiriček 1983; Jiriček & Říha 1990) and therefore its recovery in the fourth biofacies indicates the Middle Badenian, Biozone (NO8) *Eocytheropteron inflatum*–*Olimfalunia spinulosa*. This biofacies is characterized by mixed deep-water and shallow-water ostracod assemblages, with *Phlyctenophora affinis*, *Paracypris polita*, *Olimfalunia spinulosa*, *Cytheridea* sp., *Pontocythere* cf. *P. curvata*, and, less numerous, *Aurila cicatricosa*, *Bosquetina* sp. and *Senesia* sp. We also noticed the last occurrence of *Ruggieria ex gr. carinata* in this level.

**Fifth biofacies.** The samples from the KA IV group (13818, 13821) are classified as a separate biofacies. The most significant feature of this facies is the presence of *Miocyprideis* sp. Though it is not the marker species of the well known Upper Badenian Zone *Miocyprideis elongata* (Jiriček 1983), the recovery of this genus nevertheless indicates paleoecological changes, such as decreasing water salinity and depth, which are characteristic of the region during the lowest part of the Upper Badenian, namely the *Miocyprideis elongata* (NO9) Biozone (Jiriček 1983; Jiriček & Říha 1990).

The samples are dominated by the shallow-water genera *Cytheridea* and *Costa*; less abundant are *Olimfalunia plicatula*, *Carinocythereis carinata*, *Senesia cinctella* and *Aurila cicatricosa*. Environmentally cued polymorphous changes (Peypouquet et al. 1988) on valves of the *Olimfalunia* and *Costa* genera have also been noticed.

**Sixth biofacies.** This biofacies includes samples from the Upper Badenian groups of Pokupsko I, Pokupsko II, Trepča, Bučica, Jabukovac, Petrinja, KA V (13822, 13671), and KA VI (15271). This is the richest biofacies, according to both the number of analysed samples and the number of determined species.

The differences in ostracod faunas within the analysed samples are most clearly visible in the distribution of deep-water species and different shallow-water assemblages. Thus, the Pokupsko II group contains more abundant, typically deep-water species, *Henryhowella asperrima*, *Pterygocythereis calcarata*, *Krithe* sp., *Parakrithe dactylomorpha* and *Echinocythereis scabra*, whereas in the Pokupsko I group we found only three deep-water species, *Henryhowella asperrima*, *Pterygocythereis calcarata* and *Echinocythereis scabra*.

The recovery of *Echinocythereis scabra* is particularly interesting, because in addition to Pokupsko, it has been identified only in the KA V sample, and is generally rarely found in the Paratethys. That species is most frequently found in

the contemporaneous deposits of the Aquitanian Basin, France (Moyes 1965; Ducasse & Cahuzac 1997).

Each of the above-mentioned samples or groups also contains a recognizable dominant shallow-water ostracod association. Thus, Pokupsko I is characterized by the *Aurila-Tenedocythere-Costa* association, and Pokupsko II by the *Semicytherura-Cytheridea-Cytheretta* association.

In the Karlovac IV group, the dominant genera are *Cytherella*, *Paranesidea*, *Aurila*, and in Karlovac V, *Costa* and *Cytheridea*. The Jabukovac and Petrinja samples are characterized by the shallow-water *Pontocythere-Costa-Cytheridea* assemblage, whereas Trepča and Bučica contain the *Aurila-Costa-Olimfalunia* association.

The entire ostracod assemblage — except some species — is well known from the Badenian deposits of Central Paratethys. It is most similar to the Badenian fauna of the Vienna Basin, Lower Austria (unpublished Huber-Mahdi 1984; Zorn 2003, 2004; Gross 2006; Gebhardt et al. 2009). The shallow-water part of the fauna correlates well with the shallow-water Badenian fauna of Podvin, Vienna Basin, southern Moravia (Zelenka 1985), and the deeper water fauna of Pokupsko shows similarities with the Middle Miocene deeper water fauna of the pre-Karpatian depression of Poland (Szczechura 1994). The described fauna is also comparable with the Badenian fauna from six wells in southwest Poland (Paruch-Kulczycka 1992).

A non-isolated realm for the studied samples is further suggested on the basis of similarities with the Middle Miocene ostracod assemblages of a wider geographical area. Thus, we may distinguish a dozen species that are common within the Middle Miocene ostracod fauna of Libya and Egypt (Szczechura & Abd-Elshafy 1988), the island of Crete (Sissingh 1972), the Langhian ostracods from Sicily (Dall'Antonia et al. 2001), Northern Sardinia (Bossio et al. 2006), the Rhodanian Basin (Carbonnel 1969), the Miocene fauna of the NW Basin of northern Germany (Uffenorde 1981) and the Middle Miocene ostracods from the West Coast of India (Bhandari et al. 2001).

#### *Ostracod paleoecology of the surroundings of Pokupsko*

The regional Middle Miocene geological events are closely associated with the ostracod fauna distribution. The openings or closings of sea straits, transgressions, regressions, as well as climatic changes, had a deep impact on composition of the ostracod association, preservation state of the valves, frequency of particular genera and species, and the occurrence of polymorphous changes on ostracod valves.

Differences in the state of preservation and composition of biocoenoses are probably the result of different energy conditions and sedimentation rates (Whatley 1983; Boomer et al. 2003).

Slow sedimentation typically results in well preserved, separated valves, and complete biocoenoses are found. The Lower and Middle Badenian samples analysed in this paper are an example of such a rate of sedimentation.

During high-energy conditions and/or rapid sedimentation, unfavourable conditions for preservation occurred, resulting in selectively sorted valves. Complete, selectively

sorted carapaces (usually lacking juvenile specimens), with non-separated valves, are found mostly in Upper Badenian samples of the Pokupsko surroundings.

The lack of autoecological data on Badenian species impedes the paleoecological reconstruction. However, general assumptions on living conditions of the representative genera may partly compensate for the absence of data and yield reliable conclusions. Thus, in this paper, indicative genera were selected, and their occurrence may be associated with a particular type of environmental conditions.

In the ostracod fauna of the surroundings of Pokupsko, heavily calcified genera with strongly ornamented valve surfaces are dominant, indicating shallow marine habitats. These include *Aurila*, *Senesia*, *Tenedocythere*, *Callistocythere*, *Costa*, *Grinioneis*, *Hemicytherura*, *Cytheridea*, *Xestoleberis*, *Semicytherura* and *Olimfalunia*.

Within this shallow-water fauna, two specific groups of genera may be distinguished. The species within the first group are limited to tropical and subtropical seas, and most frequently suggest reefal areas. These include *Paranesidea*, *Loxoconcha* and *Cytherelloidea*. The second group is distinguished by the *Miocyprideis* genus, indicating a brackish environment.

The transitional, shallow-water/deep-water group is identified by the following genera: *Pterygocythereis*, *Echinocythereis*, *Bosquetina*, *Cytherella* and *Ruggieria*.

A separate group is represented by the deep-water genera *Krithe*, *Parakrithe*, *Eocytheropteron*, *Henryhowella*, *Argilloecia*, *Acanthocythereis*, *Paracypris* and *Bythocythere*, whose recent representatives live at a depth of about 100 m.

On the basis of the different genera identified, the ostracod fauna from the surroundings of Pokupsko can be defined as a shallow-water marine fauna, a shallow-water brackish-marine fauna, a shallow-water reef marine fauna, and a deep-water marine fauna. Note that the majority of samples contain predominantly mixed fauna.

The dependence of ostracods on environmental conditions can be very helpful in the paleoenvironment reconstruction. The analysis of the entire fauna suggests that the ostracod fauna of the Pokupsko surroundings lived in a shallow marine environment, down to 50 m depth, and had a connection with the open sea. The water was warm, as indicated by findings of several warm-water new-entry species, as well as by an abundance of the foraminifer *Borelis* (the Pokupsko sample), which prefers very warm water and implies tropical to subtropical water temperatures. The species is also found in a similar ostracod assemblage from the Middle Miocene deposits of North Africa (Szczechura & Abd-Elshafy 1988).

The majority of ostracods are robustly built, indicating high-water energy and well-oxygenated water conditions, except for the Šljivovac sample that contains pyritized valves. The pyritized valves in a sample of the Middle Badenian age agree well with the conclusions of Šútovská (1990), who, in the Middle Badenian of the Carpathians, assumes the occurrence of an anoxic facies although; stratification is not fully developed due to shallow-water depths.

Salinity of the water was similar to the salinity of the present-day seas. In closed lagoons it was higher, and in near-shore areas lower due to freshwater influxes.

Lithologies of the analysed samples (clay, sandy clay, marly sand, and sand) reinforce the conclusions obtained by the microfauna analyses and suggest a tripartite division of the marine environment into a near-shore zone, transitional zone and shelf.

The near-shore zone limits the estuaries and semi-open lagoonal environments shorewards. The near-shore environment is wave-influenced, especially during storms. Locally, it is also influenced by tides, wind-driven currents, and freshwater influx. This type of environment is moderately stable, characterized by moderately high-energy, with sand, silt and clay as typical sediment types.

The transitional zone is made up of commonly alternating fine-grained sand, silt, and clay, and is characterized by maximum development of both the species and individuals. The environments more distal from the shore are beyond the river-induced freshwater influence and wave motion, except during storms. This is a stable, low energy environment.

The ostracod fauna of the shelf environment varies from poor to rich; the sediment is clayey, partly sandy or silty.

Each of the above zones, striking parallel to the shore, has its own "inhabitants" that may be grouped into ecozones that coincide with the above mentioned depth distribution of ostracods.

Given all the available data, the paleoenvironment of the Pokupsko ostracods was probably shallow marine and often turbulent and periodically connected to the open sea and freshwater influx.

## Conclusion

A very rich and diverse fauna of ostracods has been identified within the Badenian layers at seventeen locations around Pokupsko.

The ostracods belong to the suborders of Platycopa and Podocopa, and their families of Cytherellidae, Bairdiidae, Cyprididae, and Cytheridae. Forty-four genera and sixty-six ostracod species have been identified altogether. The entire ostracod fauna has locally been classified into six biofacies based on similarities/differences between different faunas.

The Lower Badenian Zone NO7 *Acanthocythereis hystrix*-*Bythocypris lucida*, encompasses the samples of the first biofacies and was identified based on findings of the index species *Acanthocythereis hystrix*, "new-entry" species *Ruggieria* ex gr. *carinata*, and *Cytherelloidea sissinghi*, and numerous deep-water ostracods. According to the faunal composition and comparison with the same biozone recognized in other areas of the Paratethys, it is presumed that samples from Pokupsko belong to the youngest part of the NO7 Zone.

The second Biozone NO8 (Middle Badenian) *Eocytheropteron inflatum*-*Olimfalunia spinulosa*, continuously overlies the previous zone. The samples of the second, third, and fourth biofacies were included in this biozone. This is based on identification of the index species *Eocytheropteron inflatum* in the fourth biofacies, the numerous species of *Olimfalunia* in the second and third biofacies, as well as the different composition of ostracod communities in the three biofacies.

The third Biozone NO9 *Paijenborchella* (*E.*) *laskarevi-Miocyprideis sarmatica elongate* marks the beginning of the Late Badenian in the Central Paratethys. The samples of the fifth biofacies belong to this zone; they are also characterized by the occurrences of *Miocyprideis* sp.

The fourth ostracod Biozone NO10 *Carinocythereis carinata*-*Phlyctenophora farkasi*, marks the latest Late Badenian in the Central Paratethys. The samples of the sixth biofacies are assigned to this zone and are the most abundant in this area. There are certain indications that two subzones can be distinguished within this zone in the wider area in Croatia.

As in some other areas, changes in the ostracod distribution closely follow regional geological events. Transgressive phases resulted in very diversified faunas, while regressive phases resulted in a great number of specimens and species.

Diversified ostracod fauna is the main feature of the Lower Badenian and Middle Badenian samples. The discovery of "new-entry" species from the Tethys, *Cytherelloidea sissinghi* and *Ruggieria* ex gr. *carinata*, both of which were not frequent in the Paratethys, shows free connections between the Tethys and Paratethys areas.

Sea-level drop and the disconnection between the Tethys and Paratethys caused paleobiogeographic 'disintegration'. According to the isotopic studies of Badenian foraminifers occurring below evaporates in the Carpathian Foredeep basin Peryt D. & Peryt T. (2010) suggest that the interrupted communication of the Paratethys with the ocean was a consequence of eustatic sea-level fall, possibly related to climatic cooling, and it was coupled with a tectonic closure of the connection with the Tethys. The deep-water ostracods became less abundant and shallow brackish-marine fauna became dominant in all paleogeographic domains. Sea-level drop and the probable isolation of the area in the south-western margin of the North Croatian Basin resulted in the Badenian freshwater sediments and coal-bearing horizons (Bakrač et al. 2010).

A regressive trend, which continued in the later Badenian, resulted in the recovery of numerous shallow-water species. However, the presence of deep-water species in the Upper Badenian samples implies oscillations of water level, as well as occasional penetration of deep-water ostracod fauna in response to renewed flooding in the Late Badenian (*sensu* Haq et al. 1988).

The analyses of Ca, Mg, Sr and Mn were carried on carapaces of the selected Late Badenian genera, including *Aurila*, *Cytherella*, *Cytheridea*, *Bairdoppilata* and *Tenedocythere*. The results obtained contributed to the reconstruction of the paleo-environment.

**Acknowledgments:** The authors wish to thank professors Ana Sokač, Ivan Gušić and Zlatan Bajraktarević for their helpful and fruitful suggestions. Particular thanks to Slobodan Miko, for performing the analysis of trace elements. The authors are very grateful to Ivo Suša from the Croatian Geological Survey for technical support, and to Renata Slavković and Zdenka Barbić from INA, Zagreb, for preparing SEM microphotographs. The present investigation is part of the research that was supported by the Department of Geology, Croatian Geological Survey, and the Ministry of Science, Education and

Sports Project Grant No. 181-1811096-1093: "Basic Geological Map of the Republic of Croatia 1:50,000". For improvement of the English text we warmly thank to Ivan Gušić and Antun Husinec. We are grateful to Elsa Gliozzi and Irene Zorn for their valuable and helpful reviews.

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