ABSTRACT

Middle and Late Miocene palynological biozonation of the south-western part of Central Paratethys (Croatia) is presented based on organic-walled phytoplankton. Nine characteristic palynozones of regional palynostratigraphic range are recognized, e.g. Early Badenian (Langhian) Cribroperidinium tenuitabulatum (Cte), Badenian (Late Langhian – Earliest Serravallian) Unipontidinium aquaeductum (Uaq), Late Badenian (Early Serravallian) Cleistosphaeridium placacanthum (Cpl), Sarmatian (Middle and Late Serravallian) Polysphaeridium zoharyi – Lingulodinium machaerophorum (Pzo-Lma), early Early Pannonian s.l. Mecsekia ultima – Spiniferites bentorii pannonicus (MulSpa), middle Early Pannonian s.l. Spiniferites bentorii oblongus (Sob), late Early Pannonian s.l. Pontiadinium pectvaradensis (Ppe), early Late Pannonian s.l. Spiniferites validus (Sva), and late Late Pannonian s.l. Galeacysta etrusca (Get). As inferred from the regional palynostratigraphic correlation, the signals of two transgressions after the isolation of Paratethys during the Sarmatian are recognised: the first one in the late Early Pannonian, when Mediterranean dinoflagellates migrated into the Pannonian Basin, and the second one in the Late Pannonian, when endemic Paratethyan taxa migrated into the Mediterranean.

Keywords: palynology, Miocene, biozonation, dinoflagellate, Paratethys, Mediterranean

1. INTRODUCTION

The first dinoflagellate zonations for the Neogene of south-western Europe were proposed by POWELL (1986a, b, c), BIFFI & MANUM (1988), and ZEVENBOOM (1995), and for the Tertiary of north-western Europe by COSTA & MANUM (1988), respectively. Miocene dinocyst assemblages from Central Paratethys were studied by several authors, e.g., BALTES (1967, 1969), HOCHULI (1978) and JIMÉNEZ-MORENO et al. (2006) for the Early and Middle Miocene, and SÚTÓ-SZENTAI (1985; 1988; 1989; 1991; 1994, 2005) for the Late Miocene. JIMÉNEZ-MORENO et al. (2006) presented the first dinocyst biostratigraphy for the Ottmangian, Badenian and Sarmatian (pro parte) deposits of the western and middle part of the Paratethys. Two short reports have been published from the Karpatian – Badenian strata of the Styrian Basin (SOLIMAN & PILLER, 2007).

Marine Paratethys deposits are comparable with the Mediterranean biostratigraphy zones proposed by RÖGL (1998), and POPOV et al. (2006). Problems arise in brackish and freshwater Paratethyan environments in the Sarmatian, after the isolation of the Pannonian Basin. Marine fossils were extinct and replaced by a new endemic fauna. Therefore, the local biozonation of the Pannonian Basin deposits was established on the basis of the organic-walled phytoplankton index fossils.
Successful applications of dinocyst studies were carried out in sequence stratigraphy starting with HAQ et al. (1987). The key to recognizing the 3rd and 4th order depositional sequences is the maximum flooding surface, marked by the abrupt changes in dinocyst abundance. Stratigraphic timing of this surface is extremely important in sequence stratigraphic analysis. Therefore, the main goal for future work will be recognition of the maximum flooding surface in the Pannonian Basin, and based on it, correlation of proposed palynological zones with established zones in the Mediterranean area.

2. GEOLOGY OF THE STUDY AREA

Paratethys was an enclosed sea existing from Oligocene to Middle Miocene times, consisting of a chain of basins of various tectonic origins (BÁLDI, 1980). These basins were covered most of the time by the same mass of water, sharing a similar aquatic biota, with communication between the Mediterranean and the Indo-pacific realms. When Paratethys became separated from other seas at the beginning of the Late Miocene, the Lake Pannon individualized with decreasing salinity (MAGYAR et al., 1999a). As both Paratethys and Lake Pannon were characterized by an increasing rate of endemism, a local chronostratigraphic scheme was developed.

The Karpatian/Badenian boundary is characterized by a significant sea level fall (HAQ et al., 1988; HARDENBOL et al., 1998), expressed as a hiatus (“Styrian unconformity”), traceable throughout Central Paratethys (RÖGL et al., 2002, HARZHAUSER & PILLER, 2007). Continuous sedimenta-

Figure 1: Location of the studied area: (A) Pannonian Basin; (B) Study area; (a) Žumberačka gora; (b) Hrvatsko zagorje and Medvednica Mt.; (c) Slavonija.
tion from the Karpatian to the Badenian has never been observed (PILLER et al., 2007). In Early Badenian times (Čuč-I, Vej-III; Fig. 1b) (AVANIĆ et al., 1995), the entire area was under marine transgression, and only the uppermost parts of the mountains remained as islands in the newly formed sea (KOVAČ et al., 2007). ČORIĆ et al. (2009) suggest a distinctly younger age for the Neogene sedimentation in the North Croatian Basins than was formerly considered. They correlate the initial marine transgression with the Middle and Late Miocene, Badenian stage. They write that probably the complete depositional cycle of its lower basinal infill, comprising the Middle to Late Miocene, Badenian stage. They correlate the initial marine transgression with the middle part of the Early Badenian, which is more than 2 m.y. younger than the previously inferred datum, and at least 1 m.y. younger than the lower boundary of the Badenian and the Middle Miocene. They write that probably the complete depositional cycle of its lower basinal infill, comprising the lacustrine and the early marine sediments, belongs to the Middle Miocene, Badenian stage.

In the proximal part of the basin a paralic environment was formed (Vrh-I; Fig. 1a) (BAKRAČ et al., 2010). Late Badenian re-opening of the Indo-pacific seaway (ROGL, 1996) caused the sea-level rise. Certain areas emerged from the sea while other parts were subjected to transgression (LSt-II, Zaj-I, Nac-I; Figs. 1b, c). At the end of the Badenian, some oscillation of the sea level occurred, particularly in the marginal parts of the basin (Jur-II; Fig. 1a).

The Badenian is conformably overlain by the Sarmatian sediments, locally developed over the whole of the studied area (Zaj-I, LSt-I, Fig. 1b; Jur-I, Figs. 1 a; Nac-I, Fig. 1 c). The transition from the Badenian to Sarmatian deposits is observed in Žumberak (VRSALJKO et al., 2005), Hrvatsko zagorje (Zaj-I; Fig. 1b) and Slavonija (Nac-I; Fig. 1c) (PAVELIĆ et al., 2003; VASILIEV et al., 2007). Important palaeoecological changes occurred after disconnection of Paratethys and Tethys that conditioned major facies changes. The Sarmatian Sea was reduced in size. The terrestrial influence gradually increased, followed by the decreased salinity. Strata between the Pannonian Basin and the rest of the sea resulted in the complete mixing of waters. In the central part of the basin however, the littoral facies of the Sarmatian rocks indicate that many islands existed there (MAGYAR et al., 1999a). PILLER & HARZHAUSER (2005), subdivided the Sarmatian into a short Early Sarmatian period with normal marine conditions, in marginal areas probably mixohaline conditions and a longer Late Sarmatian period of normal marine to occasional hypersaline conditions.

A relative sea level fall resulted in isolation of the intra-Carpathian waters from the rest of Paratethys, forming Lake Pannon. A previously shallow-water central part of the basin became dry land. Only small, scattered patches of the originally thin Sarmatian deposits escaped complete erosion. Correlation outside of Central Paratethys is problematical, due to the restricted connection of Paratethys to the Mediterranean and the lack of almost all stenohaline faunas. Planktonic foraminifers are almost entirely absent, and the only survivors are calcareous nanoplankton, low in diversity and with endemic taxa (PILLER et al., 2007).

The transition from the Sarmatian to the Pannonian deposits is observed on the south-western slopes of Medvednica Mt. (Kst-I; Fig. 1b), and in Slavonija (Nac-II; Fig. 1c) (PAVELIĆ et al., 2003).

The Lower Pannonian s.l. sediments cover significant areas in every basin or depression in the Croatian part of the Pannonian Basin. The reduction in salinity continued, so brackish and freshwater sediments prevail. Based on endemic molluscs, the Paratethys deposits of the Late Miocene in Croatia were stratigraphically divided into four acrozones (range zones). The Lowest Pannonian deposits (“Croatica beds”) are observed in Hrvatsko zagorje (Krš-I; Fig. 1b), Medvednica Mt. (Kst-I; Fig. 1b), Slavonija (Nac-II; Fig. 1c), and Upper Lower Pannonian deposits (“Banatica beds”) (Mal-I; Fig. 1a) at Medvednica Mt. (Kst-I; Fig. 1b), and Slavonija (Nac-II; Fig. 1c).

The lake water gradually flooded significant land areas. At the end of the Lower Pannonian, during the Spiniferites paradoxus Biochron, ca. 9.5 Ma, Lake Pannon reached its largest areal extent (MAGYAR et al., 1999a). Sediments of this age often overlap more old formations in the basin margins, indicating transgression (Krš-I, Mal-I, Fig. 1 a; KoB-I, Sam-I, Piš-I, Pož-I, And-I, And-II, Mir-I, Tol-II, Fig. 1 b). Progradation from the northwest started during this biochron, and the Vienna basin dried up by the end of it. This could be seen in the geological column in Hrvatsko zagorje (Pož-I, Tol-II; Fig. 1b) where much more sand is observed.

During the Congeria praerhomboidea Biochron (ca. 9.0 Ma), the lake area shrank to half its former size (MAGYAR et al., 1999a). Deltas from the northwest and northeast advanced towards the centre of the basin. In the Early Late Pannonian s.l., a connection between the Pannonian and Danian Basins was established. The Lower Upper Pannonian sediments, known as the “Abichi beds”, are mostly fine-grained sandstones in alternation with clayey and silty marls. The “Rhomboidea beds” were deposited during the Late Pannonian, and cover very large areas of the Pannonian Basin (LUČIĆ et al., 2001).

Water levels rose again during the Early Congeria rhomboidea Biochron, ca. 8.0 Ma (MAGYAR et al., 1999a). Only a few islands remained above the lake level (Išć-I, Sel-I, Bek-I, Bek-II, Fig. 1b; Nac-III, Kra-I; Fig. 1c). The effect of the water-level rise however, was balanced by high terrigenous influx in the north-eastern part of the lake, where aggradation occurred at this time (IUHASZ, 1994). Terrigenous influx was even greater in the northwest, where progradation of deltas continued towards the south (Mal-I, Sel-I, Bek-II). As the basin filled with sediments from the north and northwest, the lake was limited to north-eastern Croatia (Nac-III, Kra-I; Fig. 1c).

Rare and sporadic findings of polyhaline nannofossils (KOLLÁNYI, 2000; GALOVIĆ, pers. comm.), and the presence of supposedly marine elements in dinocyst associations (SUTŐ-SZENTAI, 1991; BAKRAČ, 1999, 2005; POPEŠCU et al., 2009), seem to suggest that marine connections were not fully severed. A benthic fauna of molluscs and ostracods was almost fully endemic, reflecting the persistent occurrence of a brackish lacustrine environment (MÜLLER et al., 1999).
During the Late *Congeria rhomboidea* Biochron, ca. 6.5 Ma, delta progradation from the northwest almost completely filled up the western part of the basin. Only the Drava (Slavonia), and the Sava depressions remained subaqueous in the western Pannonian basin. As subsidence continued, the accommodation space on dry land was filled with fluvial, terrestrial deposits. The deep sub-basins became gradually shallower as turbidites were deposited in the central parts of the depressions. A deep lacustrine environment was restricted to what is presently southeast Hungary, northeast Croatia and northern Serbia. The endemic mollusc and ostracod faunas of Lake Pannon flourished, and migrated probably episodically into the Eastern Paratethys during the Pontian, via an outflow of the lake (MÜLLER et al., 1999).

During the Pliocene, depositional basins in the SW part of the Pannonian Basin disintegrated into many small lakes (LUČIĆ et al., 2001), and lignite seams are frequent.

### 3. MATERIAL AND METHODS

This work is based on outcrop study, in contrast to most other studies which are based on subsurface data. Surface sediment samples were collected at 28 outcrops during the research project entitled “Basic Geological Map of Republic Croatia 1: 50000”. Sampling density was adjusted to the thickness of the layers with the same lithological and palaeontological characteristics. Each change was sampled, and thickness of the layers with the same lithological and palaeontological characteristics. Each change was sampled, and correlation of palynological slides was performed under the light microscope combined with the interference contrast, resulting in identification of 88 palynomorph taxa. A fluorescence technique was used to distinguish *in situ* forms from reworked palynomorphs. Each slide was counted for 200 palynomorphs for the purpose of quantitative analysis. Important species are illustrated in Pl. 1-2. Dinocyst taxonomy is in accordance with that cited by LENTIN & WILLIAMS (1998).

### 4. PALYNOLOGICAL RESULTS

Palynomorphs are generally well preserved in the studied samples. Dinocysts dominate the assemblages, but some samples are dominated by prasinophyte phycomas or sporomorphs (spores and pollen).

#### 4.1. Palynological zonation

The most consistent and characteristic dinocyst events have been selected to establish nine palynomorph zones, as defined below. The definitions of the zones are based on the first occurrence (FO), last occurrence (LO), first and last common occurrence (FCO, LCO) of one or more taxa of palynomorphs (Fig. 2).

The presented palynological zonal scheme (based on organic-walled phytoplankton – dinocysts and prasinophyte phycomas) for the Middle and Late Miocene in the Croatian part of Central Paratethys, was calibrated against macrofossil and microfossil distribution.

##### 4.1.1. *Cribroperidinium tenuitabulatum* Zone (Cte)

**Definition:** The upper boundary is the LO of *Cribroperidinium tenuitabulatum*. The lower boundary is not defined because of the lack of deposits (Styrian hiatus).

**Characteristics:** *Cribroperidinium tenuitabulatum* in association with *Lingulodinium machaerophorum*, *Cleistosphaeridium placacanthum*, *Labyrinthodinium truncatum*, *Tuberculodinium vancampoae*, *Spiniferites spp*. and *Conusaudinium aubryae*. Common forms are heterotrophic proteridinoid cysts, e.g. *Selenopemphix* and *Lejeunecysta* indicating volcanically induced nutrification. (Pl. 1, Figs. 31–36)

**Calibration:** Lower Lagenid Zone and Upper Lagenid Zone of GRILL (1943), NN4-NN5 (MARTINI, 1971).

**Correlation:** Central Paratethyan *Cribroperidinium tenuitabulatum* Assemblage Zone (JIMENEZ-MORENO et al., 2006), Mediterranean Uaq zone (ZEVENBOOM, 1995), and to a certain extent, the eastern United States DN4 zone (de VERTEUIL & NORRIS, 1996).

**Age:** Early Badenian (Langhian) – Middle Miocene.

**Type section:** Čuĉerje – I (Čuĉ-I) and Vejalnica – III (Vej-III).

##### 4.1.2. *Unipontidinium aquaeductum* Zone (Uaq)

**Definition:** The interval from the LO of *Cribroperidinium tenuitabulatum* to the LCO of *Unipontidinium aquaeductum*.

**Characteristics:** A very rich and diverse phytoplankton assemblage composed of offshore dinocysts including: *Baticasphaera micropapillata*, *Baticasphaera sphaerica*, *Unipontidinium aquaeductum*, *Nematosphaeropsis lemniscata*, *Impagidinium putatum* in co-occurrence with nearshore dinocysts; *Spiniferites ramosus*, *Melitsphaeridium chaoanophorum*, *Opeculodinium centrocarpum*, *Opeculodinium crassum*, *Opeculodinium israeliannum*, *Opeculodinium wallii*, *Lingulodinium machaerophorum*, *Polysphaeridium zoharyi*, *Cleistosphaeridium placacanthum*, *Spiniferites pseudofucatus*, *Labyrinthodinium truncatum*, *Tuberculodinium vancampoae*. (Pl. 1, Figs. 26–29)

**Calibration:** Spiroplectaminina Zone, NN5-NN6.

**Correlation:** Central Paratethyan *Unipontidinium aquaeductum* Interval Biozone (JIMENEZ-MORENO et al., 2006), Mediterranean Uaq zone (ZEVENBOOM, 1995), and to a certain extent eastern the United States DN5 zone (de VERTEUIL & NORRIS, 1996).

**Age:** Badenian (Late Langhian – Earliest Serravallian) – Middle middle Miocene.
Type section: Laz Stubički – II (LSt-II), Zaježda – I (Zaj-I).

4.1.3. Cleistosphaeridium placacanthum Zone (Cpl)

Definition: The interval from the LCO of Unipontidinium aquaeductum to the LCO of Cleistosphaeridium placacanthum.

Characteristics: Along with the most characteristic Cleistosphaeridium placacanthum, there are also nearshore dinocysts including: Spiniferites ramosus, Melitasphaeridium choanophorum, Operculodinium centrocarpum, Operculodinium israelianum, Lingulodinium machaerophorum, Polysphaeridium zoharyi, Hystrichosphaeropsis obscura. (Pl. 1, Fig. 30)

Calibration: Bulimina – Bolivina Zone, NN6.

Correlation: The Central Paratethyan Cerebrocysta poulsseni Assemblage Zone (JIMÉNEZ-MORENO et al., 2006); lower part of the Hpo zone (ZEVENBOOM, 1995);

<table>
<thead>
<tr>
<th>Langhian</th>
<th>Serravallian</th>
<th>Tortonian</th>
<th>Messianian</th>
<th>Mediterranean</th>
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<td>Sarmatian</td>
<td>Pannonian s.l.</td>
<td></td>
<td>Mediterranean</td>
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<tr>
<td>Lagenidae Zone</td>
<td>ApL.F. Zone</td>
<td>Bu-Bo Zone</td>
<td></td>
<td>Pannonian Age</td>
</tr>
<tr>
<td>Cte</td>
<td>Uaq</td>
<td>Cpl</td>
<td>Pzo-Lma</td>
<td>Mul-Spa</td>
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<tr>
<td>NN4</td>
<td>NN5</td>
<td>NN6</td>
<td>NN7-8</td>
<td>NN9a-b</td>
</tr>
</tbody>
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Figure 2: Range chart of the stratigraphically indicative dinoflagellate cysts used in this study.
and to some extent with the upper part of the eastern United States DN5 zone (de VERTEUIL & NORRIS, 1996).

Age: Late Badenian (Early Serravallian) – Middle Miocene.

Type section: Našice cementara – I (Nac-I), Jurjevčani – II (Jur-II).

4.1.4. *Polysphaeridium zoharyi* – *Lingulodinium machaerophorum* Zone (Pzo-Lma)

Definition: The open marine environment of the zone is characterized by the relatively diverse dinocyst assemblage, of which the most common forms are euryhaline dinocysts *Polysphaeridium zoharyi* and *Lingulodinium machaerophorum*. Restricted environments of this zone are recognized by a high proportion of prasinophycean genera.

Characteristics: Along with abundant *Polysphaeridium zoharyi* and *Lingulodinium machaerophorum* of the open marine environment, occurrences of *Cleistosphaeridium placacanthum*, *Hystrichokolpoma cinctum*, *Operculodinium crassum*, and *Melitasphaeridium choanothecum* were also recorded. Restricted environments are dominated by prasinophyte phycomas including; *Tythodus mesekeensis*, *Hidasia racemosa*, *Hidasia rugosa*, *Cymatosphaera mioaeuëncica*, *Cymatosphaera pseudoundulata* and *Cymatosphaera spinosa magna*. In the upper part of the zone, endemic *Spiniferites* dinosauri occurred. (Pl. 1, Figs. 20–25)

Calibration: *Anomalinoides dividens* Zone; *Ervilia Zone*, NN7.

Correlation: The open marine environments of the zone correlate with the Central Paratethyan *Cleistosphaeridium placacanthum* Assemblage Zone (JIMÉNEZ-MORENO et al., 2006); to a lesser extent, the Mediterranean Hpo zone (ZEVENBOOM, 1995) and the eastern United States DN6 zone (de VERTEUIL & NORRIS, 1996), while the restricted environment part correlates with *Spiniferites* dinosauri *buda-jenoensis* (SÜTŐ-SZENTAI, 1988).

Age: Sarmatian (Middle and Late Serravallian)

Type section: Našice cementara – I (Nac-I), Jurjevčani – I (Jur-I), Laz Stubički – I (LSt-I), Našice cementara – II (Nac-II), Kostanjek – I (Kst-I).

4.1.5. *Mecsekia ultima* – *Spiniferites bentorii pannonicus* Zone (Mul-Spa)

Definition: The FCO to LCO of *Mecsekia ultima* in a restricted environment, and from the FO of *Spiniferites bentorii pannonicus* to the FO of *Spiniferites bentorii oblongus* in the hydrographically unstable environment.

Characteristics: Prasinophyte algae *Mecsekia ultima*, *Mecsekia spinosa*, *Mecsekia spinulosa* and *Mecsekia incrassata* dominate the phytoplankton assemblages in the restricted lagoon and shallow water carbonate facies. The endemic dinocyst *Spiniferites* dinosauri *pannonicus* was observed in the hydrographically unstable environment.


Correlation: Central Paratethyan *Mecsekia ultima* zone – *Spiniferites bentorii pannonicus* zone (SÜTŐ-SZENTAI, 1988).

Age: Early Pannonian s.l.

Type section: Krapinske Toplice – I (KrT-I), Kostanjek – I (Kst-I), Našice cementara – II (Nac-II).

4.1.6. *Spiniferites bentorii oblongus* Zone (Sob)

Definition: The interval from the FO of *Spiniferites bentorii oblongus* to the FCO of *Pontidiadinium pescvaradensis*.

Characteristics: These are the most diverse and rich assemblages in the Early Pannonian, characterized by *Spiniferites* bentorii *oblongus*, *Virgodinium asymmetricum*, *Chytroeisphaeridia cariacensis* and *Chytroeisphaeridia hungarica*. (Pl. 1, Figs. 8–13)

Calibration: *Spiniferites bentorii oblongus* Biochron – ca. 10.8 Ma (MAGYAR et al., 1999b), and *Congeria banticata* – *Lymnocardium gorjanovici* – *Gyraulus tenuistriatus* Cenozone (VRSALJKO, 1999).

Correlation: Central Paratethyan *Spiniferites bentorii oblongus* zone (SÜTŐ-SZENTAI, 1988).

Age: Middle Early Pannonian s.l.

Type section: Kostanjek – I (Kst-I), Našice cementara – II (Nac-II), Pušča – I (Psč-I).

4.1.7. *Pontidiadinium pescvaradensis* Zone (Ppe)

Definition: The interval from the FO of *Pontidiadinium pescvaradensis* to the FO of *Spiniferites bentorii coniunctus*.

Characteristics: Proximate forms from distal, open environments represented by *Pontidiadinium pescvaradensis*, *Impagidinium spongianum*, *Virgodinium baltesii*, and *Virgodinium asymmetricum* and the rare Mediterranean dinocysts *Achomosphaera*, *Spiniferites* and *Operculodinium*. (Pl. 1, Figs. 1–7)


Correlation: Central Paratethyan *Pontidiadinium pescvaradensis* zone (SÜTŐ-SZENTAI, 1988).

Chronostratigraphic age: Late Early Pannonian s.l.

Type section: Našice cementara – II (Nac-II), Pušča – I (Psč-I), Požarkovec – I (Pož-I).

4.1.8. *Spiniferites validus* Zone (Sva)

Definition: The interval from the FO to the LCO of *Spiniferites validus* in proximal, or from the FO of *Spiniferites bentorii coniunctus* to the FO of *Galeacysta etrusca* in distal environments.

Characteristics: A diverse and rich dinocyst assemblage dominated by *Spiniferites bentorii coniunctus*, *Spiniferites balcanicus*, *Spiniferites maisensis*, *Spiniferites virgulaeformis*, *Achomosphaera andalousiensis*, *Nematospaeropsis bicorpis*, *Spiniferites bentorii coniunctus*, *Spiniferites cf.
always correspond to theca bioecoenosis. The dinocyst record can be a mixture of cysts transported by currents and cysts derived from theca, living in the water mass above the bottom where the cysts are finally accumulated. Relative sea level fluctuations in neritic settings are usually reflected in the varying abundance of taxa, which typically occur in restricted marine or inner neritic water masses versus those that characteristically occur in outer neritic waters (BRINKHUIS, 1994; JARAMILLO & OBOH-IKUENOBE, 1999).

High abundance of proteropinidinoid cysts (Selenopemphis and Lejeunecysta) were used to indicate phases of enhanced nutrient availability, (by either stronger terrigenous input or volcanic activity).

Studies on modern dinoflagellate cysts have shown that oxygen availability exerts a strong control on cyst germination, with anaerobic conditions completely inhibiting the excystment of most taxa (ANDERSON et al., 1987). PROSS (2001) proposed a model for Thalassiphora pelagica, characterized by a wing-like membrane on the dorsal side of most specimens, which may have facilitated a holoplanktic life cycle in contrast to most other cyst-producing dinoflagellates. This may also apply to Galeacysta etrusca and Unipontidinium aquaeductum. Oxygen depletion on the sea floor prohibits excystment and causes dinocyst diversity to decrease. Thalassiphora pelagica (or S. balcanicus in our samples) is not affected because its excystment occurs in the water column.

Decreasing temperatures may be responsible for changes in the dinocyst assemblage as can be seen through zone Cte, including the disappearance of Cribroropinidinium tenuitabulatum (also recognized by JIMÉNEZ-MORENO et al., 2006). Karpatian and Early Badenian floras reflect the Miocene climate optimum (MCO) as they are extremely rich in thermophilous elements. A progressive decrease in thermophilous elements immediately follows, and floral diversity occurred during the Late Badenian and Sarmatian. This has been interpreted as climatic cooling during the “Monterey Cooling Event”, which occurred at 14.2 Ma, correlated with the increase in development of the East Antarctic Ice Sheet (JIMÉNEZ-MORENO et al., 2005).

Morphological changes in dinocysts as a result of low salinity or other environmental stress were first described by WALL et al. (1973) based on the Holocene material from the Black Sea. They observed that in low-salinity environments, as compared to normal-salinity assemblages, an increased number of dinocysts with reduced processes, variations in septal development and cruciform (rather than rounded) endocysts occur. Moreover, changes in archeopyle formation have also been attributed to salinity fluctuations (WALL et al. 1973). The hypothesis that salinity was a factor in determining process length in various chorate dinocysts has been corroborated by studies on Lingulodinium machaerophorum/L. polyedrum (NEHRING, 1994), Operculodinium centrocarpum (e.g., de VERNAL et al., 1989; MATTIESSEN & BRENNER, 1996) and Spiniferites spp. (e.g., DALE, 1996; ELLEGÅRD, 2000; LEWIS et al., 1999, 2003). The suggestion that a cruciform endocyst may indicate the influence.
of a low-salinity environment has also been corroborated by DALE (1996) and a study on cruciform Spiniferites cysts from a lacustrine setting in northern Greece (KOULI et al., 2001). KOULI et al. (2001), recorded S. cruciformis together with the freshwater species Goniothalamus apiculata in lacustrine sediments, suggesting that S. cruciformis is a freshwater species and that any occurrences in (brackish) marine environments, with the exception of specimens with strongly reduced ornamentation, may be due to transportation, short-lived freshwater surface conditions and/or tolerance of the species to brackish conditions. MUDIE et al. (2002), also use S. cruciformis to reconstruct brackish water environments and freshwater input from glacial lakes.

An increase of outer neritic to oceanic taxa, (such as species of Nematosphaeropsis and Impagidinium) was interpreted as indicating a sea level rise, whereas increasing abundances of neritic to coastal taxa were interpreted as denoting a regressive trend. The majority of dinocyst range bases were positioned in transgressive systems tracts (Ppe zone), which can probably be attributed to a widening of shelf dinoflagellate habitats, fostering the evolution of new dinoflagellate taxa. Accordingly, range tops were predominantly discovered in highstand systems tracts (Cpl zone).

The low diversity of microplankton associations may be indicative of stressed, restricted conditions with often unstable salinities (GORIN & STEFFEN, 1991). Prasinophytes are attributed as “disaster species” (TAPPAN, 1980) being most abundant in the absence of other plankton, suggesting ecological conditions which cannot support the development of other phytoplankton communities. However, the abundance of prasinophytes phycomata is at least partly a consequence of reduced dinocyst production in permanently stratified basins, and does not reflect the original phytoplankton assemblage, i.e. phytoplankton dynamics (TYSON, 1995). Phycomata abundance indicates therefore, hydrographic stability of stratified basins where motile dinoflagellate assemblages participate in the overall composition of phytoplankton assemblages much more than is actually recorded in the palynological record as dinocysts. These ecological conditions usually include low temperature, enhanced productivity and a stratified water column, exhibiting brackish or low-salinity surface waters overlying low oxygen to anoxic bottom waters (TYSON, 1987; TYSON, 1995). Dominance of prasinophyte algae has been recorded from some restricted lagoon and shallow water carbonate facies (TYSON, 1995). This happened in the investigated area during the middle Badenian and Sarmatian – earliest Pannonian.

5.2. Zonation based on the organic-walled phytoplankton

Palynological characterization of 28 lithostratigraphic columns of the investigated area, as well as the known stratigraphic relationships of Paratethyan Miocene species (RÖGL, 1998; MAGYAR et al., 1999b; HUDAČKOVÁ et al., 2000; KOVÁČ et al., 2004) facilitated compilation of a palynological zonation of the Middle and Late Miocene which was correlated with the palynological zonation of contemporaneous deposits in the Mediterranean realm (POWELL, 1986a,b,c; ZEVENBOOM, 1995; JIMÉNEZ-MORENO et al., 2006; SÚTÓ-SZENTAI, 1988, 1991).

Unfortunately, the geochronology of the Miocene in Croatia has not yet been established. Therefore, the age assignment is mostly based on biostratigraphy. At present, the main criteria for the biostratigraphic zonation of Miocene deposits are characteristic molluscs due to their relatively effective usage already established during field work. However, the distribution of the molluscs depends on environmental conditions and they react relatively slowly to global changes. In addition, their occurrence is usually relatively rare. In contrast, the response of organic walled phytoplankton to ecological change as well as their spread to new living space is much faster. Furthermore, organic walled phytoplanktons are often abundant even in small samples. For regional correlation, the recognition of Neogene biohorizons which contain cosmopolitan dinocysts (FCO and LCO) is very important, although this may be hampered due to environmental change causing variations in diversity and composition of dinosporin assemblages (STOVER et al., 1996). These relationships are best revealed by the divergent organic walled phytoplankton developments as Paratethys began to separate from Tethys during the Sarmatian, Formation of the Pannonian Basin resulted in endemism of organic walled phytoplankton species. Consequently, the Middle Miocene marine assemblages are regionally correlated, while the Late Miocene of Paratethys is limited and mostly depends on other biostratigraphy. Fortunately, the Paratethyan Late Miocene is characterized by two short lasting events indicating connections with the Tethyan realm which facilitates the correlation between these two areas.

Correlation is based on palynological zones from several authors. ZEVENBOOM (1995) presented the palynological zonation of several micropalaeontologically and magnetostratigraphically defined Miocene type sections in Italy. JIMÉNEZ-MORENO et al. (2006), documented palynological zones for the Badenian and the lower part of the Sarmatian, based on the material from Austrian outcrops and a Hungarian borehole. De VERTEUIL & NORRIS (1996) proposed the zonation of Miocene deposits from the middle Atlantic Coastal Plain.

The boundary between the Cribroperidinium tenuitabulatum and Unipontidinium aquaeductum zones is marked by the disappearance of Cribroperidinium tenuitabulatum, and a decrease in the thermophilous element (Labyrinthodinium truncatum, Tuberculodinium vancampoae). This was interpreted as a response to climatic cooling during the “Monte- rey Cooling Event” correlated with the increase in development of the East Antarctic Ice Sheet (JIMÉNEZ-MORENO et al., 2006).

JIMÉNEZ-MORENO et al. (2006) proposed the Cleistoxsphaeridium placacanthum Zone for the Lower Sarmatian, however it seems more likely that Polysphaeridium zoharyi and Lingulodinium machaerophorum are more characteristic due to local environmental conditions. This may be deduced from their material as it can be seen that Polysphaeridium sp. A and Lingulodinium machaerophorum are very common
forms in their Cpl zone. Their ranges extend from the older strata, and their presence has environmental significance. *Polysphaeridium zoharyi* has been recorded from subtropical and tropical regions, generally in coastal sites, near upwelling cells and river mouths. The highest relative abundances have been observed in the tropical low-salinity areas, where this species can dominate the assemblages (Marret & Zonneveld, 2003). *Lingulodinium machaerophorum* can be considered to be a temperate to tropical, coastal euryhaline species. An increased number of specimens with reduced process lengths can be observed related to low or high salinity. Blooms of *L. polyedrum* can be related to high nutrient input and warm, stratified surface water conditions. It is distributed within a very broad salinity range and has been recorded from brackish to fully marine environments (Marret & Zonneveld, 2003). *Lingulodinium machaerophorum* can be considered to be a temperate to tropical, coastal euryhaline species. An increased number of specimens with reduced process lengths can be observed related to low or high salinity. Blooms of *L. polyedrum* can be related to high nutrient input and warm, stratified surface water conditions. It is distributed within a very broad salinity range and has been recorded from brackish to fully marine environments (Marret & Zonneveld, 2003). *Lingulodinium machaerophorum* has its LCO in the Pannonian Basin during this zone. We think that it is more proper to extend the *Polysphaeridium zoharyi* – *Lingulodinium machaerophorum* Zone up to the end of the Sarmatian. *Lingulodinium machaerophorum* could be found in the open environment, while *Cymatiosphaera mioicaenica* and *Mecsekia incrassata* may interfere with facies dominated by dinocysts. This could also explain why SUTÓ-SZENTAI (2005) placed the *M. ultima* zone between the *S.b. pannonicus* – *L. machaerophorum* and *S.b. pannonicus* zones. SUTÓ-SZENTAI (2005) placed the *S.b. pannonicus* – *L. machaerophorum* Zone above the Late Sarmatian *S.b. budajenoensis* – *M. incrassata* zone. The assemblages were most likely contemporaneous. However, the “younger” assemblage existed within a relatively distal, more open environment characterized by conditions which continued from the Sarmatian times, enriched with some new Pannonian inomers. The assemblage characteristic of this zone was seen in the Kostanjek-I (Kst-I) (Fig. 1b) column just below the “Croatica beds”. On the basis of the ostracods and diatoms, these deposits belong to the Latest Sarmatian, which justifies the placement of the boundary between the Sarmatian and Pannonian above the *S.b. pannonicus* – *L. machaerophorum* Zone.
fore, it is considered that the ecozone Pzo-Lma should be extended up to the end of the Sarmatian since *L. machaerophorum* occurs continuously in open environments while *C. miocaenica* consistently occurs in more restricted environments. Due to eustatic fluctuations, the facies migrated which may have caused the prasinophytes *C. miocaenica* and *M. incrassata*, (abundant in restricted, quiet, stratified and brackish environments), to be located together in deposits with assemblages dominated by the dinosporin cysts of more open environments. These relationships were recorded in the Našice cementara-II (Nac-II) (Fig. 1c) column where layers dominated by dinosporin cysts alternate with layers dominated by prasinophytes, suggesting cyclic alteration of stratified with hydrographically unstable water columns.

In the Earliest Pannonian, salinity was so low that the environment became oligohaline, and locally even fresh. Such environmental conditions enabled the expansion of endemic species. Ecological conditions were unfavorable for dinoflagellates, which is evidenced by the absence of dino-

demic species. Ecological conditions were unfavorable for

Such environmental conditions enabled the expansion of en-

assemblages dominated by the dinosporin cysts of more open

In our opinion, SÜTŐ-SZENTAI (1988) presented the best zonation for the Pannonian. The *Spiniferites bentorii* zone (SÜTŐ-SZENTAI, 1988), subdivided into the *Spiniferites bentorii* pannonicus, *Spiniferites bentorii* oblongus and *Pontiadinium pecsvaradensis* subzones, indicates an Early Pannonian age, while the *Spiniferites validus* zone, subdivided into the *Spiniferites validus* and *Spiniferites paradoxus* subzones, indicates a Late Pannonian age. Later, SÜTŐ-SZENTAI (1991; 1994) presented a more detailed zonation described as the *Spiniferites balcanicus* main zone, which is divided into the *Spiniferites validus* and *Spiniferites bentorii coniunctus* – *Spiniferites paradoxus* zones, and remained as Late Pannonian in age. MAGYAR et al. (1999b) correlated dinoflagellate zones with other biozones and suggested that their new *Spiniferites paradoxus* zone is of Early Pannonian age. In the investigated area under consideration, this is not the case, since the *Spiniferites bentorii coniunctus* – *Spiniferites paradoxus* zones are contemporaneous with the *Spiniferites validus* zone from a more proximal environment. Therefore, we joined these two zones into one zone; the *Spiniferites validus* Zone.

*Nematosphaeropsis* sp. and membranous forms of *Spiniferites bentorii* indicate water-level rise and a distal environment. In the upper part of the *Pontiadinium pecsvaradensis* Zone, a few Mediterranean dinocyst species (*Achomosphaera, Spiniferites* and *Operculodinium*) were recognized, indicating communication between the Mediterranean and Paratethys at that time. Also, significant findings of the dinocysts *Spiniferites cruciformis* and *Galeacysta etrusca* most

**Plate 1**

<table>
<thead>
<tr>
<th>No.</th>
<th>Image Description</th>
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<tbody>
<tr>
<td>1</td>
<td><em>Pontiadinium pecsvaradensis</em> SÜTŐ-SZENTAI 1982, Pič-I 5/1, ventral view at low focus.</td>
</tr>
<tr>
<td>2</td>
<td><em>Pontiadinium pecsvaradensis</em> SÜTŐ-SZENTAI, And-II 3-1, dextra-lateral view at high focus.</td>
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<td>3</td>
<td><em>Pontiadinium pecsvaradensis</em> SÜTŐ-SZENTAI, And-II 3-1, dextra-lateral view at high focus in fluorescence illumination.</td>
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<td>4</td>
<td><em>Impagidinium spongianum</em> SÜTŐ-SZENTAI 1985 &quot;type A&quot;, Nac-II 94/1, ventral view at low focus.</td>
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<td>5</td>
<td><em>Impagidinium spongianum</em> SÜTŐ-SZENTAI 1985 &quot;type A&quot;, Sam-I 1-1 2, dextra-lateral view at low focus in interference contrast illumination.</td>
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<tr>
<td>6</td>
<td><em>Virgodinium asymetricum</em> SÜTŐ-SZENTAI 2010, Sam-I 1-2, sinistro-lateral view at low focus in interference contrast illumination.</td>
</tr>
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<td>7</td>
<td><em>Spiniferites bentorii</em> pannonicus SÜTŐ-SZENTAI 1986, Nac-II 81/1, sinistro-lateral view.</td>
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<td>8</td>
<td><em>Spiniferites bentorii</em> oblongus SÜTŐ-SZENTAI 1986, Nac-II 81/1, dextra-lateral view.</td>
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<td>9</td>
<td><em>Spiniferites bentorii</em> oblongus SÜTŐ-SZENTAI 1986, Mir-I 4-6, dextra-dorsal view.</td>
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<td>10</td>
<td><em>Achomosphaera andalouoensis</em> JAN DU CHÈNE 1977, Nac-II 65/1, ventral view.</td>
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<td>11</td>
<td><em>Spiniferites bentorii</em> pannonicus SÜTŐ-SZENTAI 1986, Nac-II 81/1, dextra-lateral view.</td>
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Scale bar is 25 μm.
likely represent their oldest occurrence indicating that they evolved in the Pannonian Basin.

The southern shoreline, running parallel to the Sava River along the northern foot of the Dinarides, changed very little during the lifetime of Lake Pannon. Rare and sporadic findings of polyhaline nannofossils (KOLLÁNYI, 2000; GALOVIĆ, pers. comm.), and the presence of supposedly marine elements in dinocyst associations (SÜTŐ-SZENTAI, 1991; BAKRAČ, 1999, 2005; POPEŞCU et al., 2009), seem to suggest that marine connections were not fully severed. Moreover, the “Lago Mare” brackish fauna contained Late Messinian endemics, suggesting that their origin is related to the oldest Late Miocene–Pannonian Paratethyan biota (POPOV et al., 2006). The endemic mollusc and ostracod faunas of Lake Pannon flourished, and migrated, probably episodically into the Eastern Paratethys during the Pontian via an outflow of the lake (MÜLLER et al., 1999).

Correlation with Mediterranean/global chronostratigraphy is based on scattered biostratigraphic tie points, particularly those of calcareous nannoplankton and planktonic foraminifera. No boundary stratotypes are defined for any of the Miocene Central Paratethyan (PILLER et al., 2007).

Based on the dinocyst diversity and abundance, four maximum flooding surfaces during the Middle and Late Miocene were recognized in the south-western parts of the Central Paratethys, and are subject of our recent research.
Dinoflagellates are shown to be highly effective organisms for establishing the connection and/or isolation phases of various basins adjacent to the Mediterranean. This is particularly true when comparing the vertical distribution of Galeacysta etrusca and Congeria molluscs at Eraclea Minoa. There, Galeacysta etrusca was recorded in relative high sea-level deposits represented by diatomite turbidites preceding the last gypsum bed, and in the Arenazzolo Formation, while Congeria molluscs are present within the “Lago Mare” Formation which corresponds to a relative lowering of sea-level. As Congeria molluscs may develop in invading coastal lagoon environments, they are more significant of local brackish conditions (possibly continuing after the invasion event) than Galeacysta etrusca which precisely demarcates the exchange events at high sea-level between basins.

Connections between the Pannonian and Dacian basins during the Late Pannonian s.l. have long been considered to facilitate mutual exchange of the aquatic fauna. Now it seems that this connection worked as a biogeographic filter which allowed primarily a one-way traffic out of Lake Pannon towards the Eastern Paratethys (MÜLLER et al., 1999; POPOV et al., 2006).

6. CONCLUSION

Palynological characterization of the Middle and Late Mio- cene from the south-western parts of the Pannonian Basin in Croatia allowed recognition of nine continuous palynological zones which were correlated with contemporaneous strata in the Mediterranean.

The Early Badenian (Langhian) Cribroperidinium tenuitabulatum (Cte) Zone is the oldest recognized zone of deeper and distal marine environments. The zone corresponds to the Central Paratethyan Cte zone (JIMÉNEZ-MORENO et al., 2006), Mediterranean Tgo, Ise and Ltr zones (ZEVEN-BOOM, 1995), and to a certain extent, the eastern United States DN4 zone (de VERTEUIL & NORRIS, 1996).

The Middle Badenian (Late Langhian – Earliest Serravalian) Unipontidinium aquaeductum (Uaq) Zone also reflects deeper and distal environments and it may be well correlated with the Central Paratethyan Uaq zone (JIMÉNEZ-MORENO et al., 2006), Mediterranean Uaq zone (ZEVEN-BOOM, 1995), and to a certain extent, the eastern United States DN5 zone (de VERTEUIL & NORRIS, 1996).
A Late Badenian (Early Serravallian) *Cleistosphaeridium placacanthum* (Cpl) Zone is defined in a proximal, open marine environment. This zone correlates with the Central Paratethyan Cpo zone (JIMÉNEZ-MORENO et al., 2006), lower part of the Mediterranean Hpo zone (ZEVENBOOM, 1995), and to some extent, the upper part of the eastern United States DN5 zone (de VERTEUIL & NORRIS, 1996).

The Sarmatian (Middle and Late Serravallian) *Polyosphaeridium zoharyi – Lingulodinium machaerophorum* (Pzo-Lma) Zone is recognized in open marine environments dominated by dinocysts and in restricted environments dominated by prasinophyte phycomas. The open environments of the zone correlate with the Central Paratethyan Cte zone (JIMÉNEZ-MORENO et al., 2006), to a small extent with the Mediterranean Hpo zone (ZEVENBOOM, 1995), and the eastern United States DN6 zone (de VERTEUIL & NORRIS, 1996), while restricted environments correlate with the *Spiniferites bentorii budajenoensis* zone of SÜTŐ-SZENTAI (1988).

The Pannonian Basin experienced environmental changes during the Earliest Pannonian which were conducive for phytoplankton developments absolutely dominated by prasinophytes up to only few and very rare endemic dinocysts. Accordingly, the earliest Pannonian zone, comprising most of the “Croatica beds” is assigned to the *Mecsekia ultima – Spiniferites bentorii pannonicus* (Mul-Spa) Zone which is typical for local Paratethyan environments, as well as the
Mesekia ultima zone and Spiniferites bentorii pannonicus zone of SUTÔ-SZENTAI (1988), and may not be correlated with any Tethyan zone.

The Spiniferites bentorii oblongus (Sob) Zone was defined within the lower part of the “Banatica beds” of the Middle part of the Early Pannonian s.l., and represents a correlative of the Spiniferites bentorii oblongus zone of SUTÔ-SZENTAI (1988).

The Late Early Pannonian s.l. Pontiadinium pessvaradensis (Ppe) Zone was recognized within the upper part of the “Banatica beds” and may be correlated with the Pontiadinium pessvaradensis zone (SUTÔ-SZENTAI, 1988).

The Early Late Pannonian s.l. Spiniferites validus (Sva) Zone was defined within the “Abichi beds”. This zone correlates with the Spiniferites balcanicus main zone of SUTÔ-SZENTAI (1989), and the Spiniferites validus zone of MAGYAR et al. (1999b).

The Late Late Pannonian s.l. Galeacystra etrusca (Get) Zone was defined in the “Rhomboidea beds”, and may be correlated with the Interval zone Dinoflagellata – Zygometaceae / Mougeotia laetevirens zone of SUTÔ-SZENTAI (1988, 2011), as well as the Galeacystra etrusca zone of MAGYAR et al. (1999b), and the Get zone of ZEVENBOOM (1995).

After isolation of Paratethys during the Sarmatian, two transgressions are documented: the first one in the Late Early Pannonian, when Mediterranean dinoflagellates migrated into the Pannonian Basin, and the second one in the Late Pannonian, when endemic Paratethyan taxa migrated into the Mediterranean.

Based on the dinocyst diversity and their abundance, four maximum flooding surfaces (mfs) were recognized, and are the subject of recent research.

ACKNOWLEDGEMENT

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