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Middle and Late Miocene palynological biozonation of the south-western part of Central Paratethys (Croatia)

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ABSTRACT

Middle and Late Miocene palynological biozonation of the south-western parts 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* (Mul-Spa), middle Early Pannonian s.l. *Spiniferites bentorii oblongus* (Sob), late Early Pannonian s.l. *Pontiadinium pecsvaradensis* (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 SÜTŐ-SZENTAI (1985; 1988; 1989; 1991; 1994, 2005) for the Late Miocene. JIMÉNEZ-MORENO et al. (2006) presented the first dinocyst biostratigraphy for the Ottnangian, 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-

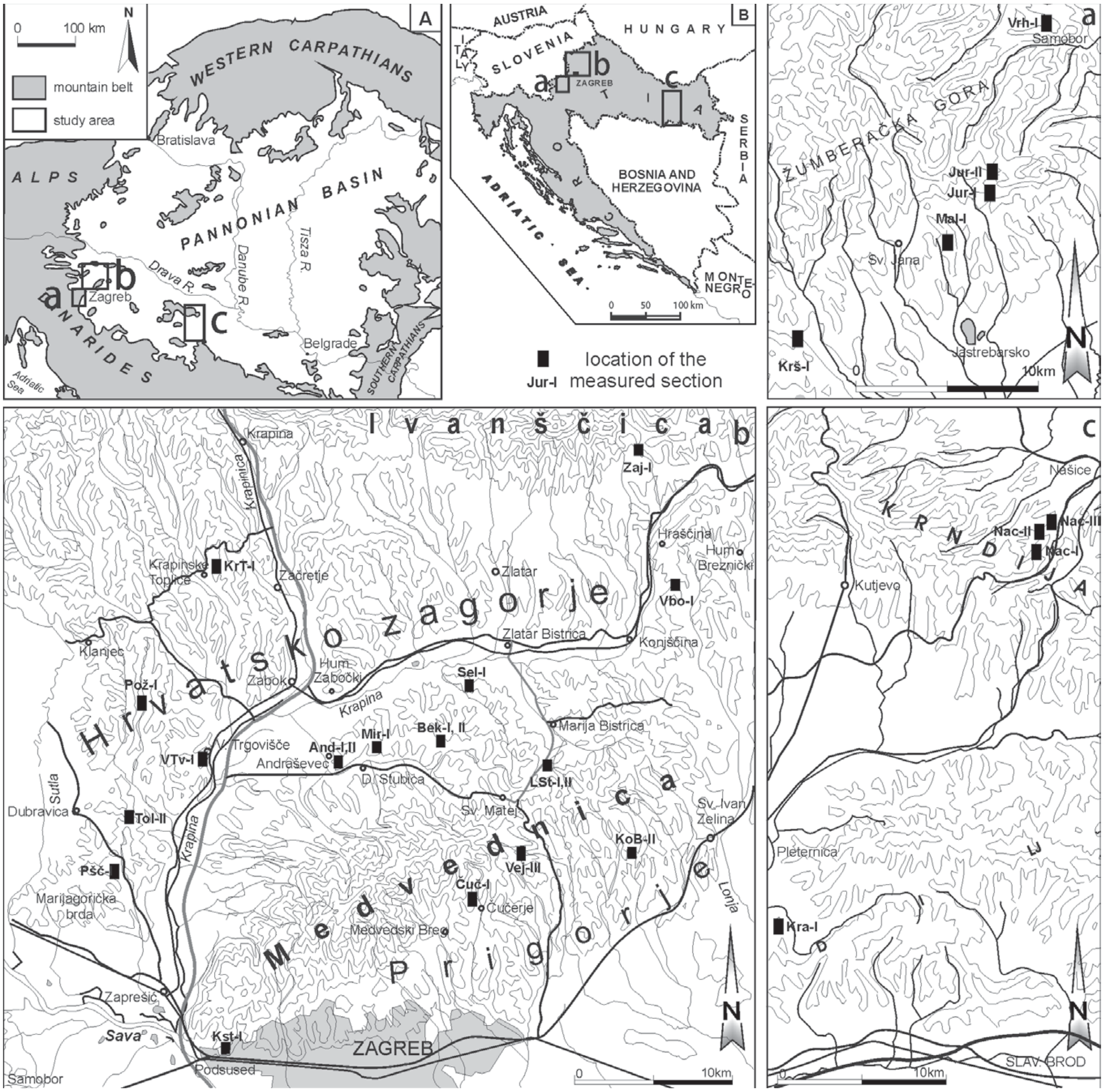

Figure 1: Location of the studied area: (A) Pannonian Basin; (B) Study area; (a) Žumberačka gora; (b) Hrvatsko zagorje and Medvednica Mt.; (c) Slavonija.

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 (KOVÁČ et al., 2007). ĆORIĆ 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 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 (RÖGL, 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. Straits 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 foraminifera are almost entirely absent, and the only survivors are calcareous nannoplankton, 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 (KrT-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 overlie much older formations in the basin margins, indicating transgression (Krš-I, Mal-I, Fig. 1 a; KoB-I, Sam-I, Pšć-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 columns 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 Dacian 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 (JUHÁSZ, 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 (SÜTŐ-SZENTAI, 1991; BAKRAČ, 1999, 2005; POPESCU 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 (Slavonija), 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 98 samples were prepared. Standard palynological processing techniques were used to extract the organic matter. The samples were treated with cold HCl (15%) and HF (40%), removing carbonates and silica. Heavy liquid ($ZnCl_2$, s.g. 2,1kg/l) was used to separate the organic matter from the undissolved inorganic components. The residue obtained was sieved through a 20-µm sieve, and palynological slides were prepared using glycerin gelatin as the mounting medium. The samples were not oxidized at any stage. Analysis 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 *Cousteaudinium aubryae*. Common forms are heterotrophic protoperidinoid 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 (JIMÉNEZ-MORENO et al., 2006), Mediterranean Tgo, Ise and Ltr zones (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: Čučerje – I (Čuč-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; *Batiacasphaera micropapillata, Batiacasphaera sphaerica, Unipontidinium aquaeductum*, *Nematosphaeropsis lemniscata, Impagidinium patulum* in co-occurrence with nearshore dinocysts; *Spiniferites ramosus, Melitasphaeridium choanophorum, Operculodinium centrocarpum, Operculodinium crassum, Operculodinium israelianum, Operculodinium wallii, Lingulodinium machaerophorum, Polysphaeridium zoharyi, Cleistosphaeridium placacanthum, Spiniferites pseudofurcatus, Labyrinthodinium truncatum, Tuberculodinium vancampoae*. (Pl. 1, Figs. 26–29)

Calibration: Spiroplectammina Zone, NN5-NN6.

Correlation: Central Paratethyan *Unipontidinium aquaeductum* Interval Biozone (JIMÉNEZ-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), Zajezda – 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 poulsenii* Assemblage Zone (JIMÉNEZ-MORENO et al., 2006); lower part of the Hpo zone (ZEVENBOOM, 1995);

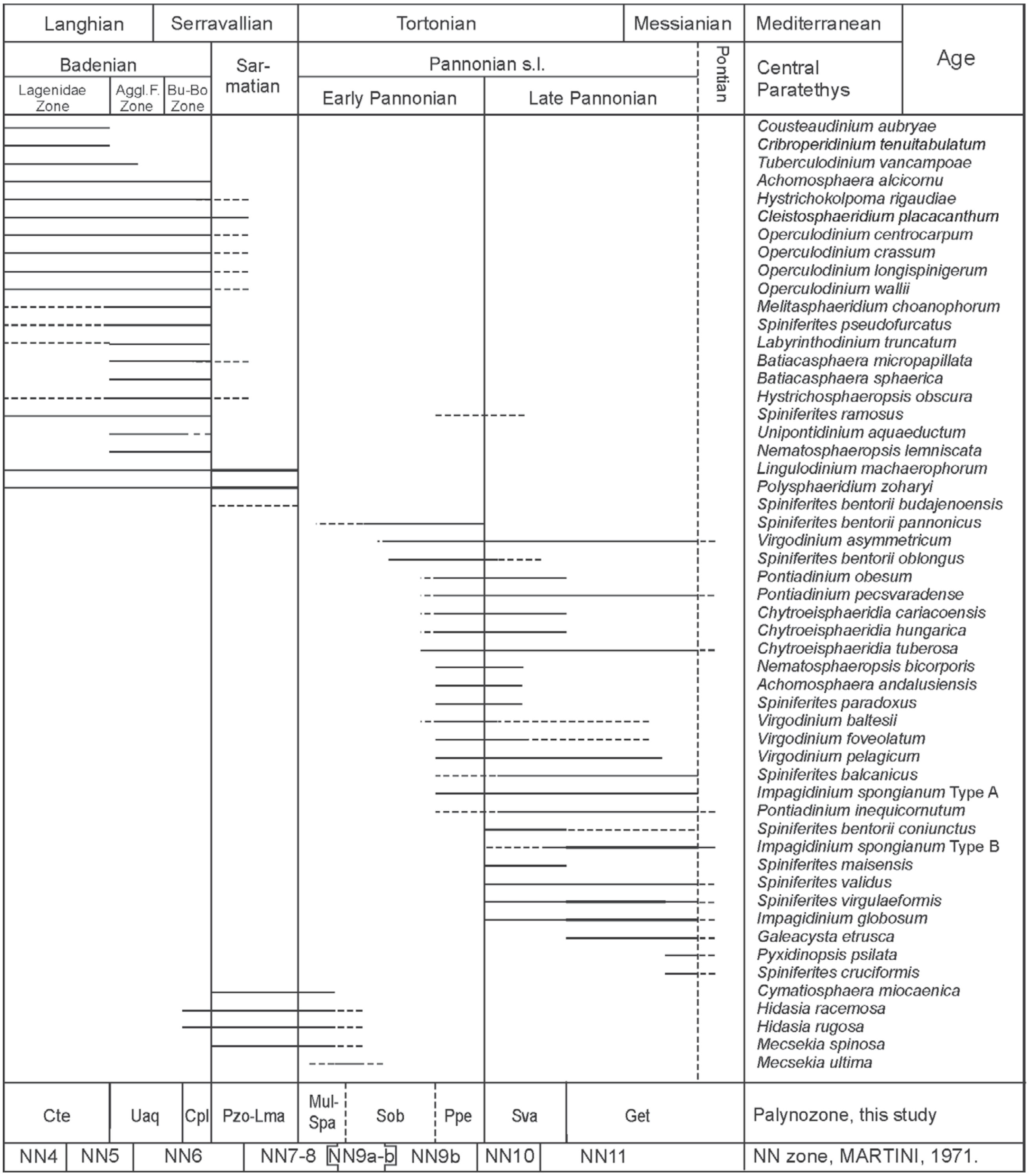

Figure 2: Range chart of the stratigraphically indicative dinoflagellate cysts used in this study.

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 choanophorum* were also recorded. Restricted environments are dominated by prasinophyte phycomas including; *Tytthodiscus mecsekensis, Hidasia racemosa, Hidasia rugosa, Cymatiosphaera miocaenica, Cymatiosphaera pseudoundulata* and *Cymatiosphaera spinosa magna*. In the upper part of the zone, endemic *Spiniferites bentorii budajenoensis* 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 bentorii budajenoensis* (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 bentorii pannonicus* was observed in the hydrographically unstable environment.

Calibration: *Lymnocardium praeponticum* acrozone and Cenozone *Radix croatica – Lymnocardium plicataeformis – Gyraulus praeponticus* (VRSALJKO, 1999). (Pl. 1, Figs. 14–19)

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

Age: early 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 *Pontiadinium pecsvaradensis*.

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

Calibration: *Spiniferites bentorii oblongus* Biochron – ca. 10.8 Ma (MAGYAR et al., 1999b), and *Congeria banatica – 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), Pušća – I (Pšć-I).

4.1.7. *Pontiadinium pecsvaradensis* Zone (Ppe)

Definition: The interval from the FO of *Pontiadinium pecsvaradensis* to the FO of *Spiniferites bentorii coniunctus*

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

Calibration: *Congeria czjzeki – Lymnocardium winkleri – Gyraulus tenuistriatus* Cenozone (VRSALJKO, 1999).

Correlation: Central Paratethyan *Pontiadinium pecsvaradensis* zone (SÜTŐ-SZENTAI, 1988).

Chronostratigraphic age: Late Early Pannonian s.l.

Type section: Našice cementara – II (Nac-II), Pušća – I (Pšć-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, Nematosphaeropsis bicorporis, Spiniferites bentorii coniunctus, Spiniferites cf.*

bentorii (membranous forms)*, Spiniferites bentorii oblongus, Spiniferites* cf. *paradoxus, Spiniferites ramosus, Spiniferites virgulaeformis, Chytroeisphaeridia cariacoensis, Virgodinium asymmetricum, Virgodinium baltesii, Virgodinium transdanuvianum, Pontiadinium inequicornutum, Pontiadinium pecsvaradensis.* Proximal environments are dominated by *Spiniferites validus*, *Virgodinium pelagicum, Chytroeisphaeridia* sp.*, Impagidinium globosum, Impagidinium spongianum "type B",* and green algae *Botryococcus braunii.* (Pl. 2, Figs. 21–39)

Calibration: "Abichi beds".

Correlation: *Spiniferites balcanicus* main zone (SÜTŐ-SZENTAI, 1989); *Spiniferites validus* zone (MAGYAR et al., 1999b).

Age: Early Late Pannonian s.l.

Type section: Požarkovec – I (Pož-I), Tolovajčići – II (Tol-II). Bekini – II (Bek-II). Pušća – I (Pšć-I), Požarkovec – I (Pož-I), Mirti – I (Mir-I), Andraševec – I (And-I), Malunje – I (Mal-I).

4.1.9. *Galeacysta etrusca Zone* (Get)

Definition: The zone is defined by the dominance of *Impagidinium globosum* in proximal, and by *Galeacysta etrusca* in more distal environments.

Characteristics: Proximal environments are characterized by the proximate dinocysts with thicker walls, e.g. *Impagidinium globosum, Virgodinium asymmetricum, Chytroeisphaeridia tuberosa, Brigantedinium* sp., *Impagidinium spongianum "type B", Virgodinium pelagicum,* and *Spiniferites validus.* In distal environments, *Galeacysta etrusca, Spiniferites balcanicus, Spiniferites maisensis, Spiniferites virgulaeformis* and *Spiniferites cruciformis* dominate (Pl. 2, Figs. 1–20).

Calibration: "Rhomboidea beds"

Correlation: Interval zone Dinoflagellata – Zygnemataceae / Zone Mougeotia laetevirens (SÜTŐ-SZENTAI, 1988); *Galeacysta etrusca* zone (MAGYAR et al., 1999b); *Galeacysta etrusca* Interval Zone (ZEVENBOOM, 1995);

Age: Late Late Pannonian s.l.

Type section: Selnica – I (Sel-I), Bekini – II (Bek-II), Tolovajčići – II (Tol-II), Vrbovo – I (Vrv-I), Našice cementara – III (Nac-III), Krajačić – I (Kra-I).

5. DISCUSSION

5.1. Palaeoecology of the organic-walled phytoplankton

Dinoflagellate cysts are sensitive environmental indicators, and are therefore of potential use in palynological analysis of environmental conditions. Several studies (e.g., WALL et al., 1977; DALE, 1996) have indicated that four types of environmental signals can be deduced from recent cyst distributions: (1) surface water temperature, (2) a coastal-oceanic distribution, (3) salinity, and (4) productivity. However, it is important to keep in mind that cyst thanatocoenosis may not always correspond to theca biocoenosis. 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 protoperidinoid cysts (*Selenopemphix* and *Lejeunecysta)* were used to indicate phases of enhanced nutrient availability, (by either stronger terrigenous input or volcanic activity).

Studies on modern dinoflagellates 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 *Cribroperidinium 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., 1977). 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; MATTHIESSEN & BRENNER, 1996) and *Spiniferites* spp. (e.g., DALE, 1996; ELLEGAARD, 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 *Gonyaulax 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 prasynophyte 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; HUDÁČKOVÁ 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; SÜTŐ-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. JIMENEZ-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 “Monterey 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 *Cleistosphaeridium 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

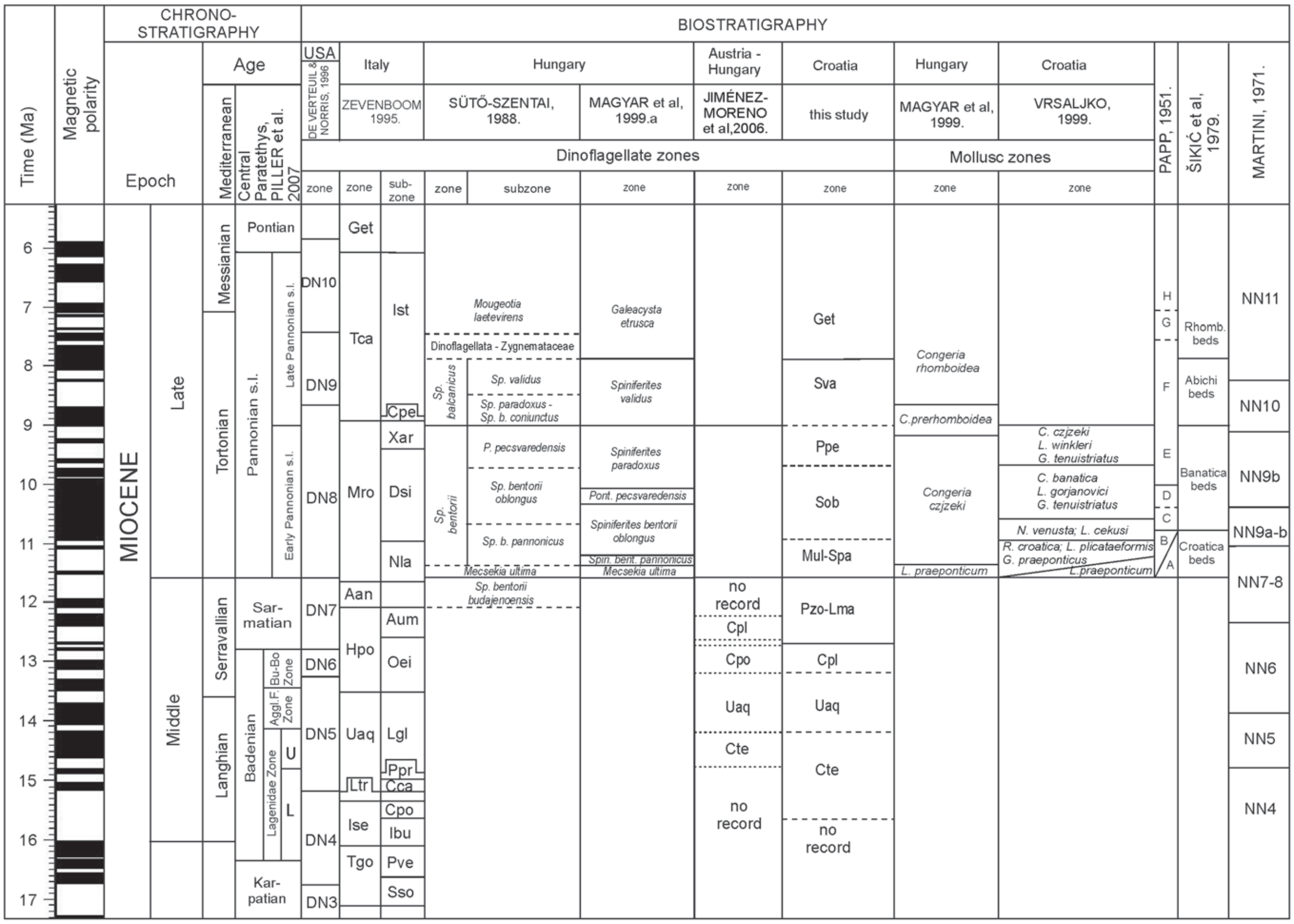

Figure 3: Palinostratigraphic zonation and correlation with other biozones based on GRADSTEIN et al. (2004), PILLER et al. (2007), showing the dinocyst zones of de VERTEUIL & NORRIS (1996), ZEVENBOOM (1995), SÜTŐ-SZENTAI (1988), MAGYAR et al. (1999a), JIMÉNEZ-MORENO et al. (2006) and the proposed zonation correlated with zones proposed by PAPP (1951), ŠIKIĆ et al. (1979), MARTINI (1979).

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* 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 miocaenica* dominated the restricted environment. Due to fluctuations in sea level, facies migrations are common. So, deposits with prasinophytes *Cymatiosphaera miocaenica* and *Mecsekia incrassata* may interfinger with facies dominated by dinocysts. This could also explain why SÜTŐ-SZENTAI (2005) placed the *M. ultima* zone between the *S.b. pannonicus – L. machaerophorum* and *S.b. pannonicus* zones. SÜTŐ-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 incomers. 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. The taxon *S.b. budajenoensis* is questionable since there is no description, and according to Sütő-Szentai (pers. comm.), the difference between *S.b budajenoensis* and *S.b. pannonicus* is small, if any, suggesting that they may represent the same species, i.e. morphologically altered *S. bentorii* with a much more reduced processes as a consequence of environmental changes due to decreased salinity. At that time, the species *L. machaerophorum* occurs in high abundance for the last time in the Pannonian basin. Therefore, 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 dinocysts in these sediments. Consequently, prasinophyte algae dominate the phytoplankton assemblages.

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) correlate 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

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Plate 1

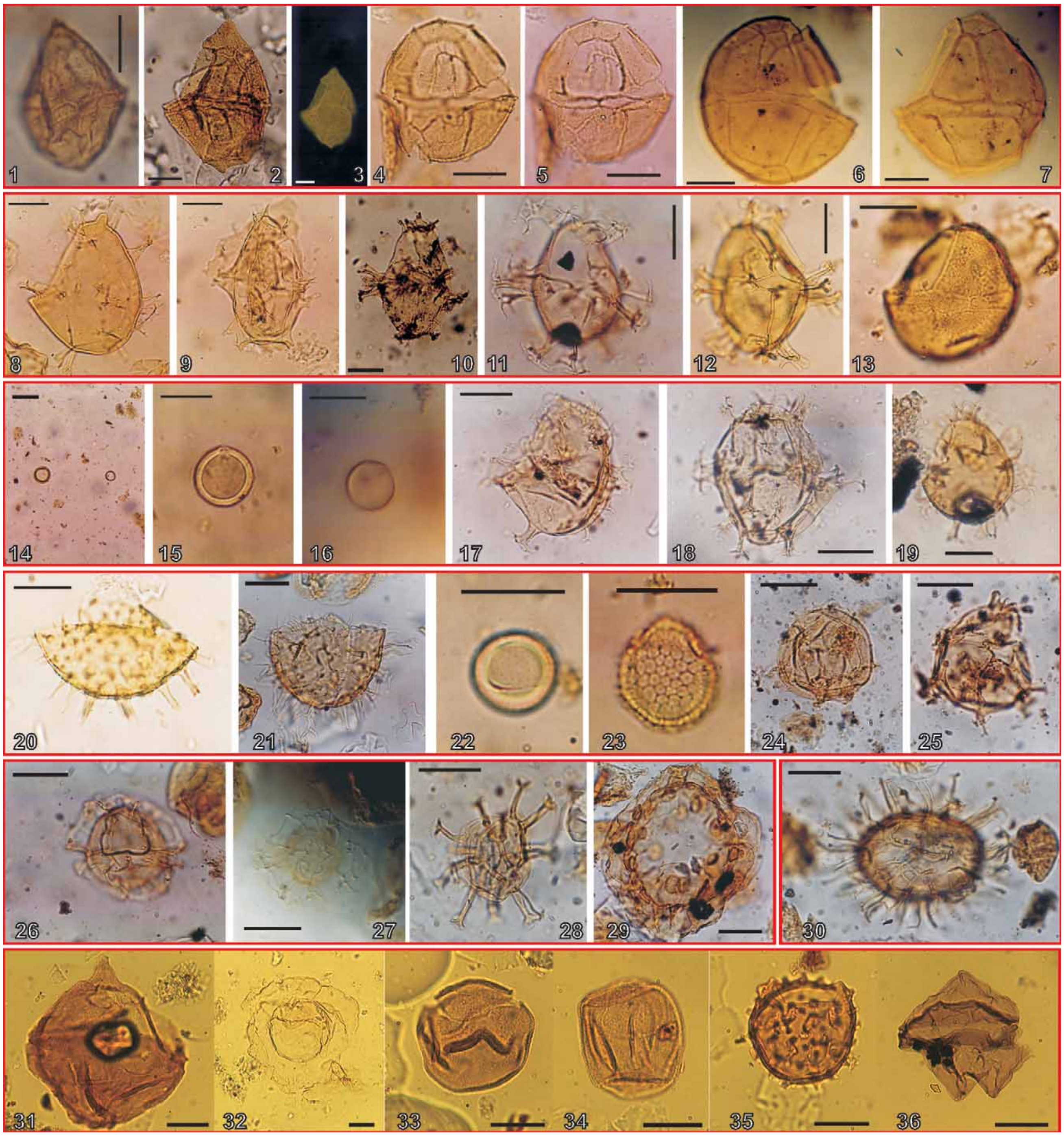
1 *Pontiadinium pecsvaradensis* SÜTŐ-SZENTAI 1982, Pšć-I 5/1, ventral view at low focus.
2 *Pontiadinium pecsvaradensis* SÜTŐ-SZENTAI, And-II 3-1, dextro-lateral view at high focus.
3 *Pontiadinium pecsvaradensis* SÜTŐ-SZENTAI, And-II 3-1, dextro-lateral view at high focus in fluorescence illumination.
4 *Impagidinium spongianum* SÜTŐ-SZENTAI 1985 "type A", Nac-II 94/1, ventral view at low focus.
5 *Impagidinium* spongianum SÜTŐ-SZENTAI 1985 "type A", Nac-II 94/1, ventral view at high focus on archeopyle.
6 *Impagidinium spongianum* SÜTŐ-SZENTAI 1985 "type A", Sam-I 1-12, dextro-lateral view at low focus in interference contrast illumination.
7 *Virgodinium asymmetricum* SÜTŐ-SZENTAI 2010, Sam-I 1-12, sinistro-lateral view at low focus in interference contrast illumination.
8 *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI 1986, Nac-II 81/1, sinistro-lateral view.
9 *Spiniferites bentorii oblongus* SÜTŐ-SZENTAI 1986, Nac-II 81/1, dextro-lateral? view.
10 *Spiniferites bentori oblongus* SÜTŐ-SZENTAI 1986, Mir-I 4/6, dextro-dorsal? view.
11 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977, Nac-II 65/1, ventral view.
12 *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI 1986, Nac-II 81/1, dextro-lateral view.
13 *Impagidinium spongianum* SÜTŐ-SZENTAI 1985 "type A", Nac-II 65/1, sinistro-lateral view.
14 *Mecsekia ultima* SÜTŐ-SZENTAI 1982, Nac-II 7/1.
15 *Mecsekia ultima* SÜTŐ-SZENTAI 1982, Nac-II 7/1.
16 *Mecsekia ultima* SÜTŐ-SZENTAI 1982, Kst-I 10, interference contrast illumination.
17 *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI 1986, Kst-I 36, sinistro-lateral view.
18 *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI 1986, Kst-I 36, dextro-lateral view.
19 *Spiniferites bentorii pannonicus* SÜTŐ-SZENTAI 1986, Kst-I 48.
20 *Lingulodinium machaerophorum* (DEFLANDRE & COOKSON, 1955) Wall 1967, Nac-II 5/1, lateral view.
21 *Polysphaeridium zoharyi* (ROSSIGNOL 1962) BUJAK et al. 1980, LSt-I 3/1, lateral view.
22 *Mecsekia spinosa* HAJÓS 1966, Nac-II 3/7.
23 *Cymatiosphaera miocaenica* SÜTŐ-SZENTAI 1964,Nac-II 3/7.
24 *Spiniferites bentorii budajenoensis* SÜTŐ-SZENTAI 1986, Kst-I 6, view uncertain.
25 *Spiniferites bentorii budajenoensis* SÜTŐ-SZENTAI 1986, Kst-I 6, dextro-lateral view.
26 *Unipontidinium aquaeductum* (PIASECKI 1980) WRENN 1988, LSt-II 6/1, ventral view at high focus on archeopyle.
27 *Nematosphaeropsis lemniscata* BUJAK 1984, LSt-II 6/1, high focus on trabeculae.
28 *Melitasphaeridium choanophorum* (DEFLANDRE & COOKSON 1955) HARLAND & HILL 1979, LSt-II 6/1, oblique apical view.
29 *Tuberculodinium vancampoae* (ROSSIGNOL 1962) WALL 1967, LSt-II 6/3.
30 *Cleistosphaeridium placacanthum* DEFLANDRE & COOKSON 1955, LSt-II 6/1, apical view at low focus.
31 *Cribroperidinium tenuitabulatum* (GERLACH, 1961) HELENES, 1984, Čuč-I/1.
32 *Cousteaudinium aubryae* de VERTEUIL & NORRIS, 1996, Vej-III/5.
33 *Batiacasphaera sphaerica* STOVER, 1977, Čuč-I/1.
34 *Habibacysta tectata* HEAD et al., 1989, Čuč-I/1.
35 *Operculodinium piaseckii* STRAUSS & LUND, 1992, Čuč-I/1.
36 *Lejeunecysta sp.*, Čuč-I/1.
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; POPESCU 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 diatomitic 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 Miocene 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 (ZEVENBOOM, 1995), and to a certain extent, the eastern United States DN4 zone (de VERTEUIL & NORRIS, 1996).

The Middle Badenian (Late Langhian – Earliest Serravallian) *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 (ZEVENBOOM, 1995), and to a certain extent, the eastern United States DN5 zone (de VERTEUIL & NORRIS, 1996).

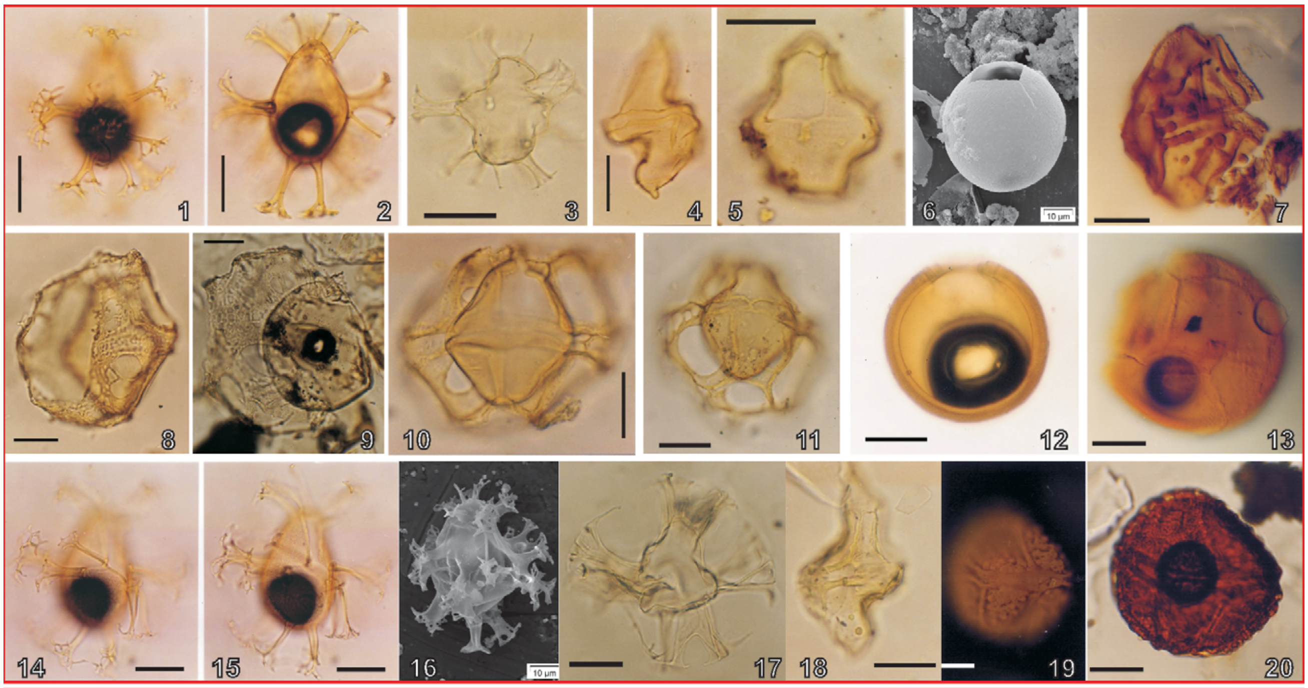
Plate 2

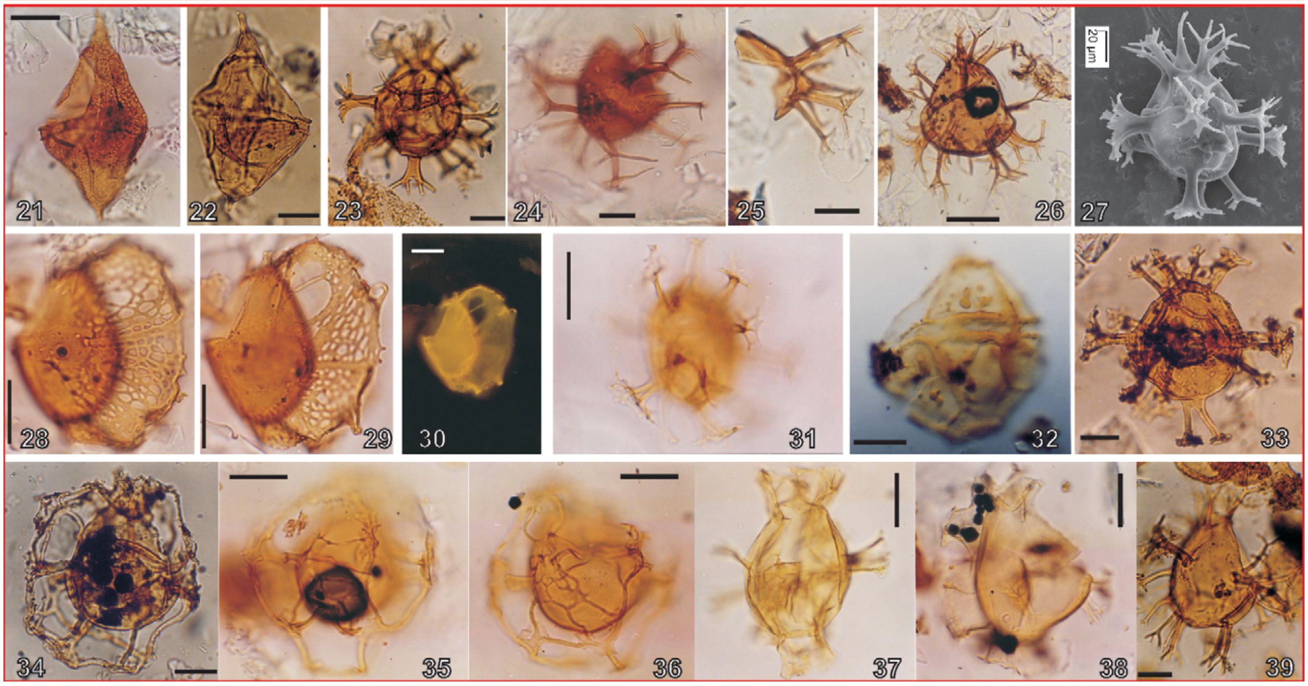
1 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977; Kra-I 1/6, ventral view at high focus on trabeculae.
2 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977; Kra-I 1/6, ventral view at mid focus.
3 *Spiniferites cruciformis* WALL & DALE 1973; Kra-I 1/6, view uncertain.
4 *Pontiadinium inequicornutum* BALTES 1971; Kra-I 1/6, lateral view.
5 *Pyxidinopsis psilata* (WALL & DALE 1973) HEAD 1994; Kra-I 1/7, dorsal view at low focus on archeopyle.
6 *Pyxidinopsis psilata* (WALL & DALE in WALL et al., 1973) HEAD, 1994; Kra-I 1/3, scanning electron micrographs.
7 *Impagidinium* (?) sp 1 sensu CORRADINI & BIFFI, 1988; Išć-I 19/1.
8 *Galeacysta etrusca* CORRADINI & BIFFI 1988; SKOPS 31B-2.
9 *Galeacysta etrusca* CORRADINI & BIFFI 1988; Išć-I 19-1.
10 *Galeacysta etrusca* CORRADINI & BIFFI 1988; Kra-I 1/6, ventral view.
11 *Galeacysta etrusc*a CORRADINI & BIFFI 1988; SKOPS 31B-2.
12 *Tectatodinium* sp.; SKOPS 31B-0.
13 *Impagidinium spongianum* SÜTŐ-SZENTAI, 1985; Išć-I 19/1, lateral view at high focus in interference contrast illumination.
14 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977; Kra-I 1/3, ventral – dextral-lateral view at high focus on trabeculae.
15 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977; Kra-I 1/3, ventral – dextral-lateral view at mid focus on surface.
16 *Achomosphaera andalousiensis* JAN DU CHÊNE, 1977; Kra-I 1/3, scanning electron micrographs.
17 *Spiniferites cruciformis* WALL & DALE 1973; Kra-I 1/3, view uncertain.
18 *Pontiadinium inequicornutum* BALTES 1971; Kra-I 1/3, lateral view.
19 *Impagidinium globosum* SÜTŐ-SZENTAI 1985, Išć-I 19/1, lateral view at high focus in fluorescence illumination.
20 *Impagidinium globosum* SÜTŐ-SZENTAI 1985, Išć-I 19/1, lateral view at high focus.
21 *Pontiadinium inequicornutum* BALTES 1971; Tol-II 1/1, ventral – sinistro-lateral view.
22 *Pontiadinium inequicornutum* BALTES 1971; Išć-I 18-1.
23 *Spiniferites validus* SÜTŐ-SZENTAI 1982; Tol-II 1/1, dextro-lateral? view.
24 *Spiniferites validus* SÜTŐ-SZENTAI 1982; Tol-II 1/1, dextro-lateral? view.
25 *Spiniferites validus* SÜTŐ-SZENTAI 1982; Tol-II 1/1, fragment.
26 *Spiniferites validus* SÜTŐ-SZENTAI 1982; Tol-II 1/1, dextro-lateral? view.
27 *Spiniferites validus* SÜTŐ-SZENTAI 1982; Kra-I 1/3, scanning electron micrographs.
28 *Spiniferites balcanicus* (BALTES 1971) SÜTŐ-SZENTAI 1988; Mir-I 4/10, sinistro-lateral view at high focus.
29 *Spiniferites balcanicus* (BALTES 1971) SÜTŐ-SZENTAI 1988; Mir-I 4/10, sinistro-lateral view at mid focus.
30 *Spiniferites balcanicus* (BALTES 1971) SÜTŐ-SZENTAI 1988; Mir-I 4/10, sinistro-lateral view in fluorescence illumination.
31 *Achomosphaera andalousiensis* JAN DU CHÊNE 1977; And-I 1/2, view uncertain.
32 *Millioudodinium pelagicum* SÜTŐ-SZENTAI 1990; Mir-I 4–6.
33 *Spiniferites virgulaeformis* SÜTŐ-SZENTAI 1994; And-I 1/2, dorsal? view at mid focus.
34 *Nematosphaeropsis bicorporis* SÜTŐ-SZENTAI 1990, And-I 1–2.
35 *Nematosphaeropsis bicorporis* SÜTŐ-SZENTAI 1990; Mal-I 1/1, ventral view at high focus on trabeculae.
36 *Nematosphaeropsis bicorporis* SÜTŐ-SZENTAI 1990; SKOPS 37, antapical view at high focus on trabeculae.
37cf. *Spiniferites paradoxus* (COOKSON & EISENACK 1968) SARJEANT 1970; SKOPS 37, ventral view.
38 *Spiniferites bentorii* (ROSSIGNOL, 1964) WALL & DALE, 1970 (membranous form) Mal-I 1/1, dextral-lateral view and pyrite grain in membrane.
39 *Spiniferites bentorii coniunctus* SÜTŐ-SZENTAI, 1990; Kob-II 3–7.
Scale bar is 25 μm.

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) *Polysphaeridium 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





Mecsekia ultima zone and *Spiniferites bentorii pannonicus* zone of SÜTŐ-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 SÜTŐ-SZENTAI (1988).

The Late Early Pannonian s.l. *Pontiadinium pecsvaradensis* (Ppe) Zone was recognized within the upper part of the "Banatica beds" and may be correlated with the *Pontiadinium pecsvaradensis* zone (SÜTŐ-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 SÜTŐ-SZENTAI (1989), and the *Spiniferites validus* zone of MAGYAR et al. (1999b).

The Late Late Pannonian s.l. *Galeacysta etrusca* (Get) Zone was defined in the "Rhomboidea beds", and may be correlated with the Interval zone Dinoflagellata – Zygnemataceae / *Mougeotia laetevirens* zone of SÜTŐ-SZENTAI (1988, 2011), as well as the *Galeacysta 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.

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