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EARLY TITHONIAN DEEP-WATER COLONIZATION BY BENTHIC FORAMINIFERA IN THE MAGURA BASIN (PIENINY KLIPPEN BELT, WESTERN CARPATHIANS): A CLUE TO THE ORIGINS OF DEEP-WATER FORAMINIFERA

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*Abstract***.** Deep-water benthic foraminifera appear in lower Tithonian abyssal deposits lying above a barren interval of radiolarites in the Magura Basin (Western Carpathians). The analysis of morphogroups shows that the assemblage is represented by increased globular chambered morphogroups of both agglutinated and calcareous benthic foraminifera and planoconvex calcareous benthic foraminifera. The composition of the benthic foraminiferal assemblage points to a stressed setting particularly occurring in environments with increased organic flux and depleted oxygen in bottom and pore waters, as indicated by the scarcity of strictly epifaunal agglutinated foraminifera and the absence of strictly epifaunal calcareous benthic foraminifera. The assemblage is compared with Oxfordian – Tithonian assemblages reported from deep-water facies and shelf assemblages from the Boreal, Tethys and Atlantic realms.

INTRODUCTION

The Pieniny Klippen Belt (PKB) represents a complex morphotectonic structure with a sedimentary succession ranging from the Jurassic to the Paleogene. Among the Upper Jurassic formations, the two most typical lithostratigraphic units are the Czajakowa and Czorsztyn formations. The Czorsztyn Formation includes a variety of relatively shallow water carbonates deposited on the so-called Czorsztyn Elevated Ridge, whereas the Czajakova Formation is represented by radiolarites, and it is deposited below the calcite compensation depth (CCD) in the deepest parts of Magura Basin and Pieniny Klippen Belt Basin (Birkenmajer 1977). The Czorsztyn Ridge represents the shallowest part of a so-called Oravicum, a continental crust ribbon derived from the North European Platform and drifting to the south (Froitzheim et al. 2008; Aubrecht et al. 2009). The thermal subsidence between the Callovian and the Tithonian, resulted in the greatest deepening of the Oravicum, which triggered the sub-CCD sedimentation of radiolarites in the basins surrounding the Czorsztyn Ridge (Bireknmajer 1977). During the Jurassic, the rift arms of the Central Atlantic propagated to the east and led to the opening of the Alpine Tethys Basins (Frich 1979; Stampfli 1994). The Western Carpathian zones were linked to these Alpine oceanic domains (Plašienka 2001).

The Callovian-Kimmeridgian deposits of the Czorsztyn Ridge are poorly known due to a long hiatus, and are found mostly in fissures (Mišík 1994; Schlögl et al. 2009). These fissures were formed during extensional tectonics which caused the differentiation of the Czorsztyn Ridge into a series of tectonic blocks (Birkenmajer 1977; Mišík 1994; Aubrecht 2001; Aubrecht & Túnyi 2001). The Upper Jurassic sedimentary successions belonging to the Magura Basin are characterized by the presence of rusty red siliceous marlstones of the Palenica Mem-

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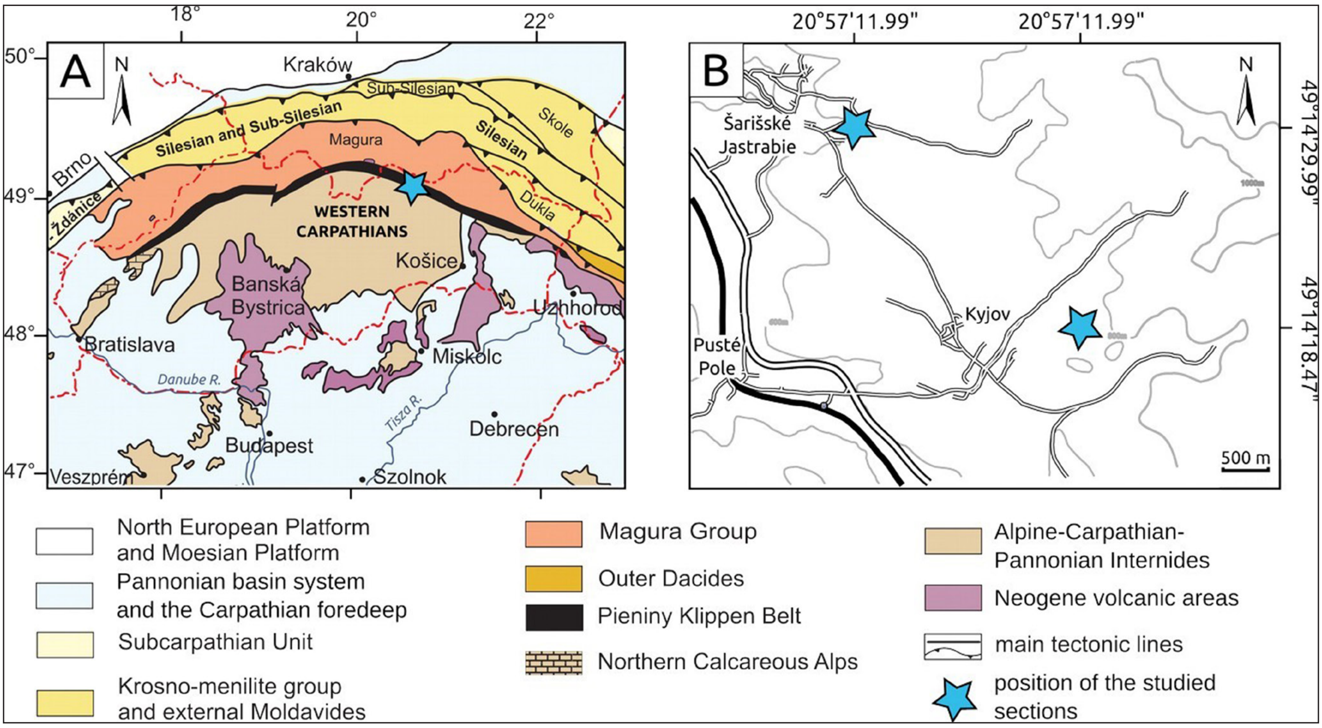


Fig. 1 - A) Geological sketch map of the Carpathians (after Kováč et al. 1998). The study area in the Šariš sector of Pieniny Klippen Belt is shown by a blue star. B) Location of the studied sections near Kyjov (upper left) and Šarišské Jastrabie (lower right).

ber, forming the uppermost part of the Czorsztyn Formation (Birkenmajer 1977). So far, these sediments were reported only from the Polish sector of the Magura Succession (Grajcarek Unit), and are for the first time reported in this paper from the Šariš Unit (Údol Succession) of the Slovak sector of the Pieniny Klippen Belt (PKB). Similarly as in the Grajcarek Unit, the Upper Jurassic of the Šariš Unit is represented by the deepest basinal deposits (Birkenmajer 1977; Plašienka & Mikuš 2010). The studied area is situated in North-East Slovakia, in the eastern part of the Pieniny sector and western part of the Šariš sector of the Pieniny Klippen belt (PKB) (Fig. 1). As observed in the PKB, the radiolarite sedimentation ceased at the end of Kimmeridgian similarly as in the rest of the Tethyan Realm (Birkenmajer 1977). The reason might be the decline of siliceous plankton bioproductivity (Baumgartner 1987) and/or might be compensated by a deepening CCD level since the Callovian in the Atlantic (Jansa et al. 1979; Roth 1983).

The microbiostratigraphy of the Oxfordian-Kimmeridgian deep-water deposits in the PKB is based mostly on radiolarians (Ožvoldová et al. 2000; Rojkovič et al. 2003) and on calcareous dinoflagellate cysts (Nowak 1973; Reháková 2000). The existing biostratigraphic studies from the Czajakowa Formation carried out on the Šarišské Jastrabie section (Fig. 1B) point to a Callovian-Kimmeridgian age (radiolarian zones U.A.Z. 8 to U.A.Z. 10) (Rojkovič et al. 2003). In the Polish sector of the PKB the Palenica Member yielded lower Tithonian calcareous dinoflagellate cysts of the Malmica Zone (Nowak 1973).

Paleoenvironmental reconstructions using Late Jurassic foraminiferal morphogroups (Nagy 1992; Reolid et al. 2008; Nagy et al. 2009; Reolid et al. 2010; Józsa 2017) are based on modern studies which show that benthic foraminifera with similar morphologies are influenced by environmental factors such as the flux of organic matter and oxygen concentrations in both bottom and pore water (Jones & Charnock 1985; Corliss & Chen 1988; Jorissen et al. 1995; Van der Zwaan et al. 1999; De Rijk et al. 2000).

The scope of this paper is the analysis of the basinal deep-water microfossil assemblage from the Upper Jurassic of the Magura Basin with the emphasis on the reconstruction of the paleoenvironment, taxonomic composition of the foraminiferal assemblages and the comparison with the North Atlantic, Boreal and other Tethyan Realm occurrences. In light of the presented and the reviewed data, the possible origin of the deep-water assemblage is here discussed.

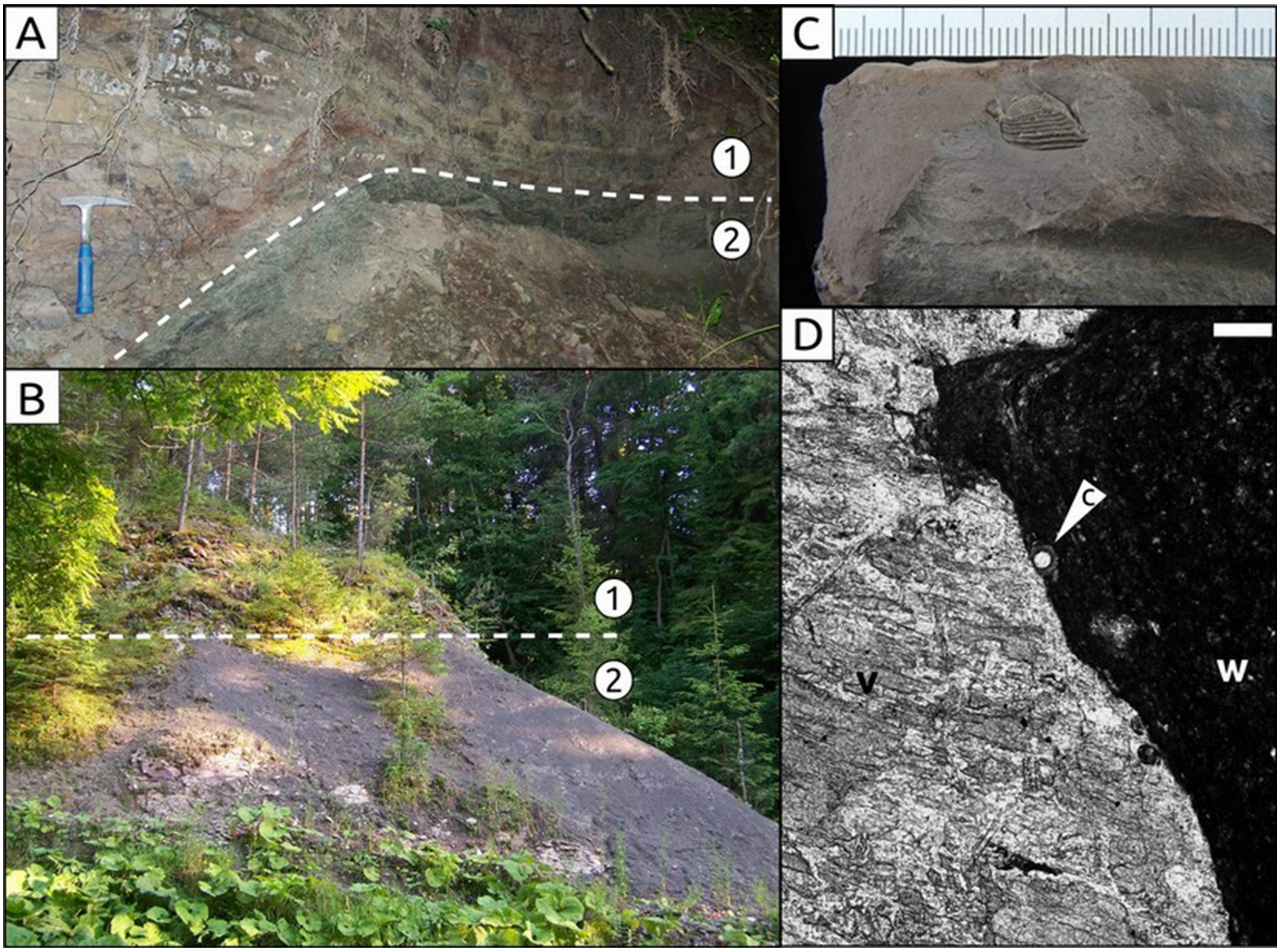


Fig. 2 - A) The studied section near Šarišské Jastrabie. B) The studied section near Kyjov 1 - Radiolarites (upper Kimmeridgian). 2 - Rusty-red marlstones (lower Tithonian). C) marlstone with an aptychus from Kyjov section (scale bar = 5.5 cm). D) Microfacies of a rusty-red marlstone from the Kyjov section (sample Ky2). Wackestone (w) with calcareous dinoflagellate cysts *Colomisphaera cieszynica* Nowak (c) and a lithoclast of a volcanic rock (v). Scale bar = 100 μm.

Geological settings and stratigraphy of the Palenica Member

The studied sections are located close to Kyjov village (Fig. 1B) (49°13'18.47"N; 20°57'11.99"E) and near Šarišské Jastrabie village (Fig. 1B) (49°14'29.99"N; 20°55'3.58"E). The section near Kyjov village north of Lysá Hora Mt. exposes a contact of radiolarites (Czajakowa Formation) and variegated marlstones with occasional macrofossils (Czorstyn Limestone Formation, Palenica Member). The same contact of these marlstones with the radiolarites, has been analysed also in the Vesné stream channel in the Šarišské Jastrabie village only with the base of the Palenica Member exposed. In both sections the beds are overturned (Fig. 2A-B). The base of the Palenica Member is characterized by greenish-violet marlstones without any fossil content. The overlaying strata with macrofaunal content appear as brown or rusty red (Fig. 2C). A peculiar finding of a single well rounded dropstone of a volcanic rock (?dacite) was observed at the Kyjov section (Fig. 2D). Macrofossils in the marlstones are represented mostly by belemnites, aptychi (Fig. 2C) and scarce vertebrate teeth. Among the aptychi, common *Beyrichilamellaptychus beyrichi* (Oppel, 1865) were noted (Vašíček pers. comm.). This taxon occurs through the Tithonian-Berriasian (Luterbacher 1972; Källin et al. 1979).

MATERIAL AND METHODS

Exactly 100 g from 6 samples from Kyjov and 4 samples from Šarišské Jastrabie were dried and gently crushed to about 0.5 cm fragments. REWOQUAT detergent was poured on the frag-

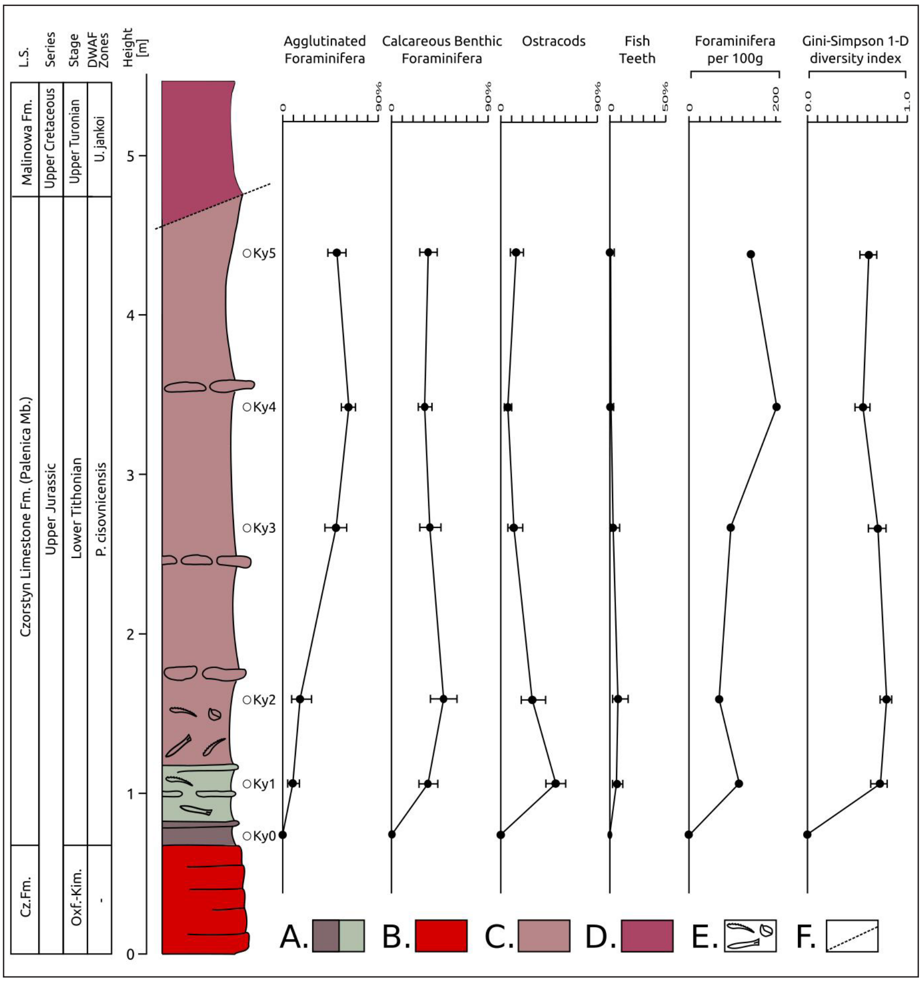


Fig. 3 - Relative distribution of agglutinated and calcareous benthic foraminifera, ostracods, fish teeth and abundance of foraminifera in the Kyjov section. L.S.= Lithostratigraphy, DWAF= deep-water agglutinated foraminiferal biozones according to (Geroch & Nowak 1984). Abundance of foraminifera (specimen/100 g). The error bars in the Gini-Simpson 1-D diversity index are represented by 95% confidence intervals. A= Variegated siliceous marlstones. B= radiolarites. C= Rusty red and brown siliceous marlstones. D= Variegated marls and marlstones. E= Macrofauna. F= Tectonic contact.

ments. After two days the samples were washed through 71, 125 and 200 µm sieves. All microfossils from a dry residue >125 micron were picked and stored in cardboard microslides. The absolute abundance of benthic foraminifera per 100g of bulk dried sediment and the relative abundances of calcareous benthic foraminifera, agglutinated foraminifera, ostracods and fish teeth (Fig. 3, Fig. 6) and relative abundances of benthic foraminiferal morphogroups (Fig. 6) were calculated for the >125µm fraction. The most representative species were mounted on an aluminum stub for observations under SEM at the Slovak Academy of Sciences, Institute of Informatics using a Quanta FEG 250. Microslides with picked foraminifera are stored in the micropaleontological collections at the Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava (J01P23 no.13-20).

The Gini-Simpson diversity index (1-D) represents a measure of the evenness of the sample abundance distribution, where D is the Simpson index. This index is the probability that two specimens randomly drawn from a given sample belong to two different species. It was calculated using the PAST software (Hammer et al. 2001). Because the analyzed samples show geometric species-abundance distributions, the Gini-Simpson index, which is a distribution-free biodiversity metrics, was used instead of the commonly used Fisher's alpha index, suitable only for log-series abundance distributions. To account for uncertainties in the index estimation, 95% confidence intervals (CI) were estimated for each sample through nonparametric bootstrap. The 95% confidence intervals of the estimates of species and morphogroup relative abundances were computed using the Clopper–Pearson method with the PAST software.

The morphogroup scheme for the agglutinated morphogroups (Fig. 4) was modified with respect to the Jurassic – Paleogene foraminiferal data (Nagy 1992; Nagy et al. 1995; Tyszka 1994; Kaminski & Gradstein 2005; Reolid et al. 2008; Nagy et al. 2009; Reolid et al. 2014; van den Akker 2000; Setoyama et al. 2011) and modern studies (Jones & Charnock 1985; Bernhard 1986; Corlis & Chen 1988; Enge et al. 2012). The morphogroup analysis of calcareous benthic foraminifera was carried out using the categories of Tyszka (1994) complemented by data of Frenzel (2000), Reolid (2008) and Cetean et al. (2011) (Fig. 5).

RESULTS

Microfacies, microfossils and microbiostratigraphic analyses

Besides benthic foraminifera (Pls 1-3), frequent ostracods and fish teeth have been washed out the samples (Fig. 3). The ostracods are particularly abundant in the green fossiliferous marlstones below the rusty red ones. Fish teeth are subordinate but increased in the lower fossiliferous marlstones. Calcareous dinoflagellate cysts *Parastomiosphaera malmica* (Borza), *Colomisphaera pulla* (Borza), *Colomisphaera cieszynica* Nowak (Fig. 2E-F) where identified

SAMPLES / SPECIES	*Hyperammina* sp.	*Rhizammina* sp.	*Ammolagena clavata*	*Saccammina* sp.	*Glomospira charoides*	*Glomospira gordialis*	*Reophax helveticus*	*Reophax* sp.	*Scherochorella minuta*	*Pseudoreophax cisovnicensis*	*Trochammina* cf. *sablei*	*Pseudonodosaria vulgata*	*Nodosaria apheilocula*	*Nodosaria* sp.	*Dentalina* cf. *guembeli*	*Dentalina* cf. *vulgata*	*Ramulina tappaneae*	*Ichthyolaria nikitini*	*Falsopalmula deslongchampsi*	*Planularia* cf. *folium*	*Planularia* cf. *erucaeformis*	*Lenticulina informis*	*Lenticulina muensteri*	*Lenticulina hebetata*	*Lenticulina varians*	*Lenticulina subalata*	*Lenticulina* cf. *exgaleata*	*Lenticulina fraasi*	*Lenticulina quenstedti*	*Lenticulina* sp.	*Vaginulinopsis* aff. *enodis*
KY5	-	-	r	a	r	r	-	-	-	-	-	r	-	-	r	-	f	-	-	r	-	-	f	f	r	-	-	r	f	-	-
KY4	-	-	-	a	r	r	-	-	-	-	r	r	-	-	r	-	f	-	-	-	-	-	f	f	r	-	-	-	f	-	-
KY3	r	r	-	a	r	r	r	-	-	r	r	r	r	r	r	-	f	r	r	-	-	-	f	r	r	-	-	-	f	r	r
KY2	r	r	-	f	r	r	-	-	-	-	r	r	-	-	r	r	f	r	r	r	r	r	f	r	r	r	r	r	f	-	r
KY1	-	-	-	f	-	-	r	r	r	r	-	r	-	-	r	r	f	-	-	-	-	-	f	f	r	r	-	r	f	-	-

Tab. 1 - Semiquantitative distribution of foraminifera in the samples from the Kyjov section. (r) - rare (1-5 specimen), (f) - frequent (6-20 specimen), (a) - abundant (<20 specimen), (-) absent.

in thin sections. Their occurrence overlaps in the lower Tithonian (Reháková 2000).

Benthic foraminifera

Rare (1-5), frequent (6-20) to abundant (<20) specimens of benthic foraminifera included in 32 species have been recovered from the siliceous marlstones (Tab. 1). The assemblage is represented by deep-water agglutinated foraminifera (DWAF) and nodosariids. The abundance of foraminifera varies between 44 and 203 specimens per sample (Fig. 3). The DWAF are represented by rare tubulothalamids such as *Hyperammina* sp. (Pl. 1A), *Rhizammina* sp. (Pl. 1B), *Ammolagena clavata* (Jones & Parker) (Pl. 1C), *Ammodiscus* aff. *cretaceus* (Reuss) (Pl. 1F), *Glomospira gordialis* (Jones & Parker) (Pl. 1G) and *Glomospira charoides* (Jones & Parker) (Pl. 1H). *Saccammina* sp. (Pl. 1D-E) is abundant. The polythalamids are represented by rare *Reophax helveticus* (Häusler) (Pl. 1I-J), *Pseudoreophax cisovnicensis* Geroch (Pl. 1L), *Scherochorella minuta* (Tappan) (Pl. 1M), and *Trochammina sablei* Tappan. (Pl. 1N-P). The calcareous foraminifera are represented exclusively by nodosariids dominated by *Lenticulina* spp. Frequent are *Lenticulina muensteri* (Roemer) (Pl. 3A-D), *Lenticulina quenstedti* (Roemer) (Pl. 3U-Y) and *Lenticulina hebetata* (Schwager) (Pl. 3E-F). *Ramulina tappanae* (Bartenstein & Brand) (Pl. 2I) is also frequent. Rare taxa are represented by *Dentalina* spp. (Pl. 2A-E), *Nodosaria* spp. (Pl. 2H, J), *Pseudonodosaria bajociana* (Terquem) (Pl. 2F-G), *Lenticulina varians* (Bornemann) (Pl. 3G-J), *Lenticulina informis* (Schwager) (Pl. 3W-X), *Lenticulina* sp. (Pl. 2AC-AD), *Ichthyolaria nikitini* (Uhlig) (Pl. 2K-P), *Planularia* cf. *folium* (Wiśniowski) (Pl. 2S-T), *Planularia* cf. *erucaeformis* (Wiśniowski) (Pl. 2U-V), *Vaginulinopsis* aff. *enodis* Loeblich & Tappan (Pl. 2Y-AB) and *Falsopalmula deslongchampsi* (Terquem) (Pl. 2Q-R).

Morphogroup analysis of the foraminiferal assemblage

The foraminiferal genera recognized in the studied section were allocated in four agglutinated morphogroups (M1-M4) and their subgroups (Fig. 4) and four calcareous (C2, C6, C7, C8) morphogroups (Fig. 5). The M1 morphogroup includes the tubular sessile suspension feeders with an epifaunal life strategy (*Hyperammina, Rhizammina*). The M2a morphogroup is represented by species with a globular test shape, and with an epifaunal to semi infaunal life strategy (*Saccammina*). Other epifaunal morphogroups are represented by planoconvex M2b (*Trochammina*) and discoidal flattened morphotypes M3a (*Ammodiscus* and *Glomospira*). The attached epifaunal species are included in the morphogroup M3b (*Ammolagena*). The globular morphotypes from the epifaunal agglutinated morphogroup M2b* and infaunal agglutinated morphogroup M4a were not observed. Infaunal morphotypes of agglutinated foraminifera included in the M4b morphogroup

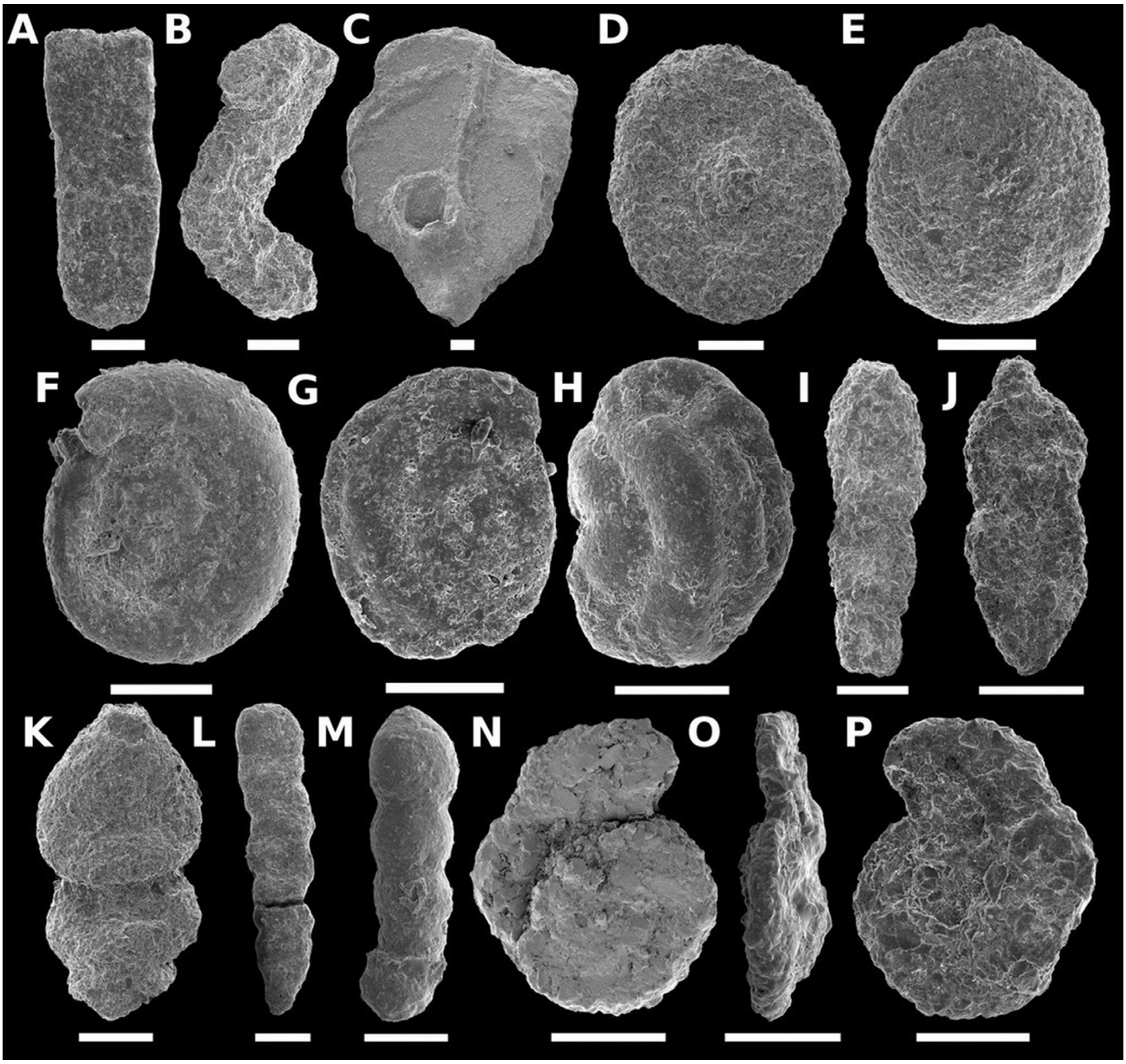


PLATE 1

A - *Hyperammina* sp. B - *Rhizammina* sp. C - *Ammolagena clavata* (Jones & Parker). D-E - *Saccammina* sp. F - *Ammodiscus* aff. *cretaceus* (Reuss). G - *Glomospira gordialis* (Jones & Parker). H - *Glomospira charoides* (Jones & Parker). I-J - *Reophax helveticus* (Häusler). K - *Reophax* sp. L-M - *Pseudoreophax cisovnicensis* Geroch. N-P - *Trochammina* cf. *sablei* Tappan.
Scale bar = 100 μm. M: Ky1. B-C, F, I-K, N-P: Ky2. A, D-E, G-H: Ky3.

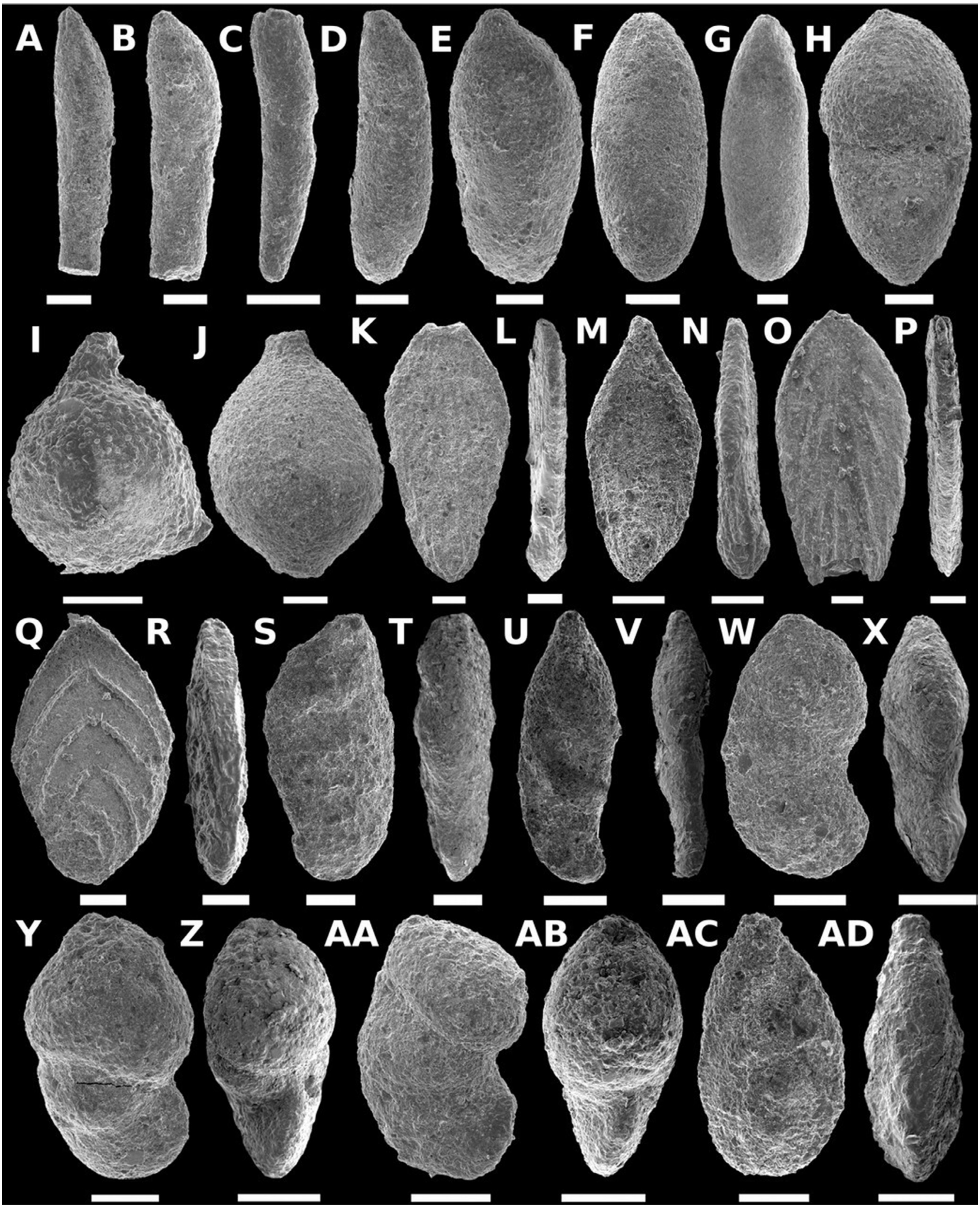


PLATE 2

A-C - *Dentalina* cf. *guembeli* Schwager. D-E - *Dentalina* cf. *vulgata* Hedinger. F-G - *Pseudonodosaria bajociana* (Terquem). H - *Nodosaria* sp. I - *Ramulina tappanae* Bartenstein & Brand. J - *Nodosaria apheilocula* Tappan. K-P - *Ichtyolaria nikitini* (Uhlig). Q-R - *Falsopalmula deslongchampsi* (Terquem). S-T - *Planularia* cf. *folium* (Wiśniowski). U-V - *Planularia* cf. *erucaeformis* (Wiśniowski). W-X - *Lenticulina informis* (Schwager). Y-AB - *Vaginulinopsis* aff. *enodis*. AC-AD - *Lenticulina* sp.
Scale bar = 100 μm. E-G: Ky1. A-D, I, M-N, Q-Z: Ky2. H, K-L, O-P, AA-AD: Ky3.

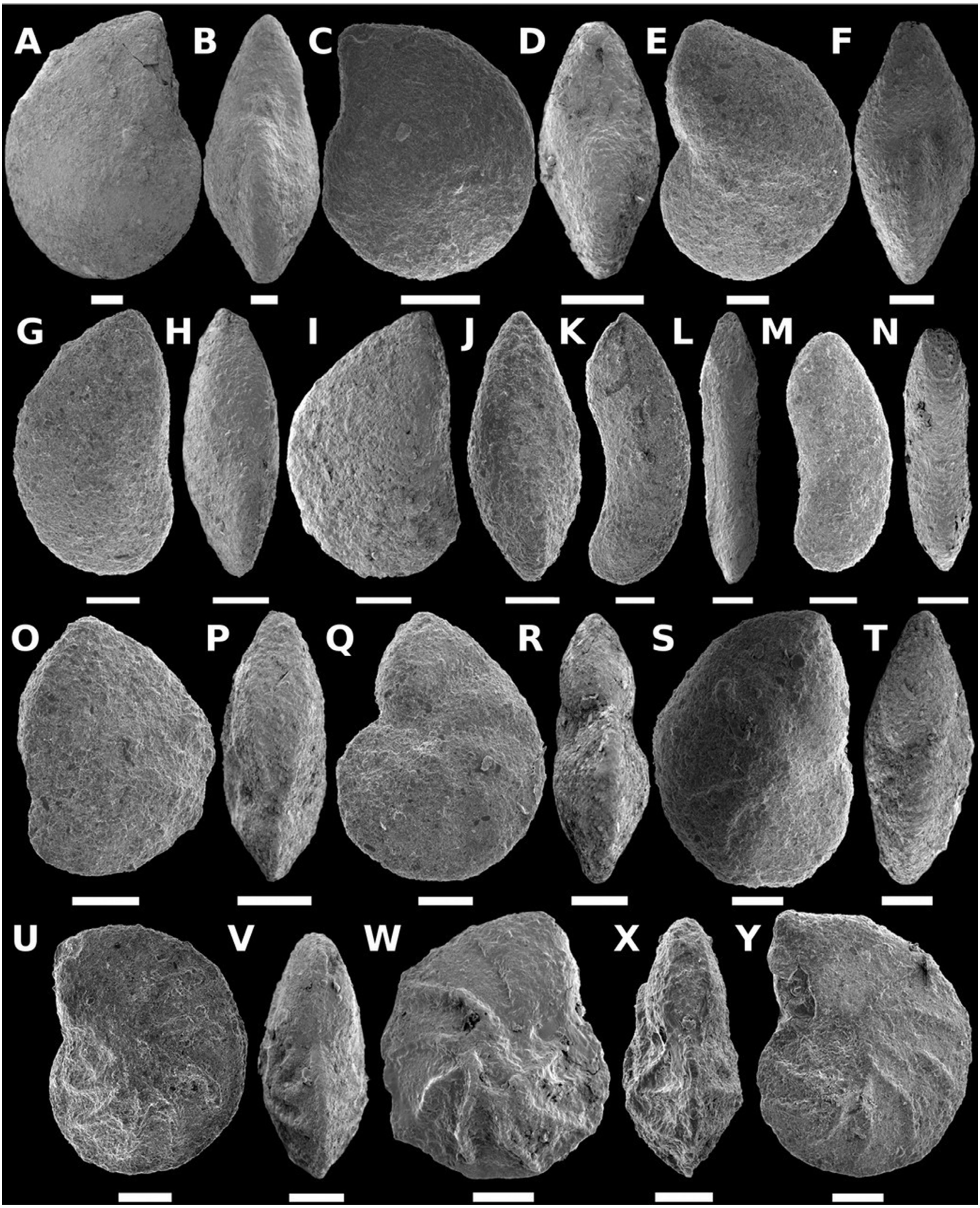


PLATE 3

A-D - *Lenticulina muensteri* (Roemer). E-F - *Lenticulina hebetata* (Schwager). G-J - *Lenticulina varians* Bornemann. K-N - *Lenticulina fraasi* (Schwager). O-P - *Lenticulina* cf. *exgaleata* Dieni. Q-T - *Lenticulina subalata* (Mjatliuk). U-Y - *Lenticulina quenstedti* Gümbel.
Scale bar = 100 μm. A-F, S-T: Ky1. K-N, O-R, U-Y: Ky2. G-J: Ky3.

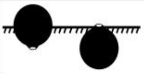
MORPHO-GROUP	MORPHO-TYPE	TEST SHAPE	LIFE POSITION	GENERA	FEEDING HABIT	ENVIRONMENT
M1		Tubular	Epifaunal erect	*Batysiphon* *Hyperammina* *Rhizammina*	Suspension feeding	Tranquil bathyal and abyssal with low organic flux
M2a		Globular	Epifaunal to shallow infaunal	*Saccammina*	Suspension feeding - passive deposit feeding	Shelf - abyssal (bathyal and abyssal)
M2b		Planoconvex	Epifaunal	*Trochammina*	Active deposit feeding	High energy lagoon and estuary to abyssal
M2b*		Rounded	Epifaunal to shallow infaunal	*Recurvoides**	Active deposit feeding	Shelf to deep marine
M3a		Discoidal flattened	Epifaunal	*Ammodiscus* *Glomospira*	Active deposit feeding	High energy lagoon and estuary to abyssal
M3b		Tubular attached	Epifaunal attached	*Ammolagena*	Passive deposit feeding	Upper bathyal to abyssal
M4a		Rounded flattened	Shallow infaunal	*Haplophragmoides** *Cribrostomoides**	Active deposit feeding	Inner shelf to upper bathyal
M4b		Elongated tapered	Shallow to deep infaunal	*Reophax* *Pseudoreophax* *Ammobaculites** *Bicazammina**	Active deposit feeding	Inner shelf to abyssal with increased organic matter flux
M4b*		Elongated subcylindric	Shallow to deep infaunal	*Uvigerinammina** *Verneuilinoides** *"Praedorothia"** *Pseudomorulaeplecta** *Pseudomarssonella**		

Fig. 4 - Agglutinated foraminiferal morphogroups, with interpreted habitat and feeding strategy. Modified from Nagy (1992); Nagy et al. (1995); van den Akker et al. (2000); Kaminski & Gradstein (2005); Cetean et al. (2011); Setoyama et al. (2011). Groups in gray not present in the Kyjov section. *= examples of Upper Jurassic genera not present in this study.

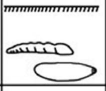
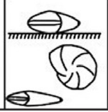
MORPHO-GROUP	MORPHO-TYPE	TEST SHAPE	LIFE POSITION	GENERA	FEEDING HABIT
C1		Bi/plano-convex	Epifauna	*Epistomina**	Primary weed fauna grazing herbivores
C2		Irregular, meandrine	Epifaunal to shallow infaunal	*Ramulina*	?
C3-C4		Discoidal flattened	Epifaunal	*Spirilina** *Ophthalmidium**	Primary weed fauna grazing herbivores, detritovores/active deposit feeders
C5		Elongated, flattened	Shallow infaunal	*Nodosaria*	Deposit feeders, grazing omnivores and/orbacterial scavengers
C6		Elongated, flattened	Shallow to deep infaunal	*Ichtyolaria* *Falsopalmula* *Planularia*	Active deposit feeders, Grazing omnivores
C7		Elongated (uniserial)	Shallow to deep infaunal	*Dentalina* *Pseudonodosaria*	Deposit feeders, grazing omnivores and/or bacterial scavengers
C8		Biconvex round or elongated	Epifaunal to deep infaunal	*Lenticulina*	Active deposit feeders, Grazing omnivores

Fig. 5 - Calcareous benthic foraminiferal morphogroups, with interpreted habitat and feeding strategy. Modified from Tyszka (1994); Frenzel et al. (2000); Cetean et al. (2011). Groups in gray not present. * =Examples of Upper Jurassic genera not present in this study.

are recognized by their elongated tapered test shape (*Reophax* and *Pseudoreophax*). The infaunal subcylindric morphotypes included in the M4b* were not observed. Infaunal to epifaunal calcareous benthic foraminiferal morphogroup is represented by the C2 (*Ramulina*) and C8 (*Lenticulina*). Strictly epifaunal benthic foraminiferal morphogroups such as those included in the C1 (*Epistomina*) and C3 and C4 (*Spirillina*, *Ophthalmidium*) are missing. The infaunal morphogroups C6 and C7 are represented by elongated and flattened (*Ichtyolaria, Falsopalmula, Planularia*) and elongated cylindrical morphotypes (*Dentalina, Pseudonodosaria, Eoguttulina*). The biconvex epifaunal to deep infaunal morphogroup (C8) includes mostly rounded and occasionally elongated morphotypes of *Lenticulina*.

The epifaunal to semi-infaunal M2a morphogroup and the epifaunal to deep infaunal C8 morphogroup are dominant in the investigated section (Fig. 6). Subordinate are epifaunal to shallow infaunal calcareous benthic foraminifera included in the morphogroup C2. Attached or sessile and mobile epifaunal morphogroups of agglutinated foraminifera (morphogroups M1, M2b, M3a and

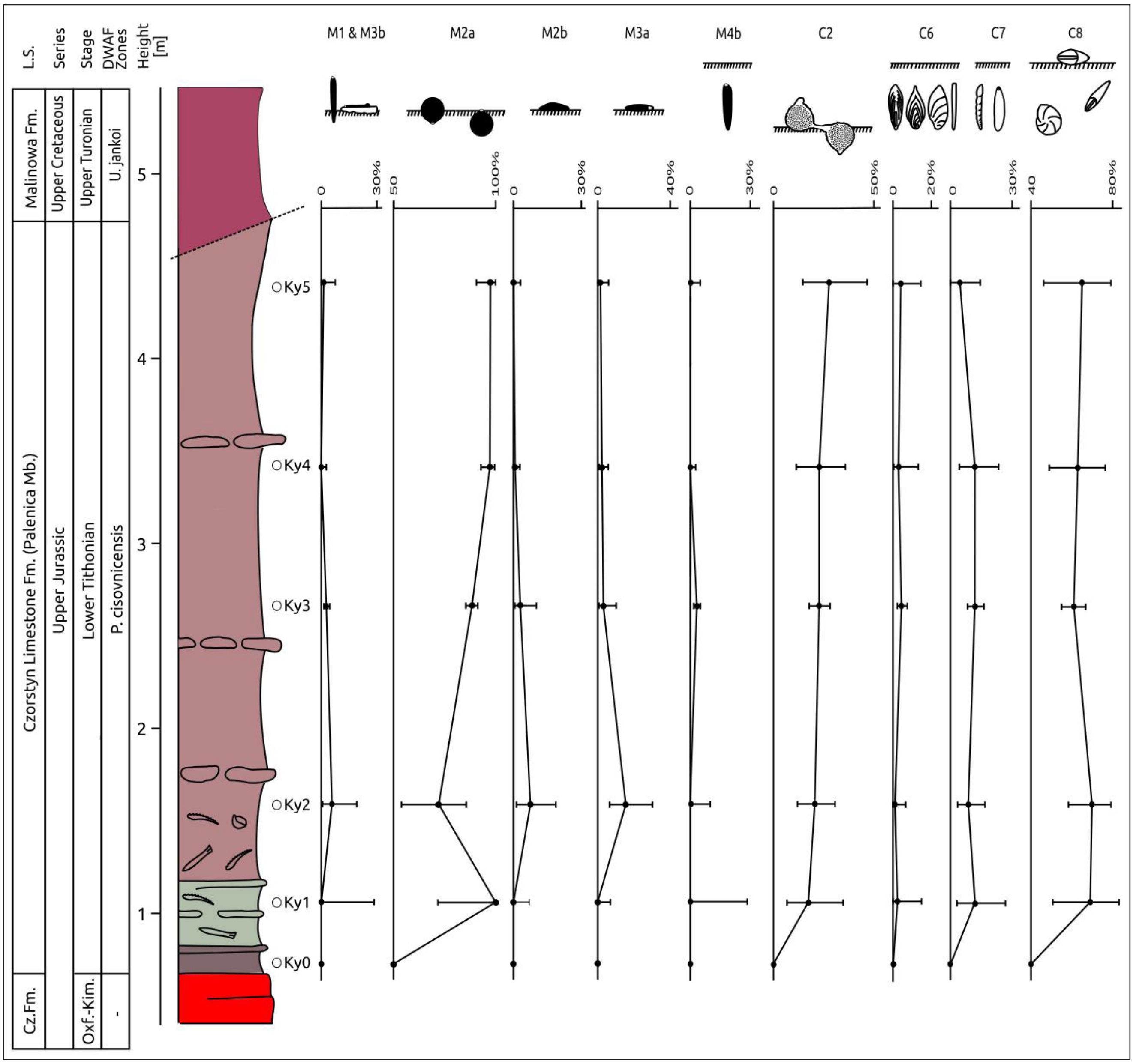


Fig. 6 - Morphogroup analysis of the benthic foraminifera of the Kyjov section. M= Agglutinated morphogroups. M1= Epifaunal sessile tubulothalamids. M2a= Epifaunal-shallow infaunal globular monothalamids. M2b= Epifaunal trochospiral polythalamids. M3a= Epifaunal discoidal tubulothalamids. M4b= Infaunal elongated tapered polythalamids. C= Calcareous morphogroups. C2= Epifaunal – semi-infaunal calcareous rounded. C6= Calcareous shallow to deep infaunal morphogroup - uniserial and planispiral (elongated and flattened). C7= Calcareous deep infaunal morphogroup - uniserial (elongated and straight periphery). C8= Calcareous epifaunal to deep infaunal morphogroup - planispiral (rounded periphery, biconvex). The error bars are represented by 95% confidence intervals. The relative abundances of agglutinated (M) and calcareous (C) foraminiferal morphogroups were calculated separately.

M3b) and strictly infaunal morphogroups of both agglutinated and calcareous benthic foraminifera (M4, C6 and C7) are scarce (Fig. 6).

Notes on biostratigraphy and paleogeographic distribution of smaller benthic foraminifera

The common presence of *Lenticulina quenstedti* Gümbel (Pl. 3U-Y) agrees with its known range from the late Aalenian to Tithonian (Tyszka 1999; Tyszka in Birkenmajer et al. 2008; Gedl & Józsa 2015; Ozdínová & Józsa 2017). Other characteristic Upper Jurassic taxa are represented by *Ichthyolaria nikitini* (Uhlig) (Pl. 2L-P), *Planularia* cf. *folium* (Wiśniowski) (Pl. 2S-T), *Planularia* cf. *erucaeformis* (Wiśniowski) (Pl. 2U-V) and *Lenticulina informis* (Schwager) (Pl. 2W-X) (Fig. 7). Specimens similar to *Vaginulinopsis* aff. *enodis* (Pl. 2U-X) with a more

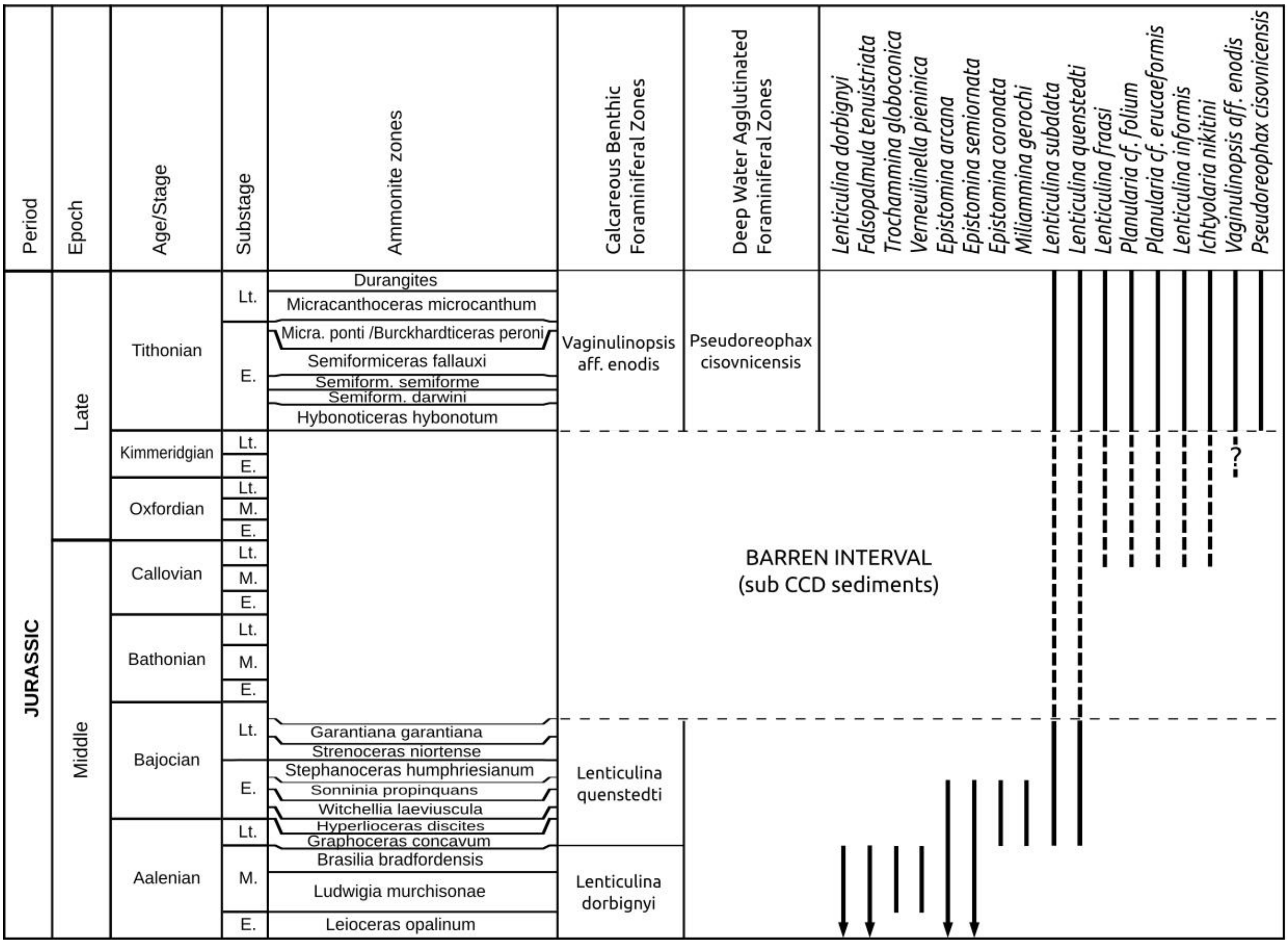


Fig. 7 - Stratigraphic ranges of some smaller benthic foraminifera in the Magura Basin (Middle Jurassic foraminifera modified after Tyszka 1999; Gedl & Józsa 2015). Barren interval represents the sedimentation of radiolarites in the Outer Carpathian basins. Ranges for the Upper Jurassic foraminifera drawn with the dashed lines are according to Wiśniowski (1890); Siebold & Siebold (1956); Luterbacher (1972); Geroch & Nowak (1984); Morris & Coleman (1989); Riegraf & Luterbacher (1989); Shipp (1989). Ammonite zonations are according to Contini et al. (1997); Rioult et al. (1997); Geyssant (1997).

developed uniserial portion are reported from the ?Kimmeridgian – Tithonian of the DSDP site 100 of the NW Atlantic (Luterbacher 1972). The occurrence of *Ichthyolaria nikitini* (Uhlig) in the NW Atlantic is reported in the ?Oxfordian – Tithonian (Luterbacher 1972; Riegraf & Luterbacher 1989) and the Callovian – Tithonian of UK (Morris & Coleman 1989; Shipp 1989). In the Magura Basin the FO for the most of the above mentioned species is in the lower Tithonian (Fig. 7). The FO of *Pseudoreophax cisovnicensis* Geroch in the Magura Basin is in line with the Outer Western Carpathian zonation of Geroch & Nowak (1984), and confirms a Tithonian age for the investigated section Zone (Fig. 7). This taxon occurs in the Tithonian – Barremian of the Outer Western Carpathians (Geroch & Nowak 1984) and in the upper Tithonian – Berriasian of the Indian Ocean sub-CCD assemblages from the Argo abyssal plain (Holbourn & Kaminski 1997). In the Atlantic Ocean *Pseudoreophax cisovnicensis* is reported in the Valanginian (Gradstein 1983; Riegraf et al. 1989; Geroch & Olszewska 1990).

DISCUSSION

Paleoenvironment of the Palenica Member

The increase in dimensions of the tubular morphotypes (M1) is common on the continental rise and slope of the recent North Atlantic and represents environments with increased carbon flux (Kaminski & Kuhnt 1995). Large tubular forms also thrive in environments with bottom currents which re-suspend organic matter (Murray et al. 2011; Kuhnt et al. 2000). Due to strong currents, the more delicate tubular forms may not be present, but robust forms and attached sessile forms may be common. The sessile M1 morphogroup is scarce and is composed of such robust forms (Pl. 1A-C) and sessile forms (Pl. 1C). Epifaunal to shallow infaunal globular morphogroups (M2a, C2) are dominant. In the upper part of the section the assemblage is dominated by the M2a morphogroup represented by *Saccammina* sp. The present-day saccamminids are epifaunal, semi-infaunal or living just below the sediment surface (De Laca 1986; Enge et al. 2012). Similarly in the fossil record most of the saccamminids are considered as epifaunal (Reolid et al. 2010), semi infaunal (Nagy et al. 1995) or represent shallow infauna (Van den Akker et al. 2000; Kaminski & Gradstein 2005). The present day saccamminids are opportunists living in areas with a seasonal dysoxia (Kaminski et al. 1995; Murray et al. 2011) in organically enriched sediments and are able to colonize quickly habitats after sediment disturbance (Kaminski 1985; Kaminski et al. 1995).

The strictly epifaunal mobile morphotypes from the M2b and M3a agglutinated morphogroups are rare. The present day tubulothalamid species *G. charoides* is tolerant to oxygen depleted conditions, and it seems to respond more to changes in productivity rather than to oxygen availability (Kaminski & Gradstein 2005). This species was also observed to flourish under conditions of very low carbon flux (De Rijk et al. 2000). The low relative abundances of species of *Glomospira* and *Ammodiscus* in the studied material might point to eutrophic settings.

Alike the agglutinated globular morphotypes (M2a), the dominant planoconvex morphotypes of calcareous benthic foraminifera (*Lenticulina*, C8) also reflect stressed environments (Tyszka 1994). The same might be inferred for *Ramulina*, included in the C2 morphogroup which is generally the third most abundant group in all samples (Fig. 6). An environmental instability is suggested by a significant difference in the Gini-Simpson index (Fig. 3) between the stratigraphically higher samples (Ky4-Ky5) and the lower sample (Ky2). Also a significant difference between the CIs among agglutinated foraminifera occurs between samples Ky2 and above (Fig. 3). Similarly the CIs show significant changes in the strictly epifaunal M3a mobile morphogroup and the M2a morphogroup (between samples Ky2 and Ky4-Ky5) (Fig. 6). The change in the Gini-Simpson 1-D diversity index and changes in the morphogroups composition above the Ky2 sample well correlate with the increase of agglutinated foraminifera (mainly *Saccammina* sp.) and the decrease of the calcareous benthic foraminifera, mainly represented by *Lenticulina* spp. (Samples Ky3-Ky5) (Fig. 3). The high abundances of *Lenticulina* are typical for the Jurassic and are reported from a wide range of environments (Bernhard 1986; Koutsoukos et al. 1990; Rey et al. 1994; Tyszka 1994). The dominance of *Lenticulina* also indicates basinal settings (Reolid et al. 2013). According to the TROX model of Jorissen et al. (1995), the dominance of infauna and lack of epifauna might indicate a poorly-oxygenated environment at the top of the sediment. The very low relative abundance of the sessile M1 and the absence of strictly epifaunal mobile calcareous benthic morphogroups (C3-C4) points to such an environment (fig. 6).

The DWAF assemblage lacks elongate taxa with final bi- or more-serial chamber arrangement such as *Verneuilinoides*, *Spiroplectammina*, *Uvigerinammina* and *"Praedorothia"*. All of these taxa with subcylindric test shape belong to the deep infaunal morphotypes (morphogroup M4b* of this study). Representatives of the elongated tapered to elongated subcylindric morphotypes are interpreted as inhabiting mostly inner shelf to upper bathyal environments (Nagy et al. 1995; Van der Akker et al. 2000; Kaminski & Gradstein 2005; Setoyama et al. 2011). It seems that such morphotypes in the Late Jurassic thrive also deeper in the abyssal paleodepths (Luterbacher 1972; Gradstein 1983; Riegraf et al. 1987; Kaminski et al. 1992; Holbourn & Kaminski 1997; Kaminski et al. 1999). The only representatives of such deep infaunal morphotypes in this study belong to rare uniserial taxa such as *Reophax* (Pl. 1I-K), *Pseudoreophax* (Pl. 1L) and *Scherochorella* (Pl. 1M). *Reophax* is a typical recolonizer in both fossil and modern assemblages (Nagy 1992; Tyszka 1994; Kaminski et al. 1995; Galeotti et al 2002; Hess et al. 2002; Murray et al. 2011; Reolid & Martínez-Ruiz 2012).

The documented benthic foraminiferal assemblage is dominated by taxa tolerating oxygen depleted conditions and increased organic flux. The distribution of some of the agglutinated morphogroups reflects environmental instability. The assemblage appears just above the radiolarites which are barren of benthic foraminifera and il-

REALM	AGE	LOCATION	FORAMINIFERAL MORPHOGROUPS															PF	GENERA	AGG. GENERA	GENERA IN M4b*
			M1	M2a	M2b	M2b*	M3a	M3b	M4a	M4b	M4b*	C1	C2	C3	C4	C5-C7	C8				
ATLANTIC	TITHONIAN	901	-	-	-	-	+	-	-	-	-	+	+	+	+	+	+	+	23	1	0
	OXFORDIAN-LOWER TITHONIAN	547 B	-	-	+	+	+	+	+	+	+	+	+	+	+*	+	+	-	22	10	2
	OXFORDIAN-KIMMERIDGIAN	105	-	-	-	-	+	+	+	+	+	-	+	+*	+*	+	+	-	18	6	2
	KIMMERIDGIAN-TITHONIAN	105	+	+	-	+	+	+	+	+	+	+	+	+*	+*	+*	+	-	31	13	3
	UPPER OXFORDIAN	100	-	+*	-	-	+	+	+	+	+	-	+	+	+*	+	+	-	32	14	4
	KIMMERIDGIAN-TITHONIAN	100	-	+	+	-	+	+	-	+	+	-	+	-	+*	+	+	-	30	12	1
	OXFORDIAN-TITHONIAN	391 C	+	+	-	+	+	-	+	+	+	+	-	+	+*	+	+	+	22	10	1
TETHYS	OXFORDIAN-LOWER KIMMERIDGIAN	SA^1	-	-	-	-	-	-	+	+*	+	-	+	+	-	+	+*	-	18	4	2
	MID. OXFORDIAN	SA^2	-	+*	+	-	+	+	+	+	+	+	+	+*	+*	+*	+	+	51	20	4
	KIMMERIDGIAN	EC	-	+	+	+	+	-	+	+	+	n/a	n/a	n/a	n/a	n/a	n/a	n/a	⑯	16	6
	OXFORDIAN-KIMMERIDGIAN	CR	-	+	+	+	+	+	+	+	+	n/a	n/a	n/a	n/a	n/a	n/a	n/a	⑲	19	7
	UPPER TITHONIAN	SI	+	+	+	+	+	+	+	+*	+*	+	-	-	+	+*	+*	-	60	21	10
	LOWER TITHONIAN	MB	+	+*	+	-	+	+	-	+	-	-	+	-	-	+	+*	-	17	8	0
	KIMMERIDGIAN-LOWER TITHONIAN	U	-	-	-	-	-	-	-	-	-	-	+	-	+*	+	+*	-	13	0	0
	LOWER OXFORDIAN-MID. KIMMERIDGIAN	NE	+	+	+*	+	+	+	+	+	+*	-	+	-	-	+	+	-	30	26	7
	LOWER TITHONIAN OR OLDER	765 C	+	+*	+*	-	+*	+	-	+	+	-	-	-	-	-	-	-	⑮	15	1
	UPPER TITHONIAN-BERRIASIAN	765 C	+*	+	+*	+	+*	+	+	+	+*	-	-	-	-	-	-	-	㉓	23	6

░ Deep(er) shelf or ridge deposits (lower neritic-upper bathyal foraminiferal assemblages)

▓ Deep marine deposits (lower bathyal - abyssal foraminiferal assemblages)

Tab. 2 - Presence (+) and absence (-) of smaller foraminiferal morphogroups and number of genera in neritic to abyssal environments from Tethyan and Atlantic during Oxfordian-Tithonian. * = increased relative abundance. Circled= data available only from smaller agglutinated foraminifera. Full line= sub-CCD assemblage. Dashed line= DWAF. Underlined= data available only from smaller calcareous benthic foraminifera. CR= Czorstyn Ridge, Slovakia (Mišík & Soták 1998). EC= Eastern Carpathians, Romania (Neagu & Neagu 1995). MB= Magura Basin, Slovakia (present study). NE= Thakkhola, Nepal (Nagy et al. 1995). SA^1 = Swabian Alb, Germany (Siebold & Siebold 1956). SA^2 = Swabian Alb, Germany (Siebold & Siebold 1960). SI= Silesian Basin, Poland (Szydlo 2004; Szydlo 2005). U= Umbria, Italy (Farinacci 1965). 901= DSDP Site 901, North Atlantic (Collins et al. 1996). 100, 105, 391C, 547B= DSDP Sites 100, 105, 391C and 547B, North Atlantic (Riegraf et al. 1989). 765C= DSDP Site 765C, Indian Ocean (Kaminski et al. 1992). PF= Planktonic foraminifera.

lustrates the composition of an opportunistic assemblage colonizing the Outer Carpathian Magura Basin's abyssal zone.

Paleogeographic distribution of similar foraminiferal assemblages

Common occurrence of saccamminids in the Oxfordian-Kimmeridgian seems to represent a paleogeographically widely distributed event. Increased saccamminids are noted in the Oxfordian organic rich shelf deposits of Svalbard in the Boreal Realm (Lardyfjellet Fm.) (Nagy et al. 2009; Reolid et al. 2010) and in the Laptev Sea (Nikitenko et al. 2015), both accompanied with blooms of *Trochammina* and *Recurvoides* (morphogroup M2b of this study) (Tab. 2). In the Subboreal Realm, increased saccamminids (8-10% of the assemblage) were noted in the Oxfordian Hazelbury Brian Formation in the UK (Henderson 1997) and in the mid-Oxfordian siliceous sponge biofacies close to the North Tethyan paleomargin from the Swabian Alb (Birmenstorf Member of the Wildegg Formation) (Siebold & Siebold 1960; Oesterle 1968; Munk 1994). According to Gygi (1986), the Wildegg Fm. was deposited at depths not exceeding 150 m. The present-day common occurrence of saccamminids is however observed below 200 m (Jones & Charnock 1985; Murray et al. 2011). In deeper slope facies such as the Impressamergel Formation in the Swabian Alb (Schmidt et al. 2005), the agglutinated foraminifera seem to be of low diversity and lacking saccamminids, however with frequent other mostly infaunal species of foraminifera (Siebold & Siebold 1956; Riegraf et al 1989). Close to the northern Gondwana margin, deeper-shelf assemblages with common globular morphotypes are reported from the lower Oxfordian – middle Kimmeridgian black shales of Nupra Formation (Nagy et al. 1995). In the Kimmeridgian saccamminids are reported from red nodular limestones from the Eastern and Southern Carpathians ("Acanthicum" Limestone Formation) (Neagu & Neagu 1995). Lazar et al. (2011) reported, among calcareous benthic foraminifera from thin sections, mostly epifaunal morphotypes (nubecularids, involutinids and numerous epistominids) and indicated a depth for this formation not deeper than 100 m. These Late Jurassic events with increased saccamminids seem to be restricted to shelf and deeper shelf areas (Tab. 2). The absence of *Epistomina* (morphogroup C1) or planktonic foraminifera with aragonitic tests in the Kyjov section points to depths below the aragonite compensation depth (ACD). The absence of aragonitic foraminifera in the Atlantic abyssal sediments was noted in the upper Oxfordian-Tithonian of Site 100 and in the Oxfordian-Kimmeridgian of Site 105 (Tab. 2). Such a case points also to a deep paleobathymetric position, although, according to Riegraf (1989), their absence might be caused by diagenetic dissolution. It is noteworthy that the Upper Jurassic deep-water carbonatic facies from the Umbria and Sicily ("Calcari Diasprigni" and "Calcari a Saccocoma e Aptici" formations), are barren of agglutinated foraminifera, and the assemblages consist exclusively of calcareous foraminifera (nodosarids and spirillinids) and ostracods (Farinacci 1965) (Tab. 2).

Ophthalmiids and spirillinids were not found in the investigated assemblage (Tab. 2). A significant decrease in ophthalmiids occurs in the Kimmeridgian of the Boreal Realm and is interpreted as a result of decreasing oxygenation (Colpaert et al. 2016). Ophthalmiids seem to be absent in the Tithonian of the Silesian Basin in Poland (Geroch & Olszewska 1990; Szydlo 2004). In contrast, blooms of small ophthalmiids and spirillinids are documented from the Atlantic abyssal assemblages (Luterbacher 1972; Gradstein 1983; Riegraf & Luterbacher 1989). A single exception is reported for the Kimmeridgian – Tithonian of Site 100 (Riegraf & Luterbacher 1989) (Tab. 2).

Possibly redeposited foraminiferal assemblages which are similar to the shelf assemblages were reported in the upper Tithonian of the Cieszin Fm. (Szydlo & Jugowiec 1999). The assemblages already contain diverse agglutinated foraminifera comparable to the diverse deep-water agglutinated foraminiferal assemblages from the Indian Ocean (Geroch & Olszewska 1990; Kaminski et al. 1992; Szydlo 2004). Ksiazkiewicz (1975) suggested a neritic paleodepth for the lower Tithonian Cieszyn shale member and upper bathyal for the upper Tithonian Cieszin Fm.

Despite diverse and rich assemblages of DWAF that have been reported from the Upper Jurassic limestone formations of the Czorstyn Ridge in the PKB (Mišík 1994; Mišík & Soták 1998), yet no DWAF has been reported from the radiolarites, below the CCD. Younger Cenomanian radiolarites in the Pieniny Klippen Belt contain common planktonic foraminifera (Józsa & Aubrecht 2008) and also common calcareous benthic foraminifera and DWAF. Although the sedimentation of these radiolarites has occurred above the CCD, they demonstrate the preservation potential of DWAF in such lithology. This observation testifies that in the Magura Basin, the DWAF did not thrive under the CCD prior to the lower Tithonian. In the Atlantic, the CCD was deeper in comparison with the Tethyan Realm (Baumgartner 1989), and the foraminifera inhabited also deeper environments. Equivalent facies to the Palenica Member (brown, red or green mudstones with aptychy), with diverse and abundant foraminifera, are reported from the ?Oxfordian – Tithonian of the NW Atlantic (Cat Gap Formation) (Luterbacher 1972; Gradstein 1983; Riegraf & Luterbacher 1989). The Cat Gap Fm. was deposited in a deep bathyal - abyssal environment above, but close to the CCD (Jansa et al. 1979; Gradstein 1983).

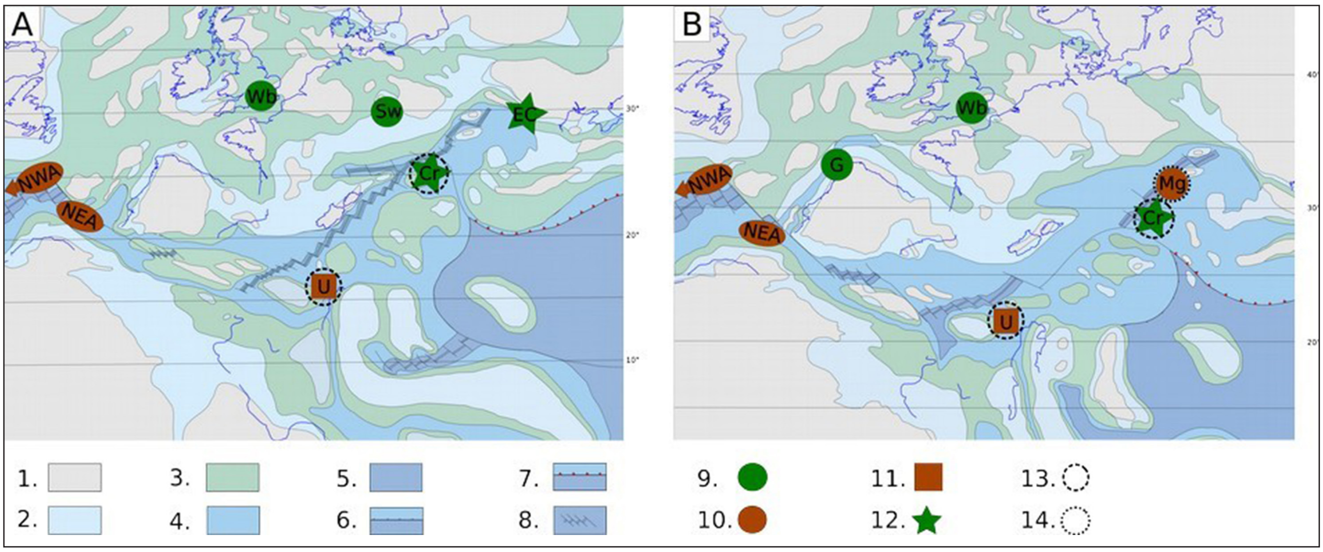


Fig. 8 - A) Early Kimmeridgian and B) Early Tithonian paleogeography of the peri-Tethys area (modified after Thierry et al. 2000). 1 - Exposed land, non-deposition. 2 - Coastal to shallow marine deposits (Platforms, buildups and ramps). 3 - Deep(er) carbonates, (hemi)pelagic oozes. 4 - Deep marine. 5 - Deep oceanic basins. 6 - Thrust/reverse fault. 7 - Oceanic subduction. 8 - Rift. 9 - Oxfordian-Tithonian shallow - deep(er) mixed assemblages. 10 - Oxfordian-Kimmeridgian deep-water mixed assemblages. 11 - Kimmeridgian-lower Tithonian deep-water calcareous assemblages. 12 - Oxfordian-Tithonian DWAF from deep(er) carbonates. 13 - Assemblages lacking morphogroups C1 and C3. 14 - Assemblage lacking morphogroups C1, C3 and C4 (present study). Cr - Czorsztyn Ridge. G - Galician Bank. NWA - North-Western Atlantic. EC - Eastern Carpathians. Mg - Magura Basin. NEA - North Eastern Atlantic. Wb - Wessex Basin. Sw - Swabian Platform. U - Umbria.

The taxonomical composition of the nodosariids in the Palenica Member is similar to the foraminiferal assemblages from the Cat Gap Fm. and the shelf assemblages from NW Europe (Tab. 1). This includes *Ramulina* spp., *Ichthyolaria nikitini, Falsopalmula deslongchampsi, Lenticulina quenstedti, Lenticulina fraasi* and *Vaginulinopsis* aff. *enodis*.

The deep-water agglutinated foraminifera (DWAF) (Tab. 2, MB) are rather depleted in comparison with the ? Oxfordian-Tithonian lower bathyal - abyssal assemblages of the NW Atlantic (Luterbacher 1972; Riegraf & Luterbacher 1989) (Tab. 2, DSDP Sites 100, 105, 391, 547B). The DWAF assemblage in this study is the most similar to the lower Tithonian abyssal sub CCD assemblage from the Indian Ocean (Kaminski et al. 1992) (Tab. 2, DSDP Site 765C). Similar is the age of the assemblage, absence of the elongate taxa with final bi- or more-serial chamber arrangement and abundant saccamminids. In the DSDP Site 765C the taxa with final bi- or more-serial chamber arrangement appear later in upper Tithonian – Valanginian (Kaminski et al. 1992; Holbourn & Kaminski 1997; Kaminski et al. 1999) (Tab. 2).

The composition of the agglutinated and calcareous foraminiferal morphogroups in this study shows affinity with the upper Oxfordian – Tithonian assemblages of the Atlantic DSDP Site 100. This affinity might be inferred from the increased M2a morphogroup and the absence of the M2b*, M4a, C1, and C3 morphogroups. Also the absence of the M1 at the DSDP Site 100 is similar to very low relative abundances of the M1 and M2b morphogroup in the Magura Basin assemblage.

The genera included in the M4b* morphogroup that are reported from the Oxfordian-Tithonian Atlantic and NW Europe are fewer than most coeval Tethyan shelf or ridge assemblages (Tab. 2). Yet the M4b* morphogroup in Tethyan deep-water assemblages is absent prior upper Tithonian (DSDP Leg 765C, Argo abyssal Plain in the Indian Ocean) (Kaminski et al. 1992; Holbourn & Kaminski 1997) (Tab. 2). Together with the results of this study, this observation suggests that the distribution of the M4b* morphogroup of this study is limited to the shelf areas before the late Tithonian in the Tethyan Realm, whereas they are present in older abyssal deposits in the Atlantic Realm (Tab. 2).

Most of the similarities regarding the facies, taxonomy and morphogroup composition point to an existence of a corridor for migration of foraminifera from deep-water environments of the

Atlantic (Tab. 2, cf. MG with 100). This migration was possible through the Atlantic - Alpine Tethys connection (Frich 1979; Stampfli 1994; Thierry et al. 2000; Plašienka 2001) (Fig. 8).

Conclusion

Although numerous and diverse Callovian-Kimmeridgian smaller agglutinated foraminifera are reported from shelf areas and submarine ridges, they were not observed so far in abyssal sediments from the Carpathian Tethys. Since the early Tithonian, both calcareous and agglutinated smaller benthic foraminifera started to colonize the abyssal siliceous marly facies in the Magura Basin. The colonizing assemblage is of low diversity and dominated by opportunistic foraminifera included in the biconvex (C8) and globular chambered morphogroups (M2a, C2). Morphogroup M4b is rare and it is represented only by opportunists. The distribution of agglutinated foraminifera including the epifaunal mobile morphogroup M3a and the M2a morphogroup show significant changes indicating instabilities in the environment. Such an assemblage points to a stressed environment with increased organic flux and decreased oxygenation of the bottom and pore waters. There are reports of increases in saccamminids from the Boreal - Tethyan shelf areas down to the abyssal paleodepths in the Atlantic during the Oxfordian - Kimmeridgian. The abyssal paleodepths in the Tethys were colonized later by assemblages with increased saccamminids such as found in the Magura Basin and the Indian Ocean (Argo Abyssal Plain). Compared to the Atlantic occurrences the Tethyan assemblages are of low-diversity. Based on taxonomic and morphogroup similarities, the abyssal foraminifera from the Tethys may represent the successors of the Atlantic abyssal foraminifera.

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