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Sedimentological and palaeocological records of the evolution of the southwestern part of the Carpathian Foredeep (Czech Republic) during the early Badenian

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The depositional environment of the southern part of the Carpathian Foredeep in the Czech Republic was studied in two boreholes using sedimentological and palaeontological methods. Eight lithofacies were recognised within cores of the early Badenian deposits, comprising two facies associations, namely deposits of a coarse-grained Gilbert delta and offshore deposits. Assemblages of foraminifers document the early Badenian (Middle Miocene age). Two types of assemblages were recognised: (1) primary taphocoenoses reflecting the original environment of sedimentation, i. e. a relatively deep sublittoral (circalittoral) environment with low to normal oxygen bottom conditions and deep-water euryoxibiont foraminifers, numerous planktonic foraminifers, agglutinated foraminifers and mixed assemblages of deep- and shallow-water foraminifers, (2) secondary taphocoenoses of shallower sublittoral (infralittoral) condition redeposited into the basin by gravity currents. These assemblages contain shallow-water foraminifers coupled with an abundant and diverse bryozoan fauna.

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INTRODUCTION

The transition from the Early to the Mid Miocene coincides with a significant sea level fall (Haq *et al*., 1988, Hardenbol *et al*., 1998), a changing tectonic regime in the Alpine-Carpathian realm (Kováč *et al*., 2007) while extensive marine transgression followed during the early Mid Miocene (the early Badenian). All these factors directly influenced the evolution of basins in the foreland of the Alpine-Carpathian thrust wedge. Although the ruling factors of deposition and basin development are widely accepted for the broad area of the Central Paratethys (Kováč, 2000) opinions about the development of Early to Mid Miocene sedimentary successions in two adjacent foreland basins i.e., the Carpathian Foredeep and the Alpine Molasse Zone differ substantially. Many authors (Cicha, 1995, 2001; Švábenická and Čtyroká, 1998, 1999; Čtyroká and Švábenická, 2000; Rögl *et al*., 2002; Švábenická, 2002; Ćorić, 2003; Ćorić and Švábenická, 2004; Ćorić and Rögl, 2004; Ćorić *et al*., 2004) have published various statements about the evolution, biostratigraphy, and chronostratigraphic correlation of the individual sedimentary packages. The principal aim of this article is to provide new data and interpretations of the depositional environment and of its evolution within the studied part of the Carpathian Foredeep during the early Badenian.

GEOLOGICAL SETTINGS

The Carpathian Foredeep (CF) is a peripheral foreland basin developed on the European plate margin due to the Western Carpathian accretionary wedge overthrust and deep subsurface load. The western part of the Carpathian Foredeep is located on the eastern margin of the Variscan Bohemian Massif. The part of the Carpathian Foredeep studied is filled with Neogene clastic deposits. The sedimentary record started in the late Egerian/Eggenburgian (20.00 Ma) and terminated by the early Badenian (15.97 Ma) *sensu* Gradstein *et al*., 2004. The central Paratethys regional stages and their comparison with nannoplankton NN zones are given in Figure 1.

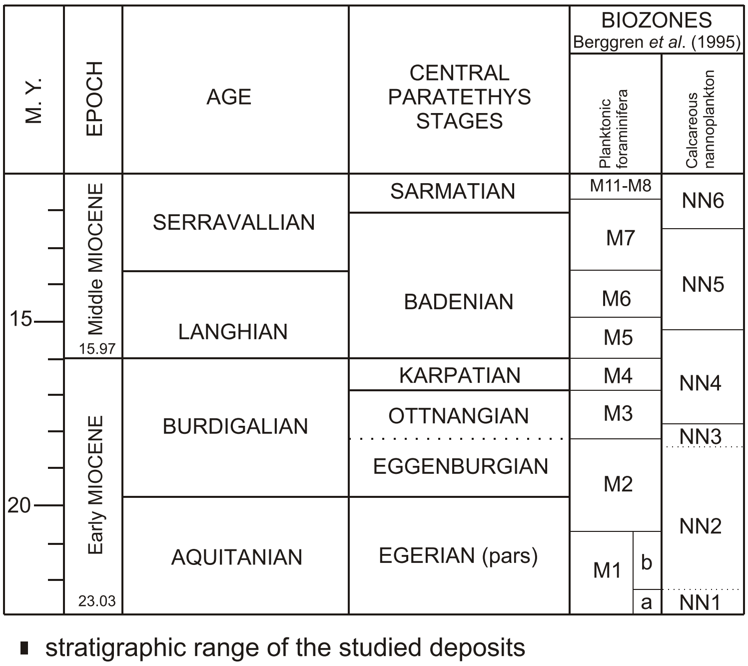

Fig. 1. Correlation of the Early and Mid Miocene with the Central Paratethys stages by Cicha *et al.* (1998) and Gradstein *et al.* (2004), modified

Five 3rd-order depositional sequences were recognized within the Carpathian Foredeep sedimentary infill (Nehyba and Šikula, 2007). The fifth, uppermost sequence is early Badenian in age (16.5–15.97 Ma). Their deposits are located in the central parts of the basin, with the maximum thickness (800 m) situated almost symmetrically along the axis of the Carpathian Foredeep. The preserved early Badenian deposits represent only an erosional relic of the original basin. Its original extent is partly reflected by the occurrence of isolated relics of marine deposits located on the Bohemian Massif (Hladilová *et al*., 1998; Nehyba and Hladilová, 2004) and by their characteristics. Two facies of early Badenian deposits strongly predominate in the Carpathian Foredeep. Gravels, sandy gravels and gravelly sands represent the first of these, assigned as "marginal or basinal clastics" according to their position. Their maximum thickness is about 175 m, but the area of their occurrence is restricted. According to Krystek (1974) they represent beach deposits, but Nehyba (2001) interpreted them as deposits of coarse-grained Gilbert deltas. The second dominant facies consists of dark green, green-grey or brown-grey calcareous pelites/mudstones, that vary in their content of silt and clay, shell debris and intensity of bioturbation. They are traditionally assigned as "tegel" and have been interpreted as shallow-marine (shelf) to deep-water deposits (bathyal; Brzobohatý, 1989). These mudstones are almost uniformly distributed across the entire depositional area with a maximum thickness of about 600 m. The areal and volumetric distribution of all other facies (sands, red algal limestones, distal airfall tephra, *etc*.) is restricted. There is a remarkably low occurrence/preservation of coastal and shallow-marine facies within the area studied.

Tectonic activity and eustatic sea level change were the dominant ruling factors of basin formation and deposition during the late Karpatian and early Badenian (Nehyba and Šikula, 2007). Compression of the Carpathian orogenic wedge oriented towards the NNW and NW changed its orientation towards the NNE and NE during the late Karpatian and early Badenian (Kováč, 2000). This shift led to the dominant formation of accommodation space (flexural subsidence) in the northern part of the CF whereas its southwestern part (the one studied) was affected by relative uplift. Older basin infills (predominantly Karpatian in age) were eroded and deformed. A longitudinal depression along the basin axes (i.e. NE–SW direction) was formed (an incised valley). This led to the formation of Gilbert deltas along the basin margin with basinward transport direction and sources from both opposing NW and SE margins. Final flooding of the "entire" basin was dominated by deposition of basinal pelites (Nehyba, 2001). This process was combined with eustatic sea level change (TB 2.3 of Haq *et al*., 1988; CPC 3 of Kováč, 2000). Two early Badenian transgressive phases of sea level rise have been identified in the CF (Brzobohatý and Cicha, 1993) with the latter probably the most extensive. Stepwise flooding of the entire Pannonian Basin System during two early Badenian transgressions have also been inferred (Kováč *et al*., 2007).

Detailed correlations of individual early Badenian beds within the Carpathian Foredeep and a widely accepted lithostratigraphy for them are still lacking.

METHODS OF STUDY

Early Badenian deposits are generally poorly exposed in the Carpathian Foredeep. Two boreholes, Ivaň IK-1 and Vranovice VK-1, were newly drilled in South Moravia, the Czech Republic (Fig. 2) by the Czech Geological Survey (Brno branch). The boreholes were situated close to the contact of Early and Mid Miocene deposits as indicated by geological mapping. They reached a depth of 60 m and were fully cored. Detailed description of the cores allows recognition of lithofacies and a general recognition of fossil content. Laser particle size analysis (*CILAS 1064 L*) was used for the description of the grain-size distribution of the mudstones. Samples for grain-size study were taken for analysis of facies distribution within the profile. At least two samples were taken from each 1 m interval and altogether 211 samples were studied. Distiled water and ultrasonic technology were used for sample preparation. Median (P50) grain-size, content of clay and sand in the samples studied along the borehole, profiles are shown in Figures 3 and 4. Pebble composition (5 analyses) was studied in the >4 mm fraction. Further data (5 analyses) were obtained from the study of the 2–4 mm fraction. Heavy minerals (11 analyses) were studied in the 0.063–0.125 mm fraction.

For micropalaeontological studies the sediment was soaked in warm water with sodium carbonate for dissaggregation. It was washed under running water through 0.063 mm mesh sieves. Approximately 200 specimens of foraminifers were identified with a WILD binocular microscope. The ratio of planktonics (p)/benthics (b)was counted as a percentage of

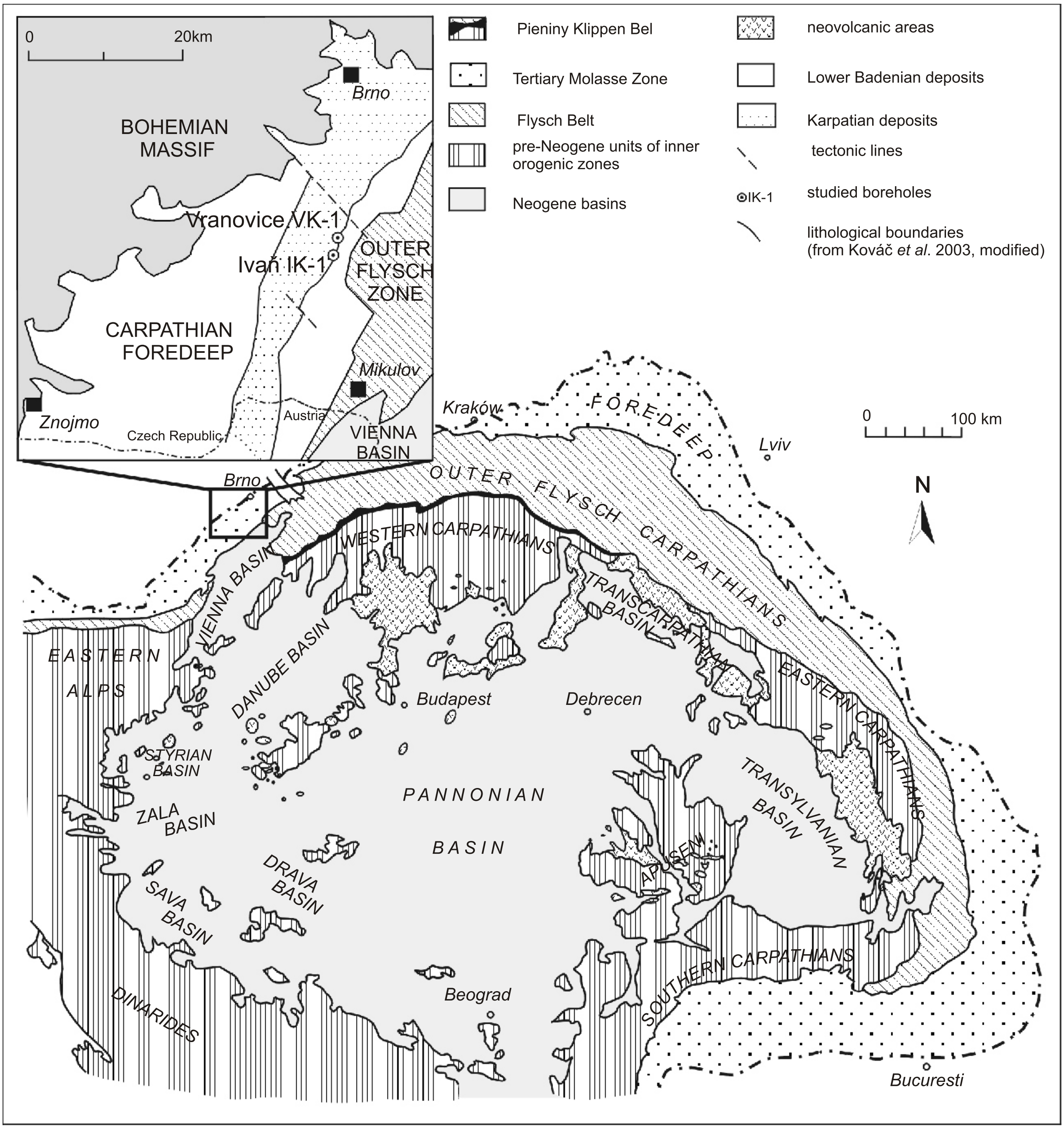

Fig. 2. Location of the Ivaň IK-1 and Vranovice VK-1 boreholes and the position of the area studied within the Carpatho-Pannonian region

planktonic specimens in the assemblage i. e., p/(p + b) × 100 in per cents. In total 56 foraminifer assemblages were studied.

Bryozoans were studied from 19 samples, where fragments of macrofossils were recognized. Samples were washed and sieved as described by Zágoršek and Vávra (2000) on the minimum 0.09 mm mesh. Selected bryozoans were cleaned using ultrasonic treatment and studied under the scanning electron microscop *Jeol JSM 6400*; all measurements were made by *SemAfore 3.0 pro Jeol* software at the institute of Palaeontology in Vienna University.

FACIES ANALYSES

Eight lithofacies were recognised within the studied cores of early Badenian deposits (Table 1, Fig. 3). The occurrence of individual facies within the borehole succession and their thickness variation are shown in Table 2. The lithofacies were distinguished on the basis of descriptive sedimentological criteria. The terminology used follows Collinson and Thompson (1982). Lithofacies are considered to be the basic "building blocks" of the sedimentary succession (Walker, 1984; Ilgar and

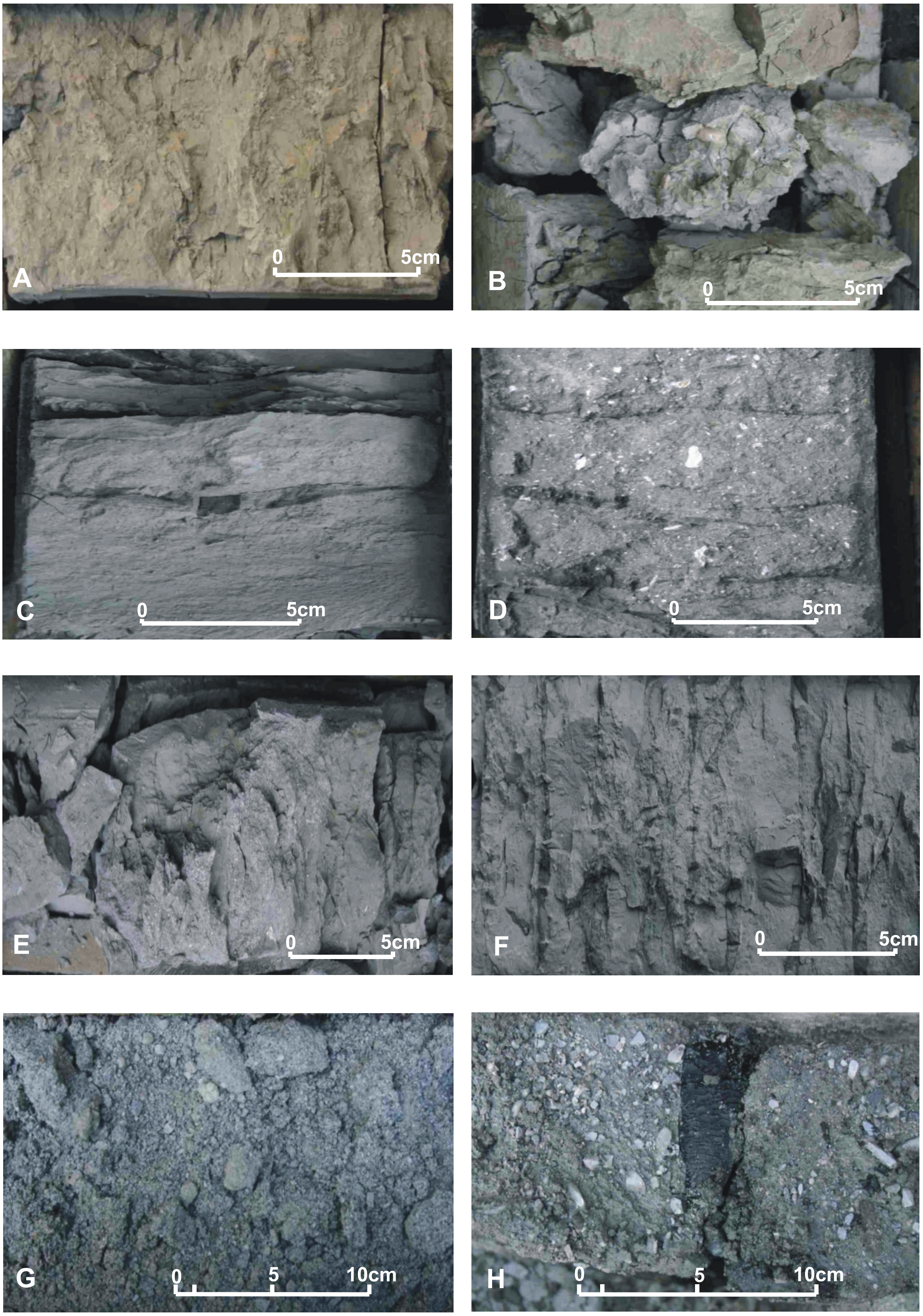

Fig. 3. Selected examples of lithofacies of studied early Badenian deposits

A — facies M1 — calcareous massive or horizontal laminated mudstone; **B** — facies M2 — mudstone with irregular or chaotic bedding, scattered small pebbles and angular intraclasts; **C** — facies M3 — calcareous clayey silt, massive or horizontal lamination, admixture of fine to very fine sand; **D** — facies M4 — mudstone with abundant shell debris; **E** — facies M5 — calcareous mudstone, strongly bioturbated; **F** — facies Sf — fine to medium sand massive, rarely horizontal lamination or flaser bedding; **G** — facies Sg — medium to coarse sand with scattered granules or small pebbles; **H** — facies G — pebbly gravel or conglomerate, locally preserved cross-bedding

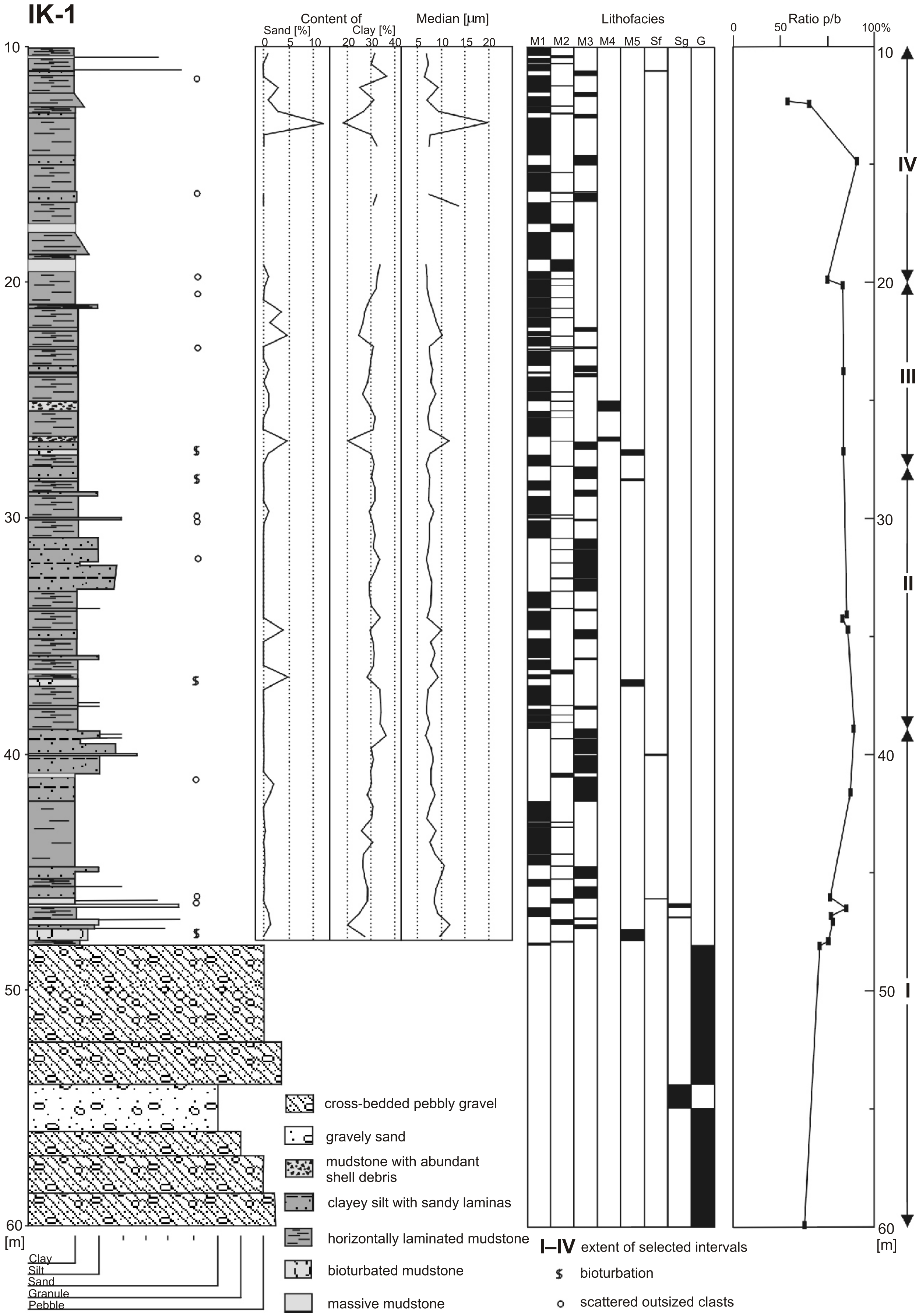

Fig. 4. Lithological profile of the IK-1 Ivaň borehole, distribution of selected grain-size parameters, distribution of facies and the ratio of plankton/benthos (foraminifers)

Lithofacies symbols are explained in Table 1

Table 1

Description and interpretation of the lithofacies M1, M2, M3, M4, M5, Sf, Sg and G

Facies	Description	Interpretation
M1	Light grey, greyish green calcareous silty clay or clayey silt, massive or horizontal lamination. Occurrence of shell debris is rare.	Alternation of deposition from hemipelagic and hemiturbidite/ hyperpycnal flows (concentrated suspension). Environment hostile to burrowers. Deeper depositional environment (distant from clastic input).
M2	Green gray clay, irregular or chaotic bedding with scattered subangular or suboval clasts (quartz, granitoids, quartzites — diameter up to 1 cm) or angular intraclasts and deformed laminas of grey mud, silt or sand. Rarely small admixture of shell debris.	Textural inversion — mixing of deposits of several depositional environments. Gravitational deformation, bioturbation?
M3	Light grey calcareous clayey silt. Massive, horizontal lamination, occasionally grading connected with presence of fine to very fine sand on the base. Usually sharp base and the top of beds.	Rapid deposition from concentrated suspension (hemiturbidite, distal tempestites, hyperpycnal currents). Alternation of periods of deposition and erosion.
M4	Grey or light grey mudstone with abundant shell debris (molluscs, bryozoans, rarely corals). Occurrence of rounded clasts (mainly quartz, max. 3 mm in diameter) is very rare.	Erosion and redeposition of shells in coastal and shallow-marine environments and their transport offshore (suspension clouds — gravity currents?, tempestites). Rapid deposition.
M5	Grey to green grey calcareous silty clay or clayey silt with subvertical burrows filled by light grey to whitish fine sand. Bed thickness varies between 0.05 m to 0.4 m (average 0.3 m).	Condition suitable for bottom colonization (sediment input, time, oxygen content). Benthic reworking of facies M1–M4. Facies also reflect massive erosion of sandy beds (sand preserved only within burrows).
Sf	Fine rarely fine to medium sand massive, horizontal lamination or flaser bedding. Form laminas or thin beds within facies M3 or M1. Sharp (often loaded) base, top sharp or gradual. Beds are often deformed. Bed thickness varies between 0.01 m to 0.5 m (average 0.1 m).	Hyperpycnal or fine-grained turbidity currents.
Sg	Coarse rarely medium to coarse sand sometimes with scattered granules or small quartz pebbles (up to 0.7 cm in diameter). Beds are often deformed.	Deposition from the gravity currents (debris flows, high density turbidity currents — distal part of coarse-grained delta) or tempesites (outer shelf). Sharp base reveal the erosion prior to deposition.
G	Pebbly gravel or conglomerate, locally preserved cross-bedding. Typical is varied but generally high content of coarse sand.	Deposition of high concentration gravity currents, deposition connected with foresets of coarse-grained Gilbert delta.

Table 2

Occurrence of selected lithofacies within the boreholes and their thicknesses

	M1	M2	M3	M4	M5	Sf	Sg	G
VK-1	61.2 %	4.4 %	11.2 %	12.3 %	6.4 %	2.3 %		
Bed thickness range [m]	0.1–5.2	0.05–0.4	0.1–0.7	0.05–1.0	0.05–2	0.05–0.5		
Average thickness [m]	0.5	0.1	0.2	0.3	0.3	0.1		
IK-1	35.7 %	6.8 %	18.8 %	2.1 %	3.0 %	0.2 %	0.7 %	35.2 %
Bed thickness range [m]	0.1–1.1	0.05–0.2	0.1–1.0	0.2–0.6	0.2–0.4	0.05	0.05–0.2	0.55–1.9
Average thickness [m]	0.4	0.1	0.3	0.4	0.4	0.05	0.1	1.32

Nemec, 2005). They are indicated in the borehole logs (Figs. 4 and 5) and serve as the basis for interpretation of the depositional processes. Based on spatial grouping and distribution of lithofacies, two facies associations/depositional environments were recognised i.e., deposits of coarse-grained Gilbert deltas and offshore deposits. These facies associations are described and interpreted with reference to depositional environment together with micropalaeontological data.

DEPOSITS OF A COARSE-GRAINED GILBERT DELTA

This facies association is formed by lithofacies G and Sg typically with a highly variable content of pebbles and sand. Lithofacies G was found only in the basal parts of borehole IK-1. A characteristic feature of lithofacies G is a transition from clast-supported texture to sandy matrix-supported gravels and a lack of silt and clay within the sandy matrix. Mudstone intraclasts occur relatively often and are significantly larger than extraclasts. The average diameter of pebbles varies within the beds between 0.5 to 1 cm. The largest pebble is about 6 cm in diameter. Pebbles are generally rounded to subrounded, though no restriction of or markedly higher occurrence of specific pebble shape in various localities or beds was recognised. Gravels are polymict with a high content of carbonate rocks (limestones, dolomites — 44.6–49.3%), metamorphics (gneisses, quartzites, phyllites, mica schists — 20.8–23.8%) and quartz (12.5–18.2%). Pebbles of cherts, sandstones and

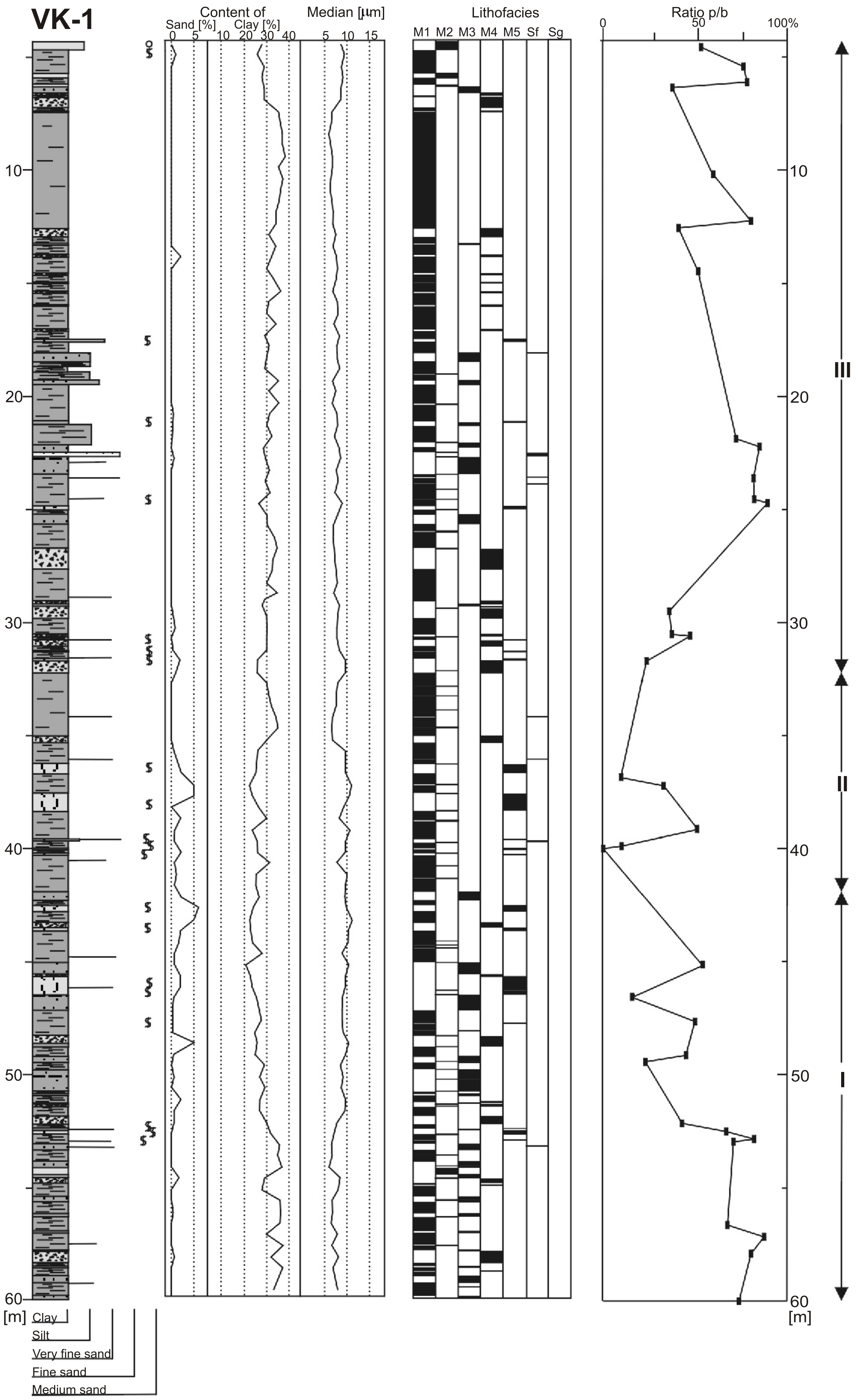

Fig. 5. Lithological profile of the VK-1 Vranovice borehole, distribution of selected grain-size parameters, distribution of facies and the ratio plankton/benthos (foraminifers)

Explanations as in Figure 4

granitoids were also recognised. The presence of clasts of black coal (xylitic) was noted. The prominent structural feature of facies G is cross-bedding interpreted as evidence of foresets. The facies is identical with that of early Badenian gravels described in the broader area (Krystek, 1974) where foresets of coarse-grained Gilbert deltas can be observed.

The composition of the coarsest fraction in facies Sg is slightly different to that of facies G. It is characterized by a higher content of quartz, a lower content of carbonates and the presence of authigenic pyrite. These differences can be mainly explained by the slightly different grain-size fraction but generally the same source of granules and pebbles can be supposed. Garnet typically dominates in the transparent heavy mineral spectra forming 64.5–83.3%. The occurrence of other minerals (tourmaline, epidote, monazite, pyroxene, amphibole, zircon, sillimanite, rutile, titanite and staurolite) is usually low, only several percent except for staurolite, which amounts to more than 10% in some samples. Small differences only in the transparent heavy mineral spectra (data from both facies Sg and Sf) confirm the common source of the deposits. Facies Sg forms thin interbeds within the mudstones and its occurrence is interpreted as the most distal high density gravity flows generated on the delta slopes into the offshore depositional environment.

A sharp contact with the offshore deposits in superposition reveals the sudden drowning of the delta front due to rapid relative sea level rise. Drowning of the coarse-grained deposits at the base of the early Badenian succession is widely recognised and connected with the early Badenian transgression (Brzobohatý and Cicha, 1993). Deposits of Gilbert deltas may represent lowstand systems tracts and marine flooding surfaces can be located at their top.

OFFSHORE DEPOSITS

The offshore facies association strongly dominates within the successions and consists of lithofacies: M1, M2, M3, M4, M5 and Sf. Deposition of thick mudstone successions containing marine fossils is usually associated with a pelagic environment, deeper depositional settings, steady-state style of deposition and an important role of suspension fallout. The principal question is how the coarser material was emplaced into this environment. In the samples studied, the admixture of silt and sand forms fine horizontal lamination, normally graded beds, chaotic bedding and textural inversion (lithofacies M2, M3, M4 and M5) or it forms lithofacies Sf itself.

Sands of lithofacies Sf are generally well-sorted, form probably extensive sheet-like beds a few centimetres thick, with sharp, often erosional bases. Tops of the layers are often gradational, deformed and rarely sharp. The beds show planar parallel lamination or cross-lamination. Sand occurrences on the bases of mudstone beds are associated with normal grading (lithofacies M3). Graded laminae can result from nepheloid layer transport, tails of turbidity currents and hemipelagites from outflowing river floods (Scott *et al*., 2004). Erosional bases, normal grading, and planar parallel and cross-lamination, all give evidence for the role of low-density turbidity currents (Lowe, 1982). The sandy and silty interbeds with sharp bases and tops may be also associated with the activity of storms (Dott and Bourgeois, 1982; Ilgar and Nemec, 2005). The generation of some of these flows can be traced on the slopes of coarse-grained deltas, where they can be triggered episodically by hyperpycnal stream effluent (Nemec, 1990, 1995).

Preserved sedimentary structures in the offshore deposits studied are consistent with influence by density flows/gravity currents. Deposition from sediment gravity currents typically occurs in an episodic fashion against background deposition. This interpretation is supported by palaeontological data, mainly by studies of foraminifers. Horizontal lamination can be connected with a pulsed nature of sedimentation. A combination of high-energy benthic hydrodynamics and sufficient fine sediment supply can result in extensive gravity-driven flows. The source of the mud material may be connected with the marine dispersal of fluvial sediments (Rotondo and Bentley, 2004). Abundant shell debris (lithofacies M4) also suggest erosion in the coastal area. Alternation of clay and silt layers can be caused by segregation of silt and mud from boundary shear processes (Scott *et al*., 2004). Lithofacies M1, which plays a dominant role in the succession, reveals little influence of gravity currents due to its typical massive fabric.

Biological/benthic activity also played an important role in the distribution and preservation of sandy material within the offshore deposits (M5). Sands are often preserved only as burrow infills. Absence of the sandy interbeds above and below lithofacies M5 may be associated with the erosional activity of gravity currents. Gradation of laminites into bioturbated beds may reflect low sedimentation periods. The rare presence of lithofacies M5 and Sf within the offshore association in borehole IK-1 compared to VK-1 may indicate relative deeper depositional.

Vertical facies organization in the offshore succession has been evaluated with the use of embedded Markov-chain analysis (Harper, 1984). A conventional chi-square test of difference matrix indicates a relatively low value of "depositional tendency", which means that the facies succession cannot be considered to be "cyclic" in stochastic terms. However some preferred vertical facies transitions/small cycles can be recognised. The bases of the cycles are formed by lithofacies M1 with thin interbeds of M2. The upper part of the cycle is formed by lithofacies M3 or M4. Lithofacies M5 and Sf, which are relatively rare (see Table 2), were recognised either above lithofacies M4 or M3 or directly above lithofacies M1. These transitions indicate episodically stronger or weaker influence of gravity currents in the environment relatively distant from their source.

PALAEONTOLOGICAL DATA

Foraminifers were studied from the VK-1 Vranovice and IK-1 Ivaň boreholes (Tomanová-Petrová and Švábenická, 2007). Tests of foraminifers are well preserved in spite of being carried in suspension. The assemblages of foraminifers from the IK-1 boreholes document a low-oxygen sea-floor in a deeper sublittoral (circalittoral) environment. The plankton/benthos ratio ranges between 60–92% and usually reaches about 80% (Fig. 4). The character of foraminiferal assemblages of borehole VK-1, as well as the plankton/benthos ratio varying between 0.45–85.20%, rapidly change across the entirely profile (Fig. 5). In an internal of several centimetres there were recorded distinctive divergences in the plankton/benthos ratio and in the total character of assemblages. Assemblages of foraminifers are locally coupled with bryozoan colonies of well-oxygenated warmer waters of normal salinity of a shallow sea (infralittoral) with high wave energy, assemblages of a low-oxygen sea-floor of deeper sublittoral (circalittoral) conditions, assemblages with numerous agglutinated foraminifers indicating a deeper colder sea (circalittoral to probably upper bathyal) of normal salinity without dysoxic indicators (Kaiho, 1994) and mixed assemblages of shallow-water and deeper-water benthic foraminifers (see Fig. 6).

Bryozoans were recorded only from borehole VK-1. Altogether 56 species have been recognized from 19 samples (the list of species is given in Table 3).

The dominant species in the entire association are cyclostome (*Hornera* and *Polyascosoecia*), which show the pioneer character of the assemblage (Zágoršek *et al*., 2005). The average number of species varies from 20–25, except sample from the 32 metres depth, where 34 species were determined. On the other hand, there are samples, where less than 10 species occur. According to the species distribution and distribution of the growth forms (Hagemman *et al*., 1997) three groups can be distinguished. The first association (A) occurs in the samples from 6.3 metres to 27.5 metres depth and is characterized by a dominance of erect rigid forms (the number of species of erect growth forms is about 10–15, other growth forms are represented by less than 5 species). The second association (B) is the best developed one, while almost 35 species being determined in the samples from 32.0 and 35.0 metres. The third association (C), is the most poorly developed one, and less than 15 species have been distinguished in the samples from 51.2 to 58.0 metres. Figure 7 shows the distribution of the taxa determined in the samples studied. No bryozoans have been found in the other samples. Characteristic bryozoans are shown in Figure 8.

INTERPRETATION OF THE DEPOSITIONAL ENVIRONMENT

Results of study of sedimentary structures, facies, changes in content of detrital silt and sand, the ratio of plankton/benthos in the foraminiferal assemblages, intensity of bioturbation, supposed oxicity during deposition, and content of pyrite all allowed an interpretation of the evolution of depositional environments and conditions (Almon *et al*., 2004).

Three intervals can be recognised within the succession of borehole VK-1 (Fig. 5). The rising content of silt and sand, occurrence and thickness of lithofacies M5 can be seen in the depth internal from about 57 m to about 42 m (interval I). This can be explained by a relative shallowing of depositional environment. The number of bryozoan species is very low, which indicates a changeable environment in shallow water with a high content of terrigenous material in the water column (McKinney and Jackson, 1989). Interval II between the depths 42 to 32 m reveal variable conditions that can be connected generally with relative deepening. The most diverse bryozoan association has been found in this interval, which indicates deepening or the introduction of cold water (Zágoršek, 1996). Interval III between the depths of 32 m and 10 m reveals further relative deepening of the depositional environment which can be observed in the rising content of clay, decline in the median grain-size, low occurrence of lithofacies M5, Sf and sand. Bryozoans are common in this interval and dominated by cyclostome genera, which indicates a changing environment in a deepening basin and slope unstability (McKinney and Jackson, 1989).

The foraminifers *Praeorbulina sicana* (de Stef.) and *Praeorbulina glomerosa circularis* (Blow) document the Middle Miocene, M5b Zone of planktonic foraminifers *sensu* Berggren *et al.* (1995) that is correlated with the lower Badenian in Central Paratethys regional stages. From the palaeontological point of view we can see some trends in the trend of the ratio of plankton/benthos coupled with the trend of occurrence of bryozoans. 4 types of assemblages were distinguished: (1) mixed shallow-water assemblages with *Asterigerinata planorbis* (d`Orb.) and *Amphistegina mammilla* (Ficht.-Moll.) and deep-water assemblages with *Melonis pompilioides* (Ficht.-Moll.) and *Pullenia bulloides* (d`Orb.) benthic foraminifers from the depths 4.6 m, 31.6 m and 46.45 m (VK-1; Fig. 6C); (2) dominance of planktonic foraminifers (predominance of pyritized tests) accompanied by *Siphonodosaria* div. sp., *Bolivina* div. sp., *Pyramidulina raphanistrum* (L.) and *Uvigerina* div. sp. reflecting a lower oxygen supply in bottom water from the depths 6.1 m, 21.9 m, 22.2 m, 23.6 m, 30.55 m, 52.8 m (VK-1; Fig. 6D); (3) higher numbers of agglutinated foraminifers *Semivulvulina pectinata* (Rss.), *S. deperdita* (d`Orb.), *Textularia gramen* d`Orb., *T. pala* Czjzk., *Spirorutilus carinatus* (d`Orb.) accompanied by calcareous benthos with *Melonis pompilioides*, *Pullenia bulloides* and *Heterolepa dutemplei* (d`Orb.) at the depths 36.8 m, 37.2 m, 39.2 m, 47.5 m and 49.4 m (VK-1; Fig. 6E) indicate colder waters; (4) dominance of deep-water euryoxybiont foraminifers *Uvigerina macrocarinata* Papp and Turn., *U. semiornata* d`Orb., *Pappina breviformis* (Papp and Turn.), *Bolivina* div. sp., *Bulimina* div. sp., accompanied by the deep-water species *Melonis pompilioides* and *Pullenia bulloides,* a higher number of planktonic foraminifers, and by pyritized centric diatoms at the depths 5.4 m, 12.2 m, 21.9 m, 24.55 m, 24.7 m, 29.65 m, 49.2 m, 57.2 m, 57.8 m, 59.9 m, 60.0 m indicates a low-oxygen sea-floor, in deeper sublittoral environments. We suppose that these assemblages represent primary taphocoenoses and they document original environment of sedimentation.

On the other hand, the assemblages from the depths 6.3 m, 12.6 m, 14.4 m, 39.8 m, 40.05 m, 52.2 m and 52.95 m with *Amphistegina mammilla* (Ficht. and Moll), *Asterigerinata planorbis* (d`Orb.), *Ammonia viennensis* (d`Orb.) and also *Semilvulina deperdita* (d`Orb.) indicate a shallow-water depositional environment and they may document non *in situ* assemblages. The bryozoans are highly diverse, the best sample being from the depth 35.0 m, where 34 species were determined. The dominant species are cheilostome, of the genus *Reteporella*, which lived in inner shelf to outer shelf environments in high energy water (Hageman *et al*., 1997).

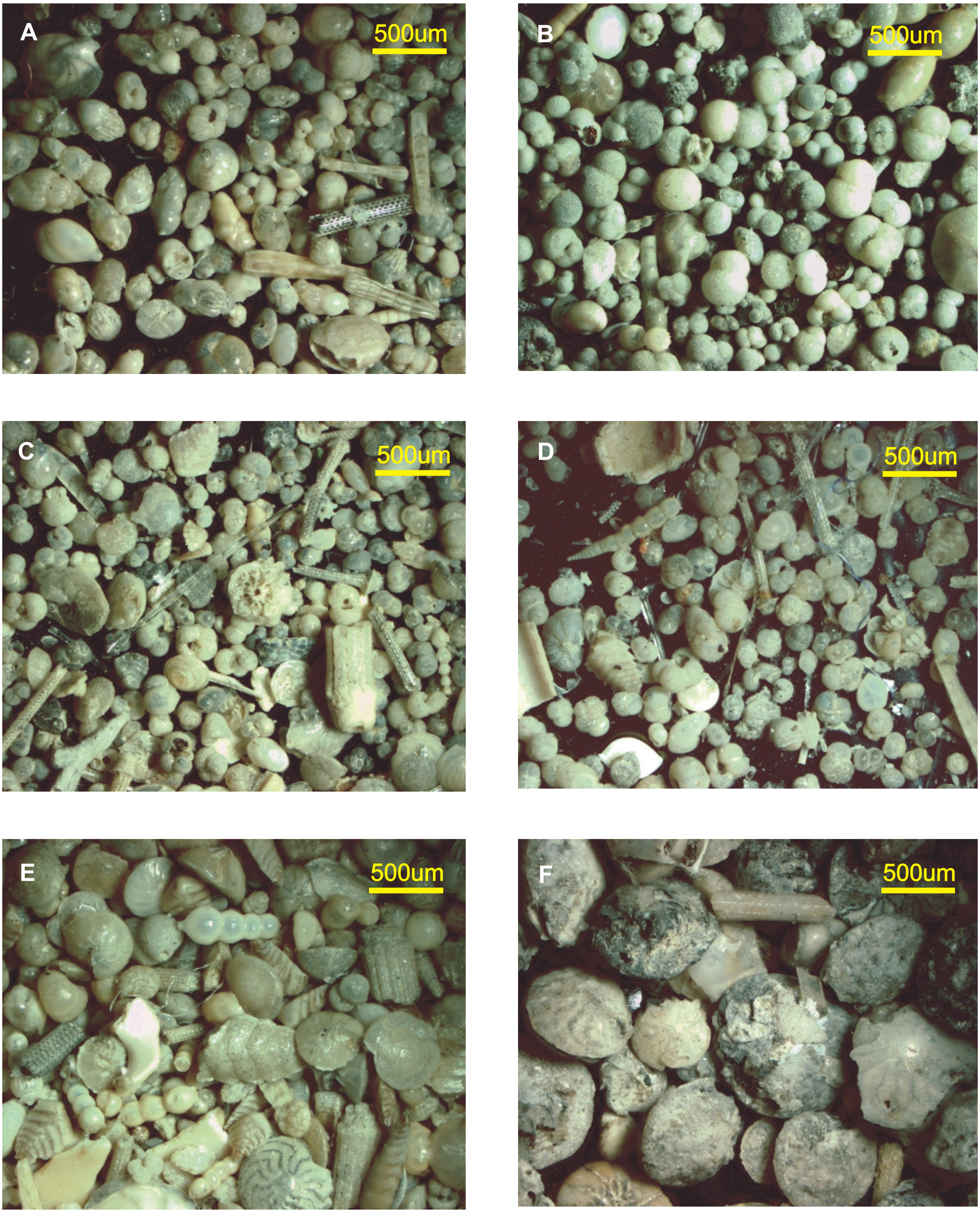

Fig. 6. Typical assemblages of the foraminifers in the VK-1 Vranovice and IK-1 Ivaň boreholes

Primary taphocoenoses: **A** — deep-water assemblage with dominance of planktonic and euroxybiont foraminifers (IK-1; 12.55 m); **B** — deep-water assemblage with globigerinas, globigerinoides and *Melonis pompilioides* (Ficht. and Moll), (IK-1; 46.95 m); **C** — assemblage documenting mixing of shallow-water and deep-water assemblages (VK-1; 4.6 m); **D** — deep-water assemblage with numerous planktonic species and *Siphonodosaria* div. sp. (VK-1; 6.1 m); **E** — assemblage with numerous agglutinated species (VK-1; 37.2 m); secondary taphocoenoses: **F** — shallow-water assemblage with *Amphistegina mammilla* (Ficht. and Moll) and *Asterigerinata planorbis* (d`Orb.) (VK-1; 40.05 m)

Table 3

The list of all species of bryozoans in the VK-1 Vranovice borehole

TAXA/depth of borehole [m]	6.3	6.4	7.0	12.5	12.6	16.8	26.5	27.5	28.8	29.7	30.7	31.5	32.0	35.0	51.2	51.4	51.9	54.8	58.0
Adeona sp.n.		*					*		*	*				*		*			
Adeonella polystomella	*	*	*	*	*	*	*	*		*		*	*	*	*	*			*
Adeonellopsis coscinophora	*			*	*	*													
Bicrisina compressa			*								*			*				*	
Callopra bobiesi		*		*															
Cellaria fistulosa	*	*	*		*					*				*		*		*	*
Cellaria salicornoides			*				*					*	*	*					
Cellepora globularis	*	*																	
Celleporaria palmata						*													
Celleporina costazi			*					*		*	*		*	*				*	*
Ceriopora indet.	*	*							*								*		
Cribellopora														*					
Crisia cf. *leicointrei*				*															
Crisia eburnea	*	*	*	*															
Crisia haueri	*	*																	
Crisia hoernesi	*	*		*	*		*	*							*	*	*	*	
Crisidmonea foraminosa		*	*	*		*		*		*			*	*					*
Diplosolen obelium					*									*					
Eximonea atlantica	*	*		*	*	*	*	*	*	*	*		*	*					*
Exochella (?) new genus	*		*			*					*	*	*	*	*	*	*		
Frondipora verrucosa														*					*
Hippopleurifera hypsostoma																			*
Hornera cf. *simplicissima*				*										*					
Hornera frondiculata	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Hornera striata	*	*	*	*		*	*	*				*	*	*			*		
Hornera verrucosa	*	*		*	*								*	*					
Idmidronea coronopus								*					*	*					
Iodictyum rubeschi					*							*							
Margaretta cereoides		*					*	*					*	*					
Mecynoecia proboscidea					*														
Mecynoecia pulchella		*	*	*	*	*	*	*		*	*	*	*	*	*		*	*	*
Metrarabdotos mallecki	*	*	*	*		*	*	*		*			*	*	*	*	*		
Micropora parvicella				*															
Monoporella venusta					*									*					
Myriapora truncata								*											
Oncousoecia biloba																	*		
Onychocella			*				*												
Pleuronea pertusa	*	*	*	*	*	*	*	*			*		*	*			*	*	*
Polyascosoecia coronopus	*	*	*	*		*	*	*		*	*	*	*	*	*	*	*	*	*

Tab. 3 cont.

TAXA/depth of borehole [m]	6.3	6.4	7.0	12.5	12.6	16.8	26.5	27.5	28.8	29.7	30.7	31.5	32.0	35.0	51.2	51.4	51.9	54.8	58.0
Porella cf. *nuda*													*	*					
Pseudofrondipora foramninosa				*		*	*						*	*					
Reteporella beaniana	*		*	*	*	*	*	*		*			*	*	*		*	*	
Reteporella cellulosa	*	*		*		*		*					*	*					
Reteporella septentrionalis					*									*				*	
Reussirella haidingeri						*	*	*		*	*		*	*					
Schizobrachiella (?)							*					*							
Schizomavella tenella				*		*													
Schizoporella geminipora	*						*	*											
Schizostomella grinzingensis					*														
Smittina cervicornis	*						*							*					
Steginoporella cuculata		*	*	*		*	*	*					*	*					
Teichopora cf. *clavata*	*			*	*									*					
Tubulipora dimidiata	*							*					*	*	*				
Turbicellepora coronopus						*	*	*						*			*		
Umbonula endlicheri	*																		
Ybselosoecia typica	*	*	*					*			*	*	*					*	
total number of taxa 56	24	22	18	23	17	19	21	22	4	12	10	10	23	34	9	8	12	11	11

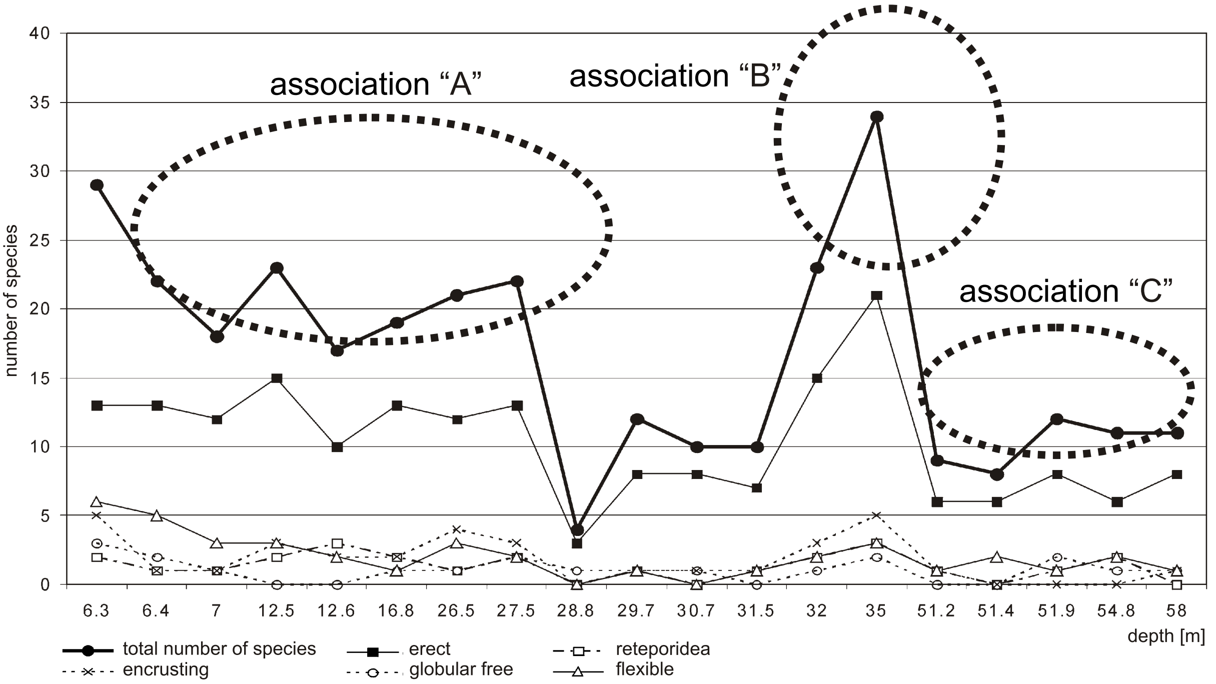

Fig. 7. Distribution of the determined taxa of bryozoans and selected bryozoan associations (A, B, C) in the VK-1 Vranovice borehole

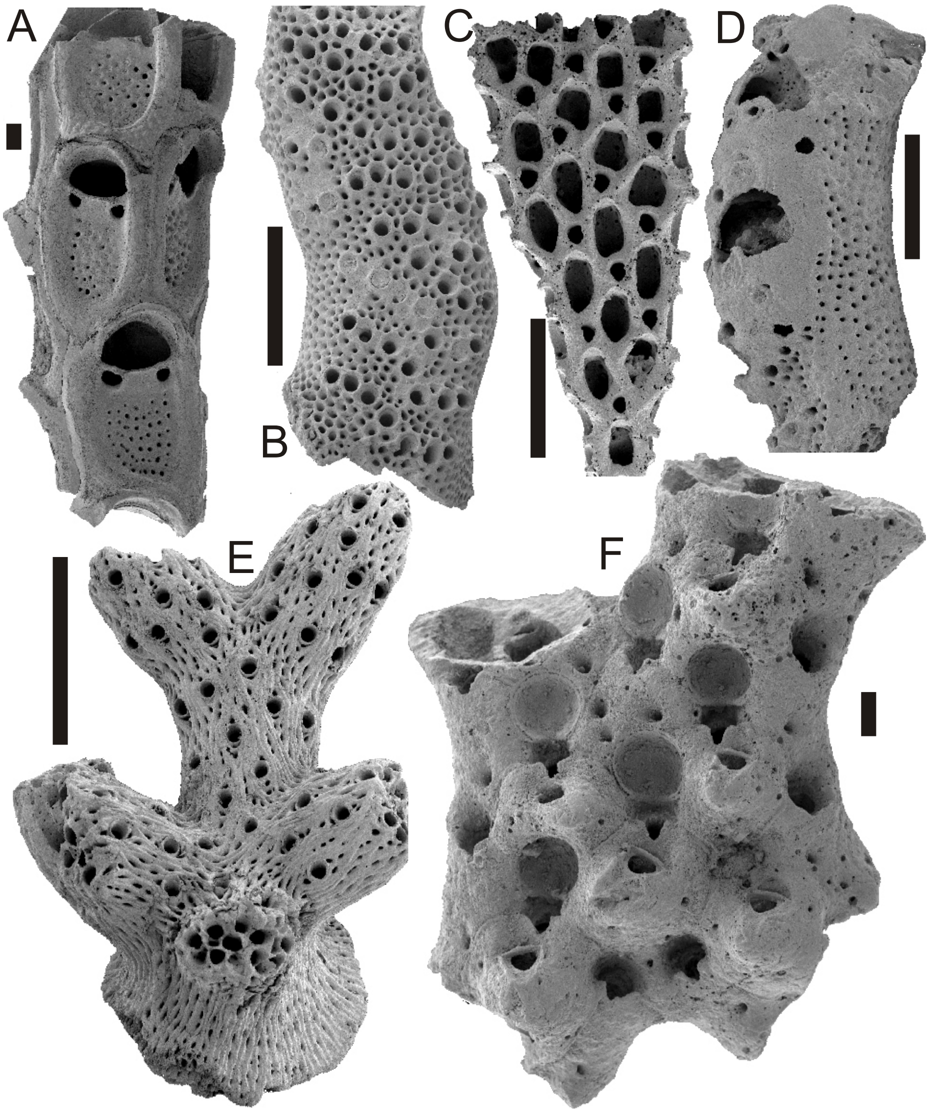

Fig. 8. Characteristic bryozoan species from the VK-21 Vranovice borehole

A — erect rigid growth form of *Steginoporella cucullata*, which usually indicates a tropical environment, scale bar 100 µm; **B** — massive erect rigid *Crisidmonea foraminosa*, very common in the "B" association, scale bar 1 mm; **C** — fragment of globular free-living *Reussirella haidingeri*, indicating hard sea bottom, scale bar 1 mm; **D** — *Polyascosoecia coronopus*, one of the commonest bryozoans from borehole VK-1 Vranovice, here with developed ovicell, scale bar 1 mm; **E** — *Hornera frondiculata*, one of the commonest bryozoans from the borehole VK-1 Vranovice; **F** — *Reteporella septentrionalis*, characteristic representative of reteporidea growth form indicating turbulent water, scale bar 100 µm

Four intervals can be recognised within the succession of borehole IK-1 (Fig. 4). A rising content of clay, a decline in median grain-size and in sand content, rapid alternation from the facies association of a coarse-grained Gilbert delta to offshore facies can be traced from the base of the profile to the depth of about 39 m (interval I). This reflects a dramatic and continuous deepening of the depositional environment. Interval II between the depths of 39 and 27 m reveals varied conditions with possible relative shallowing. Interval III between the depths of 27 and 20 m reveals relative deepening of the depositional environment and the top interval IV between the depths of 20 to 10 m reflects varied conditions with possible shallowing. Initial deepening and final shallowing are also seen in the trend of plankton/benthos (Fig. 3). The possible interpretation of these intervals within the context of sequence stratigraphy (TST, late TST, early HST, parasequences see Almond *et al*., 2004) needs further study in the broader context. The foraminiferal assemblages from the depths 12.47 m, 12.55 m, 20.05 m, 20.35 m, 23.9 m, 27.3 m, 34.2 m, 34.3 m, 34.8 m, 46.2 m, 46.7 m, 46.95 m, 47.1 m and 48.0 m are dominated by the deep-water foraminifers *Melonis pompilioides* and *Pullenia bulloides* accompanied by *Siphonodosaria* div. sp. and the euryoxybiont taxa *Uvigerina* div. sp., *Bolivina* div. sp., *Bulimina* div. sp. indicating a low-oxygen sea-floor of deeper sublittoral (circalittoral) conditions *sensu* Kaiho (1994), and also a higher number of planktonic foraminifers.

DISCUSSION

Deposits of coarse-grained Gilbert deltas reveal the existence of prominent relief and incised valleys (Nehyba and Šikula, 2007). The localised position of these deposits, their considerable thickness, variations in their provenance, and abundant occurrence of large intraclasts of older basin infill (Nehyba, 2006; Nehyba *et al*., 2006) all point to existence of the valleys oriented generally perpendicular to the basin axis (Dvořák, 1995), which represented important sources of sediment input. Deposits close to the entry point into the basin were coarse-grained, while deposits farther away were mainly fine-grained (pelagic and hemipelagic sedimentation).

When relative sea level rose, the Gilbert deltas and the valleys were flooded, which led to marine incursion deep into the foreland (Hladilová *et al*., 1998), change in the fluvial style and reduction of the coarse-grained input into the basin (Zaitlin *et al*., 1994). According to a palaeobathymetrical study (Brzobohatý, 1997) the central parts of the basin were relatively deep and the palaeodepth can reach more than 400 m.

Marine dispersal of fluvial sediments is directed by several processes. Coarse sediment is deposited near the river mouth, whereas fine silts and clays can be transported further seaward in either positively (hypopycnal) or negatively (hyperpycnal) buoyant plume. Fluid muds (high concentration near-bed suspensions of fine-grained sediments) have been observed in many estuarine, coastal and shelf environments. The regime of the basin, especially wave-currents, resuspensation and transport in the water column (auto-suspension of gravity flow, lofting) can further disperse fine material along the basin (Rotondo and Bentley, 2004; Soyinka and Slatt, 2004, Tripsanas *et al*., 2004). Tests of foraminifers and fragments of bryozoans can be transported within these gravity flows. Rising sea level and climatic changes may have also narrowed the shelf area and affected the influx of sediments into the river systems (Emmery and Myers, 1996).

The results given suggest possibilities for the subdivision of the "monotonous" pile of early Badenian basinal pelites ("tegel") into segments with distinct positions within cycles of relative sea level change. This is crucial for the application of high-resolution sequence stratigraphy. Moreover the presence of tegel intraclasts within the deposits of coarse-grained Gilbert deltas has recently been recognised (Nehyba *et al*., 2006). Elucidation of the facies architecture of the varied segments of the basin infill can provide important results for sequence stratigraphy and lithostratigraphy.

CONCLUSIONS

Eight lithofacies have been recognised within cores of early Badenian deposits and these form two facies associations i.e., deposits of a coarse-grained Gilbert delta and offshore deposits. The facies association of a coarse-grained Gilbert delta is framed by lithofacies G and Sg. A sharp contact with overlying offshore deposits reveals the sudden drowning of the delta front due to rapid sea level rise. Offshore deposits strongly predominate in the sedimentary successions studied and consist of facies M1, M2, M3, M4, M5 and Sf. The influence of gravity currents on their deposition is supported by preserved sedimentary structures and micropalaeontological data. Primary taphocoenoses of foraminifers were distinguished showing an offshore environment of sedimentation, i.e. a deeper sublittoral environment with low to normal oxygen bottom conditions and secondary taphocoenoses containing foraminifers and numerous and diverse bryozoans, documenting deposits of a shallower sublittoral environment redeposited into the basin by gravity currents.

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