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Late Proterozoic to Early Palaeozoic platform deposits of Southern Moravia (Czech Republic)

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Integrated sedimentological and palaeontological study of borehole cores through platform siliciclastic deposits of the southernmost part of Brunovistulicum (S Moravia) shows convincing evidence for the Cambrian age of a considerable portion of the succession. Well-preserved organic-walled microfossils of Late Proterozoic (Ediacaran) age have been found in a sample from the Měnín-1 borehole. Thirty genera characteristic of the Ediacaran have been recognized. Part, though, of the siliciclastic succession of S Brunovistulicum is Devonian in age. The platform deposits studied are considered to have the same source area but the degree of maturity of the Devonian clastics rocks is generally higher than that of the older strata. Facies analysis indicates a predominance of deltaic settings (braided and fan deltas); similar sedimentary environments are suggested for both the Ediacaran/Cambrian and Devonian successions.

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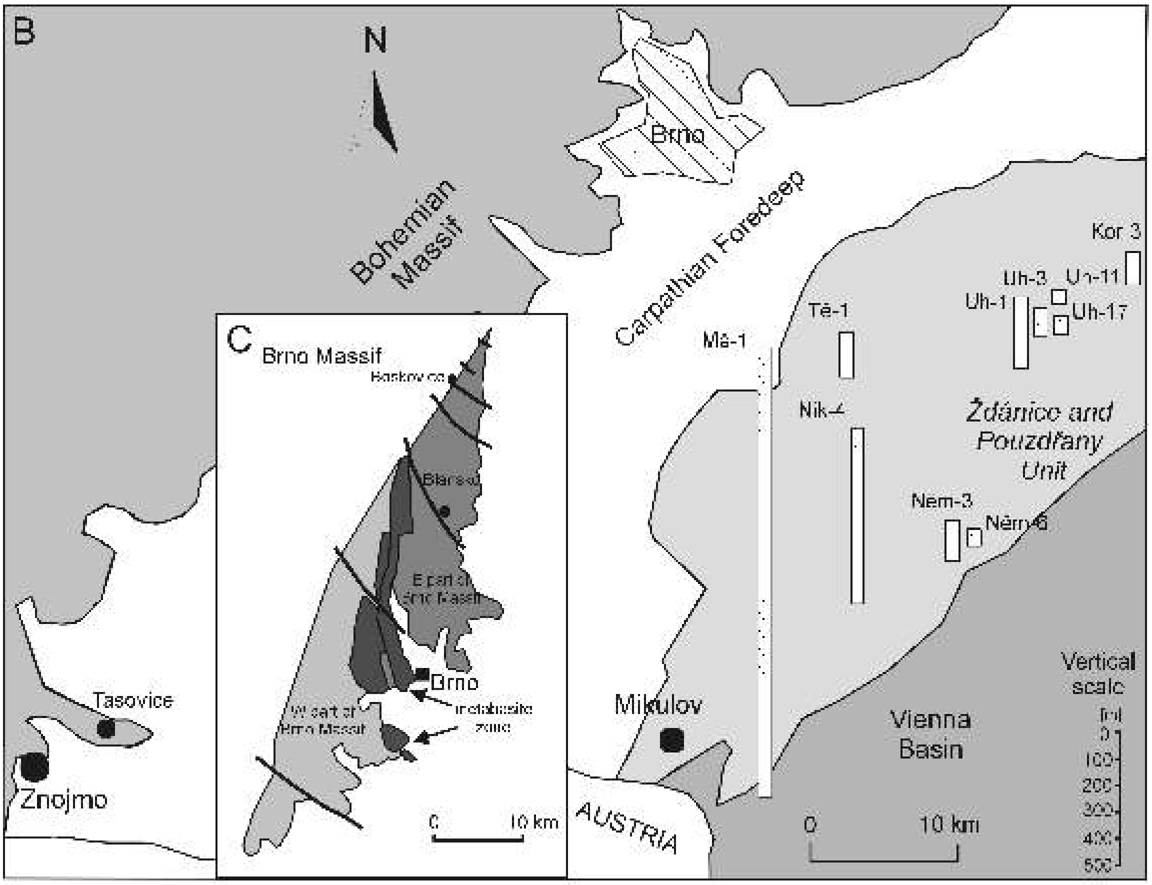
INTRODUCTION

Early Palaeozoic platform sedimentary units, often referred to as "platform cover sediments" in older literature, of Southern Moravia cover a crystalline block termed Brunovistulicum (Havlena, 1976; Dudek, 1980) or the Moravo-Silesian terrane (Pharaoh, 1999). This block contrasts with the crystalline complexes of neighbouring units; therefore, it is considered as a former microcontinent. At present, remains of the Brunovistulicum crystalline block together with its autochthonous sedimentary cover are in tectonic contact with deposits of the Carpathian Orogen to the east and south-east, and with metamorphic and volcanic rocks of the Outer Variscides to the west (*cf*. Dallmeyer *et al*., 1995).

The platform deposits related to Brunovistulicum are often colloquially called "basal clastics". They are locally considerably varied in their thickness and lithology. Reddish clastic deposits are common; therefore, the "basal clastics" were often considered analogous to the British Devonian "Old Red" strata (Reichenbach, 1834; Zapletal, 1922; Dvořák, 1998). The tendency of earlier authors to place all the "basal clastics" within the Devonian was augmented also by the fact that the sedimentary cover of Brunovistulicum (probably its uppermost part) included carbonate rocks with a Devonian fauna (Zukalová, 1977 in Skoček, 1980) and also because clastic rocks from the central part of Brunovistulicum yielded Devonian fossils (Chlupáč and Svoboda, 1963). A comparison of the "basal clastics" with Cambrian strata in the Upper Silesia region of Poland, however, provoked the opinion of a possible Cambrian age of a certain portion of the "basal clastics" (Roth, 1981). This opinion was subsequently supported by micropalaeontological investigations of borehole core material from South Moravia (Jachowicz and Přichystal, 1997; Fatka and Vavrdová, 1998; Vavrdová *et al*., 2003; Vavrdová, 2004).

Surface exposures of the platform deposits on Brunovistulicum are, however, very limited; most occurrences have been documented only by boreholes (Fig. 1). With regard to the lack of exposures, the stratigraphy, distribution of individual lithofacies, sedimentary structures and fossil content have only sporadic constraint.

The authors of the present contribution aimed to complete the investigation of the preserved borehole cores and accessible exposures in Southern Moravia by standard sedimentological and palaeontological means, to finalize this phase of the



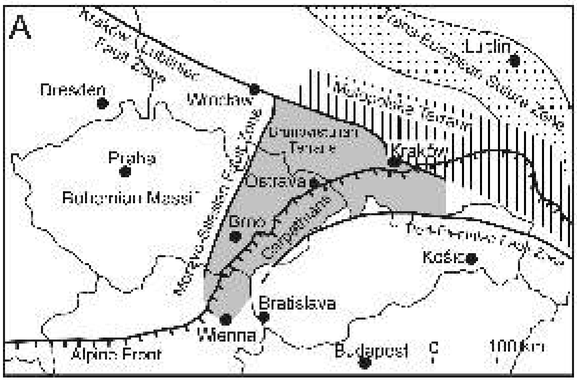


Fig. 1. Location map

A — broad geologic context and extent of Brunovistulicum (after Buła *et al*., 1977); **B** — location and depth of the boreholes studied: Kor-3 — Koryčany-3, Mě-1 — Měnín-1, Něm-3 (6) — Němčičky-3 (6), Nik-4 — Nikolčice-4, Tě-1 — Těšany-1, Uh-1 (3, 11, 17) — Uhřice-1 (3, 11, 17); **C** — geologic sketch map of the Brno Massif

research. Though part of the data presented, namely those concerning the palaeontology of the Cambrian and Devonian rocks, has already been published, mostly in local journals (e.g., Vavrdová, 1997; Vavrdová and Bek, 2001; Vavrdová *et al*., 2003), many workers remain unaware and/or disregard these results (e.g. Dörr *et al*., 2002; Raumer *et al.*, 2003). Evidence for an Ediacaran age of part of the succession is documented here for the first time, as are the results of the facies analysis.

The geographical limits of the study area reflects the fact that among the platform cover of Brunovistulicum, only Upper Silesia and S Moravia have provided demonstrably Late Precambrian and Cambrian rocks. Other parts of Brunovistulicum (especially the area north and north-west of Brno) have yielded no new data. Moreover, the number of borehole cores from S Moravia accessible to study may decrease in the future due to their reckless discarding; therefore, understanding of the area may stagnate until the next extensive phase of research.

GEOLOGICAL SETTING

The non-metamorphic siliciclastic deposits forming the sedimentary cover of the Brunovistulicum occupy the area of approx. 35 000 km^2. Brunovistulicum itself is composed of mature granitoids, tholeiitic metabasalts and metarhyolites (Central Metabasite Zone) and their metamorphic derivatives. Most of the sediments are presently deeply buried below the nappes of the Western Carpathians and below the strata of the Carpathian Foredeep. At exposure, the "basal clastics" of Southern Moravia can be observed only in few tectonic blocks, namely (1) along the eastern margin of the Brno Massif north of Brno, (2) along the Metabasite Zone (17 km long) in the central part of the Brno Massif, (3) on the eastern margin of the Boskovice Basin (filled with non-marine Carboniferous and Permian deposits), (4) around the town of Tišnov, *ca*. 40 km west of Brno, and (5) south-east of the town of Znojmo (Tasovice Quarry).

The buried area of “basal clastics” is documented only by borehole cores. About 50 boreholes reached the basal clastic units. However, not all the boreholes yielded more-or-less uninterrupted core sections. Moreover, part archived cores have been discarded. As result, only a very small portion of the drilled sections can continue to be studied.

Other than by palaeontology, methods of the determination of geological age of the “basal clastics” are uncertain. Most previous authors (e.g., Skoček, 1980) presumed that the beginning of the sedimentation of the clastic rocks was not synchronous, the oldest ones probably representing the Early Devonian (Emsian; *cf*. Chlupáč and Svoboda, 1963). This dating was supported by data from several boreholes (e.g., the Slavkov-2 borehole), which yielded carbonate intercalations with Givetian fossils (Zukalová, 1976). Roth (1981) was the first who noticed the possibility of a Cambrian age of deposits in the Měnín-1 borehole, because their character was similar to the palaeontologically documented Cambrian from the Goczałkowice IG 1 borehole in Poland (Kotas, 1973). In 1997, Cambrian acritarchs were discovered in the Měnín-1 borehole (Jachowicz and Přichystal, 1997) and in the Němčičky-6 borehole (Vavrdová, 1997).

As yet, the Měnín-1 borehole remains the only site where both Cambrian (Jachowicz and Přichystal, 1997; Vavrdová, 1997) and Devonian (Purkyňová *et al*., 2004) fossils have been recognized. The paper by Purkyňová *et al.* (2004) reported finds of the miospores *Calyptosporites velatus* (Eisenack) Richardson 1962 and *Rhabdosporites langii* (Eisenack) Richardson 1960 in the uppermost 70 metres of the clastic sequence. The position of the Cambrian–Devonian boundary in the borehole is between 470.4 m (deposits of Devonian age) to 473 m (Cambrian strata) in the Měnín-1 borehole (Purkyňová *et al.*, 2004).

The “basal clastics” differ, site by site, in their thickness, and show variable lithology. At the eastern margin of the Brno Massif, they reach a thickness of 200 m (Skoček, 1980). Boreholes in Southern Moravia yielded extremely variable data, from a total absence of clastic deposits to sequences several hundreds of metres thick. The maximum thickness was recorded in the Měnín-1 borehole noted above: the apparent thickness is 1700 m, of which *ca*. 1600 m belong to the Cambrian and Precambrian. Lithologically, conglomerates and sandstones comprise by far the greater part, but siltstones and claystones are also present (Skoček, 1980). The degree of structural and mineralogical maturity is highly variable. Monomict and polymict conglomerates, quartz sandstones and arkoses were found. The colour of the strata varies from greenish hues to grey, reddish-brown and red.

Most of the earlier palaeoenvironmental interpretations (e.g., Skoček, 1980) concluded that the “basal clastics” originated in isolated depressions and comprise proluvial, colluvial, alluvial and lacustrine sediments of alternating arid and humid climates. Carbonate intercalations were understood as a record of marine incursions (e.g., Dvořák, 1978). A detailed sedimentological study of the clastic deposits in the central part of the Brno Massif (Čevený Hill in Brno) and at Měnín (Měnín-1 borehole) was published by Nehyba *et al.* (2001) and by Vavrdová *et al.* (2003). At Červený Hill, alluvial fan deposits were recognized with evidence of catastrophic flood events, whereas at Měnín, an alternation of undoubted terrestrial and marine strata was recognized.

METHODS OF STUDY

For petrological, palaeontological and sedimentological studies, archived borehole core material, as well as archive reports and thin sections, were loaned by the Moravské naftové doly, a.s. Company.

Palynology appeared as the key source of stratigraphic information, since palynological investigation revealed the presence of abundant and relatively well preserved palynomorphs: unicellular fossil marine phytoplankton, dispersed miospores and algal filaments.

Palynomorphs were studied in thin section, isolated with the aid of routine maceration techniques and studied by scanning electron microscope (SEM). Chemical isolation employed standard maceration techniques using dilute acids (HCl, HF, HNO_3) and sieving.

Ichnofossils were observed on vertical, oblique and horizontal sections of the rocks, which enabled reliable determination of the original shape of the whole structure and its systematic determination. Combined with palynological data, the ichnofossils permitted determination of marine environments (e.g., ichnofabrics with deep *Diplocraterion* burrows are known only from the marine realm in the Cambrian; in the Devonian, similar biogenic structures may appear also in fluvial settings). The material found does not require a standard treatment on Systematic Ichnology in the present paper; for general background on Late Precambrian–Lowe Palaeozoic ichnology see, e.g., Seilacher *et al*. (2005) and references therein.

Sedimentological assessment and facies analysis were based on macroscopically visible sedimentary structures and on the study of thin sections.

RESULTS: RECENT DATA AND THEIR INTERPRETATION

The present study involved the assessment of drill cores from the Měnín-1, Němčičky-3 and Němčičky-6 boreholes. Early Palaeozoic microflora had already been recovered from these boreholes. Rock samples from the Nikolčice-4, Uhřice-1, Uhřice-3, Uhřice-11, Uhřice-17, Těšany-1 and Koryčany-3 boreholes were newly investigated. Also a large surface exposure — the quarry at Tasovice — was studied. As stated above, the archived drill cores represent only a small portion of the sections, albeit selected with the aim of saving typical samples.

The overall thickness of “basal clastics” drilled at individual sites is shown in Figure 1. Although it does not always correspond exactly with the effective thickness (the strata do not lie strictly horizontally on the basement, and not all the boreholes reached the crystalline complexes), the figure documents the substantial thickness of “basal clastics” in the area southeast of Brno (Měnín and Nikolčice boreholes).

The petrographic study showed that deposits from different boreholes and of different geological age (Cambrian, Devonian; indirectly dated Proterozoic; see below) show basically the same characteristics. This enables us to conclude that the sediments were derived basically from the same material and consequently from the same source area from the Latest Proterozoic to the Devonian.

Petrologically, quartz sandstones and subarkosic to arkosic sandstones represent the bulk of the sequences studied as documented in the borehole cores. Grain sizes represent the range from fine to coarse-grained. The colour varies from greenish shades to grey, reddish and violet, mostly determined by iron oxides and hydroxides in the matrix. The quartz sandstones are composed of grains of both monocrystalline and aggregate quartz; the grains are moderately rounded. Less frequently, mica grains (muscovite and biotite, often chloritised) are present. The arkosic sandstones and arkoses contain K-feldspar and plagioclase grains, moderately rounded. The porous matrix of the sandstones is composed of quartz, mica, clay minerals and carbonates; baryte (probably secondary) is known from the Měnín-1 borehole (in strata of Devonian age). Glauconite is present in the matrix in the Měnín-1, Němčičky-3 and Němčičky-6 boreholes.

Quartzose to arkosic conglomerates of various colours, grain sizes and clast shapes represent the greater part of the sections studied. Sorting is poor; the matrix is usually composed of poorly sorted sand grains. The size of the quartz clasts is variable: 3 mm in diameter on average, exceptionally up to 6 cm long (A-axis). Besides the monomictic quartz conglomerates, a lesser amount of polymictic conglomerates has been found. These rocks are composed of feldspar grains and fragments of volcanic rocks (?rhyolites and basaltoids), granitoids, cherts, phyllites and redeposited sediments (mostly sandstones and mudstones).

The maturity of the Cambrian sandstones and conglomerates differs from that of the Devonian ones. Generally, the Devonian rocks are more mature than the Cambrian ones. Quartzose sandstones and conglomerates with oval to rounded clasts of quartz prevail in the Devonian strata.

Sedimentology. Borehole cores from the boreholes studied, stored in the depository of the Moravian Oil Mines Company, Hodonín, have been sampled and documented sedimentologicaly. Several lithofacies have been recognized following the commonly used scheme of Miall (1978), modified by Bridge (1993). Then, dominant lithological transitions were interpreted, and a depositional model has been suggested, despite the problems and uncertainties resulting from the limited amount of preserved cores (which were sampled during the drilling as sparsely as at intervals of 50 to 150 m with a maximum length of 5 m of a continuous core). The following text, outlines the characteristics and occurrence of individual lithofacies in the area studied.

HETEROLITHIC BEDDED MUDSTONE, SILTSTONE AND FINE-GRAINED SANDSTONE (LITHOFACIES Fh)

Colour varies from greyish-green, green to red and brownish pink/violet. The deposits of lithofacies Fh usually form irregular laminae, lenses, flasers and shreds in coarse-grained sandstones of lithofacies Sh. The only exception is a several metres-thick layer of a greenish-grey mudstone found in the Měnín-1 borehole. Lithofacies Fh has been found in the Měnín-1 (Cambrian–Devonian age), Němčičky-6, Nikolčice-4, Uhřice-1, Uhřice-3, Uhřice-11 and Uhřice-17 boreholes.

BIOTURBATED MUDSTONE, SILTSTONE, VERY FINE-GRAINED SANDSTONE (LITHOFACIES Fb)

The prevailing colours are reddish-brown and green. Bioturbation often penetrates into the underlying, coarse-grained sandstones of lithofacies Sb. Lithofacies Fb has been ascertained in the Měnín-1 (Cambrian–Devonian age), Němčičky-6, Nikolčice-4, Uhřice-3 and Uhřice-11 boreholes.

HORIZONTALLY BEDDED SANDSTONE (LITHOFACIES Sh)

Horizontally bedded sandstone (lithofacies Sh) consists of fine to coarse-grained, horizontally bedded quartzose sandstones to subarkoses, grading to arkoses. Colours vary from violet-red and grey to greenish shades. Quartzose sandstones alternate with subarkoses. Bodies of coarse-grained rocks include medium and fine-grained components. This lithological heterogeneity and variability in colour makes the bedding easily visible. The sandstones are generally poorly sorted. Among the individual clasts, subangular quartz grains, pinkish grains of feldspar and mica grains can be observed. In places, “galls” of red mudstone occur in the sandstones. Lithofacies Sh has been recognized in the Měnín-1 (Cambrian–Devonian age), Němčičky-6, Nikolčice-4, Uhřice-1 and Uhřice-3 boreholes.

BIOTURBATED SANDSTONE (LITHOFACIES Sb)

Bioturbated sandstone (lithofacies Sb) is represented by bioturbated, fine- to medium-grained quartzose sandstones, sub-arkoses and arkoses. The colour is red-brown, grey to green. The rocks are penetrated by subhorizontal and vertical tunnels and shafts, usually filled with material coarser than the surrounding matter. Bioturbated sandstones often overlie the layers of bioturbated mudstone. Lithofacies Sb occurs in the Měnín-1 (Cambrian–Devonian age), Němčičky-6, Nikolčice-4, Uhřice-1, Uhřice-3, Uhřice-11 and Uhřice-17 boreholes.

PLANAR-CROSS-BEDDED SANDSTONE (LITHOFACIES Sp)

Planar-cross-bedded sandstone (lithofacies Sp) consists of planar-cross-bedded fine- to coarse-grained sandstones, sub-arkoses and arkoses. In pinkish quartzose sandstones, limonite and haematite are present as coating around grains. In arkoses and sub-arkoses the amount of iron minerals in matrix is higher and, consequently, their colour ranges from pink to brown. Pale grey, greenish-grey and greyish-green sandstones form mostly small lenses and flasers. In places, the sandstones contain thin mudstone layers (lithofacies Fh). The rocks are poorly sorted; sandstones contain irregularly dispersed subangular pebbles of brownish and whitish quartz, pink feldspar, black chert and leucocrate rocks. In the coarse-grained sandstones, flasers of red-brown and grey-green mudstone may occur. In places, positive graded bedding is present. The sandstones frequently grade into fine-grained conglomerates. Contacts of the conglomerates with underlying subhorizontal layers are mostly tangential. The usual inclination of cross-bedding is 15 to 30 degrees, with thickness of the beds up to10 cm. This lithofacies has been found in the Měnín-1, Němčičky-6, Nikolčice-4 and Uhřice-3 boreholes.

TROUGH-CROSS-BEDDED SANDSTONE (LITHOFACIES St)

Trough-cross-bedded sandstone (lithofacies St) is characterized by medium-sized to coarse-grained cross-bedded quartzose sandstones and subarkoses. Their colour varies from red-brown to green. The rocks are poorly sorted, with medium rounding of clastic particles. Semi-rounded quartz clasts are a predominant component, while pink feldspars are less common. Darker layers of fine-grained sandstones show small-scale trough-cross-bedding. This lithofacies commonly alternates with rocks of lithofacies Sp or Gp. The lithofacies has been ascertained in the Měnín-1 borehole.

MASSIVE SANDSTONE (LITHOFACIES Sm)

Massive sandstone (lithofacies Sm) consists of massive quartzose sandstones or subarkoses, red-brown, green or grey in colour. These are poorly sorted and may contain flasers of red-brown mudstone. Semiangular quartz grains and feldspar occur as the commonly recognized clasts. Normal graded bedding is exceptionally present, as well as reverse bedding near the base of beds. Lithofacies Sm commonly alternates with massive conglomerates. It has been recognized in the Měnín-1 (Cambrian–Devonian age), Uhřice-1, Uhřice-3, Uhřice-11 and Uhřice-17 boreholes.

PLANAR TO CROSS-BEDDED CONGLOMERATE (LITHOFACIES Gp)

Planar to cross-bedded conglomerate (lithofacies Gp) is composed of fine-grained to medium-grained planar cross-bedded quartzose to arkosic conglomerate with a supporting structure of medium to coarse-grained sandy matrix. The conglomerate is red, violet, to greenish-grey. Sorting is poor, and roundness of grains is variable; both angular to subangular and oval clasts are present. The clasts are composed of various materials, i.e. white or yellowish quartz, pinkish feldspar, blackish-grey chert, red mudstone, reddish sandstone, granitoids and phyllites. The size of the clasts ranges from 0.5 to 3 cm (A-axis). Individual layers are up to 10 cm thick, showing sharp, wavy bases and gradational upper contacts (conglomerates grade upwards into sandstones). Normal grading is present in places; reverse grading is rare. The conglomerates of lithofacies Gp frequently alternate with sandstones of lithofacies Sp. Lithofacies Gp has been found in the Měnín-1 and Nikolčice-4 boreholes.

MASSIVE CONGLOMERATE (LITHOFACIES Gm)

Massive conglomerate (lithofacies Gm) is represented by massive fine- to medium-grained conglomerates with a supporting structure of medium-grained sandy matrix. The conglomerates vary between pinkish and grey-green to grey-white. Rounding ranges from angular to oval, with poor sorting. The most common size of the pebbles is 0.2–3 cm (A-axis). Pebbles consist mostly of white quartz, less frequently of greyish to black chert and of quartzite. Rare clasts of sandstones, violet mudstones, granitoids and phyllites also occur. Horizontal bedding is occassionally visible; positive or inversly graded bedding can rarely be observed. Conglomerates grade upwards into massive sandstones. Lithofacies Gm occurs in the Měnín-1 (Cambrian–Devonian), Uhřice-1, Uhřice-3, Uhřice-11 and Uhřice-17 boreholes.

INTERPRETATION OF SEDIMENTARY ENVIRONMENTS

The greater part of the cores studied is composed of sandstones. Mudstones and siltstones are usually present as thin intercalations; their thickness usually does not exceed several centimetres. Conglomerates are also usually present as thin layers in the sandstones.

Two basic types of lithofacial transitions have been recognized in the Cambrian and Devonian deposits:

— Gm–Sm–Sh–Fh transition;

— Gp–(St)–Sp–Sh–Fh transition, where fine-grained deposits may be bioturbated. Such transitions correspond to an alteration of marine and terrestrial sedimentary environments (*cf.* Miall, 1996; Bridge, 2003).

A statistically significant lithofacial succession Gm–Sm–Sh–Fh was found in strata of the boreholes Měnín-1 (Cambrian–Devonian), Uhřice-1, Uhřice-3, Uhřice-11 and Uhřice-17. A lithofacial succession Gp–(St)–Sp–Sh–Fh (or Sp–Sh–Fh) was found in the strata of the boreholes Měnín-1 (Cambrian), Němčičky-6, Nikolčice-4 and Uhřice-3.

The Gm–Sm association can be best interpreted as alluvial fan deposits, more specifically as cores of levees of a coarse-grained river (Ramos and Sopeña, 1983; Rust, 1984; Miall, 1996; Bridge, 2003). The Gp–Sp(St) facial association can be interpreted as products of fluvial flow (most probably a braided river), namely as sediments of levees and transverse bars. Another possible interpretation may involve "chanelling" typical of distal parts of alluvial fans. The occurrences of lithofacies Sh in association with alluvial fan deposits suggests periodic sedimentation in a rapid flow regime and a tendency for channels to overall. The processes could be seasonally/climatically controlled. Within an alluvial fan framework, they can be expected in its distal or perhaps its middle part.

Quieter sedimentation outside of the channels can be, perhaps (*cf.* Wright and Marriott, 2007), be presumed for fine-grained clastic deposits of lithofacies Fh (overbank sediments). Lithofacies with evident biogenic activity, i.e. Fb and Sb, suggest different sedimentary conditions. Bioturbation is of a type unambiguously indicating marine or at least brackish water. Alternation of facies Fb and Sb with facies Fh and Sh suggests repeated changes of environment, ranging from terrestrial to coastal and shallow marine (*cf.* Mikuláš and Nehyba, 2001; Vavrdová *et al*., 2003).

Deposition on coarse-grained deltas is a possible explanation for the combination of the above-defined associations of lithofacies. Considering the absence of large-scale cross-bedding (delta foresets), we can more precisely consider sedimentation on braided deltas (*cf*. Postma, 1990; Fig. 3).

Positive results of palynological investigations are summarized in Tables 1 and 2; the ichnological content of the strata is given in Table 3 and Figure 6.

The palaeontologically documented Proterozoic; presumed Proterozoic. Fine-grained siliciclastics from the Měnín-1 borehole yielded diversified, well-preserved palynomorphs of Late Proterozoic (Ediacaran) age. Recovered organic remains are derived from the predominantly cyanobacterial biocoenoses, with a strong tendency to form multicellular colonies, aggregates and coenobia. Monospecific clusters of *Chabiosphaera bohemica* Drábek, 1972, *Sphaerocongregus variabilis* Moorman, 1974 and *Chlorogloeaopsis contexta* (Herman) Hofman *et* Jackson, 1994 form agglomerations of hundreds of unicells (Fig. 2A). Leiospheres dominate in the association, both smooth, i.e. *Leiosphaeridia asperata* (Naumova) Lindgren 1982 and with minor sculpture, i.e. *Valeria granulata* (Vidal) Fensome *et al.* 1990 and *V. tchapomica* (Timofeev) Fensome *et al.* 1990 (Fig. 2B). *Arctacellularia tetragonala* (Maithy) Hofman *et* Jackson 1994 is a chain-like form. Uniseriate trichomes are usually twisted (*Archaeotrichion contortum* Schopf 1968, Fig. 2D, E) and coiled, i.e. *Obruchevella valdaica* (Shepeleva *ex* Aseeva) Jankaukas *et al.* 1989 (Fig. 2C). Less frequent are planktonic unicellular eukaryotes, such as the representatives of the genera *Podolina*, *Octaedrixium* and *Tasmanites*. Vase-like vesicles of the genus *Melanocyrillium* represent protistan heteromorphs.

The absence of ichnofossils and organic-walled microfossils in the non-metamorphic clastics of Tasovice Quarry suggests a Proterozoic age, too. Organic-walled

Table 1

List of boreholes in the area studied that have provided palynological data, assemblages, zones and interpreted geologic age

Borehole	Deep [m]	Assemblage	Zone	Age
Uhřice-1	3600	*Densosporites devonicus–Granolispora naumovii*	AD Lem	Middle Devonian
Němčičky-6	5181–5184	*Volkovia dentifera–Liepaina plana*	*Protolenus*	Early Cambrian
Němčičky-6	5157–5160	*Volkovia dentifera–Liepaina plana*	*Protolenus*	Early Cambrian
Němčičky-3	5396–5401	*Volkovia dentifera–Liepaina plana*	*Protolenus*	Early Cambrian
Měnín-1	473–477	*Heliosphaeridium dissimilare–Skiagia ciliosa*	*Holmia*	Early Cambrian
Měnín-1	507–512	*Heliosphaeridium dissimilare–Skiagia ciliosa*	*Holmia*	Early Cambrian
Měnín-1	776–778	*Skiagia barren*	–	–
Měnín-1	856.2	*Skiagia ornata–Fimbriaglomerella membranacea*	*Schmidtielus*	Early Cambrian
Uhřice-17	3255-3260	*Skiagia* ornata–*Fimbriaglomerella* membranacea	*Schmidtielus* (?)	Early Cambrian
Měnín-1	1565–1566	*Asteridium tornatum–Comasptaeridium velvetum*	*Platysolenites*	Early Cambrian
Měnín-1	1299–1300.2	*Podolina minuta–Obruchevella valdaica*	unnamed	Late Precambrian (Ediacaran)

Table 2

Microfossil content of the zones close to the Precambrian–Cambrian boundary in the area studied

Zone	Age	Characteristic microfossils
Protolenus	upper Lower Cambrian	*Estiastra minima* Volkova 1969, *Liepaina plana* Yankauskas in Yankauskas et Volkova 1979, *Skiagia ciliosa* (Volkova) Downie 1982, *S. scottica* Downie 1982, *S. compressa* (Volkova) Downie 1982, *Sagatum priscum* (Kiryanov et Volkova) Vavrdová *et* Bek, 2001
Holmia	middle Lower Cambrian	*Archaeodiscina umbonulata* Volkova 1968, *Heliosphaeridium dissimilare* (Volkova) Moczydłowska 1991, *Goniosphaeridium primarium* (Yankauskas) Downie 1982, *Sagatum priscum* (Kiryanov) Vavrdová *et* Bek 2001, *Skiagia pura* Moczydłowska 1998, *Vogtlandia yankauskasii* (Fensome *et al.*) Sarjeant *et* Vardová 1997, *Tasmanites volkovae* Kiryanov 1974
Schmidtielus	low Lower Cambrian	*Asteridium lanatum* (Volkova) Moczydłowska 1991, *Comasphaeridium velvetum* Moczydłowska 1988, *Skiagia orbiculare* (Volkova) Downie 1982, *Lophosphaeridium tentativum* Volkova 1968, *L. truncatum* Volkova 1969
Platysolenites	basal Cambrian	*Asteridium tornatum* (Volkova) Moczydłowska 1991, *Lophosphaeridium bacilliferum* Vanguestaine 1974, *L. tentativum* Volkova 1968, *Comasphaerium velvetum* Moczydłowska 1988, *Granomarginata squamacea* Volkova 1968, *Tasmanites tenellus* Volkova 1968
unnamed	Ediacaran	*Arctacellularia tetragonala* (Maithy) Hofmann *et* Jakson 1994, *Chlorogloeaopsis contexta* (Hermann) Hofmann *et* Jackson 1994, *Obruchevella valdaica* (Shepeleva *ex* Aseeva) Jankauskas *et al.*,1989, *Podolina minuta* (Hermann) Vidal 1983, *Polyedrixium truncatum* (Rudavskaya) Vidal 1976, *Primoflagella speciosa* Gnilovskaya 1983

Table 3

Ichnological content and interpretation of the borehole cores studied

Borehole	Depth [m]	Lithology	Ichnotaxon	Intensity of bioturbation	Interpretation
Měnín-1	473	greenish and greyish siltstones and claystones	"small *Planolites*"	low to medium	Phanerozoic (marine if pre-Carboniferous)
	507–512	claystones	"small *Planolites*"	low	Phanerozoic (marine if pre-Carboniferous)
	770–777	black siltstone	"large *Planolites*"	medium	Phanerozoic (marine if pre-Carboniferous)
	1299	dark fine-grained sandstones to siltstones	pseudo-bioturbation	low	Precambrian (Ediacaran)
	1682–1683.8	reddish siltstones	*Diplocraterion*	low to medium	Phanerozoic (marine if pre-Carboniferous), ichnofabrics similar to the Cambrian of Baltica
Nikolčice-4	950	reddish arkosic sandstone	*Skolithos*	medium	very probably marine Lower Palaeozoic, probably Cambrian considering the low maturity of clastics
	954	arkosic sandstone	*?Planolites*	medium, rhythmically alternating intensity	very probably Phanerozoic (marine if pre-Carboniferous), probably Cambrian considering the low maturity of clastics
Němčičky-6	5157–5160	greyish sandstones and siltstones	*Diplocraterion* and *Planolites*	medium	Phanerozoic (marine if pre-Carboniferous), ichnofabrics similar to the Cambrian of Baltica
	5181	grey laminated siltstone	*Palaeophycus* and *Planolites*	low	probably marine Lower Palaeozoic, much less probably also Proterozoic
	5181–5184.5	whitish to greenish-grey sandstones	*Skolithos* and *Planolites*	moderate, rhythmically alternating intensity	very probably marine Lower Palaeozoic
Uhřice-1	3596–3600	base of slab of coarse-grained grey sandstone overlying thin silty intercalation	*Planolites*	low	very probably Phanerozoic (marine if pre-Carboniferous)
Uhřice-3	2555–2561	reddish sandstone alternating rhythmically with siltstone to claystone	*Planolites*	moderate, rhythmically alternating intensity	very probably Phanerozoic (marine if pre-Carboniferous)
	2593–2595	reddish siltstone to claystone	*Planolites* and *Diplocraterion*	medium	very probably Phanerozoic (marine if pre-Carboniferous), ichnofabrics similar to the Cambrian of Baltica
Uhřice-11	1708–1711	greenish-grey sandstone overlain by a bed with red clay rip-up clasts	*Skolithos*	low	very probably marine Lower Palaeozoic
Uhřice-17	3255–3260	coarse-grained sandstone; siltstone; claystone	*Planolites*	none, low, locally medium	very probably Phanerozoic (marine if pre-Carboniferous)

microfossils could be hardly preserved at Tasovice, where the spoil of the quarry consists chiefly of medium- to coarse-grained sandstones, rarely reddish-grey and reddish-brown siltstones. On the other hand, ichnofossils may be easily preserved in such rocks. Mechanical sedimentary structures are preserved perfectly at Tasovice, and ichnofossils have been reported from many similar units. Therefore, the Tasovice succession originated outside colonization windows of infauna either due to its ancient age or to unsuitable settings (e.g., no trace fossils have yet been found in the Cambrian fluvial deposits; *cf*. Mikuláš, 1995) or both. The only study interpreting the age of the Tasovice strata is the PhD Thesis by Schneider (2002) who attempted radiometric dating of white mica from the locality. His results suggests age close to the Precambrian–Cambrian boundary. Considering the possibilities of alteration of mica, these data cannot be regarded as unequivocal; nevertheless, they suggest an ancient provenance of the sediments in the area studied.

The characteristics of the Tasovice site apply also to rocks of the Těšany-1 (4110–4113 m) and Koryčany-3 (1856 m) boreholes.

Palaeontologically documented Cambrian; presumed Cambrian. Microflora corresponding to the Cambrian has been found in the Měnín-1, Němčičky-3, Němčičky-6 and Uhřice-17 boreholes. At Uhřice, the Cambrian microflora was ascertained at depths of 3255–3260 m. The microfossils found correspond to the associations which occur at Měnín at depths of 856–857 m. The prevailing taxa are *Asteridium tornatum* (Volkova) Moczydłowska 1991, *A. lanatum* (Volkova) Moczydłowska 1991, *Comasphaeridium molliculum* Moczydłowska *et* Vidal 1988 and *Lophosphaeridium tentativum* Volkova 1968. At Němčičky-3 and Němčičky-6, fossiliferous beds come from depths of over 5000 m and represent the Lower Cambrian *Protolenus* Zone. The late Early Cambrian fossil microplankton of the *Volkovia dentifera–Liepaina plana* palynozone characterizes abundant

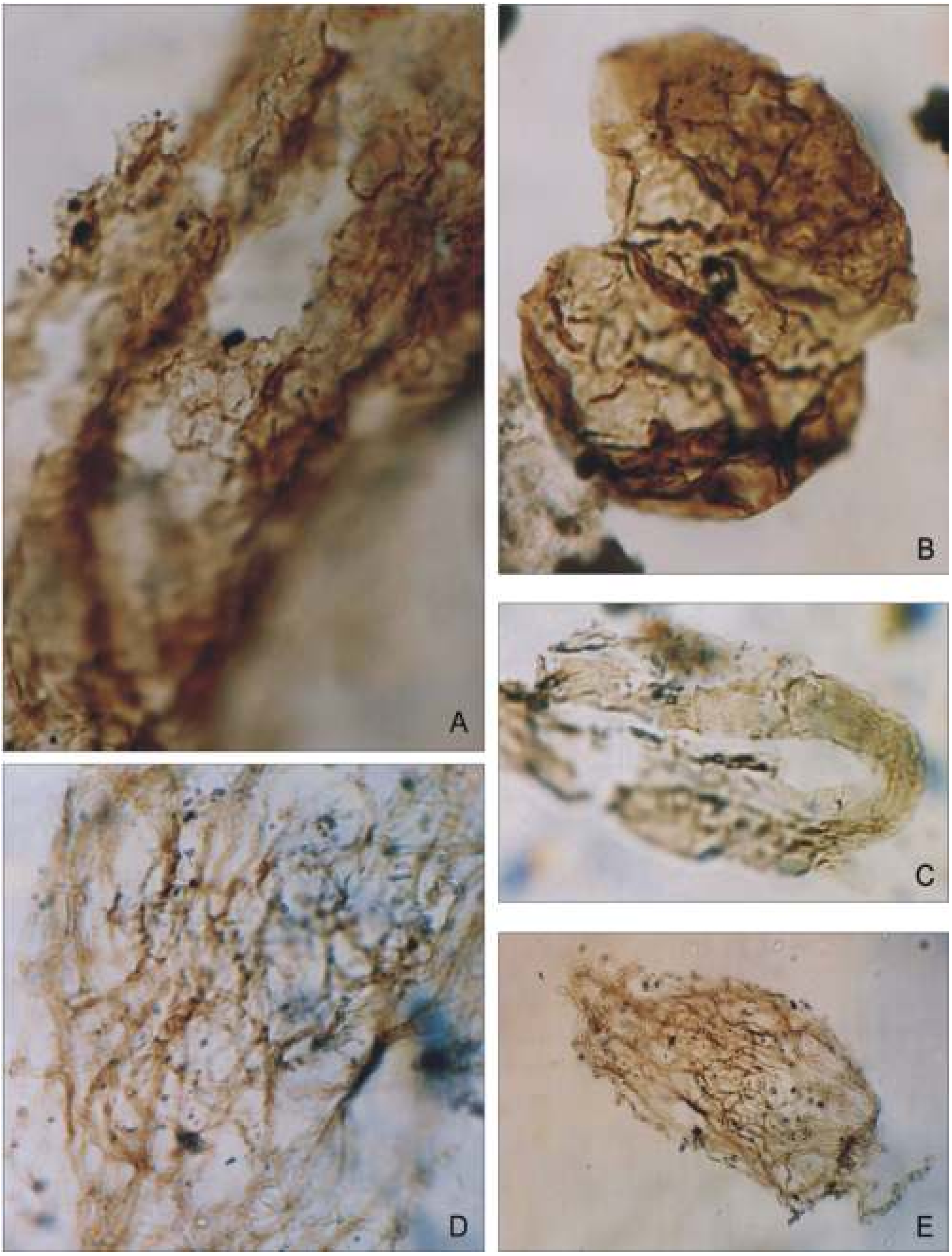


Fig. 2. Ediacaran organic-walled microfossils

A — *Chlorogloeaopsis contexta* (Herman) Hofman *et* Jackson 1994; **B** — *Valeria tchapomica* (Timofeev) Fensome *et al*., 1990; **C** — *Obruchevella valdaica* (Shepeleva *ex* Aseeva) Jankauskas *et al.*, 1989; **D**–**E** — *Archaeotrichion contortum* Schopf 1968; pear-shaped agglomeration (E) and detail of twinned trichomes (D); Ediacaran, Měnín-1 borehole, depth 1299 m; scale: A–D — × 1000, E — × 300

occurrence of the genera *Skiagia* Downie and *Sagatum* Vavrdová *et* Bek (Figs. 4 and 5).

This association shows a high proportion of filamentous algae and fragments of monospecific blue-algae growths. Considering the specific context of the Early Palaeozoic (when the diversity of ichnoassemblages increased rapidly and the biota, restricted chiefly to shallow marine settings, was greatly influenced by sea-level oscillations), the composition and preservation enable us to conclude that the blue-algal growths indicate proximity of a shoreline.

A Cambrian age for the basal clastic deposits can be presumed also for the Nikolčice-4, Uhřice-3 (2555–2561 m) and Uhřice-17 (3255–3260 m) boreholes because the ichnofabric is analogous to that in micropalaeontologically dated Cambrian occurrences. The documented ichnofabric, including very deep burrows, essentially excludes a Precambrian age for the rocks

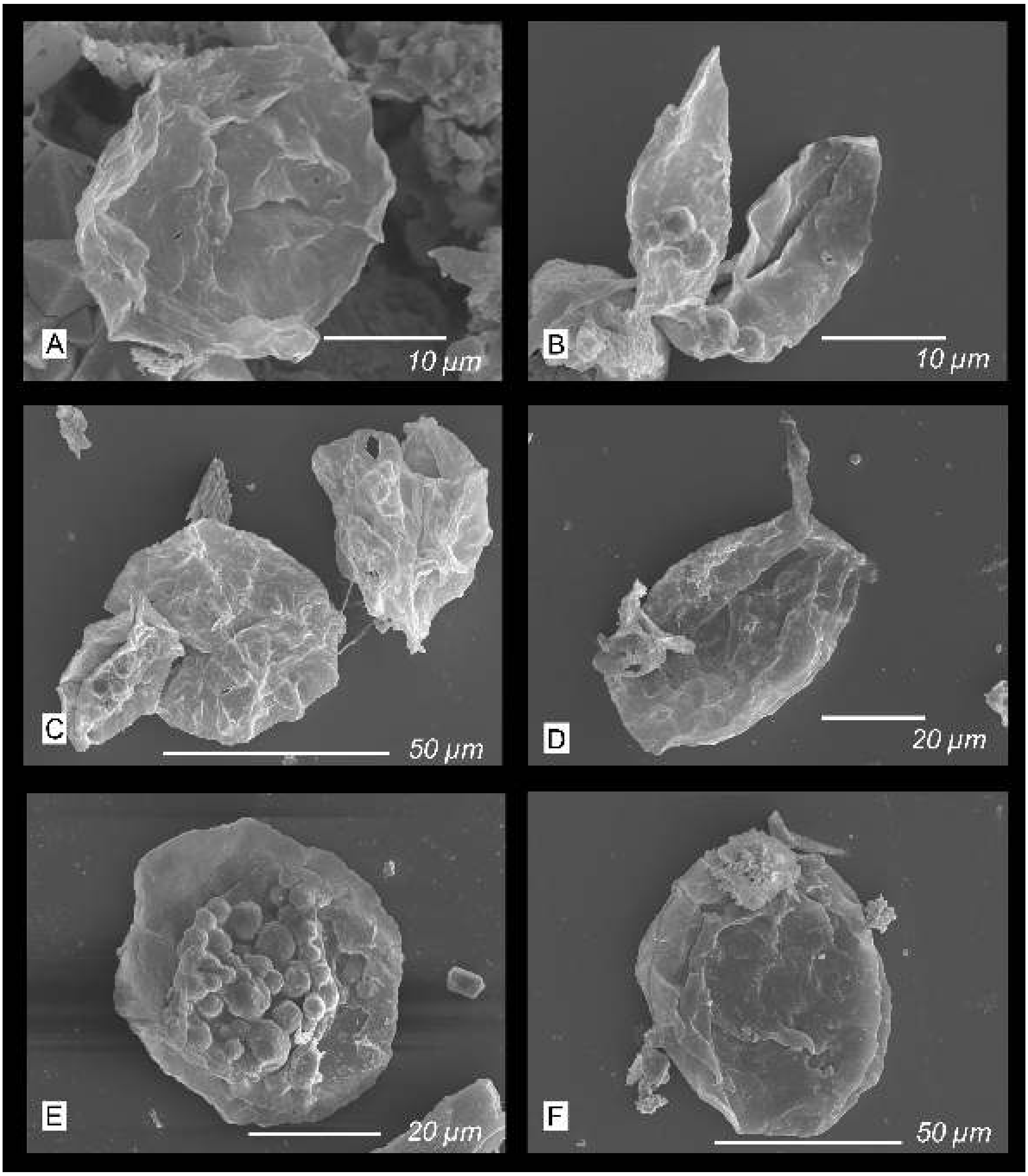


Fig. 3. SEM images of Ediacaran acritarchs

A — *Leiosphaeridia tenuissima* Eisenack 1958; **B** — *Schizofusa risoria* Grey, 2005; **C** — *Arctacellularia ellipsoidea* Hermann *in* Timofeev *et al.*, 1976; **D** — *Ceratosphaeridium glaberosum* Grey, 2005; **E** — *Pterospermella* sp. indet.; **F** — *Tappania plana* Lei-Ming 1997; Měnín-1 borehole, depth 1299 m

(*cf*. Seilacher *et al*., 2005). In the case of ichnofabrics dominated by vertical burrows (*Skolithos*, *Diplocraterion*), a Cambrian age is more probable than a Devonian age (e.g., Ekdale *et al*., 1984), which follows general trends in the evolution of the behaviour of marine benthic fauna. Yet another argument for the Cambrian age of these sections is based on the low maturity of the deposits, which contrasts with more mature clastic rocks dated to the Devonian (as documented best in the Měnín-1 borehole).

GEOLOGICAL HISTORY OF THE SOUTHERN PART OF BRUNOVISTULICUM BETWEEN THE CAMBRIAN AND DEVONIAN

Ordovician and Silurian rocks of platform character have not yet been found in the southern part of Brunovistulicum. Erosion rates were generally higher than sedimentation rates in the Cambrian to Devonian interval. Therefore, the record of marine sedimentation (presumably analogous with that in the

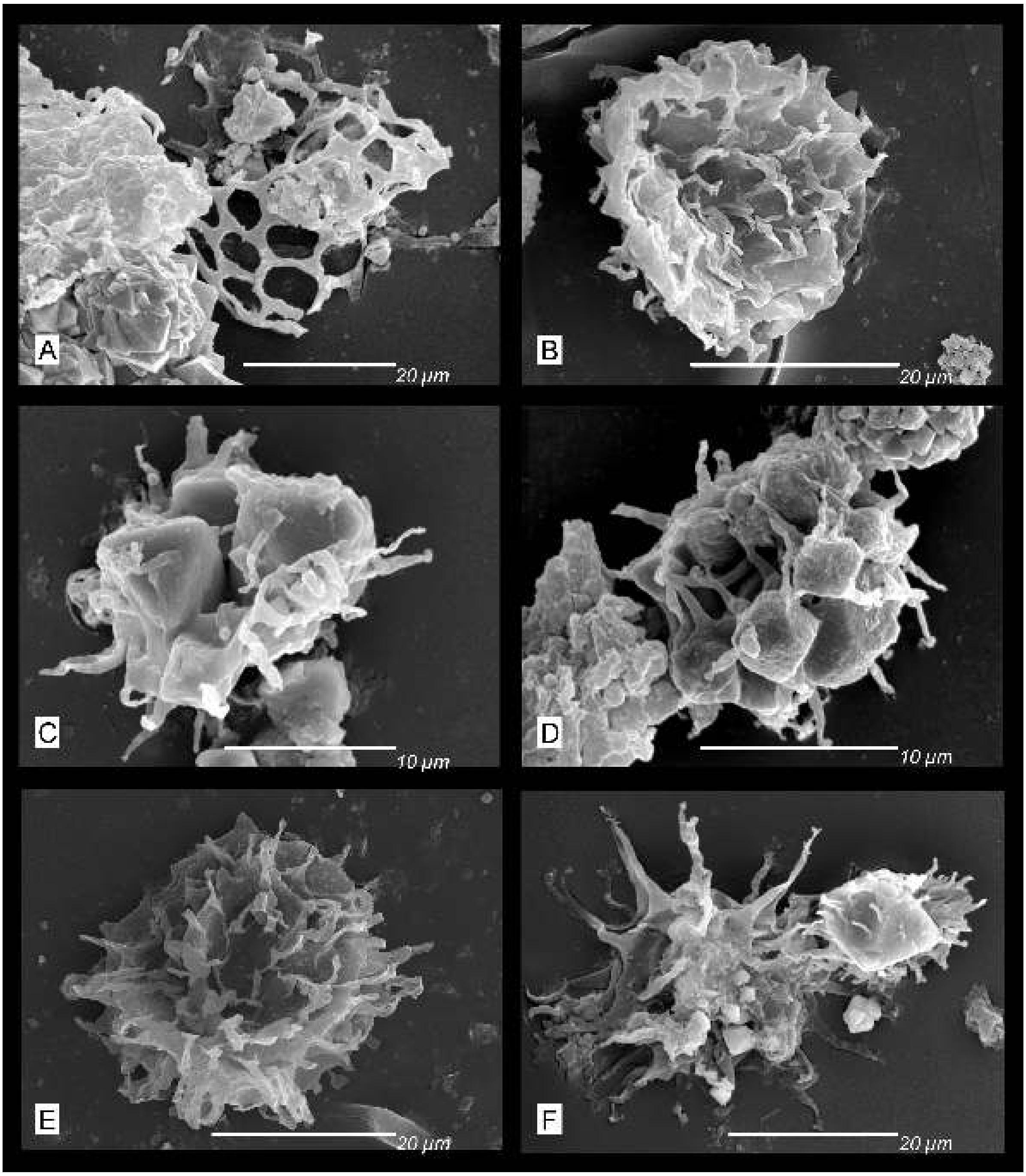


Fig. 4. SEM images of Cambrian acritarchs

A — *Sagatum priscum* (Kiryanov *et* Volkova) Vavrdová *et* Bek 2001; **B** — *Skiagia compressa* (Volkova) Downie 1982; **C**–**D** — *Evittia irregulare* Downie 1982, vesicles distorted by pyrite; **E** — *Skiagia ciliosa* (Volkova) Downie 1982; **F** — *Vogtlandia yankauskasii* (Fensome *et al.*) Sarjeant *et* Vardová, 1997; *Protolenus* Zone; Němčičky-3 borehole; depth 5396–5401 m

northern Polish part of Brunovistulicum, e.g., Belka *et al*., 2000) was completely removed by erosion. Highly variable thicknesses of the basal clastic deposits (several metres to 1500 m or more at Měnín) may be explained by the selectiveness of erosion, controlled by primary segmentation of the crystalline basement and by subsequent, chiefly vertical movements of individual tectonic blocks (*cf*. Dvořák, 1998). However, the rate of subsidence of the basin floor and deposition of Cambrian sediments was probably also differentiated; therefore, the erosion history cannot be precisely reconstructed using present field knowledge.

Undoubted Silurian rocks, known from the vicinity of Stínava in Central Moravia (Kettner and Remeš, 1935), as well as from successions assigned speculatively to the Silurian (Slušovice-1 borehole; Pacltová, 1987) have undergone relatively strong metamorphism due to both pressure and temperature effects. This metamorphism contrasts with that in the Cambrian platform deposits and leads to the possibility that the

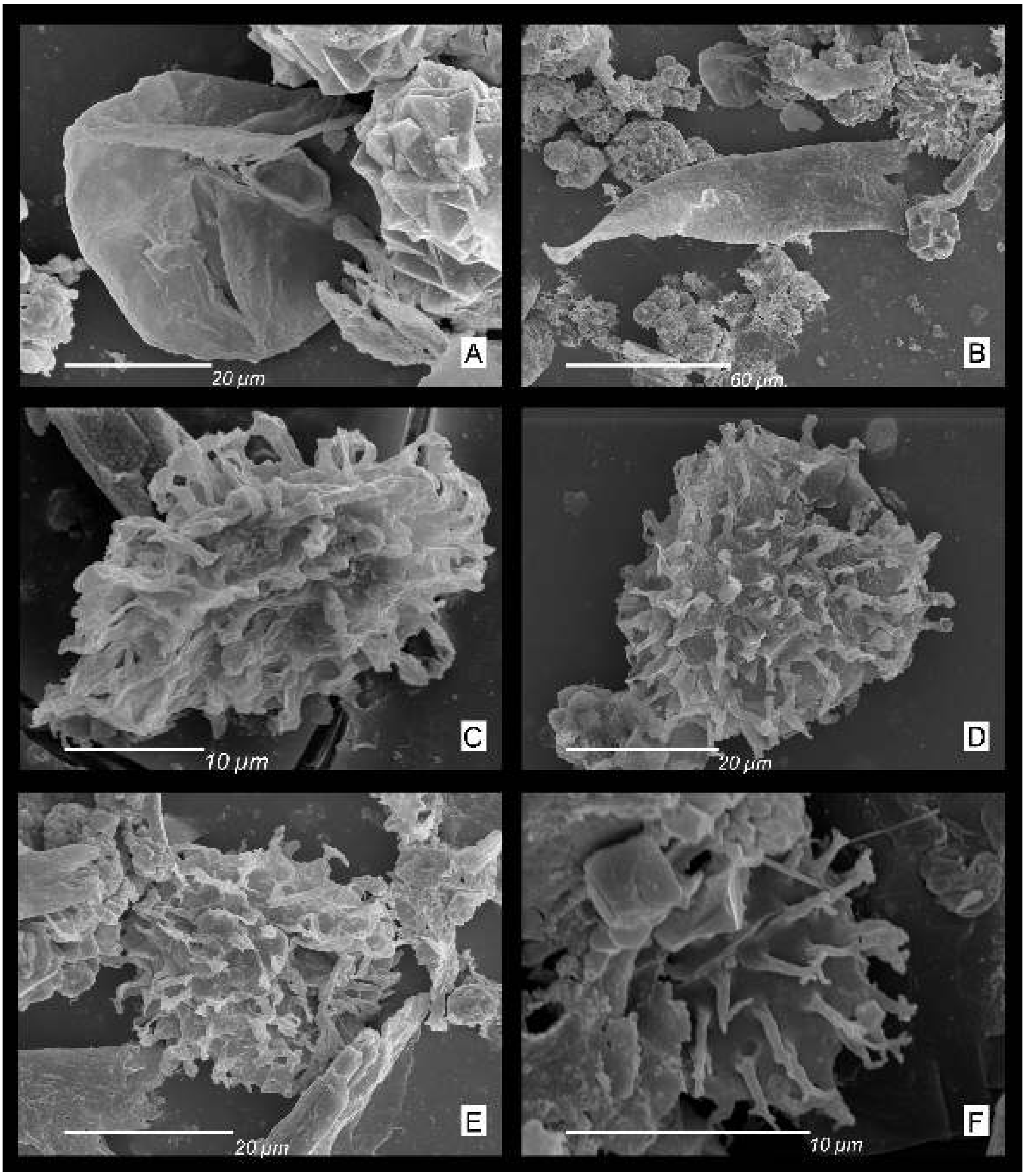


Fig. 5. SEM images of Cambrian acritarchs

A — *Leiosphaeridia asperata* (Naumova) Lindgren 1982; **B** — *Ceratophyton vernicosum* Kiryanov 1979; **C** — *Skiagia scottica* Downie 1982; **D**–**E** — *Skiagia insigne* (Fridrichsonne) Downie 1982; **F** — *Timofeevia martae* (Cramer *et* Diéz) Fensome *et al.*, 1990; *Protolenus* Zone; Němčičky-3 borehole, depth 5396–5401 m

Moravian Silurian strata are allochthonous. The allochthonous character is also apparent from the tectonic position of these occurrences, i.e. in their position in nappes.

Presumed and palaeontologically documented Devonian clastics deposits. Devonian miospores were found in the Uhřice-1 borehole. They are of terrestrial origin; marine acritarchs (*Polyedrixium*, *Multiplicisphaeridium*) and rarely chitinozoans were found together with them. The conspicuous dominance of thick-walled and coarsely sculptured forms, as well as the fragmentary preservation of spores, indicate long transport. The associated marine microfossils (especially acritarchs) may have originated in isolated, brackish lagoonal settings. There, miospores from nearby stands of terrestrial, coal-forming vegetation (e.g., *Pseudosporochnus*) accumulated.

Purkyňová *et al.* (2004) deduced that the clastic rocks in the uppermost 70 metres in the Měnín-1 borehole are Devonian in age, based on fragments of macroflora and on miospores.

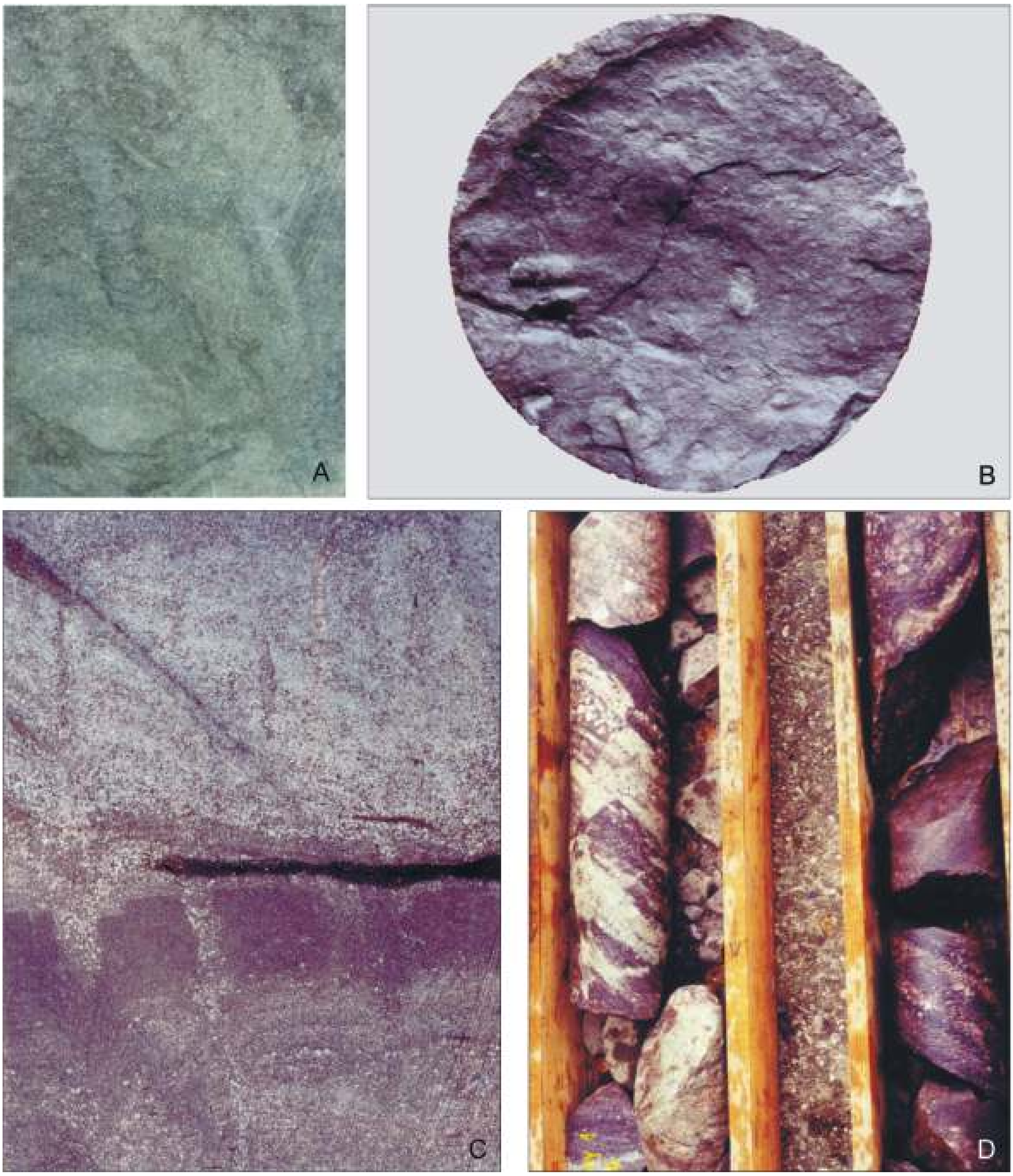


Fig. 6. Ichnofabrics in borehole cores

A — *Diplocraterion* isp., Měnín-1 borehole, depth 1370 m; **B** — *Planolites* isp., Němčičky-6 borehole, depth 5181 m; **C** — *Diplocraterion* isp. and *Skolithos* isp.; Měnín-1 borehole, depth 1682 m; **D** — „pseudoichnofossils“ — spots of Fe-oxides and hydroxides, Těšany-1 borehole, depth 4110–4130 m; diameter of the cores is 9 cm; scale: A, C — × 1.4, B — × 0.8

DISCUSSION AND CONCLUSIONS

(1) The finds/associations of ichnofossils and ichnofabric patterns in the study area are simple; although known to previous authors (e.g., Skoček, 1980), they have not yet been interpreted in detail. However, in combination with other methods of study, and considering that burrows cannot be reworked, the colonization windows with *Skolithos* and *Diplocraterion* represent convincing evidence of the marine origin of a considerable part of the pre-Devonian succession, and also exclude a Precambrian ages for the strata.

(2) Lithofacies assessment of both the Early Cambrian and Devonian parts of the sections studied indicates a close resemblance between the two successions. Although divided by a long hiatus (more than 110 m.y.), they originated in very similar settings. The presence of coarse-grained and fine-grained deposits in combination with biogenic activity and the absence

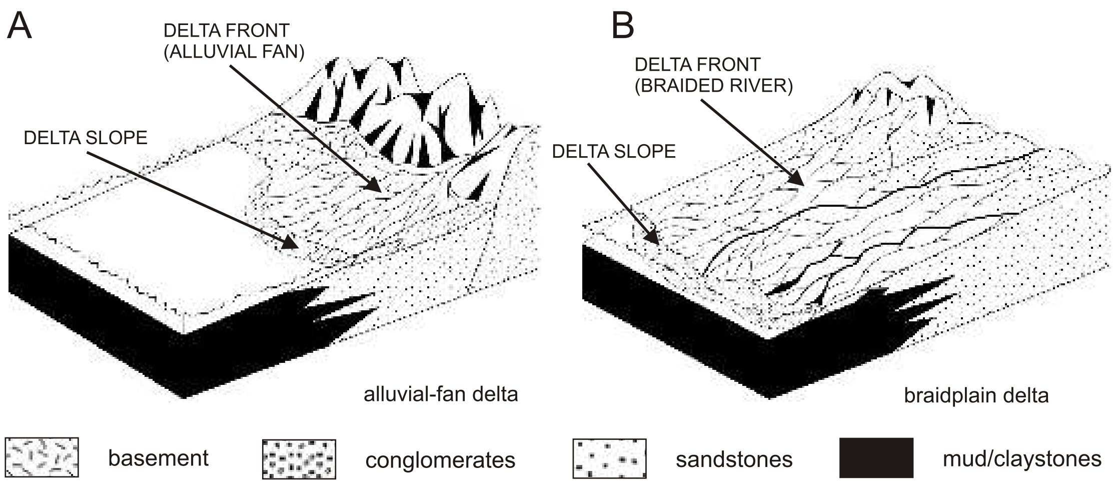


Fig. 7. Models of basic sedimentary environments for the Late Proterozoic to Early Palaeozoic platform deposits of Southern Moravia

A — fan delta — epeiric sea; B — braided delta — epeiric sea (lower); models adapted from Nemec (1990)

of large-scale cross-bedding indicate sedimentation on braided deltas (Postma, 1990; Fig. 7). The depositional system was probably responsive to relative changes in water level, which may be connected with processes both inside and outside the basin (e.g., eustatic changes). The lack of a continuous plant cover and possible high relief in the Early Palaeozoic landscape represented suitable conditions for rapid transport of large amounts of debris from terrestrial to marine environments. Lateral migration, characteristic of alluvial sedimentary systems, connected with reduced amounts of clastic detritus and accumulation rates, may have controlled the development of colonization windows in the marine environments, as manifested by bioturbated layers.

(3) The Early Cambrian palynomorphs from the deep boreholes in Southern Moravia are very similar to the Early Cambrian high-latitude assemblages of the East European Platform.

(4) Palynomorphs from the basal clastic units contain assemblages of acritarchs that are not affected by post-diagenetic thermal alteration; in conclusion, the Precambrian/Cambrian transition succession of the study area was not subjected to Cadomian or younger metamorphic processes.

(5) Plant microfossils of supposedly Ediacaran age were recovered from a level more than 250 m above the rocks of basal Cambrian age. The abundance and excellent preservation of the Ediacaran taxa excludes their long transport. Although no reliable Phanerozoic markers have been obtained, the autochthonous nature of the palynomorphs recovered is not unequivocal. The sedimentary environment is consistent with a massive redeposition of older, unlithified sediments. A common presence of irregular clusters, consisting of agglomeration of several hundreds of specimens, would be more consistent with redeposition as pellets. Such a mechanism would ensure that the fragile coenobia are undamaged. Another possibility is the tectonic repetition of strata. The palynology of the clastic deposits in Southern Moravia is supplemented by the determination of very well preserved Ediacaran microbiota, predominantly filamentous trichomes and coccoid coenobia derived from fossil populations of benthic blue-green algae. The autochthonous or allochthonous nature of the microbiota has not yet been finally elucidated. Nevertheless, the existence of Proterozoic marine sedimentation in Southern Moravia has been clearly demonstrated.

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