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Ichnology of the Cretaceous Oceanic Red Beds (Outer Western Carpathians, Czech Republic)

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Abstract: Large differences in the intensity and overall character of bioturbational structures were found in five facies containing hemipelagic red beds. Red beds (CORB) of the Godula facies of the Silesian Unit and their equivalents (mostly not red) in the Kelč facies of the Silesian Unit and the CORB in the non-calcareous sediments of the Rača Unit display a very low degree of bioturbation. The CORB facies of the Rača Unit, containing calcareous intercalations, displays a very high degree of bioturbation as expressed by a high ichnofabric index. They contain trace fossils *Chondrites*, *Zoophycos*, *Planolites*, *Thalassinoides*, *Palaeophycus*, *Teichichnus* and *Phycosiphon.* The supply of food obviously acted as the controlling factor. The "calcareous" facies of the CORB of the Rača Unit has a considerably higher proportion of sand-dominated interbeds and also carbonates than the non-calcareous facies. This (especially the presence of carbonates) suggests a relative proximity of food-rich environments and an easy transport of nutrition-rich substrate by turbidite currents into the basin directly, not only by periodical fall-out of dead plankton (which is probably responsible for the rhythmicity of poor colonization horizons in weakly bioturbated units).

Key words: Upper Cretaceous, Western Carpathians, hemipelagic, ichnofossils, ichnofabric, red beds.

Introduction

Red-coloured rocks displaying all signs of deep marine sedimentation (turbidites, hemipelagites) are called Oceanic Red Beds. This relatively rare facies is associated with specific environmental parameters. Although their presence in the geological record is not exclusively restricted to the Cretaceous Period, these sediments are common in Upper Cretaceous oceanic basins, where they are referred to as Cretaceous Oceanic Red Beds (CORB; see Hu et al. 2005). In the last 15 years, their significance for the reconstruction of paleoenvironmental conditions in Late Cretaceous oceans has been acknowledged (cf. Skupien et al. 2009 and references therein).

Upper Cretaceous CORB are present in several tectonic units in the Outer Western Carpathians. Identification of more or less complete sections as well as mutual correlation between isolated outcrops are complicated by the nappe structure, minor tectonic deformations and locally also by the high thicknesses of the red beds. The correlation is also hampered by the considerable lateral diversity of the CORBs and the existence of transitional facies (Skupien et al. 2009). Field and laboratory studies were conducted in years 2005–2007 with the aim to solve the persisting correlation problems and to lay the basis for a more detailed interpretation. These studies were focused on integrated biostratigraphy (foraminifers, dinoflagellates, calcareous nannoplankton), sedimentology, mineralogy and ichnology (Skupien et al. 2009).

The ichnological characteristics of sequences containing CORB and some transitional facies is the subject of the present paper. The following aims were outlined: 1. provide information on substrate colonization and its fluctuations, and on feeding strategies of the benthos (thus contributing to regional paleoenvironmental and paleogeographic conclusions); 2. define the Oceanic Red Beds phenomenon against the transitional facies; 3. provide comparative information for other areas with occurrences of the Oceanic Red Beds, notably CORB.

Previous ichnological studies in the Oceanic Red Beds

No synoptic ichnological study of the CORB from a large area comprising several units and lithofacies has been completed yet. Ichnological research before the early 1990s, when the ichnofabric concept was widely developed (ichnofabric; Ekdale et al. 1991), gave preference to facies and sites yielding well preserved biogenic sedimentary structures of recurrent morphology, namely trace fossils. This, however, was not the case with distal turbidites or hemipelagic/pelagic clays. Detailed studies, dealing not only with lists of determinable ichnotaxa, but also with the degree of reworking (ichnofabric index), separate phases (sequences) of substrate colonization, ichnofabric rhythmicity, hence also with the rhythmicity of colonization windows, and with the relationship between the ichnocoenosis and the substrate colour, were published after the early 1990s (Leszczyński 1993; Wetzel & Uchman 1998a, 2001). These studies mostly concentrated on muddy turbidites as a whole, without any particular reference to their colour (which is the essential indicator of substrate oxidation, cf. Potter et al. 1980). Exceptional in this respect are the papers by Leszczyński (1993; a report of sections in the Cretaceous and Tertiary turbidite sequences from Spain, with generally very low or no intensity of bioturbation in red clays/claystones) and

Bąk (1995; Cretaceous marls of the Polish Carpathians). There are also other papers, which concern mostly the Paleogene red shales, namely Leszczyński & Uchman (1991, 1993).

Wetzel & Uchman (1998a) stated that red to brown claystones deposited in the oceans are characterized by slow sedimentation, limited food sources — at least inside the sediment (a temporary accumulation of dead phytoplankton occasionally rests on the surface) — and by generally complete bioturbation. The number of tiers is, however, limited, and the depth range of the bioturbation is only a few centimeters. An increase in the sedimentation rate may result in a considerable increase in food content, hence also in the depth of burrowing (and in the diameter of burrows). The common ichnotaxa are *Chondrites*, *Zoophycos*, *Planolites*, *Thalassinoides*, *Palaeophycus*, *Teichichnus*, *Phycosiphon*, *Lophoctenium* and *Nereites*. Most of them represent burrows permanently connected to the sea floor (*Chondrites* is a typical example); such adaptation may be favoured due to the low permeability of the bottom.

In the Outer Western Carpathians, more general attention has been given to the bioturbation structures of the CORB and the surrounding units. Intensively bioturbated rocks have been reported from some units underlying the CORB (Skupien & Vašíček 2003), and simple characteristics of the CORB ichnology have been provided from some sections of the Silesian and Rača Units (Skupien et al. 2009). However, detailed studies have not been presented.

Geological settings

The Outer Carpathians represent the northernmost zone of the Alpine-Carpathian orogen. They consist of two groups of nappes (from top to bottom): Magura Group of Nappes (Bílé Karpaty, Bystrica, Rača Units) and Outer Group of Nappes (Fore-Magura, Silesian and Subsilesian Units; Fig. 1); each of the units may have its specific local lithofacies. During the Mesozoic, the Outer Western Carpathians domain rimmed the continental foreland in the SE continuation of Paleo-Europe. This domain was separated by the Penninic Oceanic Branch from the Central Carpathian–Alpine microcontinent, associated with the Adriatic microcontinental assemblage. The Penninic rifting resulted in tensional stress accelerating both the subsidence and tilting of the Outer Carpathian intraplatform basins, accompanied by local volcanism (e.g. Mišík 1992; Michalík 1994).

Locally more than 6 km thick flysch deposits are typical of the Outer Carpathian sedimentary sequences. They were deposited in several troughs separated by ridges; from South to North, these are called: 1 — Magura Basin; 2 — Silesian Basin; 3 — Subsilesian Basin. Deposition started in the Late Jurassic as a consequence of enhanced subsidence. Sedimentation of black shales with local submarine clastic fans embraced almost the whole Outer Carpathian basin in the Early Cretaceous. Slow and uniform sedimentation of green and black shales took place during the Albian and Cenomanian, followed by sedimentation of red and variegated shales (CORB) under well-oxygenated conditions (Fig. 2). The CORB formation was terminated by the progradation of sand-dominated turbidites deposited in the axial parts of the subbasins and along the continental slope during the Late Senonian.

The tectonic structure of the Outer Carpathians is a result of several tectonic events (Neo-Alpine orogenic processes). Initial folding took place during the Oligocene in the southern part of the Magura Subbasin and then pro-

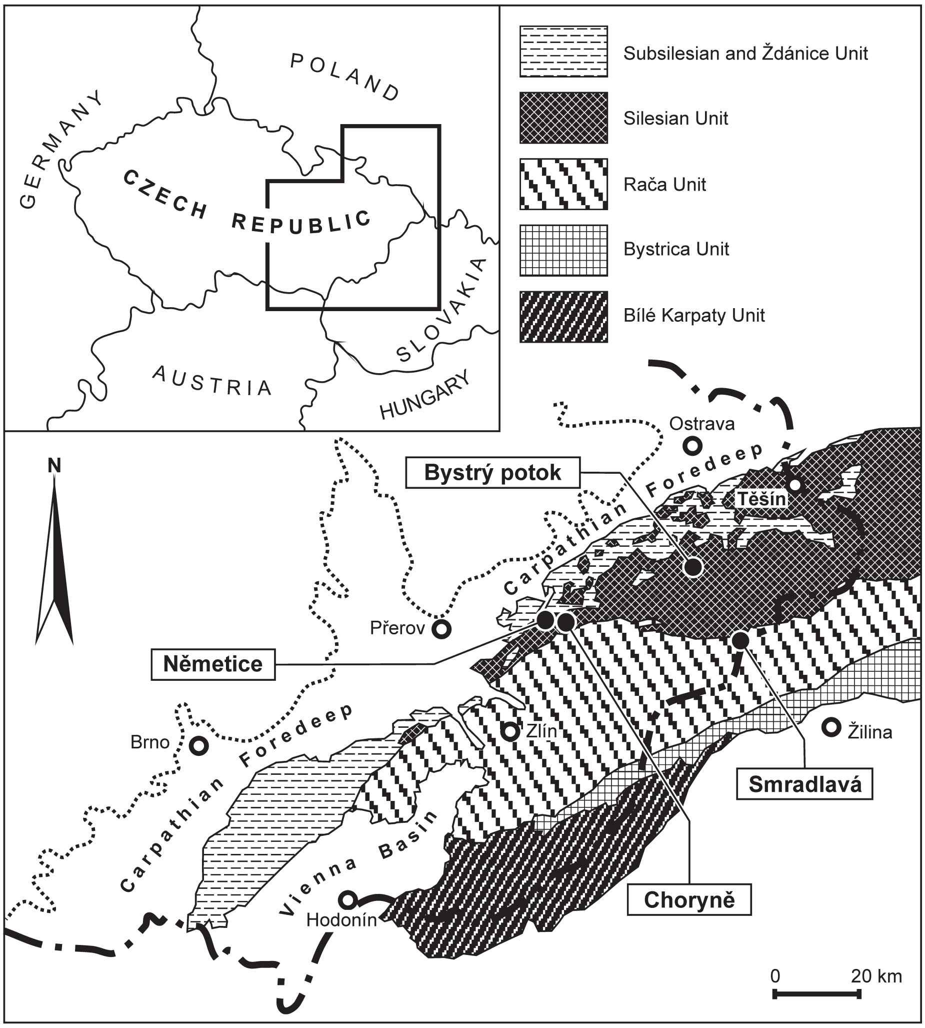
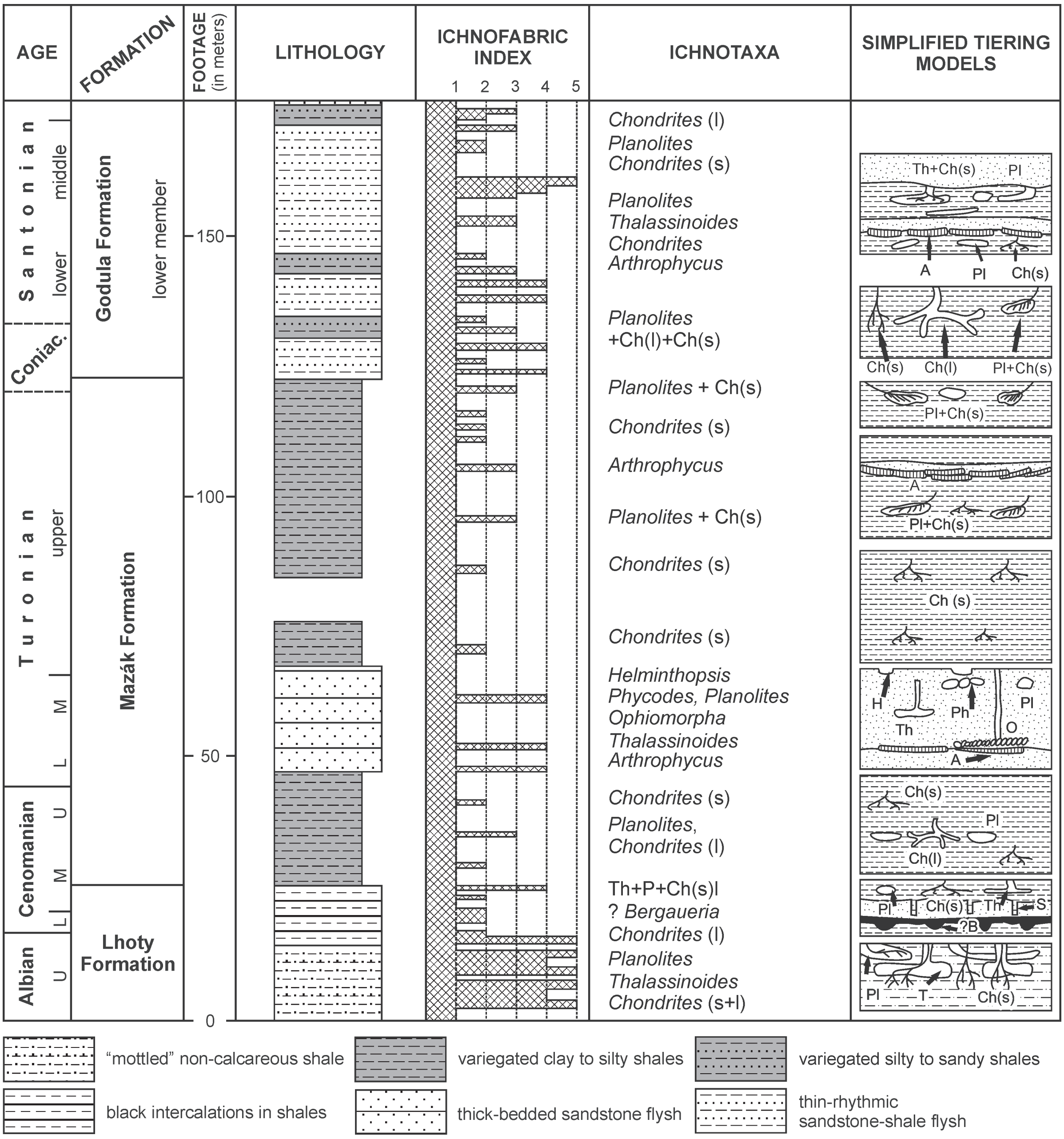


Fig. 1. Location map showing the main tectonic units of the Outer Western Carpathians in the Czech Republic. After Skupien et al. (2009).



Pl — *Planolites*, Th — *Thalassinoides*, Ch(l) — "large" *Chondrites*, Ch(s) —"small" *Chondrites*, ?B — ?*Bergaueria*, S — *Skolithos*, O — *Ophiomorpha*, A — *Arthrophycus*, Pa — *Palaeophycus*, H — *Helminthopsis*, Ph — *Phycodes*, Z — *Zoophycos*.

Fig. 2. Stratigraphy, lithology and ichnology of the Bystrý potok section (lower part).

gressed northeastwards. The formation of the thrusts and uplifting of this area was completed during the Early Miocene (e.g. Mišík 1992; Michalík 1994).

Material and methods

Ichnological study at all documented sections followed earlier lithological description and integrated biostratigraphic study (Skupien et al. 2009). The thickness of the sections from tens of meters to 300 m at Bystrý potok Stream did not allow a detailed, layer-by-layer ichnofabric documentation using an abbrasive paper (in mm-resolution). The essential resolution was on the order of tens of centimeters, with particular attention given to lithological boundaries and colonization horizons: here, documentation works were designed to achieve cm-resolution. Despite all the effort, it can be assumed that some of the weak colonization horizons have not been encountered. Information on their typical vertical spacing in the section and their overall character is, however, well substantiated.

A principal problem in the study of ichnofabrics of lithologically monotonous pelitic sediments is the differentiation between completely bioturbated facies and facies with no bioturbation. The absence of lamination is usually taken as evidence for total sediment reworking. Nevertheless, no distinct laminae may be visible in pelites with a very low proportion of detrital mica or other material subject to planar arrangement during the deposition. The most effective tool for a correct solution of this dilemma is an approximation by lithological boundaries. Such approximation should, however, always involve a consideration on the origin of the respective boundary: it may be connected with previous sea-floor erosion or a swing in environmental parameters potentially affecting the benthic biocoenosis. In any case, we are aware of the fact that the ichnofabric index (abbreviated ii further in the text; Droser & Bottjer 1986) itself in some portions of the studied sediments is a matter of interpretation rather than a mere mechanical determination.

Descriptive part

Silesian Unit — Godula facies

CORB and adjacent or similar rocks were studied in two facies of the Silesian Unit, namely the Godula and Kelč facies (or Godula and Kelč developments by Menčík et al. 1983). Different sedimentological settings resulted in separate lithostratigraphies of the facies. The Godula facies was deposited below the CCD in the continental rise setting in the form of thick turbidite fans. Upper Cretaceous strata have the character of shale-sandstone flysch up to 3500 m thick. The Kelč development represents mostly slope shales. The thickness of the Upper Cretaceous strata reaches several hundred meters.

The Godula facies, comprising turbidite fan facies, was studied in a continuous section through the CORB at the Bystrý potok locality (Skupien & Vašíček 2003). The measured section starts with the Lhoty Formation (Albian, Lower to low-Middle Cenomanian). The CORB are present within the Mazák Formation (Middle to Upper Cenomanian and Turonian) and the lower member of the Godula Formation (Coniacian, Santonian and Lower Campanian; Figs. 2 and 3).

Lhoty Formation in its typical development. The Lhoty Formation underlying the CORB-bearing complex is composed of medium grey to green-grey bioturbated shales, occasionally intercalated with non-bioturbated, thin sandstone turbidite beds. No visible ichnofabrics are displayed by most mudstones in the lowermost part (ca. 15 m) of the section. This can be explained

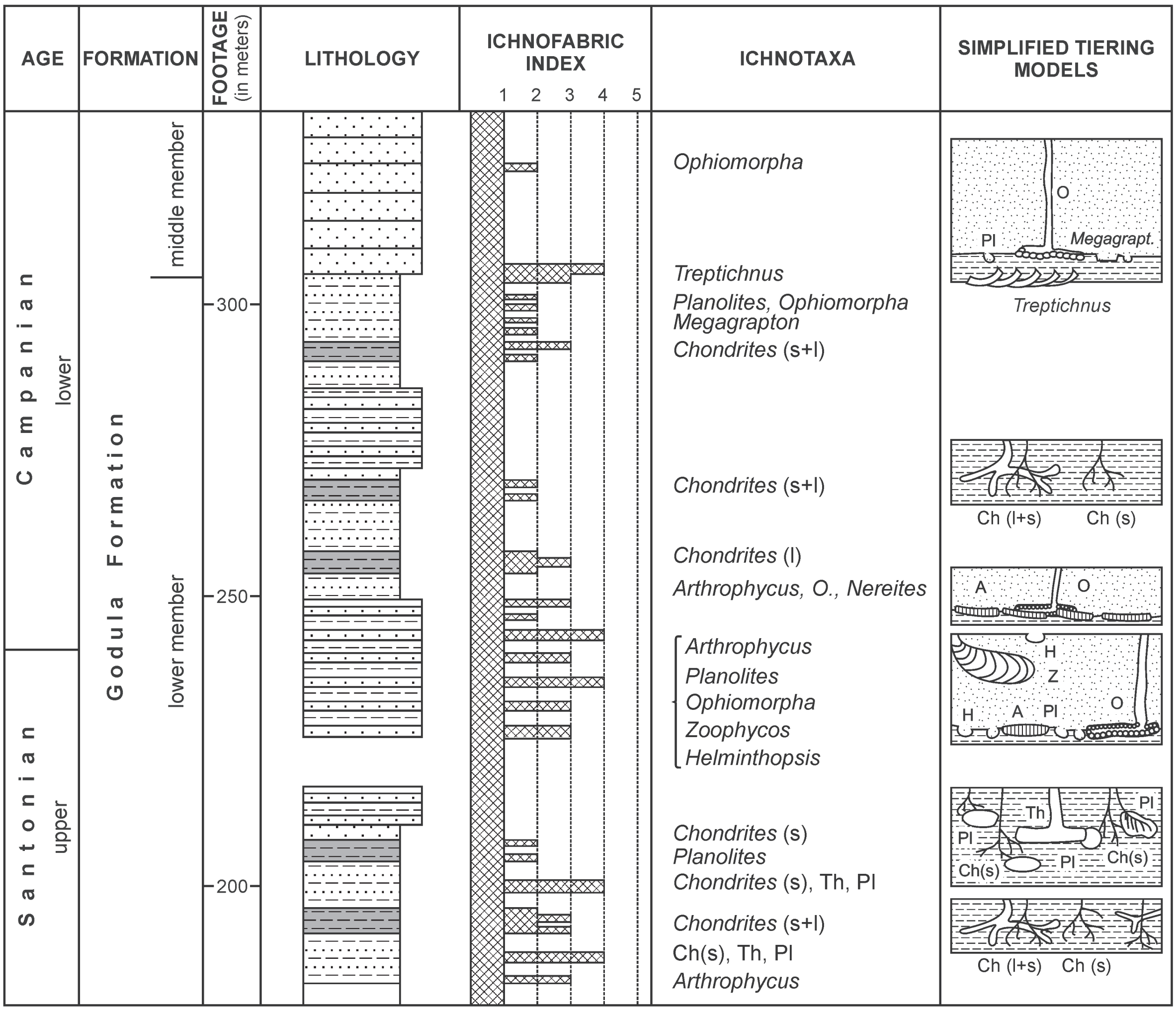


Fig. 3. Stratigraphy, lithology and ichnology of the Bystrý potok section (upper part).

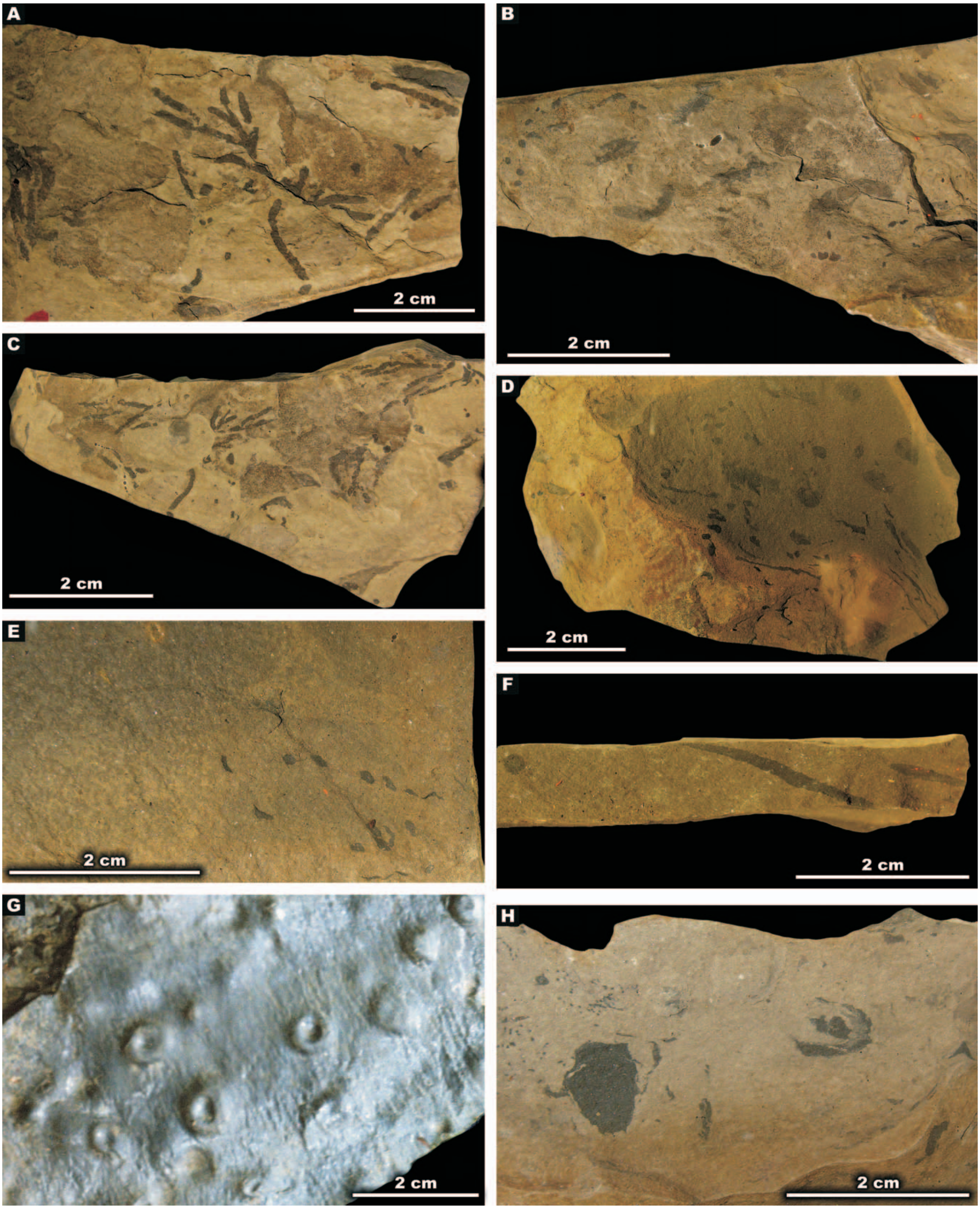


Fig. 4. Trace fossils and ichnofabrics of the Lhoty Formation, Bystrý potok section. **A, C, E** — *Chondrites* isp. (large to middle form) on a totally bioturbated background — horizontal views; 2 m at the measured section; **B, D** — various aspects of the large *Chondrites-Planolites-Thalassinoides* ichnofabric, minus 3 m at the section; **F** — vertical section of large *Chondrites* isp. on a totally reworked background; 2 m at the section; **G** — ?*Bergaueria* isp., convex hyporeliefs, at 17.5 m of the section; **H** — small *Chondrites-Planolites-Thalassinoides* ichnofabric, minus 3 m at the section.

primarily by two facts: (1) no colonization of substrate ever occurred, as indicated by the preservation of the primary lamination (especially in siltstones with sand admixture); (2) homogenization by bioturbation took place, as shown by lighter grey claystones with no preserved lamination; homogenization was followed by an episode of rapid sedimentation, which prevented colonization by deep-tier burrowers (*Chondrites*). Where neither of the above mentioned possibilities is valid, an ichnofabric *Planolites–Thalassinoides–Chondrites* is present; see Fig. 4B,D,H. Some intervals manifest a very contrasting preservation of the deepest tier, represented by "large forms" of *Chodrites* on a bioturbated background (sometimes a completely bioturbated backround, i.e. ichnofabric index = 5; Fig. 4A,C,E,F). The given order of ichnotaxa corresponds to their order of appearance in the substrate and also to the completeness of preservation of the biogenic structures. The ichnofabric index therefore oscillates between the values of 1 and 4 or 5 over more or less irregular intervals, with a prevalence of higher values (almost complete or complete bioturbation), see Fig. 2. Such ichnofabric documents normal oxygen and food conditions and has many parallels in other Mesozoic and younger flysch sediments (e.g. Wetzel & Uchman 2001).

Uppermost part of the Lhoty Formation. The uppermost part of the Lhoty Formation consists of light grey shale with few thin intercalations of dark grey shale with fish remains, silicified siltstones and cherts (Fig. 5B). Several centimeters thick intercalations of grey, fine-grained siliceous glauconitic sandstone occur in the higher part of this unit. A round biogenic structure resembling ichnogenus *Bergaueria* (interpreted as dwelling burrows of sea anemones; Fig. 4G) was found at the base of silicified siltstones. Vertical shafts are occasionally present, indicating a period of relatively stable, strong flow. The overlying part of the section reaching to the base of the Mazák Formation is dominated by light grey-green to dark grey claystones. The ichnofabric *Planolites–Thalassinoides–Chondrites* is present at only a few places. The ichnofabric index in this part of the Lhoty Formation is considerably lower than in intervals with usual development of the same formation: it generally oscillates between values of 1 and 2 over cm-intervals while values of 3 or 4 were recognized only rarely in irregular intervals tens of centimeters thick.

Mazák Formation — variegated strata. The Mazák Formation is a sequence of variegated (red, red-brown and greyish-green) non-calcareous shales, occasionally interbedded with thin beds of greenish grey quartzose sandstones. Red shales intercalated with grey or greenish grey shales represent the most frequent lithotype. At the Bystrý potok section, the formation is 94 m thick.

A preliminary study of the section revealed only a few bioturbated intervals (i.e. records of colonization windows) in the red claystones of the Mazák Formation. Small *Chondrites* was mostly the only ichnofossil encountered (e.g. at 68 m, Fig. 6F, and at 94.5 m, Fig. 6C–E). Exceptional is the interval with clearly visible *Chondrites–Planolites* ichnofabric (95 m, Fig. 6G,J), indicating a short-lived increase in nutrient supply. This is, after all, also documented by grey fillings of the *Planolites* tunnels. The overlying claystone bed is much lighter than the above mentioned fillings of ichnofossils and contains abundant, very minute *Chondrites*.

A repeated investigation of this interval (which is of key importance for the understanding of the ichnological contents of CORB in the Outer Western Carpathians due to its context, completeness of the section, and good exposure) brought finds of other weak colonization horizons, generally comprising solitary or very sparse minute individuals of *Chondrites* isp. It can be stated that records of poorly colonized bottom — difficult to document due to its low intensity — occur irregularly throughout the CORB section of the Mazák Formation, with spacings of tens of centimeters. Somewhat more compact red beds with macroscopically visible flakes of detrital mica were found at 35 m. Vertical sections in the rock show no visible lamination. Samples prepared by splitting of rock along bedding planes, however, show more or less developed lustre (orientation of mica flakes and other clasts), which is not fully homogeneous and suggests a relatively intensive bioturbation (Fig. 6A,B; ii = 3). Rather coarse (siltstone) beds with traceable lustrous bedding surfaces can be equally found elsewhere in the section; with the exception of the above mentioned red beds at 35 m, however, they show no (ii = 1) or a very weak (ii = 2) degree of bioturbation.

A sample of similar rock with notable greyish-green laminae was found in a streambed below the interval at 35 m. The greyish-green colour of "variegated" hemipelagic pelites and aleurites is either primary (iron oxides and hydroxides are never present in large proportions in the rock) or secondary ("depigmentation" by weathering processes); in the case of the mentioned find it is difficult to decide which possibility is more probable. Nevertheless, the sample found also shows "mottling" on a lithological boundary analogous to that from 35 m, moreover, with contrasting colours (Fig. 6K).

Therefore, the primary absence of bioturbation (ii = 1) from a large part of red beds is much more likely than their complete reworking (ii = 5): red, definitely non-bioturbated beds, much like bioturbated beds filled with rock of the same grain size and composition as the substrate for burrowing, were encountered. On the other hand, the find from 35 m indicates that many colonization horizons of shallow tier with relatively large tunnel diameters (maximum 10 mm) were probably overlooked. One of the reasons may be the primary extreme substrate homogeneity, preventing the identification of colonization windows by any routine method of study. We should also consider that the coarser portions with detrital mica could have been deposited at a higher rate than the surrounding clay, which may have resulted in a higher frequency of colonization windows in the clay beds (conversely, pore volume in slowly deposited clay substrates may be very low, thus restricting the bioturbation). At the present stage of field and laboratory study, the variegated strata of the Mazák Formation should be interpreted as rather weakly bioturbated, with prevailing ii = 1.

Mazák Formation — sand intercalations and rhythmic sand-dominated flysch. An interesting interval was encountered in situ around 59 m: two thin (ca. 8 cm) beds of glauconitic sandstone. Its base shows hypichnial tunnels of *Thalassinoides*/*Ophiomorpha*, *Phycodes* and *Planolites*. Similarly, tabular beds of sandy flysch, which are relatively abundant at 48–66 m, contain a rich ichnoassemblage: ?*Palaeophycus* cf. *sulcatus*, ?*Pilichnus*, *Helminthopsis* and *Arthrophycus* (Fig. 7G,H). This suggests that episodes of in-

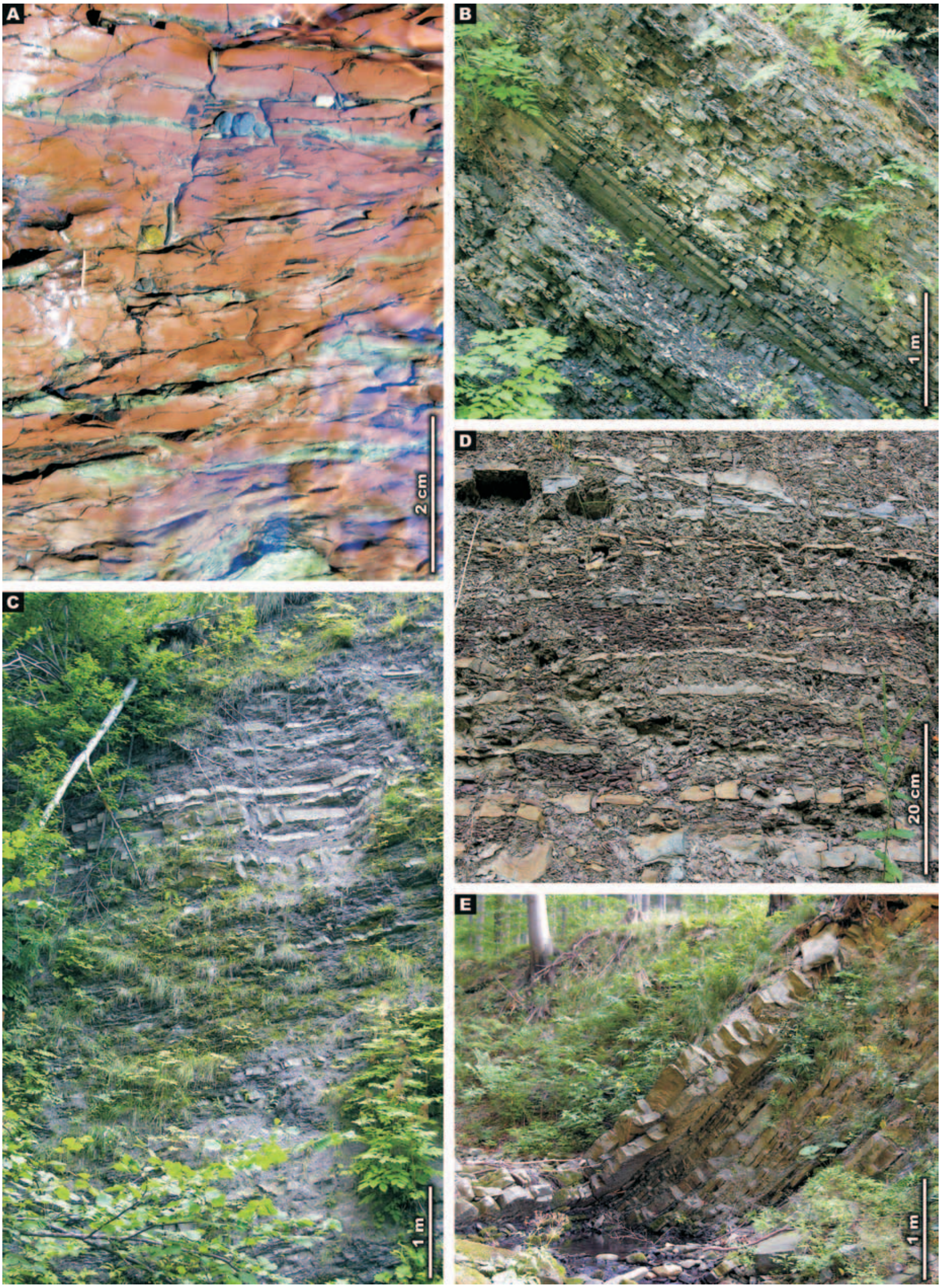


Fig. 5. Outcrops related to CORBs of the Godula facies of the Silesian Unit. **A** — red shales in the Bystrý potok section, approximately at 30 m of the measured section; **B** — top of the Lhoty Formation in the Bystrý potok section, at 18 to 22 m of the section; **C** — flysch development of the Mazák Formation, base of Turonian in the Bystrý potok section, approximately at 50 to 55 m of the section; **D** — Nořičí hora section, probably variegated intercalations in the lower part of the Godula Formation; **E** — Bystrý potok section, basal bed of the middle member of the Godula Formation (307 m at the measured section).

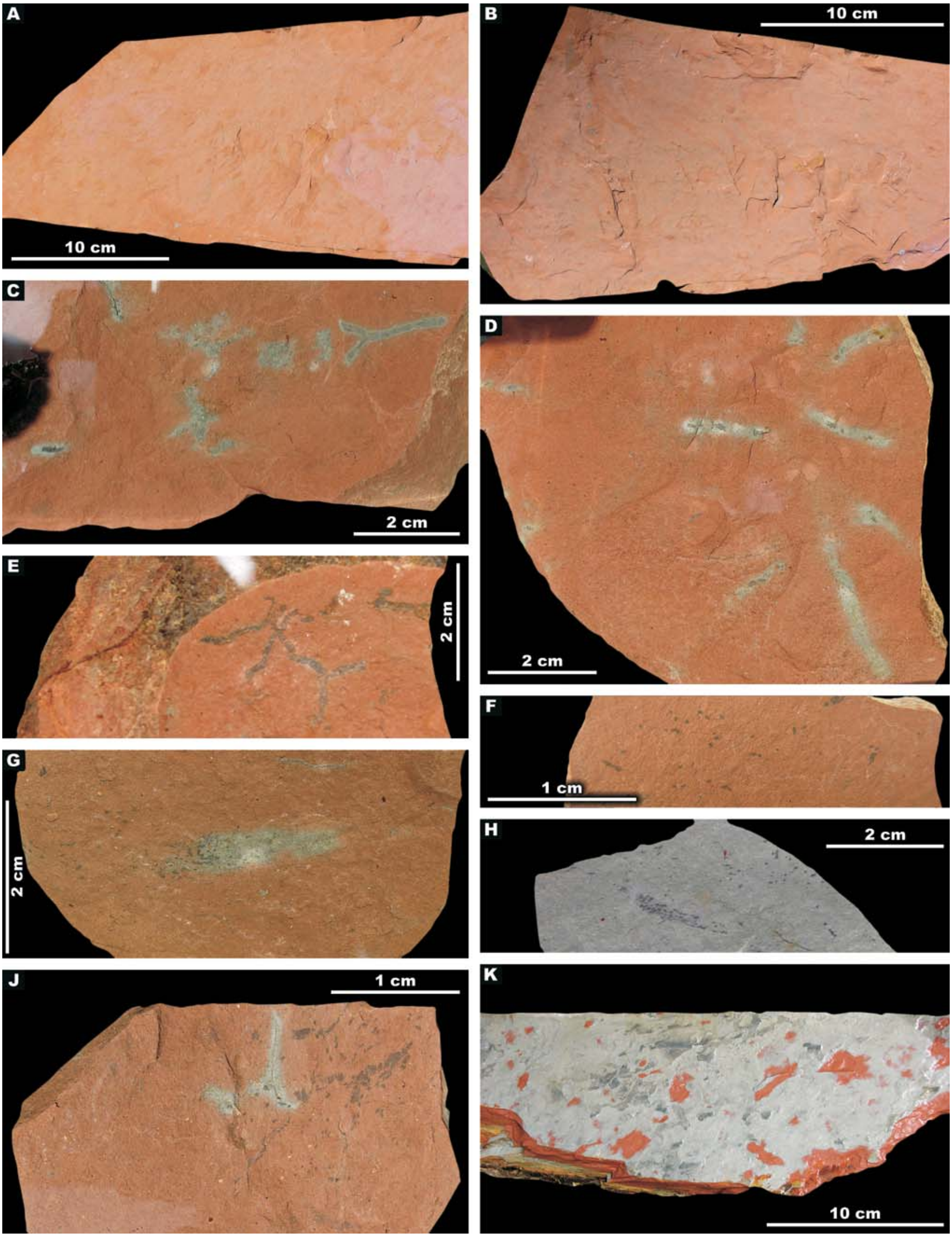


Fig. 6. Trace and body fossils of the CORBs, Bystrý potok section. **A–B** — mottled reddish shale (?*Planolites* ichnofabric), at 35 m of the section; **C–E** — probable body fossils of tubular Foraminifera, resembling the ichnogenus *Chondrites*, in a non-bioturbated rock; around 94.5 m of the section; **G, H, J** — small stenomorphic *Chondrites* following the previous *Planolites* ichnofabric; around 95.0 m of the section; **F** — solitary small *Chondrites*, at 68 m of the section; **K** — "mottled" greyish-green lamina on a red shale; *Planolites* ichnofabric; approximately 20–25 m at the section.

put of coarse detrital material implied a short-lived influx of nutrients necessary for the development of rich benthic communities. Moreover, episodes of sand deposition (probably of turbidite-flow origin) are favourable for the preservation of biogenic structures in flysch sediments and, as such, represent only a weakly filtered taphonomic record.

Lower member of the Godula Formation. It consists of thin- to medium-bedded flysch dominated by grey shales; variegated intervals still occur, but their colours are less intense: red grey, brown grey, reddish brown grey. A 15 m thick body of grey claystones with frequent clayey ironstones and no variegated intercalations (160–175 m of the section) is present in the lower part of the member. Higher up in the section, the lower member of the Godula Formation contains two bodies of sandstone flysch, which are 38 and 13 m thick. Green-grey colours of shale prevail in the uppermost part of the lower member (Figs. 2 and 3).

Greyish-green or grey mudstones contain relatively frequent intervals with *Planolites–Thalassinoides–Chodrites* ichnofabric (Fig. 7A,D). Intervals with *Chondrites* only are even more frequent (Fig. 7B). According to the above postulated criteria, however, the lower member of the Godula Formation is generally dominated by no or very weakly bioturbated rocks (ii = 1). Non-bioturbated intervals alternate with intervals of weakly to moderately bioturbated rocks every several centimeters.

Clearly visible colonization horizons in red and brownish-red shales are somewhat more frequent than in the same rocks of the underlying Mazák Formation. They contain *Chondrites* as well as *Planolites*. The topmost variegated strata host typical, markedly developed "large" *Chondrites* isp. (Fig. 7C).

Sandstone intercalations in the lower part of the lower member of the Godula Formation contain *Arthrophycus*, usually preserved in hyporelief. Intercalations of sand-dominated flysch in the middle part of the lower member of the Godula Formation contain *Helminthopsis*, *Arthrophycus* (Figs. 7E and 8B), *Ophiomorpha* and *Planolites*, rare *Zoophycos* (Fig. 8C) and occasional *Nereites* isp. (Fig. 8A). *Megagrapton* and *Zoophycos* occur in the uppermost strata of the lower member of the Godula Formation (mostly coarsely rhythmic alternation of sandstone and siltstone, seldom claystone). The basal bed of the sand-dominated flysch of the middle member of the Godula Formation (Fig. 5E) is marked by an exceptional, giant biogenic structure ascribed to the ichnogenus *Treptichnus* (Fig. 8E).

Silesian Unit, Godula facies — a summary. Four types of strongly bioturbated sediments were repeatedly identified: (1) grey hemipelagic to pelagic mudstones completely bioturbated at levels of the colonization horizons, with two well-defined tiers of biogenic activity; (2) red claystones with sporadic presence of clearly visible colonization horizons mostly represented solely by *Chondrites* with low density of individuals, more rarely by the *Planolites–Chondrites* succession with a low density of individuals. The presence of additional colonization horizons (probably outnumbering those clearly identifiable by several times, probably a shallower tier) can be assumed on the basis of an analogy with occasional beds with higher silt content in the studied sequence; (3) moderately to coarsely rhythmic sand-dominated flysch with *Thalassinoides*/*Ophiomorpha*, *Arthrophycus*, *Phycodes* and others, which roughly corresponds to a modification of the "seilacherian" *Cruziana* ichnofacies; (4) moderately to coarsely rhythmic sand-dominated flysch with *Zoophycos*, *Megagrapton* and *Treptichnus* referring to the "seilacherian" *Zoophycos* ichnofacies with elements of the *Nereites* ichnofacies. Finely to coarsely rhythmic flysch with regular alternation of pelites, siltstones and sandstones and with a suite of the *Nereites* ichnofacies is missing (*Paleodictyon*, *Nereites*, *Urohelminthoida*, *Glockerichus*, *Lorenzinia* and other graphoglyptids).

Silesian Unit — Kelč facies

In the Kelč facies, the CORB are underlain by grey and greenish-grey "mottled", usually calcareous shales with variable sand content. These are placed to the Jasenice Formation (Eliáš 1979), which is roughly analogous in age and character of sediments to the Lhoty Formation of the Silesian Unit (Skupien et al. 2009). In the Kelč facies, the CORB occur in the Němetice Formation, which was defined by Eliáš (1979) as green-grey and grey shale with sporadic red and brown-red beds; recently, several black-grey shale horizons, grey marlstones to clayey limestones, grey-green siltstones, and thin banks and lenses of fine-grained calcareous subgreywackes were also encountered in the type area near Němetice (Skupien et al. 2009). The overlying Milotice Formation (Eliáš 1979) consists of grey clays with variable contents of carbonate, silt and sand admixture. Red-brown intercalations occur rarely. Sandstones are also rare and occur in thin isolated beds (Fig. 9).

Jasenice Formation. Several outcrops of this formation including a larger one with the overlying red beds are exposed in a gorge of a stream flowing north, from the easternmost edge of Němetice to the area SE of the Pod Doubravou settlement. Greyish-green shales are "mottled", completely or almost completely bioturbated (ii = 3–5); the separate "mottles" can be interpreted as deeper tier trace fossils *Planolites* and *Thalassinoides* (Fig. 10H,J). Smaller outcrops further downstream and talus accumulations yielded fragments of tabular sandstone beds with hypichnial *Ophiomorpha* (Fig. 10G). A continuous mixing of substrates indicates favourable nutrition and oxygenation conditions on the bottom.

Němetice Formation. Approximately 4 m of mottled greyish-green shales and ca. 3 m of red beds of the lower part of the Němetice Formation crop out in a slope on the right bank gorge of a stream flowing towards the north from Němetice (ca. 1500 m SE from the Pod Doubravou settlement). These red beds show no signs of bioturbation.

Milotice Formation. It was studied in outcrops on both banks of the Bečva River downstream from its confluence with the Juhyně River at the Choryně village. Outcrops on the left bank are currently deformed by landsliding and the section cannot be fully studied. The section starts with a sill of amygdule-rich lava of the teschenite association. The overlying silty shales are baked, mostly dark grey in colour, with no bioturbation. Greyish-green claystones with tabular beds of sandstone are exposed some 20 m downstream. The claystones are strongly compressed, which hampers the identification of ichnofabrics. Ichnofabric in the proximity of sandstone

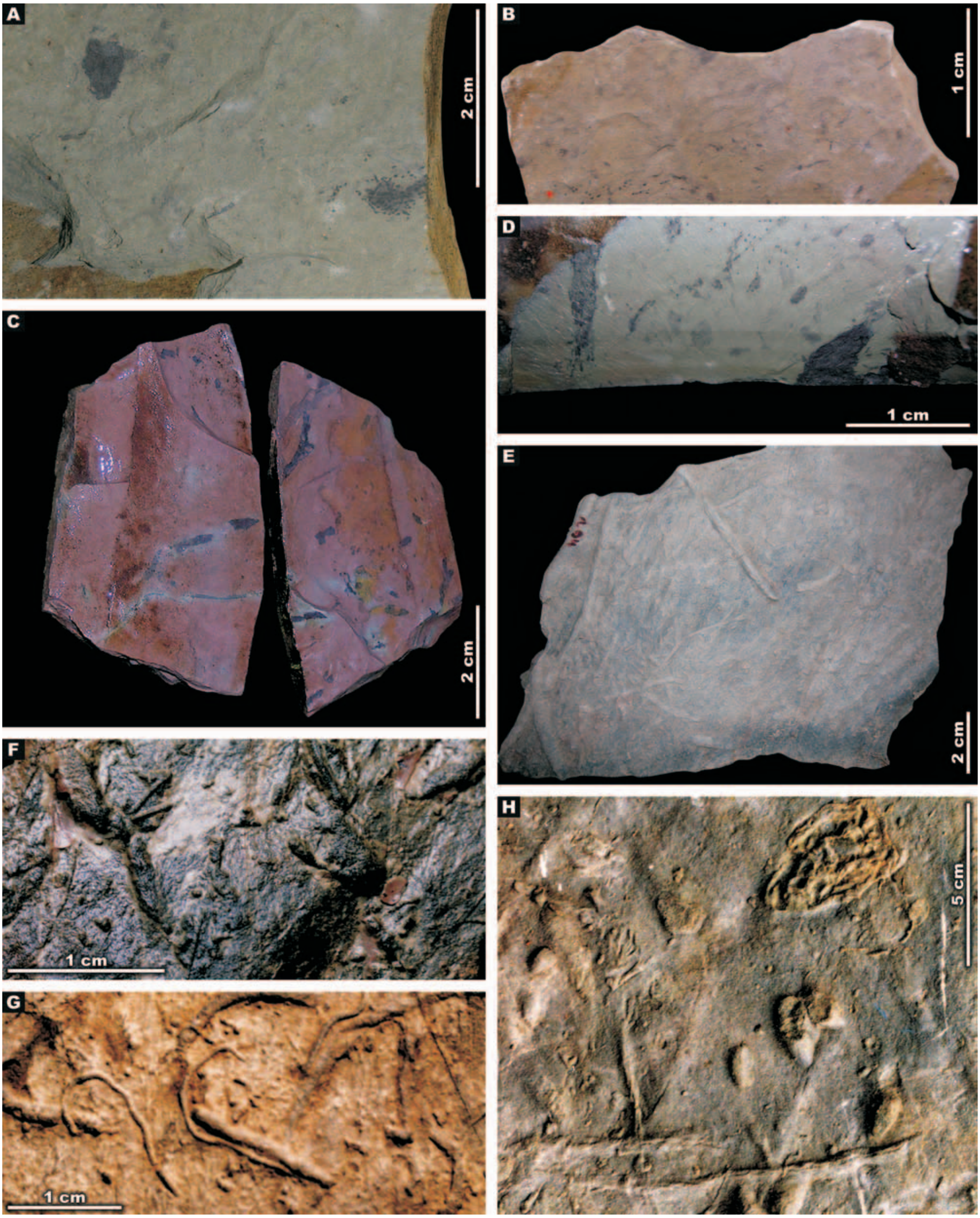


Fig. 7. Bytsrý potok section, trace fossils from the uppermost (flysch) part of the Mazák Formation and from the lower member of the Godula Formation. **A, D** — a contrast *Chondrites–Planolites* ichnofabric on a weakly mottled background, 123.5 to 125.0 m of the section; **B** — small *Chondrites* on a bioturbated background, 123.5 to 125.0 m; **C** — large *Chondrites*, at 190 m; **E** — sole of a sandstone bed with *Arthrophycus* (small) and ?*Ophiomorpha* (large tunnels), 294 m; **F** — *Arthrophycus* on a sandstone sole, 110.7 m; **G** — *Helminthopsis* isp. (curved) and *Planolites* isp. (straight); fallen sandstone block, about 48–60 m; **H** — *Palaeophycus* cf. *sulcatus* (at lower margin), ?*Phycodes* isp. (middle), *Chondrites* (left) and an undetermined elliptical cross-section (upper right), fallen sandstone block, about 48–60 m.

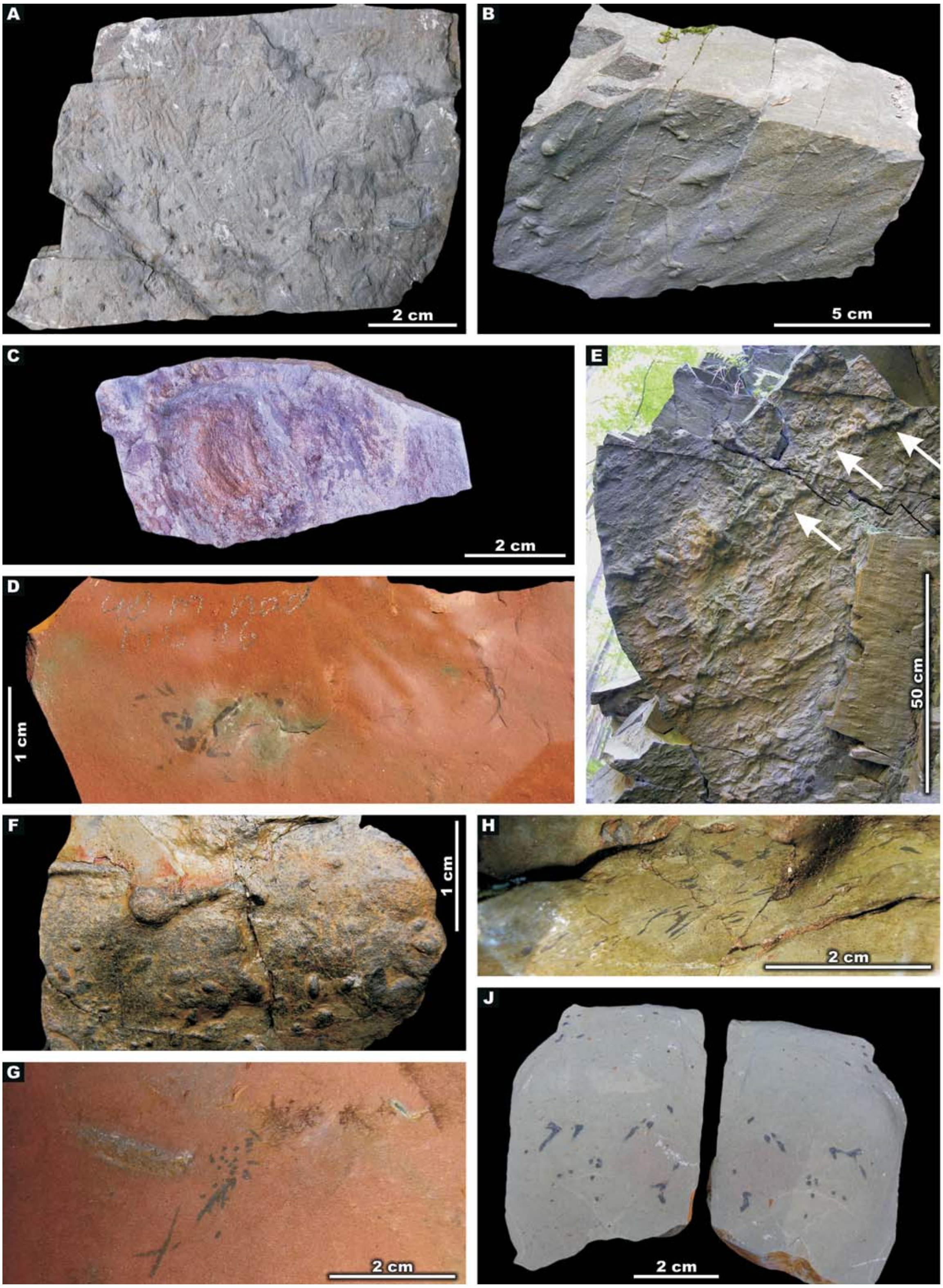


Fig. 8. A–C, E — Bystrý potok section, trace fossils from the flysch facies of the Godula Formation. A — epirelief of *Nereites* isp., 245 m; B — hyporelief with *Arthrophycus* (small) and eroded cross-sections of shafts (?*Ophiomorpha*), 235 m; C — *Zoophycos* isp., 250 m; E — *Treptichnus* isp. and segments of *Thalassinoides*/*Ophiomorpha* systems, base of the boundary layer of the middle member of the Godula Formation. **D, F–J** — trace fossils from CORBs and adjacent rocks of the Kaumberg Formation, Smradlavá Section. D, G — stenomorphic *Chondrites* (following previous shafts of *Thalassinoides*?), ca. 45 m upstream from the bridge which is the beginning of the Smradlavá section; H — idiomorphic *Chondrites* cut on the stream bottom (5 m upstream the bridge); J — idiomorphic *Chondrites* on a bedding plane (55 m upstream the bridge).

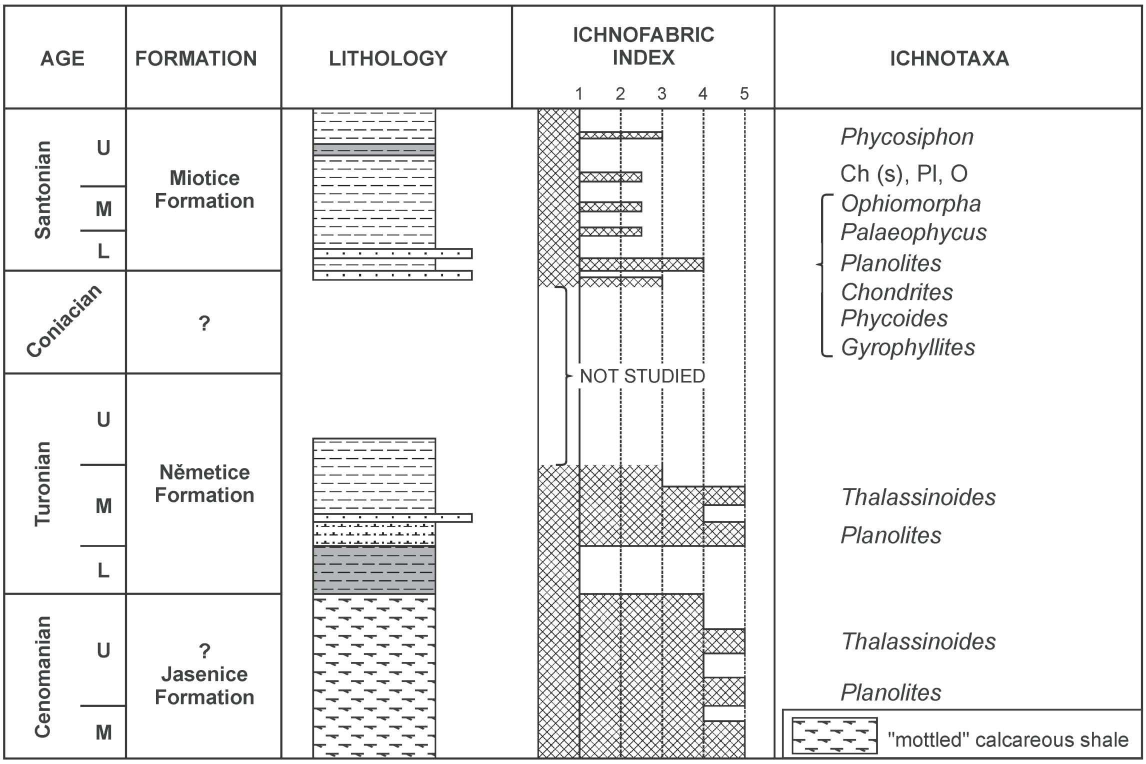


Fig. 9. Supposed stratigraphy, lithology and ichnology of the Němetice (Cenomanian to Turonian) and Choryně (Coniacian to Santonian) sections. Overall thickness of the depicted interval is hundred(s) of meters; not to scale.

beds is, however, distinct ("pressure shadow"): it can be characterized as *Planolites*-dominated with ii = 2–3 (low-intensity substrate feeding, probably in a single episode). The sandstone beds show hypichnial ?*Palaeophycus* cf. *P. sulcatus* (Fig. 10A) and more rarely *Ophiomorpha* isp., which indicates episodes of higher physical energy of the environment. Epichnial idiomorphic *Chondrites* isp. suggests an episode of low physical energy after sand deposition.

Further up in the section (not further than 50 m from the confluence), claystones with giant (≥1 m in diameter) concretions of micritic siderite ironstone are present. One of the concretions revealed ichnofabric (Fig. 10C) composed of a horizontal tunnel network (*Planolites*/*Megagrapton*) and a bundle of probable feeding tunnels (*Phycodes* isp.). The latter trace fossil is filled with glauconitic sandstone not documented elsewhere in the section. This is followed by an interval that is strongly deformed by landsliding, with first continuous outcrops of Cretaceous rocks *in situ* present 100–150 m from the confluence. These outcrops show greyish-black clays to claystones with sporadic thin (a few centimeters) tabular beds of sandstone. The sandstone bed revealed a perfectly preserved hypichnial, radial structure of the ichnogenus *Gyrophyllites* Glocker, 1841 (Fig. 10B). The base of the bed also contained *Palaeophycus* cf. *tubularis* Hall, 1847. The surrounding shales also contain sandstone-filled tunnels of *Palaeophycus* isp. or *Ophiomorpha* isp. (difficult to distinguish due to the mode of preservation). Such an assemblage documents that this part of the section probably originated under ecologically less restricted conditions than the rest of the section, with more sophisticated and long-lasting food exploitation of the substrate and rather permanent dwelling burrows of filtrators or predators. The remaining part of the section is hidden beneath ?colluvia with blocks of algal limestone.

On the right bank, a more or less continuous outcrop starts downstream of the weir on the Bečva River. It features grey claystones and siltstones, occasionally with a greenish tinge, containing very rare lenticular and tabular sandstone beds. It can probably be correlated with the middle part of the outcrop on the opposite bank. The ichnofabric is weak and colonization horizons are generally several meters apart. The true thickness and spacing of the separate colonization horizons mostly cannot be determined due to tectonic deformation. The first encountered colonization horizon is characterized by *Planolites*-dominated ichnofabric and ii = 2–3 (substrate feeding of low intensity and low efficiency, probably in a single episode). Several meters up in the section, fragments of tabular sandstone beds and of sandy lenses can be found with sporadic hypichnial and epichnial *Ophiomorpha* isp. and *Planolites* isp. Greenish claystones with perfectly developed colonization horizon of the ichnogenus *Chondrites* (Fig. 10E) are visible another several meters up in the section. After several tens of centimeters, these are followed by a sandstone bed with a suite of *Planolites–Ophiomorpha* at its base. Greyish-black claystones above the sandstone bed contain a ca. 2 cm thick interval with *Planolites* cf. *montanus* (ii = 3). The claystones are followed by a long non-bioturbated interval with a single visible red bed — the only equivalent of the CORB found in this section. Some 130 m downstream from the weir, a small but notable outcrop of

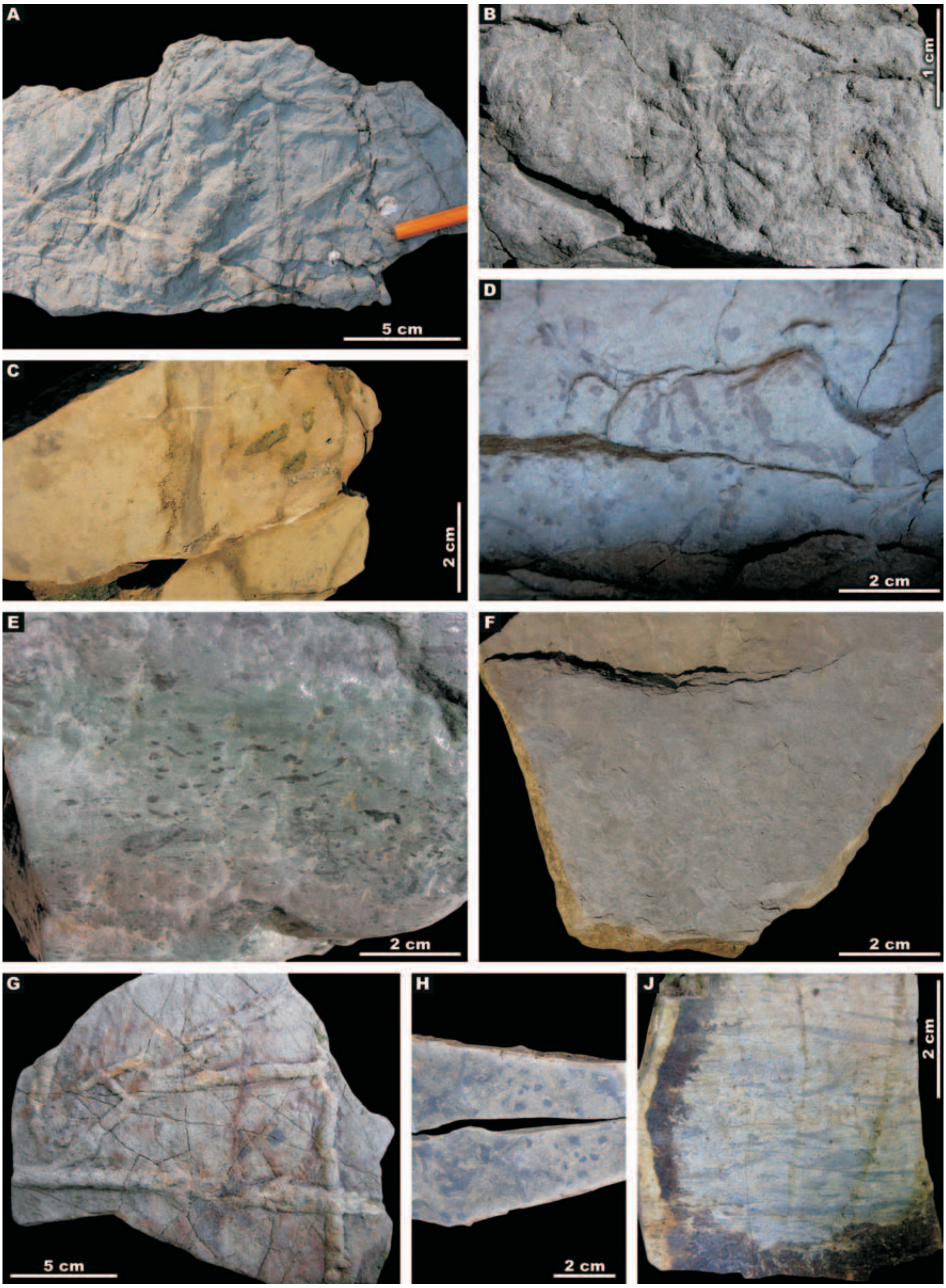


Fig. 10. Trace fossils from the Kelč facies of the Silesian Unit. **A** — convex hyporelief of ?*Palaeophycus* cf. *P. sulcatus*; Milotice Formation, Choryně locality — left bank, 20 m downstream from the lava sill; **B** — *Gyrophyllites* isp.; Milotice Formation, Choryně — left bank, 100 m downstream from the lava sill; **C** — ?*Planolites* isp. and *Phycodes* isp.; Milotice Formation, Choryně locality — left bank, 20 m downstream from the lava sill; **D** — *Chondrites* isp., Milotice Formation, Choryně locality — left bank, 20 m downstream from the lava sill; **E** — *Chondrites* ichnofabric; Milotice Formation, Choryně locality — right bank, 10 m downstream from the weir; **F** — *Phycosiphon* ichnofabric (inconspicuous minute tunnels on the bottom of the sample); Milotice Formation, Choryně locality — right bank, 130 m downstream from the weir; **G** — *Ophiomorpha annulata* (Książkiewicz 1977), convex hyporelief; Jasenice Formation, Německe locality; **H–J** — "mottled" shales bearing recognizable tunnels of *Planolites* and *Thalassinoides*; H — horizontal aspect; J — vertical section.

laminated siltstones contains a trace fossil of *Phycosiphon* isp. (Fig. 10F; very small loop-shaped spreiten-structures), that is traces of substrate feeding.

Silesian Unit, Kelč facies — a summary. The onset of CORB or their equivalents in this facies resulted in considerably restricted conditions for the development of benthic organisms. Colonization horizons with *Chondrites* isp., *Planolites/Ophiomorpha* and *Phycosiphon* indicate short incursions of conditions favourable for infauna. Lower bedding planes of rare sandstone intercalations yielded a more complex assemblage of trace fossils (*Gyrophyllites*, *Palaeophycus*, *Phycodes*, *Ophiomorpha*) showing less restricted conditions and more diversified feeding strategies.

Rača Unit

Unlike in the Silesian Unit, tectonic deformation and poor outcrops did not allow the construction of a composite section for the Rača Unit. A generalized stratigraphic chart of the Upper Cretaceous in the Rača Unit (Fig. 11) was based on biostratigraphic data from isolated outcrops and short sections. The CORB form the Kaumberg Formation as brown-red and greenish-grey shales with variable silt content. The Kaumberg Formation is 300–400 m thick; it is nearly completely non-calcareous at the Smradlavá site (Fig. 1) but it contains numerous calcareous beds ca. 20 km west of this site — at the Bučkový Stream site S of Horní Bečva. Notably, the sites also considerably differ in their ichnological contents.

The shale-sandstone flysch overlying the CORB of the Rača Unit is called the Soláň Formation, which contains several horizons of red-brown shales, reflecting short recovery episodes of oligotrophic setting controlling the CORB formation.

Kaumberg Formation at the Smradlavá site. At Smradlavá, the lower part of the CORB shows the sequence of grey-green and brown-red silty shales containing 0.5 to 4 cm thick hypoxic black-grey shale horizons with rare fish remains. Fine- to medium-grained sandstones rarely compose thin-bedded flysch. Thick banks of sandstones and slump bodies of poorly sorted muddy sandstones occur locally. Rhythmic thin- to thick-bedded turbidite sandstones appear in the upper part of the CORB. This turbidite member of the formation contains rare grey to red calcareous mudstone horizons. Most of the CORB are not bioturbated. Weak colonization horizons marked by sparse *Chondrites* and *Planolites* can be traced at intervals of approximately 2 m. A single sandstone bed provided the ichnologic record of a short-time colonization by sediment-feeders, suspension-feeders and chemichnia (ichnofossils *Planolites*, ?*Trichichnus* and ?*Arenicolites*).

The succession of red, locally greenish claystones, occasionally with secondary light grey colouration, is rather monotonous from the ichnological point of view. Colonization horizons with idiomorphic *Chondrites* isp. are developed (Fig. 8H,J). Horizons with very weak *Planolites*-dominated bioturbation are also present, accentuated by stenomorphic *Chondrites* isp. in the fillings of *Planolites* isp. (Fig. 8D,G). The average spacing of the colonization horizons is 2 m but any rhythmicity of the phenomenon is difficult to assess because the intensity of reworking is low and most horizons with trace fossils cannot be identified by routine collection techniques. It is a very restricted environment for in-fauna (oligotrophy), however, permitting episodic, highly economic life strategies with a low density of tracemakers. A bed of laminated sandstone ca. 5 cm thick immediately below the bed marked MB16C (micropaleontological sampling; Skupien et al. 2009) bears *Planolites* isp., ?*Trichichnus* isp. and ?*Arenicolites* isp. (Fig. 8F). The suite of these generally simple traces of opportunistic tracemakers and the low intensity of bioturbation point to a colonization after a short episode of elevated physical energy (probably related to the deposition of the sandstone bed).

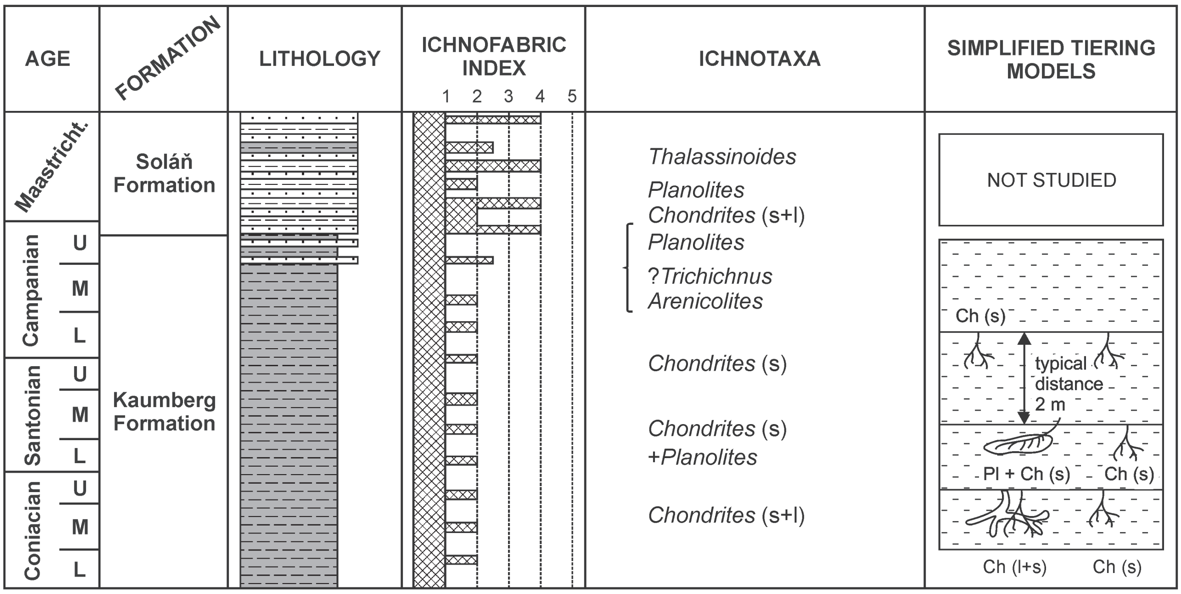


Fig. 11. Supposed stratigraphy, lithology and ichnology of the Smradlavá section. Overall thickness of the section is hundred(s) of meters; not to scale.

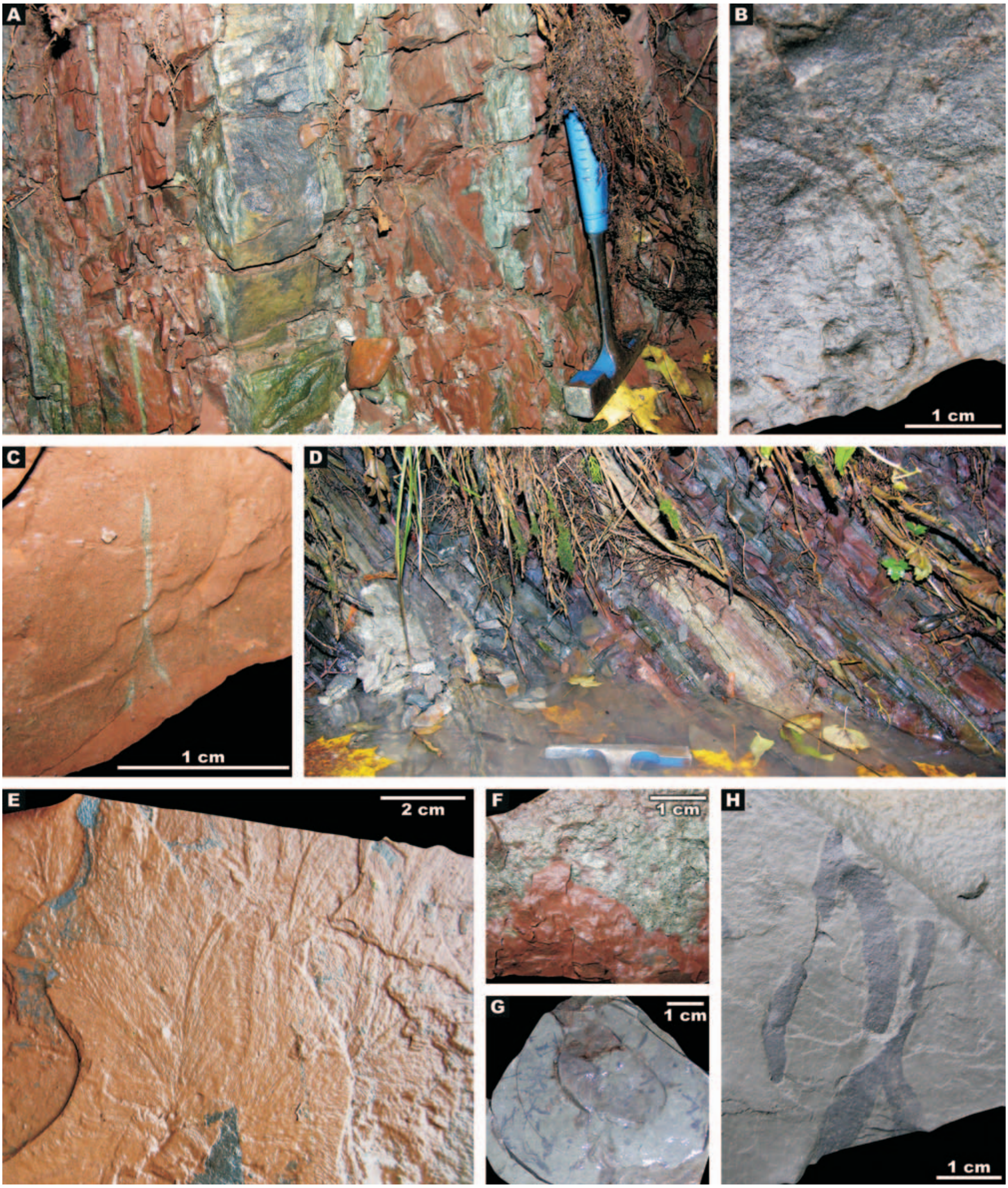


Fig. 12. A–F, H — trace fossils from the Rača Unit, Kaumerg Formation at the Bučkový potok section. A — outcrop in the right stream bank ca. 50 m below the base of the Soláň Formation. Red beds intercalated with sandstones bearing *Thalassiniodes* and *Planolites* in hyporeliefs; B — lower bedding plane of one of the sandstone beds depicted on Fig. 12A; *Planolites* isp. (upper) and *Helminthopsis* isp. (middle and lower); C — *Chondrites* isp., ca. 40 m below the base of the Soláň Formation; D — two calcareous layers ca. 10 m below the base of the Soláň Formation, left bank; E — *Zoophycos* isp. in calcareous CORBs, top of the Kaumerg Formation; F — "mottled" fine-grained sandstones and shales; outcrop in the right stream bank ca. 45 m below the base of the Soláň Formation; H — large *Chondrites* isp. in a carbonatic layer ca. 14 m below the base of the Soláň Formation. **G** — Soláň Formation of the Rača Unit, Bučkový potok section, several meters above the base of the formation. *Chondrites*–*Planolites* ichnofabric on a completely bioturbated background.

Kaumberg Formation at the Bučkový Stream site. This site exposes the upper part of the Kaumberg Formation and the lower part of the Soláň Formation. Exposure of the former unit in the stream bed is incomplete, strata are mostly overturned and monoclinally dipping. The tectonic deformation is relatively low, as revealed by tentative biostratigraphic analyses. Reddish-brown shales are the prevailing (but not absolutely prevailing) lithology. With very rare exceptions (Fig. 12C), they mostly lack ichnofabrics with *Chondrites* isp., characteristic for the preceding site. These shales are intercalated with greenish beds (cm thicknesses) to laminae (mm thicknesses) containing large flakes of detrital mica and sand with traces of shallow reworking (Fig. 12F). One of the thin green laminae yielded minute ?*Phycosiphon* isp. The red shales themselves show indications of mottled lustre in some portions (indicative of intensive reworking by in-fauna). Relatively common tabular intercalations of sandstone, centimeters to tens of centimeters in thickness, contain hypichnial *Arthrophycus*, *Helminthopsis*, *Thalassinoides* and *Planolites* (Fig. 12B) and bases of *Diplocraterion*. *Helminthopsis* is mostly the only epichnion. Thinner intercalations are richer in ichnological content: their deposition was probably not connected with such intensive erosion of the previous substrate.

Beds of strongly calcareous, light grey claystone (Fig. 12D), several centimeters thick, appear some 10–15 m below the onset of coarse-grained rhythmic flysch of the Soláň Formation. They contain only sporadic "large" *Chondrites* isp. (Fig. 12H). The ambient red shales have a variable but locally considerable proportion of carbonate, which can be seen macroscopically by their consistency and elevated resistance to mechanical weathering. At least two of these beds show intensive bioturbation: minute spreiten-structures generally attributable to small forms of the ichnogenus *Zoophycos* by the presence of helicoidal elements. A smaller proportion of these structures, however, show elements of bilateral, "feather-like" spreite symmetry, thereby representing "composites" of the ichnogenera *Zoophycos* and *Lophoctenium*.

Soláň Formation. The Soláň Formation, overlying the Kaumberg Formation, is only poorly exposed at the Smradlavá site. The degree of its exposure at the Bučkový Stream site is considerably higher. The streambed reveals thinly tabular (first tens of centimeters in thickness) to thickly tabular (maximum 0.6 m) beds of coarse-grained sandstone. The bases of these beds bear current marks and less common tunnels of deep tier trace fossils (*Ophiomorpha*, *Thalassinoides*) exhumed by erosion. The proportion of hemipelagites is very low. They are green or grey in colour and are either completely bioturbated with no visualization of any ichnotaxa or show the *Thalassinoides*–*Planolites*–*Chondrites* ichnofabric (Fig. 12G) in which the trace fossils are filled with colour-contrasting material as the last stage of bioturbation.

Discussion

As has been stated above, ichnological study of the CORB and the Tertiary oceanic red beds from a larger area with a high facies variability has not been carried out yet. A partial exception is the study of Leszczyński (1993) on Cretaceous and Tertiary turbidite sequences in Spain with generally very low-intensity or no bioturbation of red clays/claystones. Other above-mentioned studies (i.e. Leszczyński & Uchman 1991, 1993; Bąk 1995) focus on less variable geological units. A more general characteristic based on various small-scale studies and unpublished observations was provided by Wetzel & Uchman (1998a). These authors stated that red to brown claystones accumulated in the oceans are usually characterized by complete bioturbation; the number of tiers is limited and the typical depth of bioturbation is several centimeters. An increase in the rate of sedimentation may result in a considerable increase in the food content, hence also in the depth of burrow penetration and in the diameter of tunnels and shafts.

The studied units provide examples confirming the validity of both the above cited studies. A very low degree of bioturbation is displayed by the CORB of the Godula facies of the Silesian Unit, by their equivalents (mostly not red) in the Kelč facies of the Silesian Unit, and by the CORB in non-calcareous sediments of the Rača Unit. In contrast, a high degree of bioturbation was observed in the CORB with calcareous intercalations in the Rača Unit: this facies provides an almost complete list of ichnotaxa given for the CORB by Wetzel & Uchman (1998a), namely *Chondrites*, *Zoophycos*, *Planolites*, *Thalassinoides*, *Palaeophycus*, *Teichichnus* and *Phycosiphon.*

The above facts imply that the range of bioturbation of the CORB may be extremely broad, with the supply of food obviously acting as the controlling factor. The "carbonate-rich" portion of the CORB of the Rača Unit has a considerably higher proportion of sand-dominated interbeds and also carbonates than the other described facies. This suggests a relatively easy transport of nutrition-rich substrate into the basin directly by turbidite currents, not only by periodical fall-out of dead plankton.

The correlation between high diversity of ichnotaxa/strong bioturbation/food rich environments, however, cannot work outside a narrow range of parameters. In general, eutrophy favours opportunistic strategies; trace fossils resulting from them tend to be present with low diversity and high abundance. Higher productivity, however, may increase the amount of organic particles on or in the sediment but also lower oxygen contents. Considering these relations, we have to conclude that the nutrition richness of the "carbonate-rich" CORB was only relative in comparison with the "carbonate-poor" CORB facies.

Conclusions

1. In the study area, CORB in the facies of reddish non-calcareous shales display a very low degree of bioturbation with sparse colonization horizons (mostly with *Chondrites* as the only trace fossil, less often with the *Chondrites*–*Planolites* ichnofabric. The colonization horizons are roughly rhythmically distributed, several decimeters.

2. CORB facies displaying calcareous intercalations show a very high degree of bioturbation as expressed by a high ichno-

fabric index. They contain trace fossils *Chondrites*, *Zoophycos*, *Planolites*, *Thalassinoides*, *Palaeophycus*, *Teichichnus* and *Phycosiphon*.

3. The appearance of green layers in the carbonate-poor CORB usually leads to the increasing of density of colonization horizons and higher ichnofabric indices to few meters from each other. The *Chondrites–Planolites* ichnofabric remains the most frequent result of the colonization.

4. Lateral equivalents of CORB, namely monotonous greenish and grey shales, resulted in considerably restricted conditions for the development of benthic organisms. Sparse colonization horizons with *Chondrites* isp., *Planolites*/*Ophiomorpha* and *Phycosiphon* indicate short incursions of conditions more favourable for in-fauna.

Synopsis of ichnotaxa

The ichnotaxa responsible for the bioturbation of the CORB and adjacent facies are listed and briefly characterized below. With the notable exception of *Zoophycos–Lophoctenium* "composites", which could be a valuable topic for the future, the material does not bring important ichnotaxonomic data, therefore, the standard systematic ichnology and synonymy are not given here.

Arenicolites isp. is a simple U-shaped burrow without a spreite, oriented perpendicular to bedding. *Arenicolites* is generally interpreted as dwelling burrow (e.g. Fillion & Pickerill 1990).

Arthrophycus tenuis (Książkiewicz 1977) occurs gregariously in the form of subhorizontal, hypichnial, convex ridges. They are straight, usually transversely striated, rarely branched and oriented in different directions (e.g. Uchman 1998).

Bergaueria is a large, typically very regular, hemispherical pit; the "hemisphere" may represent only the bottom part of a shallow vertical cylinder. Some burrows show simple radial or concentric (central knob, rugged surface) ornamentation (e.g. Häntzschel 1975).

Chondrites is a regularly branching tunnel system, typically with radial arrangement of branchings at angles of 30–60°. Three to four orders of branches can be observed. For a more extensive discussion of the ichnogenus *Chondrites* see Fu (1991) and Uchman (1999).

Gyrophyllites is a vertically or obliquely oriented burrow that has a number of projections extending radially from the central shaft. *Gyrophyllites* is interpreted as a feeding burrow made by an animal that made repeated probes into the sediment in a radial pattern (e.g. Häntzschel 1975).

Helminthopsis is represented by smooth, unbranched, irregularly winding, strictly horizontal burrows, interpreted as repichnia and/or fodinichnia (e.g. Fillion & Pickerill 1990).

Megagrapton isp. is a system of usually lined tubular burrows, branching at obtuse angles, thus forming scarce open networks. For a detailed description of the morphology of the ichnogenus see Książkiewicz (1977).

Nereites is a tightly to loosely meandering, rarely spirally coiled endichnial trace fossil, typically 2–5 mm wide, composed of a central, light — coloured faecal string, and a dark envelope zone (e.g. Uchman 1995).

Ophiomorpha isp. is composed of cylindrical tubes lined with pellets, forming deep, three-dimensional boxworks. Vertical (at openings) and horizontal components prevail over oblique ones (e.g. Häntzschel 1975).

Ophiomorpha annulata (Książkiewicz 1977) is an exichnial, hypichnial or rarely epichnial, straight to slightly winding, vertical, oblique to horizontal, cylindrical, walled trace fossil preserved in full-relief, 3–9 mm in diameter. It is filled mostly with sand-sized material. In flysch deposits this trace fossil rarely displays a wall covered with small oval knobs, which are characteristic of the ichnogenus *Ophiomorpha* (Uchman 1995).

Paleophycus is an endichnial horizontal, unbranched to non-systematically branched, lined cylindrical burrow. For discussion of *Palaeophycus* see Pemberton & Frey (1982) and Keighley & Pickerill (1995).

Phycodes is a horizontally to obliquely oriented burrow system showing a "broomlike" branching from a central burrow. *Phycodes* is interpreted as a feeding trace made by repeated probes by an animal into the sediment (e.g. Fillion & Pickerill 1990).

Planolites — variably oriented, but mostly horizontal, cylindrical trace fossils without wall lining (Pemberton & Frey 1982; Keighley & Pickerill 1995).

Phycosiphon is observed in horizontal polished slabs as curved endichnial lobes, 2 mm wide and up to 20 mm long, encircled by a marginal tunnel, which is 0.7–1.0 mm wide. In vertical cross-sections it has the character of patches of dark, elongated spots, about 1 mm in diameter, surrounded by a light mantle (e.g. Wetzel & Bromley 1994).

Thalassinoides is a walled or unwalled trace fossil composed of wide cylindrical, mostly horizontal branched tunnels (e.g. Ekdale 1992).

Trichichnus is a vertical to oblique, rarely horizontal, straight to curved, simple or rarely branched, very thin, cylindrical trace fossil, typically less than 1 mm in diameter (Fillion & Pickerill 1990; Uchman 1995, 1999).

Zoophycos is a concave funnel structure with radially arranged spreite. The spreite laminae are straight to slightly arcuate. *Zoophycos* s.l. is generally assumed to be the trace of an as yet undiscovered deposit-feeder. For discussion of this ichnogenus see Ekdale (1992) and Bromley & Hanken (2003). Very few finds of hybrids of *Zoophycos* and other trace fossils have been reported; the *Zoophycos-Lophoctenium* hybrid structures as mentioned above deserve a more detailed report.

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