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Sedimentology and ichnology of Bathonian (Middle Jurassic) ore-bearing clays at Gnaszyn, Kraków-Silesia Homocline, Poland

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ABSTRACT:

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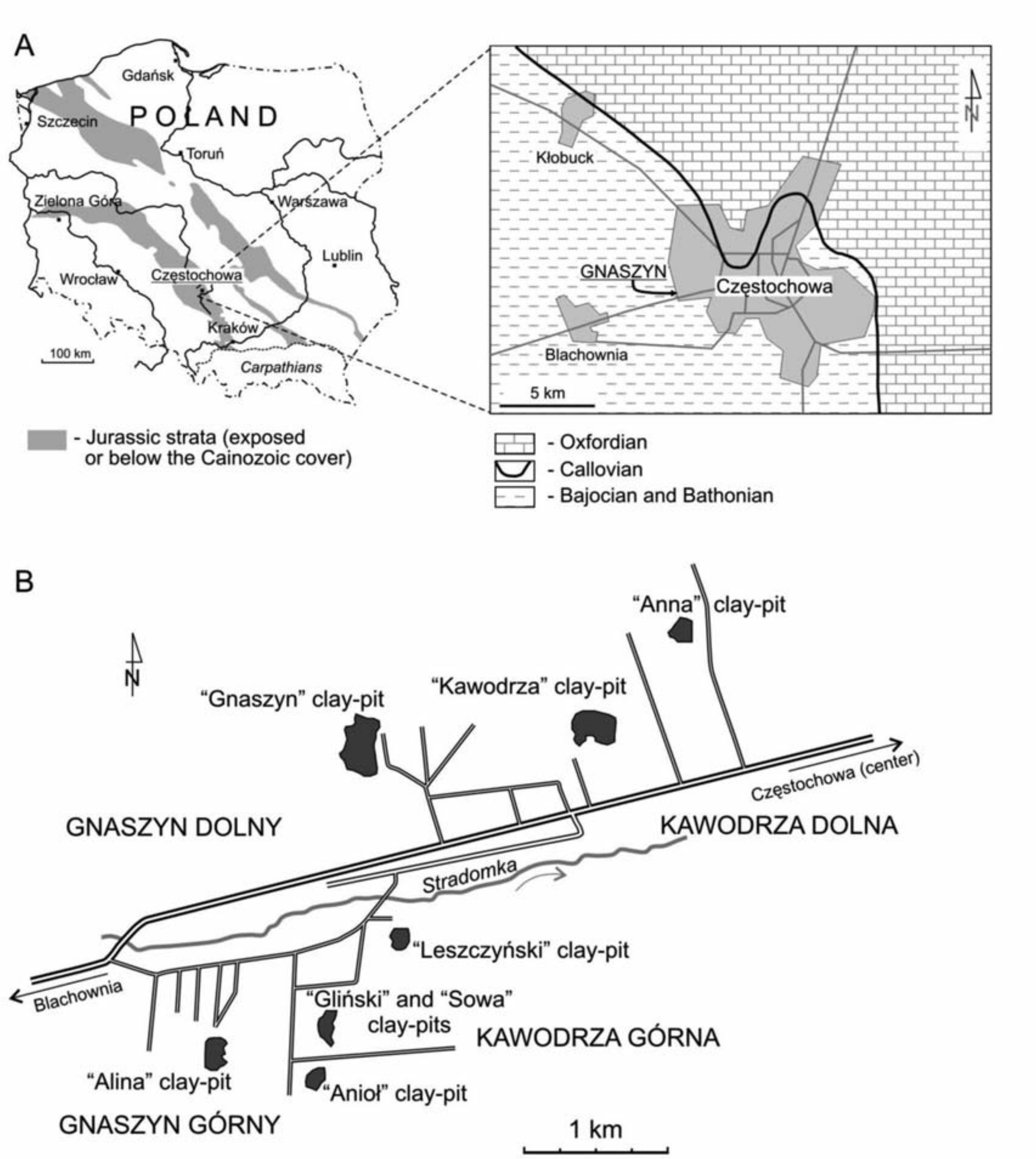
The lithology, sedimentary structures and trace fossil association from the Bathonian organic-rich mudstones from Kraków-Silesia Homocline (SW Poland) are described and a preliminary interpretation of the palaeoenvironment is presented. The ore-bearing clays exposed in the Gnaszyn clay-pit are developed as dark grey clay-silt deposits with a few horizons of sideritic concretions. Sedimentological analysis has revealed that these deposits originated in the offshore part of a marine basin, below the fair weather wave base. Relict parallel lamination suggests that the predominant mechanism of deposition was quiet settling from suspension. However, locally preserved storm deposits indicate that the sea bottom was affected by offshore flows, deriving coarser material from the nearshore area. The degree of bioturbation is high but the diversity of the trace-fossil association is low. It consists mainly of *Chondrites*, *Trichichnus*, pyritized burrows and less common *Palaeophycus*. Other traces, including *Thalassinoides*, *Planolites*, *Taenidium* and some undetermined burrows, occur mainly in the lower part of the succession. This ichnoassociation combines features of distal *Cruziana* and *Zoophycos* ichnofacies, suggesting poor oxygenation of the bottom sediment. Temporary improvements in bottom oxygenation, linked with more intense mixing of water during major storms, resulted in the more diverse trace fossil suite that is found in some intervals of the succession.

Key words: Dark grey mudstones; Trace fossil tiering; Ore-bearing clays; Middle Jurassic; Kraków–Silesia Homocline; Poland.

INTRODUCTION

Fine-grained Middle Jurassic deposits from SW Poland, referred to as the ore-bearing clays have been investigated since the second half of the 19th century due to the occurrence of abundant, well-preserved faunas and siderite horizons that were exploited for a long time as iron resources. The main subject of these studies was the biostratigraphy of the Middle Jurassic and the petrology of the siderites. Although interest in the palaeoecology of the Middle Jurassic deposits increased in the last few years, resulting in numerous geochemical and palaeontological studies (see Zatoń *et al.* 2009, 2011 for summary), the sedimentological aspects of these deposits are still underestimated. The small number of papers on the sedimentology of the Middle Jurassic concern mainly deposits from central Poland and include the study of the depositional architecture of the Middle Jurassic Polish Basin, published by Feldman-Olszewska (1997) and a few short reports by the same authors on the sedimentary environment of the Middle Jurassic deposits from the Kujawy region (Feldman-Olszewska 2003a, b, 2005, 2006). A brief sedimentological description of the ore-bearing clays from the Częstochowa vicinity was published by Merta and Drewniak (1998) and Leonowicz (in Gedl *et al.* 2006a, b, c). Apart from this, only general palaeogeographical reconstructions of the Polish Basin exist (Dadlez and Kopik 1975; Dayczak-Calikowska and Moryc 1988; Dayczak-Calikowska 1997).

The present paper is focused on the Middle Jurassic ore-bearing clays exposed in a clay-pit at Gnaszyn, in the south-western suburb of Częstochowa (Text-fig. 1). It is the first, preliminary research integrating sedimentological and ichnological analysis for the recognition of the depositional environment of these deposits. As the lithology of the studied succession is monotonous and the primary sedimentary structures are mostly obliterated by intensive bioturbation, the most useful environmental indicators are trace-fossils. They can provide important information about the oxygenation of the sea-floor, the depth and turbulence of the water, as well as the nature and property of the substrate.



Text-fig. 1. Simplified geological map of the Częstochowa town and its vicinity (A; after Majewski 2000) and location of the Gnaszyn clay-pit (B; after Matyja and Wierzbowski 2003)

GEOLOGICAL SETTING

The ore-bearing clays are composed of a characteristic series of dark grey, organic-rich mudstones with subordinate sandy intercalations, horizons of clayey siderites and siderite concretions (Dayczak-Calikowska and Kopik 1973). They were deposited in an epicontinental sea, the so-called Polish Basin, which was the eastern arm of the Central European Basin System (Pieńkowski *et al.* 2008). Sedimentation of the ore-bearing clays was linked with the Late Bajocian transgressive impulse (Dayczak-Calikowska 1997) and their age was determined as Late Bajocian–Late Bathonian (Garantiana–Retrocostatum ammonite zones; Kopik 1998; Matyja and Wierzbowski 2000, 2006a, b, c). The sedimentary environment was preliminarily interpreted as quiet offshore, probably below the storm wave base (Gedl *et al.* 2006a, b, c) with periods of shallow water (subtidal zone), in which horizons of hiatus concretions formed (Zatoń *et al.* 2011). Merta and Drewniak (1998) suggested stagnant water conditions with an extremely low rate of deposition from clouds of suspension, derived during storms by low energy bottom currents.

The succession exposed in the "Gnaszyn" clay-pit represents the middle and upper part of the ore-bearing clays. The deposits studied are of Middle and Late Bathonian age (Subcontractus–Retrocostatum zones; Matyja and Wierzbowski 2006c). A detailed description of the Gnaszyn exposure as well as information concerning the stratigraphy of the ore-bearing clays and the palaeogeography of Middle Jurassic in Poland are presented by Gedl and Kaim (2012, this issue)

METHODS

A detailed sedimentological study including primary sedimentary structure and ichnofabric analyses has been undertaken in the Gnaszyn exposure in order to reconstruct the environment of deposition of the ore-bearing clays. During the section examination all sedimentary structures, including those of biogenic origin, were documented. As the mudstones appear homogeneous and macroscopic recognition of lithological changes was uncertain, the whole succession was systematically sampled for grain-size analysis. Additionally, in order to determine whether the grain-size composition at particular levels is laterally constant, two selected horizons – located 1.5 m above the P and R siderite horizons – were each sampled at three points 50 m apart.

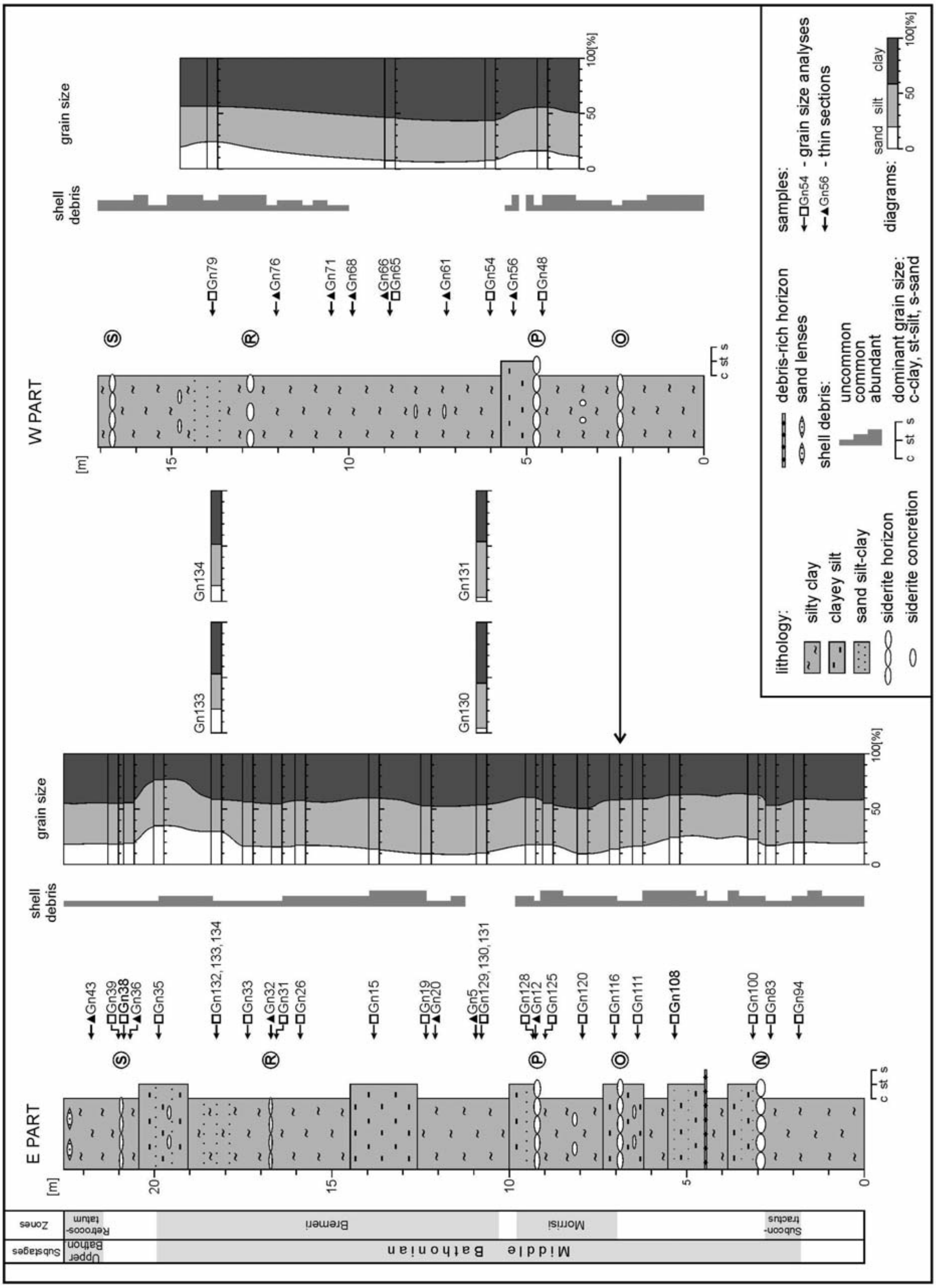
Twenty-seven samples were selected for detailed grain-size analysis (Text-fig. 2). The contents of particular grain-size classes were determined by dry sieving and areometry. In addition, twelve uncrushed, oriented samples of mudstones were selected for thin section analysis (Text-fig. 2). They were stabilized in Canada balm and sectioned. Grain-size distribution, ordering of fabric, degree of bioturbation and texture of burrow filling were noted.

RESULTS

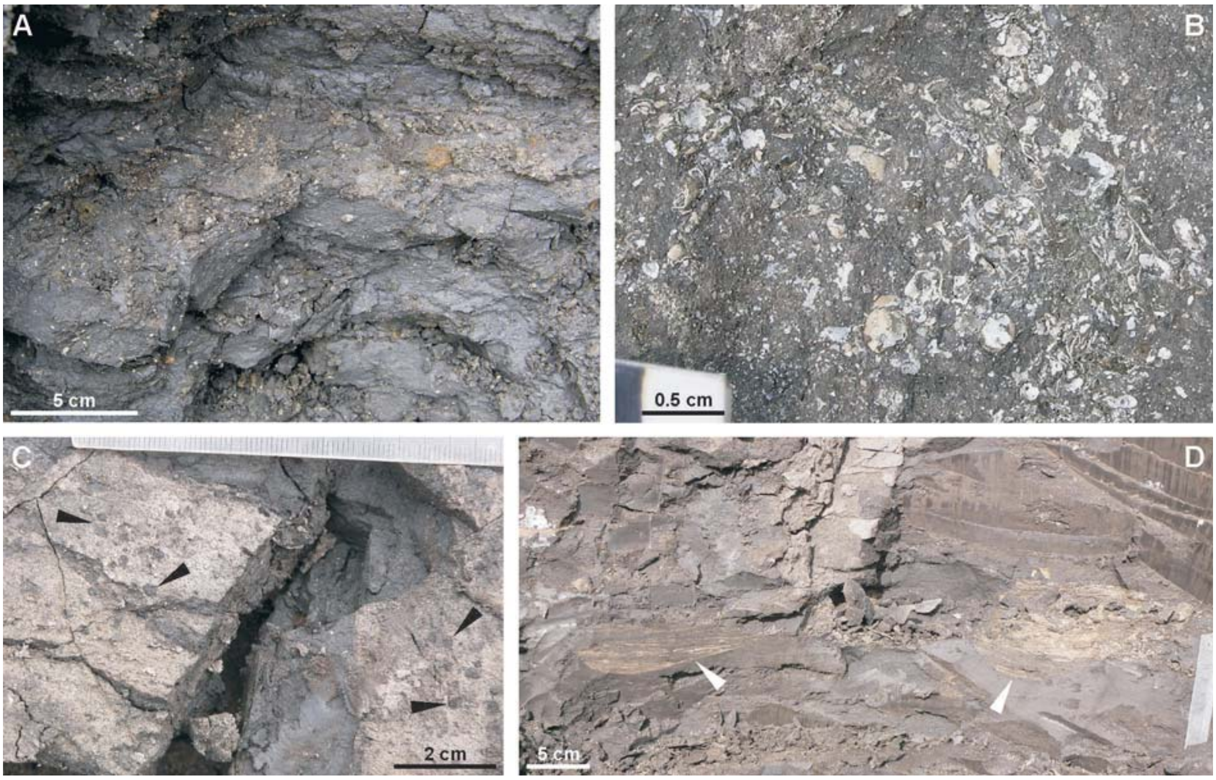
Lithology and sedimentary structures

The deposits exposed in the Gnaszyn clay-pit consist of dark grey, calcareous mudstones with five main horizons of siderite concretions (marked on figures by the symbols N–S). The mudstones are classified as silty claystones and clayey siltstones (*sensu* Shepard 1954); however, as they contain significant admixtures of sand, some samples are classified as sand-silt-claystones. Sand-sized grains are usually dispersed in the mudstone, only at some horizons were separate lenses and stripes of fine sand and silt observed (see below). All the lithological varieties of mudstone identified are barely perceptible in the exposure; however, detailed grain-size analysis reveals that the contents of clay, silt and sand change significantly vertically, as well as laterally at particular levels (Text-fig. 2). Subtle lithological differences appear also at a centimetre- and millimetre-scale, forming small-scale stratification. Horizontal bedding consisting of layers, one to a few centimetres thick, albeit almost imperceptible, was observed rarely in some places. A discrete lamination, with laminae less than 1 mm thick, can be traced in some intervals, however, it is strongly disturbed due to the organic reworking and usually takes the form of thin, long, non-continuous flasers a few millimetres long. It is noteworthy that tunnel systems of *Chondrites* often conform to horizontal lamination, enhancing the parallel fabric of the rock.

The mudstones contain an admixture of muscovite and fine shell debris, the contents of which change vertically; there is, however, no clear coincidence with the grain-size composition of the mudstones (Text-fig. 2). Shell debris, consisting mainly of comminuted shells of bivalves, rarer fragments of ammonites and occasional fragments of brachiopods and crinoids, is dispersed in the mudstone and also concentrated in irregular patches and flat lenses, 1 mm to a few centimetres thick, which locally form debris-rich horizons up to several metres in extent (Text-fig. 3A).



Text-fig. 2. Grain-size distribution and shell debris content in the Gnaszyn section. Locations of analyzed samples are marked. Four bars in the middle of the picture represent samples taken from two laterally constant horizons to illustrate lateral variability of grain-size composition

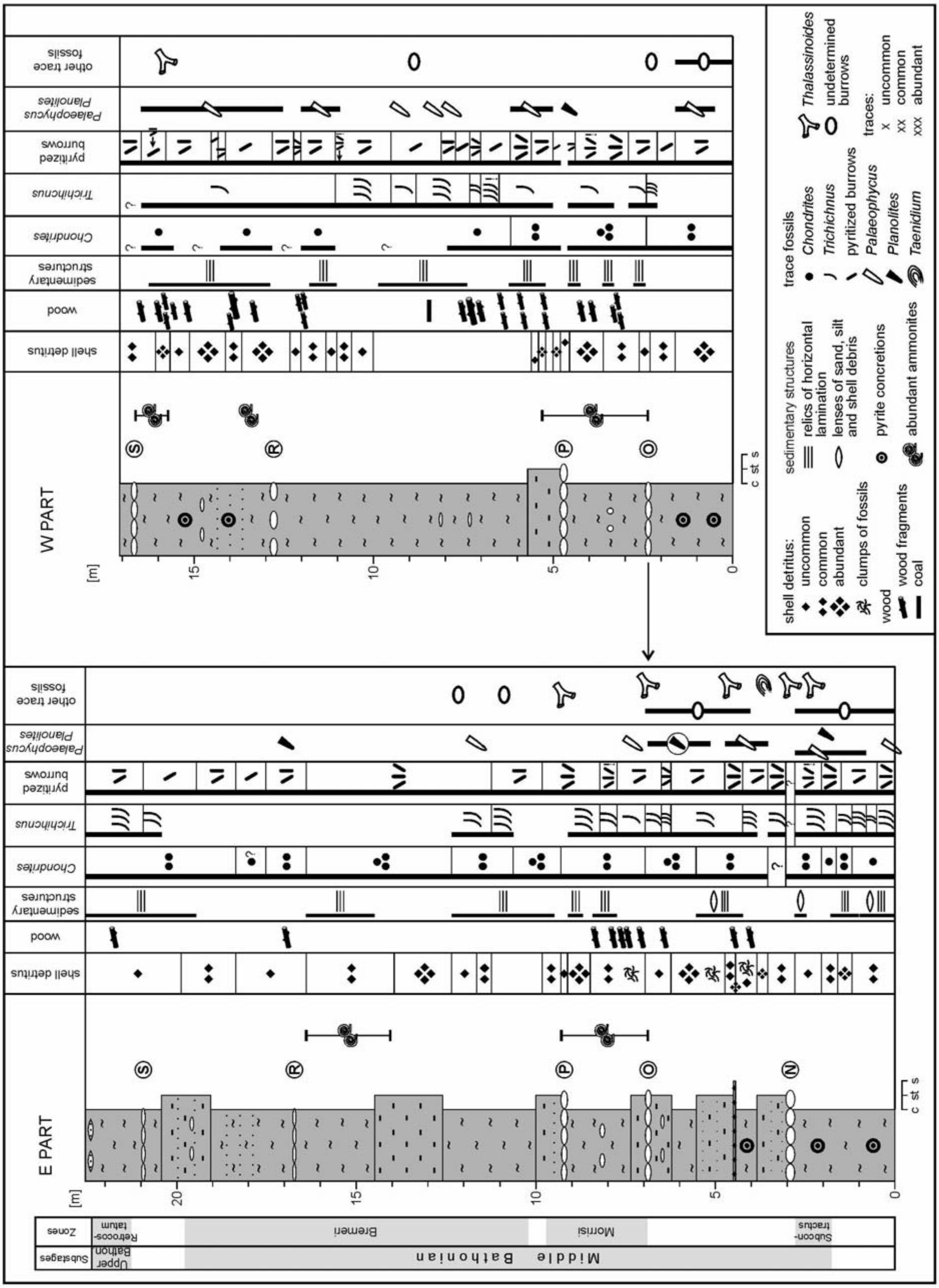


Text-fig. 3. Storm layers in black mudstones from Gnaszyn. **A, B** – shell debris concentrations: **A** – debris-rich horizon from the lower part of the section (between N and O siderite horizons), **B** – detail of the shell debris concentration. Note well preserved, disarticulated shells of small bivalves; **C, D** – fine sand accumulations: **C** – close-up view of the upper surface of sand stripe reworked by *Chondrites* (dark dots, some indicated by arrows), **D** – sand lenses from the upper part of the section (above S siderite horizon). Sand is horizontally laminated and fills an erosional scours in the mudstone (arrows). (Photos C, D – A. Uchman)

Most of the small debris patches are bioturbational structures, whereas the more extensive lenses and debris-rich horizons seem to be depositional forms. The latter usually also contain disarticulated shells of small bivalves concordant with the bedding (Text-fig. 3B) and an admixture of very fine sand and/or silt. Any other compositional differences between the debris accumulations were not observed. The thickest accumulation of shell debris appears in the lower part of the succession (between the N and O siderite horizons, Text-fig. 4), where it forms a non-continuous debris-rich level up to 6 cm thick. Distinct horizontal lamination can be observed there, with the lamination planes enhanced by the presence of thin, dark clay laminae.

Beside skeletal concentrations, there are also flat lenses and thin flasers of light grey, very fine sand and silt, occurring close to debris-rich zones, as well as in intervals devoid of shell accumulations. They are usually less than 1 mm thick, but in some cases they reach as much as a few centimetres in thickness. Thicker sandy lenses reveal horizontal lamination, which is often strongly deformed by processes of soft-sediment deformation. Thin sand stripes are often reworked by *Chondrites* (Text-fig. 3C). The thickest sand accumulation was observed in the upper part of the section (above the S siderite horizon, Text-fig. 4), where a few isolated, horizontally laminated sandy lenses, up to 6 cm thick, were found (Text-fig. 3D). These lenses have distinct erosive bases, suggesting bottom scouring before sand deposition.

Almost all of the ore-bearing clay deposits from Gnaszyn are rich in well preserved macrofauna: ammonites, belemnites, bivalves, and small gastropods, which are present throughout the section. In some intervals (between the O and P and below the R and S siderite horizons; Text-fig. 4) ammonites are quite abundant, suggesting a decrease in sedimentation rate; however, neither lithological nor ichnofabric change provides any indication of basin starvation. In addition, fragments of pyritized or carbonized wood several centimetres long, as well as single, thin lenses of coal occur throught the section.. In the lowest and the upper part some small, discoidal pyrite concretions were observed.



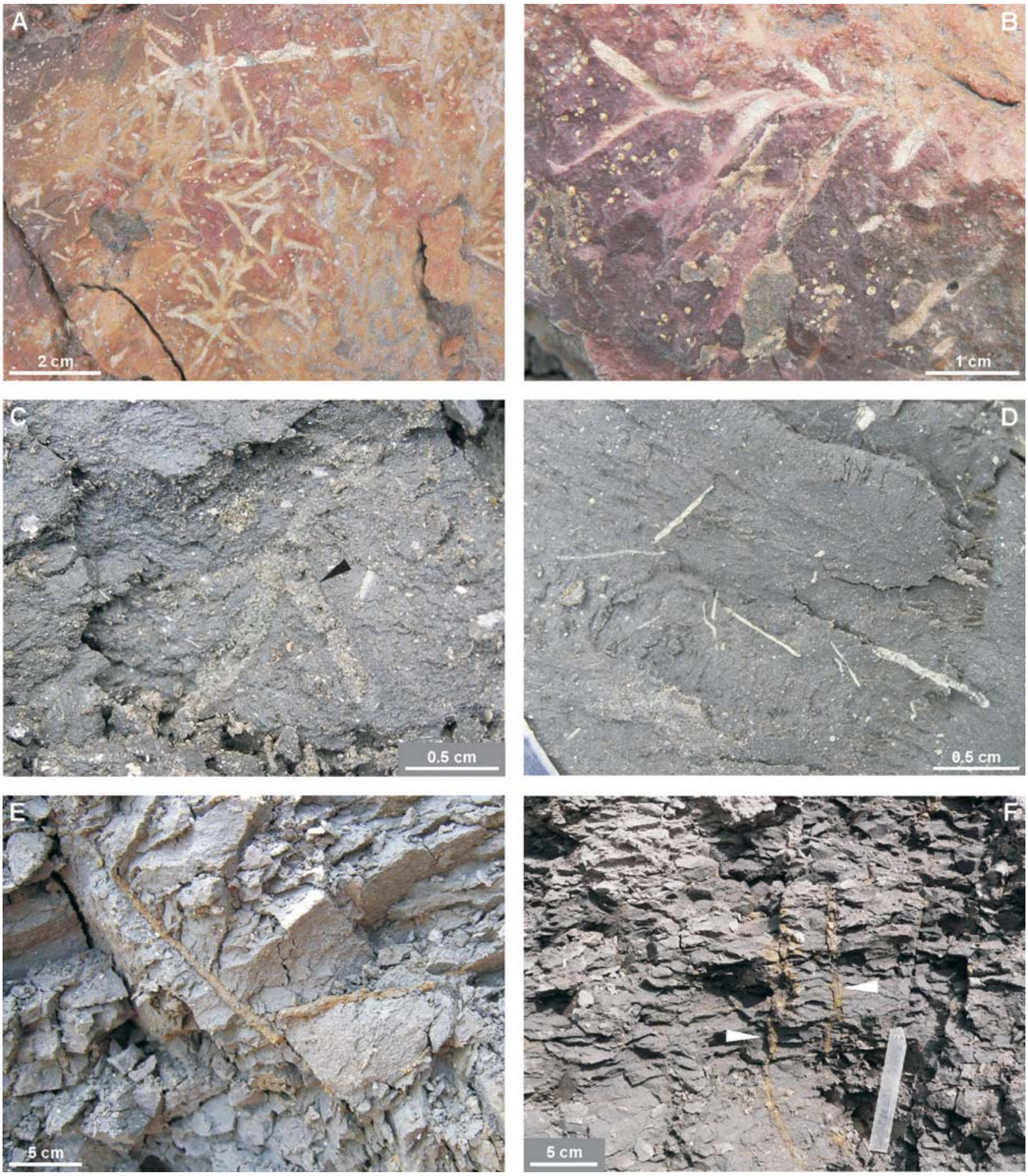
Text-fig. 4. Frequency and distribution of shell debris, wood fragments, trace fossils, sedimentary structures and ammonites in the Gnaszyn section. For lithology explanations see Fig. 2

Trace fossils

Mudstones from Gnaszyn are intensely bioturbated, but the diversity of trace-fossil association is low. Three types of burrows: *Chondrites*, *Trichichnus* and undeterminable pyritized burrow fillings were observed virtually throughout the succession. Other trace fossils, such as *Palaeophycus*, *Planolites*, *Thalassinoides*, *Taenidium* and some other undetermined forms appear only in some intervals.

***Chondrites* isp.** (Text-figs 3C, 5A–C, 8)

Description: *Chondrites* consists of regularly branching tunnel systems. The tunnels are usually flattened, 0.5–1.2 mm in shorter diameter and branch at acute angles.



Text-fig. 5. Trace fossils in black mudstones from Gnaszyn. **A–C** – *Chondrites* isp.: **A, B** – in the siderite from O siderite horizon, **C** – discrete trace in mudstone (arrow); **D** – *Trichichnus* isp.; **E, F** – pyritized burrows (arrows in F). (Photos A, B, F – A. Uchman)

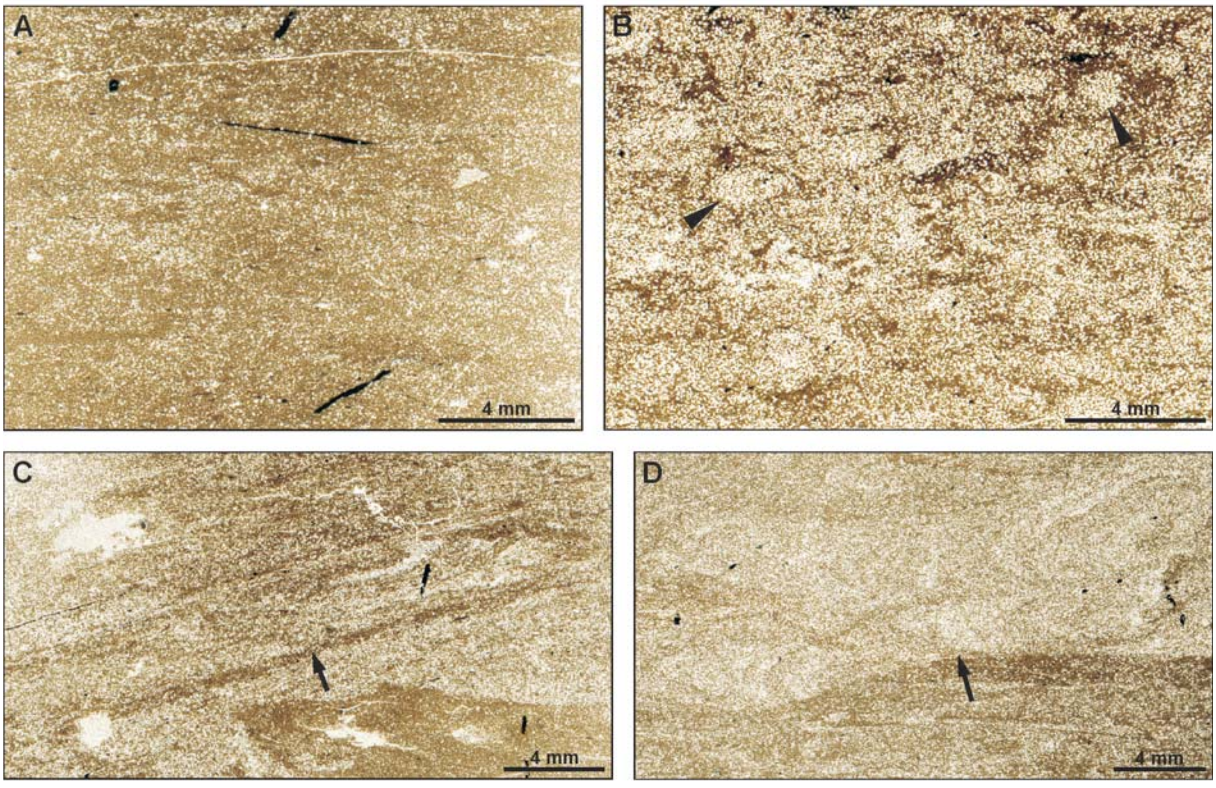
Branching and overlapping horizontal tunnels sometimes form a close network on parting planes in the mudstones and on the surfaces of the siderites. The composition of the fill depends on the lithology of the host rock and consists either of fine, silt-sized quartz grains or a clay matrix. In cross-section *Chondrites* appears as small, elliptical spots and lenses less than 2 cm long.

Remarks and occurrence: *Chondrites* is interpreted as a complex deposit-feeding structure of unknown trace makers, which are, according to some authors, chemosymbiotic organisms able to live under dysoxic conditions (Bromley and Ekdale 1984; Fu 1991; McBride and Picard 1991). Commonly associated with a fully marine environment, it can penetrate deeper into the substrate under well-oxygenated bottom water as well as to shallower levels in an oxygen-limited substrate. In the deposits studied, *Chondrites* is the most common trace fossil, locally causing almost complete bioturbation of the sediment. It is, however, difficult to observe because of its discrete appearance. Exceptions to this are the clearly visible specimens that occur commonly in the exterior parts of siderite concretions from the O horizon. Tunnels of *Chondrites* were observed within the fill of *Thalassinoides*, reworking and crosscutting it (Text-fig. 8B).

***Trichichnus* isp.** (Text-figs 5D, 6A)

Description: These are thin, hair-like, unbranched, pyritized burrows, oriented at various angles with respect to the bedding – usually oblique. Burrows are cylindrical or slightly flattened, straight, curved or sinuous, a few millimetres to a few centimetres long.

Remarks and occurrence: *Trichichnus* is interpreted as the work of deeply burrowing sipunculan worms, which were probably chemosymbiotic organisms able to live under dysoxic conditions (Romero-Wetzel 1987; McBride and Picard 1991; Löwemark 2003). In the deposits studied, *Trichichnus* is common throughout the section but the density of the burrows varies (Text-fig. 4). Pyrite in the burrow fill weathers easily, passing into brown ferruginous oxides and, as a result, thin traces of *Trichichnus* become barely visible. It is probable that the apparent lack of *Trichichnus* in some weathered parts of the section does not reflect its real absence but is the result of oxidation of their fills. Burrows of *Trichichnus* crosscut other trace fossils except pyritized burrows. Cross-cutting of pyritized burrows by *Trichichnus*was not observed anywhere in the section, although both of them are ubiquitous. It seems pro-



Text-fig. 6. Trace fossils in thin sections. **A** – silty clay with thin, pyritized *Trichichnus* burrows (black stripes); **B–D** – undetermined burrows, filled with the light grey quartz silt (arrows); in D a discrete meniscate structure is visible bablythat their trace makers avoided one another duetosimilar feeding requirements.

Pyritized burrows (Text-figs 5E, F, 8A)

Description: They are developed as straight, curved or rarely sinuous, strongly flattened, pyritized tubes 2–8 mm in longer diameter. The tube fragments vary in orientation from vertical to horizontal and they usually represent parts of long, J-shaped burrows, sometimes exceeding 40 cm in length. Tunnels sometimes cross-cut one another, sporadically they branch at approximately a right angle.

Remarks and occurrence: Ethologic classification of these ichnofossils is difficult as some important features have been obliterated by diagenetic pyritization. Thus, the designation "pyritized burrows" was applied in the same way as in previous publications ("pyritic tubes" – Sellwood 1970; Fürsich 1975; "pyritized tubes" and "pyritized burrow fillings" – Thomsen and Vorren 1984). Assuming that the trace makers of pyritized burrows and *Trichichnus* represented the same trophic group (see remarks on *Trichichnus* isp.), pyritized burrows can be interpreted as the work of deeply burrowing chemosymbiotic organisms able to live under dysoxic conditions. Pyritized burrows are the most clearly visible trace fossils in the section. They usually occur as single specimens but, in some intervals, they are re-

Text-fig. 7. Trace fossils in black mudstones from Gnaszyn. **A, B** – *Thalassinoides* isp.: **A** – preserved in siderite concretion of O siderite horizon (arrow), **B** – burrow in mudstone, light grey sandy lining is visible; **C, D** – *Palaeophycus* lined with a light grey very fine sand; **E, F** – undetermined burrows filled with shell debris (arrows). (Photos A, B, D – A. Uchman) ally abundant (Text-fig. 4). They cross-cut other trace fossils, except *Trichichnus* (Text-fig. 8A).

***Palaeophycus* isp.** (Text-figs 7C, D, 8A)

Description: It is developed as horizontal, straight, unbranched, strongly flattened tunnels up to 1 cm in longer diameter. The tunnels are lined with a thin lamina of light grey or rusty silt, very fine sand and/or fine shell debris. The fill is structureless and consists of dark mudstone, similar to the host rock.

Remarks and occurrence: *Palaeophycus* is interpreted as the dwelling burrow of a polychaete (Pemberton and Frey 1982; Pemberton *et al.* 2001). It has been reported from different high and low energy environments, from deep-marine to fresh-water (e.g. Bjerstedt 1987; Pemberton and Wightman 1992; Buatois and Mángano 1998; Uchman 1998; Pemberton *et al.* 2001). The thin lining of the burrows indicates softground consistency of the muddy substrate (Wetzel and Uchman 1998). In the deposits studied, *Palaeophycus* occurs as isolated specimens throughout the section but is less common than *Chondrites*, *Trichichnus* and pyritized burrows (Text-fig. 4). It is most abundant below the O and above the R siderite horizons.

***Thalassinoides* isp.** (Text-figs 7A, B, 8B)

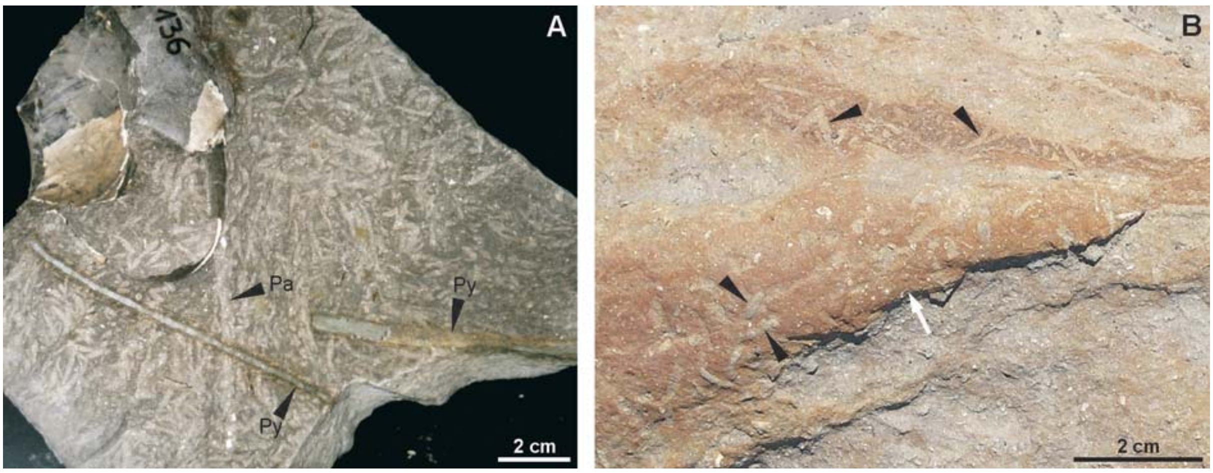
Description: *Thalassinoides* is a three-dimensional burrow system, consisting of tubes 1–4 cm in diameter, branching at acute angles. Swelling commonly occurs at points of branching. The tubes occurring in the mudstones are strongly flattened, filled with a structureless matrix similar to the host rock and thinly lined with a light grey sand/silt or, rarer, with a fine shell detritus. They are up to 1.5 cm in longer diameter. Burrows preserved in the siderites are thicker (up to 4 cm in the O siderite horizon) and only slightly flattened. *Thalassinoides* from the O siderite level is filled with structureless light grey, very fine sand.

Remarks and occurrence: *Thalassinoides* is interpreted as a dwelling and/or feeding burrow, produced mainly by deposit-feeding crustaceans (Frey *et al.* 1984; Pemberton *et al.* 2001). The structureless fill indicates that they functioned as open burrows, passively filled up by bottom sediment. The thin lining is characteristic of a fine-grained coherent substrate (Pemberton *et al.* 2001). *Thalassinoides* is known mainly from shallow marine to offshore environments; however, some occurrences from brackish-water and flysch deposits were also reported (e.g. Frey *et al.* 1984; Uchman 1998; Pemberton *et al.* 2001). In the deposits studied, *Thalassinoides* occurs mainly in the lower part of the section, below the O siderite horizon (Text-fig. 4). It is particularly abundant in siderite concretions of the O horizon, however, some specimens were also observed in mudstones below it as well as in siderite horizons N and P.

***Planolites* isp.**

Description: These are unbranched, usually straight, flattened burrows of variable orientation, a few millimetres in thickness. The tunnels are unlined. The fill is structureless and consists of light grey silt and very fine sand.

Remarks and occurrence: *Planolites* is interpreted as the work of vermiform deposit-feeders, mainly polychaetes,



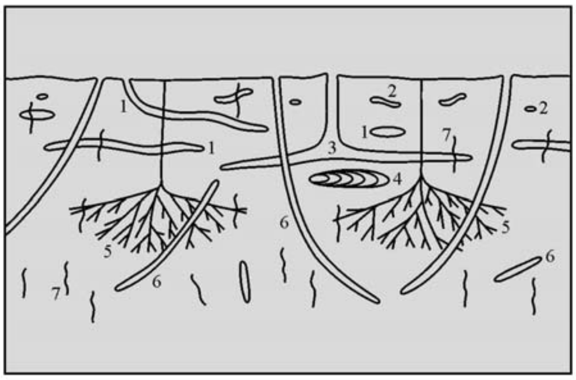
Text-fig. 8. Composite ichnofabric of mudstones from Gnaszyn. **A** – close net of *Chondrites* tunnels and single *Palaeophycus* (Pa) cross-cut by pyritized burrows (Py). View on parting plane; **B** – *Chondrites* (light grey, some indicated by black arrows) within *Thalassinoides* filling (rusty, indicated by white arrow). Burrows preserved in siderite concretion (P siderite horizon) producing active backfilling (Pemberton and Frey 1982). It is known from various deposit types and environments, from fresh-water to deep marine (e.g. Bjerstedt 1987; Beynon and Pemberton 1992; Buatois and Mángano 1998; Uchman 1998). In the deposits studied, *Planolites* occurs sporadically in the lower part of the section, below the O siderite horizon; some isolated specimens were also found near the P and R siderite horizons.

***Taenidium* isp.**

Description: It is a straight, slightly flattened, cylindrical trace fossil 8–10 mm in diameter. The fill consists of discrete, meniscus-shaped segments built of material similar to the host rock.

Remarks and occurrence: *Taenidium* is an actively filled burrow of a deposit feeding animal (D'Alessandro and Bromley 1987). In the deposits studied, it was found only in one place above the N siderite horizon.

Other **undetermined trace fossils** were observed in different intervals both in the field and in thin sections. These are mainly small burrows, 1–5 mm in diameter, filled with light grey quartz silt as well as with matrix similar to the host rock (Text-fig. 6B-D). The fill is usually structureless; only one specimen, observed in thin section, revealed a discrete meniscate structure (Text-fig. 6D). Beside these small traces, larger burrows (up to 1.5 cm in diameter) filled with the shell debris are common in the lower part of the section, between the N and O siderite horizons (Text-fig. 7E, F). These are small debris patches mentioned in the lithological description. They have more or less regular shapes, indistinct margins and are usually oblique to the bedding.



Text-fig. 9. Tiering pattern in Bathonian mudstones from Gnaszyn. Trace fossils: 1 – *Palaeophycus*, 2 – *Planolites*, 3 – *Thalassinoides*, 4 – *Taenidium*, 5 – *Chondrites*, 6 – pyritized burrows, 7 – *Trichichnus*. Tiers are described in the text

Vertical variability

Taking into account the lithology of the mudstones, the Gnaszyn section can be divided into three parts. The lower part (from the bottom to the O siderite horizon, Text-fig. 4) and the highest part (above the S siderite horizon) are more diversified. The characteristic feature of the mudstones from these intervals is the occurrence of lenses and horizons of shell debris and fine sand and silt as well as indistinct, undetermined trace fossils filled with shell debris. The middle part (between the O and S siderite horizons, Text-fig. 4) is more monotonous. Shell debris, sand and silt are dispersed in the mudstone. They do not form distinct concentrations, albeit their total contents do not diminish visibly (Text-figs 2, 4).

A similar trend occurs in the distribution of the trace fossils. The lower part of the section (below the O siderite horizon) contains a readily perceptible and more diverse association, comprising all the ichnofossils described above. Analysis of the ichnofabric enables at least three tiers to be distinguished (Text-fig. 9). The shallowest tier is represented by *Thalassinoides* and probably *Planolites*, *Palaeophycus* and *Taenidium*; however, cross-cutting of these trace fossils was not observed and the relationships between them are not clear. The second tier of this association contains *Chondrites* and the deepest one is occupied by *Trichichnus* and pyritized burrows. Such an arrangement reflects a typical trend in the vertical stacking of infaunal communities, reflecting a decrease in oxygen content with increasing depth in the sediment (Bromley and Ekdale 1986). In the upper part of the section (above the O siderite horizon), trace fossils are harder to see and their association is less diverse. It contains mainly *Chondrites*, pyritized burrows and *Trichichnus*. Other ichnofossils, such as *Planolites*, *Thalassinoides* and undetermined burrows filled with shell debris, almost disappear. *Palaeophycus* is still present; however, its discrete appearance, resulting from a thin, imperceptible lining, makes it barely visible. It declines in some intervals and is less common than in the lower part of the section. Only in the interval between the R and S siderite horizons does it become more abundant.

DISCUSSION

Reconstruction of the depositional processes responsible for the origination of the mudstones is impeded by strong bioturbation, resulting in nearly complete obliteration of primary sedimentary structures. However, scarce relicts of horizontal lamination, reflecting subtle changes in component contents, suggest predominantly quiet deposition from suspension (O'Brien 1996). The suspended sediment could have been brought by rivers from neighbouring land and by storm-induced offshore flows from shallower parts of the same basin. Lateral changes in grain-size distribution in the mudstones indicate that the composition of the suspension clouds was not uniform. It varied between as well as within particular clouds depending on the distance from river mouths and the position relative to the main transport paths.

Lenses and horizons of shell debris and fine sand/silt register higher energetic events, occurring in the prevalently quiet environment, and are interpreted here as storm deposits (compare with Pedersen 1985; Fürsich and Oschmann 1993; Jennette and Pryor 1993). Parallel lamination, well preserved in some of them, indicates that the material, which was whirled up into suspension in nearshore area and removed by offshore currents, was finally deposited by settling from suspension without later wave reworking (Reineck and Singh 1972). Thus, it is most probable that they represent distal tempestites, deposited offshore below the storm wave base (Dott and Bourgeois 1982). The transporting flows were usually too weak to cause significant erosion of the muddy bottom. Only the strongest storms resulted in deeper erosion, cutting into the firm substrate, which is marked by distinct erosional scours (Text-fig. 3D; compare with Myrow 1992; Schieber 1998). The compositional similarity of shell debris from bioturbational and sedimentary accumulations indicates a common source of the detrital material. Once deposited, the lenses and pavements were probably reworked by burrowing animals, which incorporated fine sand and comminuted shells into their burrows. The common presence of shell debris in the deposits suggests that storm episodes were much more frequent than could be inferred from the numbers of sand and shell debris accumulations. Material from thinner laminae and lenses was probably completely redistributed. Only the thickest accumulations survived bioturbational mixing and can be now observed in the section.

The sedimentation rate during deposition of the Gnaszyn succession was not uniform. There are three intervals with common ammonites (Text-fig. 4), registering sedimentation slowdown. However, identification of the factors involved in this slowdown is difficult, based only on a single section.. It could have resulted from various processes occurring in the hinterland (e.g. climate or hydrologic changes), from sea-level rise as well as from a change of bottom water circulation within the basin, leading to winnowing of sediment from some parts of it. The solution of this problem requires further investigations over a more extensive area.

The body and trace fossil associations provide some information about the conditions prevailing on the seafloor and within the sediment column during sedimentation of the mudstones. The thin linings of trace fossils which functioned as open burrows (*Palaeophycus*, *Thalassinoides*) indicate relative stability of a cohesive muddy bottom. However, the strong flattening of the ichnofossils from all the tiers suggests low consolidation and high porosity of the burrowed substrate, which can be defined as a softground. The only exceptions are uncompacted or only slightly flattened burrows from the siderite horizons, indicating that early crystallization of the siderite and consolidation preceded significant compaction.

The common presence of a diverse marine fauna, including both nektonic and benthic organisms, points to an open marine environment with well oxygenated bottom waters. On the other hand, the low diversity of ichnofossils suggests that conditions within the bottom sediment were restricted. The trace fossil association combines features of the *Cruziana* and *Zoophycos* ichnofacies. The whole suite, containing dwelling, feeding and grazing traces, could represent distal *Cruziana* ichnofacies, which is characteristic of the lower offshore zone (compare with Pemberton *et al.* 2001). Such features as low trace fossil diversity with simultaneous abundance of particular trace fossils, an organic-rich substrate and a predominance of feeding traces regarded as indicators of oxygen-poor environment (*Chondrites*, *Trichichnus*), characterize the *Zoophycos* ichnofacies, which reflects oxygen-depleted quiet settings (Frey and Pemberton 1984; Pemberton *et al.* 2001). Thus, the sedimentary environment of the Gnaszyn succession can be interpreted as a low-energy offshore environment with a poorly oxygenated bottom sediment, where an impoverished *Cruziana* ichnofacies developed. It fits the trend observed in modern and ancient deposits (Savrda *et al.* 1984; Savrda and Bottjer 1989), in which reduced oxygenation of sediment leads to exclusion of taxa with high oxygen requirements and deep tier burrows predominate. The lack of *Zoophycos* in the deposits studied can be explained by relative shallowness of the sedimentary environment, as in Mesozoic strata this ichnogenus is only known from deep water settings (Frey and Pemberton 1984).

Trace fossils of the upper tier, including *Thalassinoides*, *Palaeophycus*, *Planolites* and *Taenidium*, occur in those intervals which register improvement in oxygenation, linked with more intensive mixing of water. The lower part of the succession (below the O siderite horizon) with the most diverse ichnofossil association marks the best oxygenation of the bottom.

This is also the interval where storm deposits, represented by lenses and horizons of shell debris and fine sand/silt, are most common, suggesting that the main factor responsible for oxygenation was the storm-induced circulation of water. The succession between the O and R siderite horizons marks a decrease in bottom current intensity and/or a change in bottom current circulation, resulting in poorer oxygenation of the sediment and impoverishment of the trace fossil association. Isolated occurrences of *Palaeophycus* probably resulted from short oxygenation events linked with rare exceptionally strong storms. The next improvement in bottom oxygenation is registered by the interval between the R and S siderite horizons in which common *Palaeophycus* occur.

SUMMARY AND CONCLUSIONS

The studies in the Gnaszyn clay-pit suggest that the muddy deposits exposed there were deposited in an offshore part of a marine basin, probably below the storm wave base. The substrate was of a softground type but relatively stable due to the cohesiveness of the muddy sediment. Although sedimentation was dominated by quiet settling from suspension, the seafloor was often affected by storm-induced offshore flows, deriving fine sediment and shell debris from the nearshore and sporadically eroding the muddy bottom. Thin deposits of weaker storms were completely reworked by burrowing fauna. Only the thickest sand/silt and shell debris accumulations, which register the strongest storms, survived bioturbational mixing.

There are three intervals within the Gnaszyn section which register slowdown of sedimentation. The reasons for this have not yet been established. They could include different processes occurring in the hinterland, sea-level fluctuations or changes in bottom water circulation within the basin.

The diverse association of benthic body fossils points to a fully marine environment with well oxygenated bottom water, whereas the impoverished trace fossil suite indicates restricted conditions prevailing in the sediment. The ichnofossil association combines features of the *Zoophycos* and distal *Cruziana* ichnofacies, suggesting poor oxygenation of the sediment column. This interpretation confirms the results of geochemical studies of the ore-bearing clays (Marynowski *et al.* 2007; Szczepanik *et al.* 2007; Zatoń *et al.* 2009). The association is dominated by deep tier feeding traces, including *Chondrites*, *Trichichnus* and pyritized burrows which are common in the entire succession. The shallow-tier trace fossils, such as *Thalassinoides*, *Palaeophycus*, *Planolites* and *Taenidium* occurred during temporary improvements in bottom oxygenation, linked with more intense mixing of water during storms. The most favourable conditions prevailed during sedimentation of the lower part of the Gnaszyn succession (below the O siderite horizon), in which the whole ichnofossil association appears. Improved conditions, but to a lesser degree, are also marked by the interval between the R and S siderite horizons. The worst oxygenation is registered by the middle part of the succession (between the O and R siderite horizons), where only dispersed specimens of *Palaeophycus* occur.

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REFERENCES

Beynon, B.M. and Pemberton, S.G. 1992. Ichnological signature of a brackish water deposit: an example from the Lower Cretaceous Grand Rapids Formation, Cold Lake oil sands area, Alberta. In: S.G. Pemberton (Ed.), Applications of Ichnology to Petroleum Exploration, *Society of Economic Paleontologists and Mineralogists, Core Workshop Notes*, **17**, 199–221.

Bjerstedt, T.W. 1987. Latest Devonian – earliest Mississippian nearshore trace-fossil assemblages from West Virginia, Pennsylvania, and Maryland. *Journal of Paleontology*, **61** (5), 865–889.

Buatois, L.A. and Mángano, M.G. 1998. Trace fossil analysis of lacustrine facies and basins. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **140**, 367–382.

Bromley, R.G. and Ekdale, A.A. 1984. *Chondrites*: a trace fossil indicator of anoxia in sediments. *Science*, **224**, 872–874.

Bromley, R.G. and Ekdale, A.A. 1986. Composite ichnofabrics and tiering of burrows. *Geological Magazine*, **123**, 59–65.

Dadlez, R. and Kopik, J. 1975. Stratigraphy and palaeogeography of the Jurassic. *Biuletyn Instytutu Geologicznego*, **252**, 149–171.

D'Alessandro, A. and Bromley, R.G. 1987. Meniscate trace fossils and the *Muensteria-Taenidium* problem. *Palaeontology*, **30** (4), 743–763.

Dayczak-Calikowska, K. 1997. Jura środkowa: Sedymentacja, paleogeografia i paleotektonika. In: S. Marek and M. Pajchlowa (Eds), Epikontynentalny perm i mezozoik w Polsce. *Państwowy Instytut Geologiczny*, *Prace*, **153**, 269–282.

Dayczak-Calikowska, K. and Kopik, J. 1973. Jura Środkowa. In: Budowa Geologiczna Polski, vol. I – Stratygrafia, part 2 – Mezozoik, 237–324. Wydawnictwa Geologiczne; Warszawa.

Dayczak-Calikowska, K. and Moryc, W. 1988. Evolution of sedimentary basin and palaeotectonics of the Middle Jurassic in Poland. *Kwartalnik Geologiczny*, **32**, 117–136. [In Polish with English summary]

Dott, R.H. and Bourgeois, J. 1982. Hummocky stratification: significance of its variable bedding sequences. *Geological Society of America Bulletin*, **93**, 663–680.

Feldman-Olszewska, A. 1997. Depositional architecture of the Polish epicontinental Middle Jurassic basin. *Geological Quarterly*, **41**, 491–508.

Feldman-Olszewska, A. 2003a. Badania stopnia natlenienia wód dennych podczas sedymentacji środkowojurajskich czarnych łupków na Kujawach. *Tomy Jurajskie*, **1**, p. 115.

Feldman-Olszewska, A. 2003b. Skamieniałości śladowe w utworach jury środkowej regionu kujawskiego i ich znaczenie dla interpretacji paleośrodowiska. *Tomy Jurajskie*, **1**, p. 116.

Feldman-Olszewska, A. 2005. Rozwój sedymentacji w jurze środkowej Kujaw. *Tomy Jurajskie*, **3**, 130–131.

Feldman-Olszewska, A. 2006. Sedimentary environments of the Middle Jurassic epicontinental deposits from the central part of the Polish Basin (Kuiavian Region). *Volumina Jurassica*, **4**, p. 86.

Frey, R.W., Curran, H.A. and Pemberton, S.G. 1984. Tracemaking activities of crabs and their environmental significance: the ichnogenus *Psilonichnus*. *Journal of Paleontology*, **58** (2), 333–350.

Frey, R.W. and Pemberton, S.G. 1984. Trace fossil facies models. In: R.G. Walker (Ed.), Facies Models (2nd ed.). Geoscience Canada, Reprint Series 1, 189–207.

Fu, S. 1991. Funktion, Verhalten und Einteilung fucoider und lophoctenoider Lebensspuren. *Courier Forschungsinstitut Senckenberg*, **135**, 1–79.

Fürsich, F.T. 1975. Trace fossils as environmental indicators in the Corallian of England and Normandy. *Lethaia*, **8**, 151–172.

Fürsich, F.T. and Oschmann, W. 1993. Shell beds as tools in basin analysis: the Jurassic of Kachchh, western India. *Journal of the Geological Society*, *London*, **150**, 169–185.

Gedl, P. and Kaim, A. 2012. An introduction to palaeoenvironmental reconstruction of Bathonian (Middle Jurassic) ore-bearing clays at Gnaszyn, Kraków-Silesia Homocline, Poland. *Acta Geologica Polonica*, **62** (3), 267–280.

Gedl, P., Boczarowski, A., Kaim, A., Kędzierski, M., Leonowicz, P., Smoleń, J., Szczepanik, P. and Witkowska, M. 2006a. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.5 – Sowa's and Gliński's clay pits (uppermost Bajocian-lowermost Bathonian). Lithology, fossil assemblages and palaeoenvironment. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 149–151. 7th International Congress on the Jurassic System, 6-18 September 2006, Kraków, Poland.

Gedl, P., Boczarowski, A., Kaim, A., Kędzierski, M., Leonowicz, P., Smoleń, J., Szczepanik, P. and Witkowska, M. 2006b. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.6 – Leszczyński's clay pit (Lower Bathonian). Lithology, fossil assemblages and palaeoenvironment. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 152–153. 7th International Congress on the Jurassic System, 6-18 September 2006, Kraków, Poland.

Gedl, P., Boczarowski, A., Dudek, T., Kaim, A., Kędzierski, M., Leonowicz, P., Smoleń, J., Szczepanik, P., Witkowska, M. and Ziaja, J. 2006c. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.7 – Gnaszyn clay pit (Middle Bathonian–lowermost Upper Bathonian). Lithology, fossil assemblages and palaeoenvironment. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 154–155. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

Jennette, D.C. and Pryor, W.A. 1993. Cyclic alternation of proximal and distal storm facies: Kope and Fairview Formations (Upper Ordovician), Ohio and Kentucky. *Journal of Sedimentary Petrology*, **63**, 183–203.

Kopik, J. 1998. Lower and Middle Jurassic of the north-eastern margin of the Upper Silesian Coal Basin. *Biuletyn Państwowego Instytutu Geologicznego*, **378**, 67–129. [In Polish with English summary]

Löwemark, L. 2003. Automatic image analysis of X-ray radiography: a new method for ichnofabric evaluation. *Deep-Sea Research*, *part I*, **50**, 815–827.

Majewski, W. 2000. Middle Jurassic concretions from Częstochowa (Poland) as indicators of sedimentation rates. *Acta Geologica Polonica*, **50**, 431–439.

Marynowski, L., Zatoń, M., Simoneit, B.R.T., Otto, A., Jędrysek, M.O., Grelowski, C. and Kurkiewicz, S. 2007. Compositions, sources and depositional environments of organic matter from the Middle Jurassic clays of Poland. *Applied Geochemistry*, **22**, 2456–2485.

Matyja, B.A. and Wierzbowski, A. 2000. Ammonites and stratigraphy of the uppermost Bajocian and Lower Bathonian between Częstochowa and Wieluń, Central Poland. *Acta Geologica Polonica*, **50**, 191–209.

Matyja, B.A. and Wierzbowski, A. 2003. Biostratygrafia amonitowa formacji częstochowskich iłów rudonośnych (najwyższy bajos-górny baton) z odsłonięć w Częstochowie. *Tomy Jurajskie*, **1**, 3–6.

Matyja, B.A. and Wierzbowski, A. 2006a. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.5 – Sowa's and Gliński's clay pits (uppermost Bajocian-lowermost Bathonian). Ammonite biostratigraphy. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 149–151. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

Matyja, B.A. and Wierzbowski, A. 2006b. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.6 – Leszczyński's clay pit (Lower Bathonian). Ammonite biostratigraphy. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 152–153. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

Matyja, B.A. and Wierzbowski, A. 2006c. Field Trip B1 – Biostratigraphical framework from Bajocian to Oxfordian. Stop B1.7 – Gnaszyn clay pit (Middle Bathonian–lowermost Upper Bathonian). Ammonite biostratigraphy. In: A. Wierzbowski *et al.* (Eds), Jurassic of Poland and adjacent Slovakian Carpathians. Field trip guidebook, 154–155. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

McBride, E.F. and Picard, M.D. 1991. Facies implications of *Trichichnus* and *Chondrites* in turbidites and hemipelagites, Marnoso-arenacea formation (Miocene), Northern Apennines, Italy. *Palaios*, **6**, 281–290.

Merta, T. and Drewniak, A. 1998. Lithology and depositional environment of the Bathonian clays. In: N.E. Poulsen *et al.* (Eds), Mellem-Øvre Jura i Polen. EEP-1995 projekt: Det polske Mellem-Øvre Epikratoniske Bassin, Stratigrafi, Facies og Bassin Historie. Program Østeuropa. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1998/14, 25–41.

Myrow, P.M. 1992. Pot and gutter casts from the Chapel Island Formation, southeast Newfoundland. *Journal of Sedimentary Petrology*, **62** (6), 992–1007.

O'Brien, N.R. 1996. Shale lamination and sedimentary processes. In: A.E.S. Kemp (Ed.), Palaeoclimatology and Palaeocenography from Laminated Sediments. *Geological Society Special Publication*, **116**, 23–36.

Pedersen, G.K. 1985. Thin, fine-grained storm layers in a muddy shelf sequence: an example from the Lower Jurassic in the Stenlille 1 well, Denmark. *Journal of the Geological Society, London,* **142** (2), 357–374.

Pemberton, S.G. and Frey, R.W. 1982. Trace fossil nomenclature and the *Planolites - Palaeophycus* dilemma. *Journal of Paleontology*, **56** (4), 843–881.

Pemberton, S.G. and Wightman, D.M. 1992. Ichnological characteristics of brackish water deposits. *Society of Economic Paleontologists and Mineralogists, Core Workshop Notes*, **17**, 141–167.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D. and Sinclair, I.K. 2001. Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon Reservoirs, Jeanne d'Arc Basin. *Geological Association of Canada, Short Course Notes*, **15**, 1–343.

Pieńkowski, G. *et al.* 2008. Jurassic. In: T. McCann (Ed.): The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic, 823–922. Geological Society London.

Reineck, H. E. and Singh, I.B. 1972. Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. *Sedimentology*, **18**, 123–128.

Romero-Wetzel, M.B. 1987. Sipunculans as inhabitants of very deep, narrow burrows in deep-sea sediments. *Marine Biology*, **96**, 87–91.

Savrda, C. and Bottjer, D. 1989. Trace-fossil model for reconstructing oxygenation histories of ancient marine bottom waters: application to Upper Cretaceous Niobrara Formation, Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **74**, 49–74.

Savrda, C., Bottjer, D. and Gorsline, D. 1984. Development of a comprehensive oxygen-deficient marine biofacies model: evidence from Santa Monica, San Pedro and Santa Barbara Basins, California Continental Borderland. *Bulletin of the American Association of Petroleum Geologists*, **68**, 1179–1192.

Sellwood, B.W. 1970. The relation of trace fossils to small scale sedimentary cycles in the British Lias. In: T.P. Crimes and J.C. Harper (Eds), Trace fossils. *Geological Journal*, *Special Issue*, **3**, 489–504.

Shepard, F.P. 1954. Nomenclature based on sand–silt–clay ratios. *Journal of Sedimentary Petrology*, **24**, 151–158.

Schieber, J. 1998. Sedimentary features indicating erosion, condensation and hiatuses in the Chattanooga Shale of central Tennessee: relevance for sedimentary and stratigraphic evolution. In: J. Schieber, W. Zimmerle and P.S. Sethi (Eds), Shales and mudstones, 187–215. E. Schweizerbart'sche Verlagsbuchhandlung; Stuttgart.

Szczepanik, P., Witkowska, M. and Sawłowicz, Z. 2007. Geochemistry of Middle Jurassic mudstones (Kraków-Częstochowa area, southern Poland): interpretation of the depositional redox conditions. *Geological Quarterly*, **51** (1), 57–66.

Thomsen, E. and Vorren, T.O. 1984. Pyritization of tubes and burrows from Late Pleistocene continental shelf sediments off North Norway. *Sedimentology*, **31**, 481–492.

Uchman, A. 1998. Taxonomy and ethology of flysch trace fossils: revision of the Marian Książkiewicz collection and studies of complementary material. *Annales Societatis Geologorum Poloniae*, **68**, 105–218.

Wetzel, A. and Uchman, A. 1998. Biogenic sedimentary structures in mudstones – an overview. In: J. Schieber, W. Zimmerle and P.S. Sethi (Eds), Shales and mudstones, 351–369. E. Schweizerbart'sche Verlagsbuchhandlung; Stuttgart.

Zatoń, M., Marynowski, L., Szczepanik, P., Bond, D.P.G. and Wignall, P.B. 2009. Redox conditions during sedimentation of the Middle Jurassic (Upper Bajocian–Bathonian) clays of the Polish Jura (south-central Poland). *Facies*, **55**, 103–114.

Zatoń, M., Machocka, S., Wilson, M.A., Marynowski, L. and Taylor, P.D. 2011. Origin and paleoecology of Middle Jurassic hiatus concretions from Poland. *Facies*, **57**, 275–300.

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