Ichnofabrics of shallow-marine mudstone, the result of changing environmental conditions: an example from the Middle Jurassic ore-bearing clay from southern Poland

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Abstract Analysis of the trace fossil association and ichnofabrics from a Middle Jurassic shallow-marine mudstone, referred to as the Ore-Bearing Częstochowa Clay Formation, is used to reconstruct the seafloor conditions and identify the factors responsible for their changes. The trace fossil association contains *Chondrites*, *Trichichnus*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *†Rosselia*, *Schaubcylindrichnus*, *Taenidium*, cf. *Tasselia*, *Thalassinoides*, and five types of pyritized burrow. The association represents the distal expression of *Cruziana* ichnofacies, temporarily changing to a more proximal development. The ichnofacies suggests that the depositional site was located in the lower offshore to offshore-transition zone, periodically passing to the distal lower shoreface. Eight subtypes of the ichnofacies are recognized, reflecting variations in seafloor oxygenation, sedimentation rate, and benthic food content. The sequence of ichnofabrics 1a–1b–2a–2b reflects increasing oxygenation; ichnofabrics 4a, 4b, and 5 record high sedimentation rates, whereas ichnofabric 3 reflects sediment starvation. Vertical changes of ichnofabrics reflect major fluctuations in basin depth and distance from the shoreline, which partly correlate with previously recognized transgressive–regressive cycles. However, they do not record minor variations of the shoreline position.

Keywords Marine mudstone · Trace fossils · Ichnofabric · Ore-Bearing Częstochowa Clay Formation · Middle Jurassic · Silesian-Kraków Upland

Introduction

Ichnofabric analysis is an important source of information in paleoecological and sedimentological studies of sedimentary rocks. Careful examination of ichnofabric may supply reliable information about the degree of oxygenation of the seafloor, the nature of the substrate, salinity, benthic food availability and sedimentation rate (cf. Wetzel 1991; Taylor et al. 2003). In the present study, the analysis of the trace fossil association and ichnofabrics of a shallow-marine mudstone was applied to interpret changes of depositional conditions linked to transgressions and regressions of the sea. It focuses on Middle Jurassic deposits, referred to as the Ore-Bearing Częstochowa Clay Formation, which are exposed in the Silesian-Kraków Upland in southern Poland (Fig. 1).

This fine-grained succession has been the subject of several geochemical, micropaleontological, and sedimentological studies (e.g., Merta and Drewniak 1998; Marynowski et al. 2007; Szczepanik et al. 2007; Zatoń et al. 2009, 2011; Gedl et al. 2012; Leonowicz 2012, 2013, 2015). Geochemical investigations, including analysis of biomarkers, Th/U ratios, DOP and pyrite framboid distribution, indicated oxygenation of the bottom water and reducing conditions within the sediment (Marynowski et al. 2007; Szczepanik et al. 2007; Zatoń et al. 2009). Significant variations were not detected in the succession, suggesting that stable conditions prevailed on the seafloor. This, however, may have been the result of the relatively low resolution of the geochemical indices rather than actual paleoenvironment stability (Szczepanik et al. 2007; cf. Schieber 2003). Preliminary ichnological and micropaleontological studies of the selected 22-m-thick part of the succession showed that the bottom conditions changed with time even over a relatively short period of time (Smoleń 2006,

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Fig. 1 **a** Geological map of the Silesian-Kraków Upland (after Dadlez et al. 2000, simplified) and the location of sections studied. Detailed location of exposures from Częstochowa is shown on **c**; **b** location of the area shown on **a**; **c** location of the clay-pit sec-

tions on the geological sketch map of the western part of town of Częstochowa (after Lewandowski 1986, modified). White stars mark sections studied in detail and presented on Figs. 5 and 6; grey stars mark outcrops in which only observations of trace fossils were made

2012; Kaim and Sztajner 2012; Leonowicz 2012). Moreover, analysis of the trace fossil and benthic faunal associations from two facies varieties of the ore-bearing clay, exposed in different parts of the outcrop belt, indicated that the bottom conditions also varied laterally. The first facies, represented by laminated mudstone, was deposited in suboxic conditions, which periodically changed to dysoxic and rarely to anoxic (Leonowicz 2013). The second facies, consisting of bioturbated mudstone, accumulated in a permanently dysoxic environment prevailing within the sediment, under an oxygenated water column (Smoleń 2006, 2012; Kaim and Sztajner 2012; Leonowicz 2012). As shown by sedimentological analysis of microfabric, short-term changes in oxygen content most probably resulted from the activity of storm-generated bottom currents, redistributing sediment from shallower parts of the basin and simultaneously improving oxygenation of the seafloor (Leonowicz 2013). Longer-lasting fluctuations of

bottom-water conditions might be linked to changes in the position of the shoreline, as suggested in previous papers, based on variations of grain size, palynofacies, and sporomorph distribution (Gedl et al. 2012; Leonowicz 2015).

The aim of this study is to recognize variability of ichnofabrics in the succession of the Ore-Bearing Częstochowa Clay Formation to determine which environmental factors influenced the benthic community most significantly, and to check whether the variability of ichnofabrics corresponds to the cyclicity previously recognized by sedimentological and micropaleontological studies.

Geological setting and lithology

The Ore-Bearing Częstochowa Clay Formation, known also as ore-bearing clay, consists of dark grey, organic-rich,

calcareous mudstone with several horizons of siderite and calcareous concretions and clayey siderite bands. Mudstone is enriched in organic matter; the TOC content ranges from 0.8 to 2.5 % and this is predominantly of terrestrial origin (Marynowski et al. 2007; Szczepanik et al. 2007). The deposits which are strongly bioturbated contain a diverse benthic fauna, including bivalves, gastropods, brachiopods, scaphopods, foraminifers, and echinoderms (Gedl et al. 2012). The trace fossil association, reported in earlier papers, is of a low diversity and contains *Chondrites*, *Trichichnus*, *Palaeophycus*, *Planolites*, *Thalassinoides*, *Taenidium*, and indeterminate pyritized burrow fills (Gedl et al. 2006a, b, c; Leonowicz 2012). Laminated mudstone contains an impoverished benthic fauna, which includes mainly bivalves *Bositra*, local representatives of families Nuculidae and Nuculanidae, and small gastropods (Leonowicz 2013). The trace fossil association is also impoverished, containing *Chondrites*, *Trichichnus*, *Palaeophycus*, indeterminate pyritized burrows, and locally *Protovirgularia* (Leonowicz 2013).

Based on the common and well-preserved ammonite fauna, the age of ore-bearing clay was determined as the Upper Bajocian–Upper Bathonian (*garantiana*–*discus* zones: Kopik 1998; Matyja and Wierzbowski 2000, 2006b; Barski et al. 2004). It overlies Lower Bajocian Kościelisko Beds (Kopik 1997) and is overlain by condensed Callovian deposits (Fig. 2).

The ore-bearing clay was deposited in a marginal part of a shallow epicontinental sea, within the Polish Basin. This basin constituted the easternmost arm of an extensive system of epicontinental seas called the Central European Basin System (CEBS), which covered the area of Central Europe in the Mesozoic (Fig. 3). During the Jurassic, the Polish Basin was bordered from the east, northeast, and southwest by land (Dadlez 1989; Feldman-Olszewska 1997), whereas to the northwest and southeast it connected with CEBS and Tethys. Sedimentation in the Polish Basin began in the Aalenian, during a marine transgression, which most probably entered from the Tethyan Ocean through the East Carpathian Gate (Dayczak-Calikowska 1997). The oldest deposits occur only in the axial part of the basin, referred to as the Mid-Polish Trough (Fig. 4). As the transgression developed, the sea extended outside this zone, covering progressively still wider areas. In the Silesian-Kraków region, sedimentation started in the Early Bajocian (*sauzei* chron—Kopik 1998) and lasted, with a short break in the *subfurcatum* chron, until the end of the Middle Jurassic, continuing farther during the Late Jurassic (Matyja and Wierzbowski 2006a). This transgression was not uniform but consisted of several transgressive pulses, interrupted by short-lived regressions and periods of still-stand (e.g., Matyja and Wierzbowski 2006a; Pieńkowski et al. 2008). In the succession from central Poland,

Fig. 2 Lithostratigraphy and biostratigraphy of the Middle Jurassic deposits from the Silesian-Kraków region (after Kopik 1998; Matyja and Wierzbowski 2000, 2006b; Barski et al. 2004) with an idealized lithological log

Pieńkowski et al. (2008) distinguished eight transgressive–regressive (T–R) cycles. In the section exposed in the middle part of the Silesian-Kraków region, Leonowicz (2015) recognized seven T–R cycles, partly correlating with those from central Poland. Besides the fluctuations of the shoreline, deposition in the Polish Basin was also influenced by morphological differentiation of the seafloor into several swells and depressions, resulting from salt movements and syndepositional faults (Dadlez 1994; Feldman-Olszewska 1997; Pieńkowski et al. 2008). This differentiation is reflected by the lateral variability of thickness and facies type, which was recognized on a regional as well as local scale (Feldman-Olszewska 1997; Barski 1999).

The ore-bearing clay crops out in the Silesian-Kraków Upland in a narrow, NW–SE-oriented belt that wedges out south of Zawiercie (Fig. 1a). The succession reaches its maximum thickness of about 200 m in the central part of the outcrop belt, near Częstochowa (Kopik 1997). To

Fig. 3 Paleogeographical map of Europe in the Middle Jurassic (after Ziegler 1990, modified). AM Armorican Massif, BM Bohemian Massif, CEBS Central European Basin System, IBM Iberian Meseta, IM Irish Massif, LBM London-Brabant Massif, MC Massif Central High, MCA Meta-Carpathian Arc, RHB Rockall-Hatton Bank, UH Ukrainian High

Fig. 4 Polish Basin in the Middle Bathonian (*bremeri* chron, after Feldman-Olszewska 1998, modified) and the location of sections studied. ECG East Carpathian Gate, Cz Częstochowa, Z Zawiercie

the south, the thickness decreases, and near Zawiercie it is about 60 m (Kopik 1998). The decrease in thickness is accompanied by a reduction of the older parts of the succession that results from its onlap on to older Mesozoic rocks. The studied succession is situated in the middle and southern parts of the outcrop belt, between Częstochowa and Ogrodzieniec (Fig. 1a), where dark mudstone is exposed in several clay pits. This succession spans the interval from the Upper Bajocian *parkinsoni* zone to the Upper Bathonian *retrocostatum* zone (Fig. 2; Matyja and Wierzbowski 2003, 2006b; Zatoń 2007; Zatoń et al. 2011, 2012).

Materials and methods

Ichnological observations were undertaken in ten clay pits located in Częstochowa, Żarki, Blanowice, and Ogrodzieniec (Fig. 1a, c). Eight selected sections were examined centimeter by centimeter and two types of bioturbation structure were determined: trace fossils and bio-deformational structures (cf. Wetzel 2008). They were observed on fresh surfaces, in sections perpendicular, parallel and oblique to the bedding. Additionally, relative abundance, dimensions, cross-cutting relationships of trace fossils, and the total intensity of bioturbation were recorded. The intensity of bioturbation was estimated using the ichnofabric index (i.i.) scheme of Droser and Bottjer (1986).

Results and interpretations

Dark mudstone of the Ore-Bearing Częstochowa Clay Formation contains bioturbation in the entire succession studied, even in the intervals with preserved primary lamination (Figs. 5, 6). There is variation, however, in bioturbation intensity and diversity of the trace fossil association. Ichnofabric index i.i. ranges from 2 (0–10 %) in laminated mudstone to 5 (60–100 %) in strongly bioturbated zones. Diversity of the trace fossil association varies from low to moderate, involving ten ichnogenera and a few indeterminate forms. Their descriptions and interpretations are presented in Table 1. The trace fossils never occur all together. Four ichnofossils: *Chondrites*, *Trichichnus*, pyritized burrows type 1 and *Palaeophycus* are common throughout the entire succession. Other ichnogenera, i.e., *Planolites*, *Protovirgularia*, *?Rosselia*, *Schaubcylindrichnus*, *Taenidium*, *Tasselia*-like structures, *Thalassinoides*, and other types of pyritized burrow occur only in some intervals (Figs. 5, 6). They form five types of tiered ichnofabric with varieties reflecting degree of the association completeness. From cross-cutting relationships, at least four

Fig. 5 Distribution of trace fossils and ichnofabrics in the succession of ore-bearing clay from Częstochowa. Thick lines mark intervals with common occurrences of particular bioturbation structures,

x single occurrences. Biostratigraphy after Matyja and Wierzbowski (2000, 2003, 2006b); dated intervals are marked in grey

tiers can be distinguished in the most diverse ichnofabric (cf. Leonowicz 2012). The shallowest one comprises a bioturbated background with indeterminate biodeformational

structures. The second one is represented by different grazing, feeding, crawling, and dwelling structures. A still deeper tier consists of *Chondrites* and the deepest one is

Fig. 6 Distribution of trace fossils and ichnofabrics in the succession of ore-bearing clay from Żarki and Zawiercie area. For explanation of symbols, see Fig. 5 caption. Biostratigraphy after Zatoń (2007) and Zatoń et al. (2011, 2012); dated intervals are marked in grey

Table 1 Short description and interpretation of trace fossils and biodeformational structures observed in the succession studied

Ichnogenus	Short description	Occurrence and remarks	Interpretation	Environment
<i>Chondrites</i> isp. (Fig. 7a–c)	Regularly branching system of tunnels, ramifying at acute angles. Tunnels distinctly flattened, filled with sediment lighter or darker than the host rock. Developed as three size classes with diameters: thin—0.2–0.5 mm, medium—about 1 mm and thick—1.5–3 mm. Thick and thin <i>Chondrites</i> sparsely dispersed in the mudstone and prevalently oriented obliquely to the bedding, medium mainly parallel to the bedding and may form close network of branching and overlapping tunnels	Common; different size classes often co-occur	Feeding structure of unknown deposit feeders, probably chemosymbiotic (Fu 1991)	Typical of oxygen-deficient conditions (Bromley and Ekdale 1984); occupies shallow tier in oxygen-depleted sediment and deep tier under well-oxygenated bottom water. Three size classes may be attributed to different oxygenation levels (Savvda and Bottjer 1989); thick recording the best oxygenation, thin—the lowest oxygen content
<i>Palaeophycus</i> isp. (Fig. 7d–e)	Straight, unbranched, horizontal tunnels up to 1 cm in diameter. Tunnels strongly flattened, lined with a thin lamina of quartz silt, very fine sand or shell debris; surface of lining not ornamented. The fill structureless, similar to the host rock	Common	Dwelling burrow of predaceous polychaetes (Pemberton and Frey 1982; Pemberton et al. 2001), considered also a feeding structure (Pienkowski 1985)	Various environments, ranging from high to low energy. Common in shoreface settings; offshore in storm event deposits (Pemberton et al. 2001)
<i>Planolites</i> isp.	Straight or slightly curved, unbranched tunnels, few millimeters in diameter, mainly flattened. Tunnels unlined, filled with structureless silt and sand or with mudstone lighter than the host rock; variably orientated to the bedding	Rare	Burrow of deposit feeding worm-like organisms, producing active backfilling (Pemberton and Frey 1982)	Various environments, ranging from deep-marine to fresh-water (Pemberton et al. 2001)
<i>Protovirgularia</i> isp.	Straight or curved, horizontal, elongated trace fossil, up to 3 mm wide, comprising two symmetric, obliquely striated belts separated by an indistinct median ridge	Rare	Crawling trace of bivalves (Seilacher and Seilacher 1994)	Various environments, ranging from marine to fresh-water (Buatois and Mángano 2011)
? <i>Rosselia</i> isp. (Fig. 7f)	Funnel-shaped structures, up to 2 cm in diameter, consisting of cylindrical central burrow and surrounding it thick clayey wall. Central tunnel up to 7 mm in diameter, filled with sediment similar to the host rock. Orientated vertically or obliquely to the bedding	Rare; observed specimens incomplete and cut obliquely to the median plane	Dwelling structure of detritus feeders, most probably terebellid polychaetes (Nara 1995)	Associated with the inner shelf settings; tolerant of stressful conditions, linked to rapid storm sedimentation (Nara 2002; Netto et al. 2014)
<i>Schaubcylindrichnus</i> isp. (Fig. 7g–h)	Isolated bundles of closely spaced or detached, parallel or subparallel tubes, reaching 4 mm in diameter. Tubes strongly flattened, lined with a thin lamina of quartz silt and filled with mudstone similar to the host rock. The number of tubes does not exceed 4	Rare; only horizontal components of originally bow-like bends observed	Composite burrow system, formed by funnel-feeding animals, such as enteropneusts (Nara 2006; Löwemark and Nara 2010)	Associated mainly with shoreface settings, lying between high-energy strand and quiet offshore zone, reported also from deep sea deposits (Pemberton et al. 2001; Löwemark and Nara 2013)
<i>Taenidium</i> isp. (Figs. 8a, 10d)	Straight, horizontal or subhorizontal, unbranched and unlined, slightly flattened cylindrical trace fossils 8–10 mm in diameter. Filled with material similar to the host rock, forming discreet, meniscus-shaped segments slightly differing in the color; menisci deeply arcuate and tightly packed	Common in the lower half of Leszczyński section	Actively filled burrows of deposit feeders (D'Alessandro and Bromley 1987)	Various environments, ranging from deep-marine to fresh-water (Buatois and Mángano 2011)

Table 1 continued

Ichnogenus	Short description	Occurrence and remarks	Interpretation	Environment
cf. <i>Tasmania</i> (Fig. 8c–e)	Widening downward, pear-shaped structures, up to 6 cm in diameter, consisting of the inner axial tube and surrounding it radial portions of sediment. The inner tube orientated vertically or slightly obliquely to the bedding and commonly pyritized. The sediment directly around it is lighter-colored, probably due to the better oxygenation	Common in the lowermost part of the Sowa-Gliniński section; preserved in calcareous concretions; in observed specimens the details of internal structure not preserved	Complex feeding burrow of malanid polychaetes, combining deposit feeding, detritus feeding, and microbial-gardening activities (Olivero and López Cabrera 2010)	Well-oxygenated, shallow- to deep-water marine environments (Olivero and López Cabrera 2010); the occurrence of <i>Tasmania</i> is controlled by three factors: rapid sedimentation, high suspension input, and soupground consistency of substrate (Wetzel and Bromley 1996)
<i>Thalassinoides</i> isp. (Fig. 8b)	Horizontally orientated burrow systems, consisting of tubes 1–6 cm in diameter that branch at acute angles. Tubes observed in mudstones strongly flattened, filled with structureless mudstone similar to the host rock and lined with a thin lamina of silt, fine-grained sand and/or fine shell debris. Tubes preserved in the siderite concretions slightly flattened, filled either with material similar to the host rock or with light grey silt and do not show lining	Common	Dwelling/feeding structure of deposit-feeding crustaceans, passively filled by bottom sediment (Frey et al. 1984)	Associated with a lower shoreface and offshore environments (Pemberton et al. 2001)
<i>Trichichnus</i> isp. (Fig. 7i)	Thin, hair-like, pyritized burrows, few millimeters to few centimeters long, cylindrical or slightly flattened, non-branching. Straight, curved or sinuous, orientated at various angles to the bedding	Common	Burrow of chemosymbiotic vermiform organisms, most probably sipunculans (Romero-Wetzel 1987)	Typical of low-oxygenated conditions (Romero-Wetzel 1987; McBride and Picard 1991)
Pyritized burrows				
Type 1 (Fig. 9a, b)	Straight or curved, non-branching, flattened pyritized tubes, 2–8 mm in diameter, filled with fine-grained massive pyrite. The surface of tubes rusty, covered by Fe hydroxides, rough but devoid of distinct ornamentation. Observed fragments of tubes represent J-shaped burrows, exceeding 40 cm of length, variously orientated to the bedding	Common	Probably dwelling/feeding structures of chemosymbiotic organisms (Leonowicz 2012)	Oxygen-deficient conditions (Leonowicz 2012)
Type 2 (Fig. 9c)	Horizontally orientated, straight to sinuous, non-branching, slightly flattened tubes, 1–3 mm in diameter, filled with fine-grained massive pyrite. The surface of tube walls rough but not ornamented, usually covered by Fe hydroxides. Observed fragments of tubes up to 8 cm long	Rare	Probably grazing traces	
Type 3 (Fig. 9d)	Horizontally orientated, straight, non-branching, slightly flattened tubes, up to 1.5 cm in diameter, filled mainly with granular and massive pyrite, in places empty inside. The wall is relatively thick, with rough but not ornamented surface. Observed fragments up to 15 cm long	Rare	Probably reinforced domiciles, formed in a soft mud	
Type 4 (Fig. 9e)	Thick, in some cases exceeding 1 cm in diameter, vertically orientated branching tunnels with a subcircular cross section, filled with massive pyrite. Observed fragments tens of centimeters long	Common in the lowermost part of the Sowa-Gliniński section	Probably dwelling/feeding structures	

Table 1 continued

Ichnogenus	Short description	Occurrence and remarks	Interpretation	Environment
Type 5 (Fig. 9f)	Medium thick, 2–4 mm in diameter, vertically orientated branching tunnels, filled with massive pyrite. Observed few centimeters long fragments	Rare	Probably dwelling/feeding structures	
Biodeformational structures (Fig. 10b–e)	Burrows of various shapes and size, with indistinct outlines and chaotic filling. In strongly reworked mudstones, hardly discernible due to the homogenization of sediment; in bioturbated mudstones rich in coarse-grained material developed as irregular mottles; in laminated mudstones represented by cryptobioturbation	Constitute the background for distinct trace fossils	Shallow burrows of deposit and detritus feeders, burrowing in the soupy sediment of the “mixed layer” (Bromley 1990)	

occupied by *Trichichnus* and pyritized burrows type 1. Most probably, the second, most diverse tier, can be divided into another two. Taking into account the typical trend in vertical stacking of infaunal communities (Bromley and Ekdale 1986), sediment processors are expected to occupy a deeper level than dwelling animals; however, crosscutting of these burrows was not observed in the deposits studied and the relationships between them remain unknown. Similarly, the co-occurring three size classes of *Chondrites*, referring to diameter (Table 1), may belong to different tiers. Studies of modern and ancient deposits have shown that a decrease in oxygen availability leads to a decrease in the size of burrows of a similar type (Savrda et al. 1984; Wetzel 1991; Martin 2004). According to this, size differences of *Chondrites* from the ore-bearing clay most likely reflect various levels of oxygenation, existing at different depths of penetration, although the cross-cutting relationships between them could not be deduced.

Taking into account bioturbation intensity, composition of the trace fossil association and the type of biodeformational structures (mottles, homogenization, cryptobioturbation), eight ichnofabric variants have been distinguished.

Ichnofabric characteristics

Ichnofabric 1a: occurring in parallel laminated mudstone (Fig. 10a, b)

Description this ichnofabric is characterized by sparse to low bioturbation intensity (i.i. = 2–3) and low diversity of the trace fossil association. Biodeformational structures are represented by cryptobioturbation, which is common but discernible only in thin-section. It occupies the shallowest tier of ichnofabric. The middle tier is represented by *Palaeophycus*, *Protovirgularia* and probably pyritized burrows type 3, a deeper one by *Chondrites* and the deepest one by *Trichichnus* and pyritized burrows type 1. Trace fossils are scattered and discreet; they cut laminae but do not obliterate them and are visible mainly on horizontal parting planes, except *Trichichnus* and *Chondrites*, which are commonly oriented obliquely. *Trichichnus* and pyritized burrows occur throughout the section, similarly as cryptobioturbation, whereas *Chondrites*, *Palaeophycus* and local *Protovirgularia* were observed mainly within silt–sand laminae. This type of ichnofabric was observed in the Ogrodzieniec clay-pit (Fig. 6) and was already studied in detail by Leonowicz (2013).

Interpretation the common occurrence of cryptobioturbation and the scarcity of trace fossils, most of which were produced by animals adapted to low-oxygenated conditions, indicate that laminated mudstone records deposition in a restricted, oxygen-deficient environment. Deposits showing only cryptobioturbation, *Trichichnus* and pyritized

Fig. 7 Trace fossils from ore-bearing clay. Three size classes of *Chondrites* isp., according to diameter: thick (a), thin (b), and the net of medium-sized tunnels (c), sections oblique to the bedding; *Palaeophycus* isp.: lined with a thin lamina of silt (d) and coarse shell debris (e), views on parting planes; f ?*Rosselia* isp., seen on the edge of mudstone piece. On the upper surface, thick clayey wall (black arrow) and the central burrow, filled with matrix similar to the host

rock, are visible; the wall is reworked by horizontal *Trichichnus* (white arrow). In the vertical section, clayey wall wedges out downward; *Schaubcylindrichnus* isp.: g bundle of four closely spaced tubes, view on parting plane, h two detached tubes, vertical cross section; i *Trichichnus*, section oblique to the bedding. Scale bar is 1 cm; a, d Sowa-Gliński, b Leszczyński, c, g, h, i Gnaszyn, e Brzeziny, f Anna (photo c by A. Uchman)

Fig. 8 Trace fossils from ore-bearing clay. **a** *Taenidium*, vertical section; **b** *Thalassinoides*, view on parting plane; cf. *Tasselia*: **c** vertically oriented calcareous concretion with cf. *Tasselia* inside, **d** pyritized inner tube surrounded by reworked lighter material, verti-

cal polished section, **e** radial elements spreading out from the central tube, vertical section. Scale bar in **a**, **b**, **d**, **e** is 1 cm, in **c** is in centimeters; **a** Leszczyński, **b** Wrzosowa, **c–e** Sowa-Gliński

burrows represent quasi-anaerobic biofacies (sensu: Savrda and Bottjer 1991), developed in most severe conditions (Leonowicz 2013). Intermittent, short reoxygenation episodes, linked to deposition of silt–sand laminae, resulted in temporal improvement of oxygenation, establishment of dysoxic conditions and development of a more diverse, tiered ichnofabric.

Ichnofabric 1b: alternating laminated and bioturbated intervals (Fig. 10c)

Description this ichnofabric consists of alternating, 2–10-cm-thick intervals of parallel laminated and strongly bioturbated mudstone. Laminated deposits reveal features typical of ichnofabric 1a. Bioturbated intervals are either homogenized or show various biodeformational structures,

both clearly visible in the outcrop. Bioturbation intensity changes from sparse to low (i.i. = 2–3) in laminated intervals to moderate to high (i.i. = 4–5) in bioturbated ones. The diversity of the trace fossil association is generally low. Besides *Trichichnus* and pyritized burrows type 1, occupying the deepest tier, deep-tier *Chondrites* and representatives of the middle tier: *Palaeophycus*, local *Thalassinoides* and *Taenidium* also occur. This ichnofabric was observed in the Blanowice and Żarki exposures (Fig. 6). In the second locality, the interval revealing ichnofabric 1b passes upwards into strongly bioturbated deposits.

Interpretation the occurrence of strongly bioturbated intervals within a laminated sequence (Blanowice section) suggests that they record episodes of oxygenation improvement. In this case, the ichnofabric 1b records deposition in an oxygen-deficient environment, similarly for ichnofabric

Fig. 9 Trace fossils from ore-bearing clay. Pyritized burrows type 1: vertical (a) and horizontal (b) fragments of J-shaped tunnels; c pyritized burrow type 2, view on parting plane; d pyritized burrow type 3, view on parting plane; e pyritized burrows type 4, vertical section; f pyritized burrow type 5, vertical section; scale bar in b, d, f is in centimeters; a, b Gnaszyn, c, f Leszczyński, d Ogrodzieniec, e Sowa-Gliński (photo a by A. Uchman)

variant 1a, but with longer-lasting periods of reoxygenation. If the interval with laminated-bioturbated couplets occurs within bioturbated deposits (Żarki section), it is likely that this ichnofabric resulted from recurrent episodic sedimentation of relatively thick portions of mud in an oxygenated environment. In such a case, a high sedimentation rate would have caused only the upper part of sediment to be reworked by burrowing animals, with the lower part remaining undisturbed (cf. a “smothered bottom” in Brett 1983).

Ichnofabric 2a: impoverished trace fossil association in a homogenized background

Description this ichnofabric consists of dispersed, uncommon trace fossils occurring in the homogenized

background sediment. Bioturbation intensity is moderate to high (i.e. = 4–5) and diversity of the trace fossil association is low. The association consists of common *Trichichnus* and pyritized burrows type 1 representing the deepest tier, deep-tier *Chondrites* and middle-tier *Palaeophycus* and pyritized burrows type 2. In moderately bioturbated deposits, background sediment shows an indistinct parallel fabric, consisting of vague parallel stripes of a different color. This feature probably resulted from the incomplete bioturbation of a primary horizontal lamination (cf. Leonowicz 2013). This type of ichnofabric occurs in the middle parts of the sections at Gnaszyn and Żarki and in the uppermost parts of the sections at Anna and Ogrodzieniec (Figs. 5, 6).

Interpretation bioturbation of the whole sediment indicates that oxygenation of the seafloor was better than in

Fig. 10 Ichnofabrics from ore-bearing clay. Ichnofabric 1a: **a** laminated mudstones, vertical section; **b** discrete micro-burrows (arrows) responsible for cryptobioturbation, thin section view; **c** ichnofabric 1b: laminated mudstones alternate with bioturbated intervals showing irregular biodeformational structures, vertical section; **d** ichno-

fabric type 4a, dominated by irregular biodeformational structures filled with fine shell debris, view on parting plane; **e** ichnofabric type 4b, dominated by biodeformational structures and *Taenidium* (arrow), vertical section. Scale bar in **a**, **c–e** is 1 cm, in **b** is 1 mm; **a**, **b** Ogrodzieniec, **c** Żarki, **d** Sowa-Gliński, **e** Leszczyński

the case of ichnofabrics 1a and 1b. However, the low diversity of the trace fossil association, dominated by deep-tier ichnogenera typical of oxygen-depleted environments, points to restricted dysoxic conditions (cf. Leonowicz 2012). Most probably mudstone was deposited in predominantly dysoxic conditions, in which only animals adapted to a low oxygen content could survive. Oxygenation of the seafloor occasionally improved during reoxygenation episodes, enabling the producers of *Palaeophycus* to inhabit the seafloor.

Ichnofabric 2b: diverse trace fossil association in homogenized background

Description this ichnofabric consists of relatively common trace fossils occurring in the homogenized background sediment. Bioturbation intensity is moderate to high (i.i. = 4–5) and the diversity of the trace fossil association is moderate. The most common ichnofossils are *Chondrites*

representing the deep tier, *Trichichnus* and pyritized burrows type 1 occupying the deepest tier and *Palaeophycus*, which belongs to the middle tier. Other representatives of the middle tier, including *Thalassinoides*, pyritized burrows type 2, 3 and 5, *Planolites*, *?Rosselia*, *Schaubcylindrichnus* and *Taenidium* are rare. In some intervals, thick *Chondrites* appear. This type of ichnofabric occurs in the Alina section, in the upper part of Leszczyński section, in the lower and uppermost part of the Gnaszyn section and in the Anna section (Fig. 5).

Interpretation the relatively diverse trace fossil association indicates that oxygenation of the bottom sediment was still better than in previous ichnofabrics. However, the full set of ichnofossils does not occur throughout deposits showing this ichnofabric and some ichnogenera such as *Thalassinoides*, *Planolites*, *?Rosselia*, *Schaubcylindrichnus*, and *Taenidium* occur as single specimens scattered in the succession. It suggests that the bottom conditions changed with time and only during periods of the best

oxygenation did a more diverse association develop. When the oxygenation decreased some trace fossils disappeared and the association became impoverished.

Ichnofabric 3: dense Chondrites network

Description this ichnofabric is dominated by abundant, horizontally or subhorizontally oriented *Chondrites* (Fig. 7c), which causes strong bioturbation of the sediment. Bioturbation intensity is moderate to high (i.i. = 4–5) and the diversity of the trace fossil association is low. Besides *Chondrites* representing the deep tier, it comprises *Trichichnus* and pyritized burrows type 1 occupying the deepest tier and sparse *Palaeophycus*, pyritized burrows type 2 and some indeterminate grazing traces from the middle tier. *Chondrites* is represented by two size classes referring to diameter—medium and thin. It forms the close network, which conforms to a relict horizontal lamination, enhancing the parallel fabric of the rock. This type of ichnofabric occurs as 10–140-cm-thick intercalations within other ichnofabric types and partially coincides with intervals with common ammonite occurrences. It was observed in the Sowa-Gliński, Leszczyński, Gnaszyn, Żarki and Ogrodzieniec exposures (Figs. 5, 6).

Interpretation the strong bioturbation by one ichnogenus (*Chondrites*), produced by deeply burrowing animals, suggests that this kind of ichnofabric may record periods of decreased sedimentation rate. Limited sediment delivery led to the persistent reworking of sediment within a particular depth range, resulting in the obliteration of ichnofossils from shallower tiers (Bromley 1990). This interpretation is reinforced by the common occurrence of ammonites, interpreted as a result of sediment condensation (Leonowicz 2015), observed in the intervals with a dense *Chondrites* network.

Ichnofabric 4a: dominated by biodeformational structures (Fig. 10d)

Description the most characteristic components of this ichnofabric are well discernible biodeformational structures. The intensity of bioturbation is moderate to high (i.i. = 4–5) and the diversity of the trace fossil association is moderate, but distinct ichnofossils are scattered and not common. The association includes *Trichichnus* and pyritized burrows type 1 from the deepest tier, *Chondrites* representing the deep tier as well as *Palaeophycus*, *Thalassinoides*, pyritized burrows type 2, 3 and 4, rare *Planolites*, *Taenidium* and local *Roselia* occupying the middle tier. *Chondrites* is represented by three size classes referring to diameter and the thick variety is quite common. In mudstone rich in shell debris, biodeformational structures are usually developed as irregular, elongated accumulations of disarticulated and fragmented shells of bivalves and small

gastropods, oriented obliquely to the bedding. Skeletal mudstone, occurring in the uppermost part of the Sowa-Gliński section, contains an impoverished association of trace fossils that includes mainly thin pyritized burrows type 1, local *Trichichnus* and *Chondrites*. The ichnofabric 4a occurs in the Sowa-Gliński section, upper part of the Leszczyński section, in the lower part of the Gnaszyn section and in the middle part of the Anna section (Fig. 5).

Interpretation moderate diversity of the trace fossil association points to a relatively well oxygenated environment that is additionally confirmed by the appearance of thick *Chondrites*, especially common in this variant of ichnofabric. However, similar to the case of ichnofabric 2b, the full set of ichnofossils occurs only in some intervals that may reflect either a fluctuation of oxygenation or patchy distribution of the fauna. Patchiness is a well-known feature of benthic communities from shallow-marine as well as deep-marine settings (e.g., Tufail et al. 1989; Cosson et al. 1997; McIlroy 2007), which results from various physical and biotic processes, including varying hydrodynamic regimes, pulsed input of food, small-scale bottom topography (bedforms and biogenically produced mounds), and trophic specialization of competing organisms (Buatois and Mángano 2011). In time-averaged assemblages, this heterogeneity is not visible, but if sedimentation rate is high it may lead to incomplete reworking of sediment by animals from particular tiers, which have not enough time to pass through the whole area (Wetzel 1991). The increased sedimentation rate in ichnofabric 4a is supported by the domination of biodeformational structures, which result from burrowing of deposit and detritus feeding animals in the uppermost, soupy part of sediment. The high benthic food content, which usually accompanies a high input of sediment, causes that behavioral specialization becomes unnecessary and well-defined trace fossils, recording various feeding strategies are rare (Wetzel and Uchman 1998). Further impoverishment of the trace fossil association in skeletal mudstone could have resulted from a still higher sedimentation rate and unfavorable substrate composition, in which coarse-grained shell debris prevailed.

Ichnofabric 4b: dominated by Taenidium (Fig. 10e)

Description the most characteristic components of this ichnofabric are *Taenidium* and biodeformational structures. Bioturbation intensity is high (i.i. = 5) and the diversity of trace fossil association is moderate; however, all ichnofossils beside *Taenidium* are uncommon and scattered. The background sediment is intensively mottled. Beside *Taenidium*, which is the main component of the middle tier, trace fossil association contains *Chondrites* (deep tier), *Trichichnus* and pyritized burrows type 1 (the deepest tier) as well as *Palaeophycus*, *Planolites*, *Thalassinoides*, pyritized burrows types 2 and 4, local *Schaubcylindrichnus*

and ?*Rosselia* (middle tier). In some intervals, a thick variety of *Chondrites* appears. Thin *Chondrites* commonly occurs within elliptical or irregularly shaped, indeterminate burrows, together forming composite burrows (sensu: Chamberlain 1975). This type of ichnofabric occurs in the lower half of Leszczyński section and in the middle parts of sections at Anna and Żarki (Figs. 5, 6).

Interpretation the similarity between ichnofabrics 4a and 4b indicates that both of them reflect similar conditions, i.e., good oxygenation and relatively high sedimentation rate. However, the common occurrence of *Taenidium* in ichnofabric 4b suggests that the sediment input and benthic food content were probably lower than in the case of ichnofabric dominated only by biodeformational structures. Observations of modern benthic communities from shallow-water environments showed that the first response to the rapid input of phytodetritus was the appearance of surface deposit feeders and suspension feeders, whereas more diverse feeding strategies developed only after a few weeks (Quijón et al. 2008). In the case of ichnofabric 4b, organic matter was firstly exploited by subsurface trophic generalists, burrowing in the mixed layer. When the easy accessible organic particles became exhausted, the remaining nutrients dispersed in homogenized sediment were acquired by more specialized, deeper-burrowing deposit feeders, responsible for the production of *Taenidium*.

Ichnofabric 5: with cf. Tasselia

Description the most characteristic components of this ichnofabric are thick pyritized burrows type 4 and *Tasselia*-like structures, preserved in spindle-shaped calcareous concretions. Intensity of bioturbation is moderate to high (i.i. = 4–5) and the diversity of the trace fossil association is low. Besides the ichnofossils mentioned above, occupying the middle tier, it contains *Chondrites* (deep tier), *Trichichnus* (the deepest tier), *Palaeophycus* and locally *Planolites* (middle tier). Background sediment is homogenized or mottled. This ichnofabric variety occurs in the lower part of Sowa-Gliński section (Fig. 5).

Interpretation the occurrence of *Tasselia*-like structures points to a well-oxygenated environment. Low diversity of the trace fossil association may have resulted from stressful conditions, linked to rapid sedimentation and high suspension input that are conducive to *Tasselia* (Wetzel and Bromley 1996).

Discussion

Sedimentary environment

The muddy substrate and the predominance of feeding, grazing and dwelling traces of deposit feeders,

accompanied by structures formed by detritus feeders, chemosymbionts and carnivores, indicates that the trace fossil association from the ore-bearing clay represents the *Cruziana* ichnofacies (e.g., Pemberton et al. 2001). Low to moderate diversity of the ichnofossil suite, an organic-rich substrate and the common occurrence of trace fossils characteristic of low-oxygen conditions point to the distal expression of this ichnofacies, which combines features of ichnofacies *Cruziana* and *Zoophycos*. It is characteristic of fully marine conditions, including lower offshore, prodelta, and shelf transition (MacEachern et al. 2007). In the case of the Polish Basin, which was in the Middle Jurassic a semi-enclosed epicontinental sea, the designation “shelf” is not exactly appropriate; thus the location of the depositional site shall be defined as a lower offshore to offshore-transition, i.e., below and above the storm wave base. Such a definition does not imply a deep-water location, as effective storm wave base in epicontinental seas usually does not exceed 30 ± 10 m (Immenhauser 2009). The ichnofabrics dominated by *Taenidium* and biodeformational structures (ichnofabrics 4a and 4b) may reflect deposition in more proximal settings, in the distal lower shoreface near fair weather wave base (MacEachern et al. 2007).

The morphology of trace fossils points to variable substrate consistency, reflecting increasing compaction and dewatering of sediment that resulted from progressive burial (cf. Bromley and Ekdale 1986). Irregular shapes and indistinct boundaries of biodeformational structures, constituting the shallowest ichnofabric tier, indicate that they were produced by animals “swimming” through the soupy substrate (Bromley 1990). The thin linings of the open burrows from the middle tier (e.g., *Palaeophycus*, *Thalassinoides* and *Schaubcylindrichnus*) point to the stability of cohesive muddy substrate, whereas the strong flattening of their horizontal and subhorizontal components indicates high porosity and low consolidation of the sediment. These trace fossils as well as actively filled burrows of deposit feeders easily moving through the unconsolidated mud (*Taenidium*) were emplaced in the substrate of a softground type (cf. Buatois and Mángano 2011). Trace fossils from deep tiers (*Chondrites*, *Trichichnus*, pyritized burrows type 1), might be produced in a semi-consolidated sediment, representing a firmground (cf. Schieber 2003; Buatois and Mángano 2011). This interpretation does not concern cases where these ichnofossils constitute the only components of ichnofabric, suggesting their shallow emplacement in the poorly oxygenated substrate. In fact, *Chondrites* has often strongly flattened tunnels, pointing to its relatively shallow formation in a soft mud.

The low to moderate diversity of the trace fossil association indicates that the sedimentary environment of the ore-bearing clay was generally not favorable for a diverse macrobenthic tracemaker community. The predominance

of ichnofossils, produced by animals adapted to oxygen-deficient conditions (*Chondrites*, *Trichichnus* and pyritized burrows type 1), which maintain the connection with bottom water, and simultaneous limited occurrence (except ichnofabrics 4a and 4b) of other ichnogenera, suggest that the main factor restricting development of the benthic community was oxygenation of bottom sediment. The gradation in the succession from laminated to strongly bioturbated deposits reflects changes in seafloor oxygenation, controlling the distribution of ichnofabrics (cf. Taylor et al. 2003). According to the oxygen-related trace fossil model proposed by Savrda and Bottjer (1989) and confirmed by later studies (e.g., Martin 2004), decreasing oxygenation of the seafloor results in a decrease in the trace fossil size, diversity of the trace fossil association, and bioturbation depth, the latter leading to the disappearance of higher tiers. Applying this assumption, the sequence of ichnofabrics 1a–1b–2a–2b may be interpreted as a record of increasing oxygenation of the seafloor. The most severe conditions are recorded by quasi-anaerobic biofacies, characteristic of laminated mudstone (ichnofabric 1a). Reoxygenation episodes in this case were short and led to temporal establishment of dysoxic conditions, reflected by a more diverse but still strongly impoverished trace fossil association and low intensity of bioturbation. In ichnofabric 1b, periods of oxygenation improvement lasted longer, resulting in the formation of bioturbated intervals up to 10 cm thick. In ichnofabric 2a records permanent dysoxic conditions prevailing within the sediment that are reflected by the trace fossil association of a low diversity, occurring within a homogenized background sediment. The best but still not fully oxygenated conditions are recorded by ichnofabric 2b, characterized by a moderately diverse trace fossil association and bioturbated background sediment. The dispersed occurrence of middle tier trace fossils in ichnofabrics 2a and 2b suggests that also in these cases the oxygenation of the bottom sediment was not constant and reached the highest level during recurrent episodes of oxygenation improvement. These episodes were most probably linked to the activity of bottom currents, generated during storms that ventilated the seafloor. The occurrence of such currents was previously indicated by sedimentological analysis of the ore-bearing clay that revealed several types of storm deposit (Leonowicz 2013, 2015). They include thin and thick silt–sand laminae, bedding plane accumulations of shell debris, bundles of silt–sand laminae, small sandy lenses, and up to 6-cm-thick silt-, sand- and shell-debris-rich levels. The internal structures of these accumulations (e.g., laminae with sharp, erosional bases and gradational tops, inversely graded laminae with sharp tops, graded rhythmites, cross-, parallel-, and low-angle lamination) are characteristic of distal tempestites and point to a significant role of storm-generated currents in deposition of

studied deposits (Leonowicz 2013). If burrows recognized as *Rosselia* really represent this ichnogenera, they fit well such an interpretation, as this trace fossil is characteristic of settings in which rapid storm sedimentation occurs (Nara 2002; Netto et al. 2014). In strongly bioturbated mudstones most of the sedimentary structures are obliterated; however, the presence of relict lamination, common erosion surfaces and minor scours suggest a similar storm influence on deposition (Leonowicz 2015).

A moderate to high bioturbation intensity and low to moderate diversity of the trace fossil association in ichnofabrics 4–5 suggest that they developed under similar oxygenation levels as ichnofabric 2. In the case of ichnofabric 4, this interpretation is additionally supported by the occurrence of *Taenidium*—a trace fossil produced by animals which burrowed within the sediment but did not maintain a connection with the seafloor. Its presence indicates that conditions in interstitial waters were at least dysoxic (Ekdale and Mason 1988). Also, the occurrence of thick *Chondrites* suggests relatively good oxygenation of the bottom. However, general impoverishment of the trace fossil association points to a negative influence of factors other than oxygenation, including sedimentation rate and the input of benthic food. Ichnofabrics 4 and 5 reflect abundant sediment input and high delivery of nutrients. In ichnofabric 4a, rapid sedimentation resulted in complete reworking of sediment by subsurface trophic generalists, burrowing in the mixed layer and producing indeterminate biodeformational structures. Ichnofabric 4b reflects a slower but still increased deposition, enabling colonization of the seafloor by more specialized and deeper-burrowing deposit feeders (*Taenidium*). In ichnofabric 5, high suspended sediment input impeded development of a diverse trace fossil association, favoring formation of *Tasselia*-like structures. Rapid event sedimentation of the thick portions of mud might also have led to the formation of alternating laminated and bioturbated beds, representing ichnofabric 1b. The opposite tendency is reflected by ichnofabric 3, which records decreased sedimentation rate. Temporal sediment starvation and syndepositional erosion was already postulated in hitherto studies of the ore-bearing clay to explain the origin of horizons of siderite concretions (Witkowska 2012), calcareous hiatus concretions (Zatoń et al. 2011) and intervals with common ammonite occurrence (Leonowicz 2015).

Comparison of the equivalent intervals of the succession from different locations (Częstochowa and Zawiercie areas) shows that the conditions within the basin were not uniform. In the area of Częstochowa, all of the succession studied, assigned to the Upper Bajocian–Upper Bathonian (*parkinsoni*–*retrocostatum* zones), is bioturbated and reveals ichnofabrics 2–5, recording different grades of dysoxic conditions. The succession of the ore-bearing clay from the Zawiercie area (Ogrodzieniec and Blanowice)

represents the Middle and Upper Bathonian (*subcontractus-retrocostatum*) zones; thus, it is of the same age as the Gnaszyn and Anna sections from the Częstochowa area. However, it consists mostly of laminated mudstone with ichnofabrics 1a and 1b that reflect oxygen-restricted, sub-oxic conditions, only temporarily changing to dysoxic. This ichnofabric variability might have resulted from the morphological differentiation of the seafloor, which influenced water circulation and would have been responsible for the oxygenation of the seafloor. One of the possible explanations is an environmental model assuming the occurrence on the seafloor of local hollows with isolated pockets of oxygen-depleted water (Hallam and Bradshaw 1979; Wignall 1991). The differentiation of the seafloor into several swells and depressions has already been postulated for the whole Polish Basin (e.g., Dadlez 1994; Feldman-Olszewska 1997) and its southern part (Barski 1999, 2012; Leonowicz 2013, 2015). On the other hand, deposition of laminated mudstone in more proximal locations (Fig. 4) suggests that the important factor influencing oxygenation of the seafloor might have been increased primary production, triggered by high nutrient input from rivers. This explanation is reinforced by the common occurrence in laminated deposits of sedimentary structures recording the activity of bottom currents (Leonowicz 2013), which contradicts the notion of long-lasting stagnation of the bottom water.

Ichnofabric response to transgressions and regressions of the shoreline

The comparison of the distribution of ichnofabrics with the T–R cycles, recognized in the succession from Częstochowa (Fig. 11), reveals some correlation, although the biogenic response to the cyclic shoreline fluctuation is not conspicuous. The T–R cycles, which range in thickness from 9 to 22 m, were distinguished on the basis of sedimentological features of the mudstone (variation of sand, silt and clay contents, and relicts of sedimentary structures—Leonowicz 2015). Most of these major cycles (TR₁, TR₂₊₃, TR₅ and TR₆₊₇) correlate with cycles distinguished in the succession from central Poland and record relative sea-level changes across the entire Polish Basin. Thinner, minor cycles, which range in thickness from 4 to 10 m, were the result of local events, likely autocyclic shoreline progradation and syndepositional tectonics. The distribution of ichnofabrics has been compared with major as well as minor cycles. The most clear is the correlation of ichnofabric 3 with transgressive pulses (the beginnings of T₄ and T₆ as well as late phases of T₂, T_{4–2}, and T₅). As this ichnofabric records a decreased sedimentation rate, it indicates that some of the transgressions were accompanied by sediment starvation. Such a phenomenon is well known from the

concepts of sequence stratigraphy, according to which the condensed section is a characteristic feature of transgressive and high-stand systems tracts (Catuneanu et al. 2011). However, in the deposits studied, condensation is not inherent in every T–R cycle, suggesting that the sediment supply was generally high, also during transgressions. On the other hand, not all condensed intervals, inferred from the common occurrence of ammonites (Leonowicz 2015), coincide with the ichnofabric 3. This discrepancy may be related to different mechanisms of condensation. The strong reworking of the substrate by deeply burrowing animals requires decreased sediment delivery to the depositional site, whereas concentration of ammonites may result either from the decreased sediment supply or from the recurrent winnowing of mud from the seafloor. Taking into account the relatively shallow-water conditions, the most probable reason of condensation was the bypass of sediment to the deeper parts of the basin (Leonowicz 2015). Resulting slow mud accumulation might lead to development of ichnofabric 3. However, if the sediment bypass was accompanied by recurrent erosion of the seafloor, the intervals with common ammonites could have been formed.

A clear correlation also exists between ichnofabrics 4a and 4b, reflecting high sedimentation rates, and deposits rich in sand and shell debris from the Lower Bathonian *zigzag-tenuiplicatus* zones (T₂–T₄, Fig. 11). These deposits record a period of the significant shallowing of the sea and deposition in high-energy conditions, within the range of storm and, temporarily, fair weather waves (Leonowicz 2015). Besides the increased supply of sediment rich in coarse particles, the proximity of the shoreline and expanse of intrabasinal shoals might also account for the high delivery of nutrients, triggering plankton blooms that were an important source of benthic food. The resulting abundance of easily accessible organic particles favored the development of a shallow-burrowing community and formation of ichnofabrics 4a and 4b. Of course, the common occurrence of *Taenidium* and bioturbational structures in deposits rich in sand and shell debris could simply result from the better lithological contrast, improving visibility of trace fossils hardly discernible in lithologically homogeneous rocks. However, deposits rich in sand may also reveal ichnofabrics lacking *Taenidium* and biodeformational structures (2b in the lower and upper parts of the Gnaszyn section and 2a in the upper part of the Anna section, Fig. 5). Instead, they contain common trace fossils of deep tiers (*Chondrites*, *Trichichnus* and pyritized burrows type 1), which in turn are rare in ichnofabrics 4a and 4b. Thus, it is likely that the appearance of ichnofabric 4 reflects real environmental change, linked to the shift of the depositional site from the offshore to offshore-transition and distal lower shoreface. Similar conditions to these in the Early Bathonian also occurred twice more in the succession: in the Middle

Fig. 11 Sedimentation rate and oxygenation, inferred from ichnofabrics, compared with transgressive–regressive cycles and the grain-size variations in the succession from Częstochowa. T–R cycles and the grain-size diagrams modified after Leonowicz (2015)

Bathonian (*subcontractus* and/or *morrissi* chronos) and Late Bathonian (*retrocostatatum* chron), accompanying shorter-lasting marine regressions (R_4 and R_6 , Fig. 11).

The optimal conditions for benthic life: relatively good oxygenation of the seafloor and moderate sedimentation rate, recorded by ichnofabric 2b, usually coincide with

transgressions (T_1 , late phase of T_4 , early phase of T_5 and T_6 , Fig. 11) and early phases of regressions (R_4), when the depositional site was in a distal location. The worst conditions, resulting in development of ichnofabric 2a, occurred in the Middle Bathonian *bremeri* chron and were linked to the late phase of T_5 transgression and R_5 regression

(Fig. 11). Leonowicz (2015) suggested that in this time the depositional site reached its most distal position, passing from the bypass zone to the zone where sediment transferred from the nearshore accumulated. The increased supply of mud combined with the higher influx of organic particles, responsible for the oxygen consumption, as well as weakening of the bottom currents which ventilated the seafloor, might have resulted in the decrease of oxygen within the sediment.

Conditions unfavorable for benthic life occurred also in the Late Bajocian (late *bomfordi* subchron) and were linked to the increased delivery of suspended sediment that hindered development of a benthic community. These specific conditions, recorded by ichnofabric 5, were related to the significant regression of the shoreline (R_1 , Fig. 11) and the transition of the depositional site from a distal to a more proximal location.

Conclusions

The analysis of the trace fossil associations from Middle Jurassic ore-bearing clay revealed a variability of ichnofabrics, which reflects changes of seafloor oxygenation, sedimentation rate, and benthic food content. These changes partly correlate with T–R cycles, previously recognized on the basis of sedimentological analysis.

The trace fossil association consists of ten ichnogenera, including *Chondrites*, *Trichichnus*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *?Rosselia*, *Schaubcylindrichnus*, *Taenidium*, cf. *Tasselia* and *Thalassinoides* as well as five types of indeterminate pyritized burrows. It represents the distal expression of *Cruziana* ichnofacies, which changed in some periods to a more proximal variant of it. Ichnofossils form tiered ichnofabrics, consisting of at least four tiers. Different variants of ichnofabrics reflect changing environmental factors, which restricted development of particular tiers.

Based on the composition of the trace fossil association, bioturbation intensity, and the type of biodeformational structures, eight ichnofabric variants have been distinguished. The sequence of ichnofabrics 1a–1b–2a–2b reflects increasing oxygenation of the bottom sediment. Ichnofabrics 4a, 4b, and 5 record high rates of deposition, whereas ichnofabric 3 reflects sediment starvation. Distribution of ichnofabrics in the succession shows that the bottom-water conditions varied laterally within the basin and changed with time. This variability is undetectable based on geochemical indices that reinforces the importance of ichnofabric analysis in environmental studies of mudstone.

A comparison of the distribution of ichnofabrics with T–R cycles showed limited correlation. The shallowest and the most proximal location of the depositional site is

recorded by ichnofabrics 4a and 4b. The most distal position correlates with the occurrence of ichnofabrics 2a, reflecting poor oxygenation of the seafloor. Transgressions were linked to the improvement of seafloor oxygenation (ichnofabric 2b) and temporary sediment starvation (ichnofabric 3), related most probably to sediment bypass. It seems that ichnofabrics reflect well the major changes of basin depth and distance from the shoreline but do not record minor fluctuations, which can be deduced from other sedimentological features.

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