Geological Quarterly, 2016, **60** (2): 385–394
DOI: http://dx.doi.org/10.7306/gq.1246

Tubular tempestites from Jurassic mudstones of southern Poland

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Leonowicz, P., 2016. Tubular tempestites from Jurassic mudstones of southern Poland. Geological Quarterly, **60** (2): 385–394, doi: 10.7306/gq.1246

This paper presents tubular tempestites from southern Poland and their application for environmental and sequence stratigraphy interpretation. Tubular tempestites are present in muddy successions of the Lower Jurassic Ciechocinek Formation and in the Middle Jurassic Częstochowa Ore-Bearing Clay Formation in the Silesian-Kraków region. They occur as sand-filled tubes of *Spongeliomorpha* and *Thalassinoides* entrenched in the mudstone, which form two characteristic horizons. Tubes were emplaced in semi-consolidated substrate and filled with sand brought by storm-generated bottom currents. The trace fossils reveal features typical of *Glossifungites* ichnofacies associated firmgrounds, which record discontinuities in the stratigraphical record, linked with a depositional hiatus or condensation and erosion of the sea-floor. The coincidence of these horizons with early phases of regional transgressions suggests that they represent transgressive surfaces of erosion. Their limited spatial extent probably resulted from varying intensity of erosion, which locally scoured deeply down to already consolidated substrate, whereas in other places erosion was weaker or even absent, and thus it is not marked in the sedimentary record there.

Key words: tubular tempestite, shallow-marine mudstone, omission surface, Lower Jurassic, Middle Jurassic, Silesian-Kraków region.

INTRODUCTION

Tubular tempestites are the open tubes produced by animals burrowing in a stable, stiff or firm substrate, subsequently filled with sediment transported by storm-generated currents (Wanless et al., 1988). The infilling sediment is massive, usually coarser than the host deposit and otherwise may be not preserved in the succession from the local depositional site because of sediment bypass or swallowing of the entire storm lag by burrow systems (Tedesco and Wanless, 1991; Bromley, 1996; Gingras et al., 2007). The most common producers of such burrows are crustaceans such as crabs and shrimps that construct shafts with apertures ≥1 cm in diameter, large enough to enable sediment easily to fall inside. Taking into account the elongated shape and position in the basal part of storm beds, tubular tempestites may be mistaken for gutter casts – the narrow erosional scours filled with coarse-grained sediment, which are the common constituent of storm-influenced successions. However, the latter structures result in whole from the storm processes, whereas the formation of tubular tempestites begins earlier, during the fair-weather periods, and only the filling is linked with storms. The arrangement of tunnels as well as scratch marks observed locally on their surfaces clearly support their biogenic origin.

For the first time, tubular tempestites were described by Wanless et al. (1988) from the shallow marine carbonate Bahama Platform, where they constituted the dominant sedimentary record of Hurricane Kate. Most of the coarse-grained surface sediment, reworked by storm waves, was there entrapped by a network of large *Callianassa* burrows, causing that a thin surficial tempestite layer was difficult to distinguish from the fair-weather deposit. Tedesco and Wanless (1991) showed that the repetitive excavation and subsequent storm infilling of open burrows might lead to generation of the new fabrics and replacement facies. These authors suggested that such sediments should occur in successions from various environments throughout the Phanerozoic. Actually, tubular tempestites have been recognized in several ancient deposits, in carbonates as well as in siliciclastics (e.g., Bann et al., 2004; Droser et al., 2004). Related structures with a rhythmically laminated fill, referred to as tubular tidalites, have been described from intertidal and subtidal environments (e.g., Gingras et al., 2007, 2012; Wetzel et al., 2014).

The occurrence of tubular tempestites is especially useful in the case of bioturbated deposits, in which primary sedimentary structures have not been preserved. They are often the only evidence for the previous activity of storms, providing relevant information about the dynamics of sedimentary environment. The horizons with tubular tempestites are used in sequence stratigraphy analysis, as they often accompany omission surfaces, recording syndepositional erosion and reduced sedimentation rate. These processes are characteristic of an initial stage of transgression and transgressive system tract, during which terrigenous sediment is mostly trapped in the coastal zone, and the shallow marine environment becomes starved of sediment (Catuneanu et al., 2011).

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Received: March 19, 2015; accepted: July 22, 2015; first published online: August 31, 2015

The present paper addresses tubular tempestites from the Lower and Middle Jurassic shallow marine mudstones, referred to as the Ciechocinek Formation and the Częstochowa Ore-Bearing Clay Formation, which crop out in the Silesian-Kraków Upland in southern Poland (Fig. 1). These sand-filled tubes were previously described in studies concerning trace fossils and ichnofabrics from these successions (Leonowicz, 2009, 2012), however, they were not interpreted in relation to storm processes.

GEOLOGICAL SETTING

Jurassic deposits studied here crop out in an elongated, NW–SE-oriented belt, extending between Kraków and Wieluń (Fig. 1). They constitute part of the Silesian-Kraków Monocline constituted by Permian and Mesozoic rocks, dipping gently towards the NE. The mudstones of the Lower Jurassic Ciechocinek Formation and the Middle Jurassic Częstochowa Ore-Bearing Clay Formation are exposed in several clay-pits. Tubular tempestites were found in two of them, located in Kozłowice and Częstochowa (Fig. 1).

Permian and Mesozoic rocks from the Silesian-Kraków Upland were deposited in a shallow epicontinental sea, called the Polish Basin (Dadlez, 1989), which was an easternmost arm of an extensive Central European Basin System (CEBS; Fig. 2). The Polish Basin was a semi-enclosed sea, surrounded to the north, east and south-west by land. To the west and north-west it was connected with the CEBS, mainly through the North German and Danish basins (Dadlez, 1989; Pieńkowski, 2004). To the south-east a temporary connection with the Tethyan Ocean through the East Carpathian Gate existed repeatedly (Dadlez and Kopik, 1975; Dayczak-Calikowska, 1997). During the Jurassic these connections served as seaways for several marine transgressions, approaching from the west and north-west in the Early Jurassic (Pieńkowski, 2004) and prevalently from the south-east in the Middle Jurassic (Dayczak-Calikowska, 1997). The most complete succession was deposited in the elongated, NW–SE-oriented axial zone, called the Mid-Polish Trough (MPT; Fig. 3), which was characterized by the maximum subsidence throughout the Mesozoic. Outside the MPT the succession reveals several hiatuses and the thickness decreases gradually towards the north-east and south-west. In the Silesian-Kraków region it is reduced to a maximum of 200 m for the Lower Jurassic and 300 m for the Middle Jurassic (Dayczak-Calikowska and Moryc, 1988; Deczkowski, 1997; Feldman-Olszewska, 1997a, b).

LOWER JURASSIC

During the Early Jurassic, sedimentation developed mainly in terrestrial and restricted nearshore environments (Pieńkowski, 2004). The succession consists of various siliciclastic rocks, including sandstone, mudstone, claystone and gravel (Fig. 4A). Open-marine and brackish conditions developed

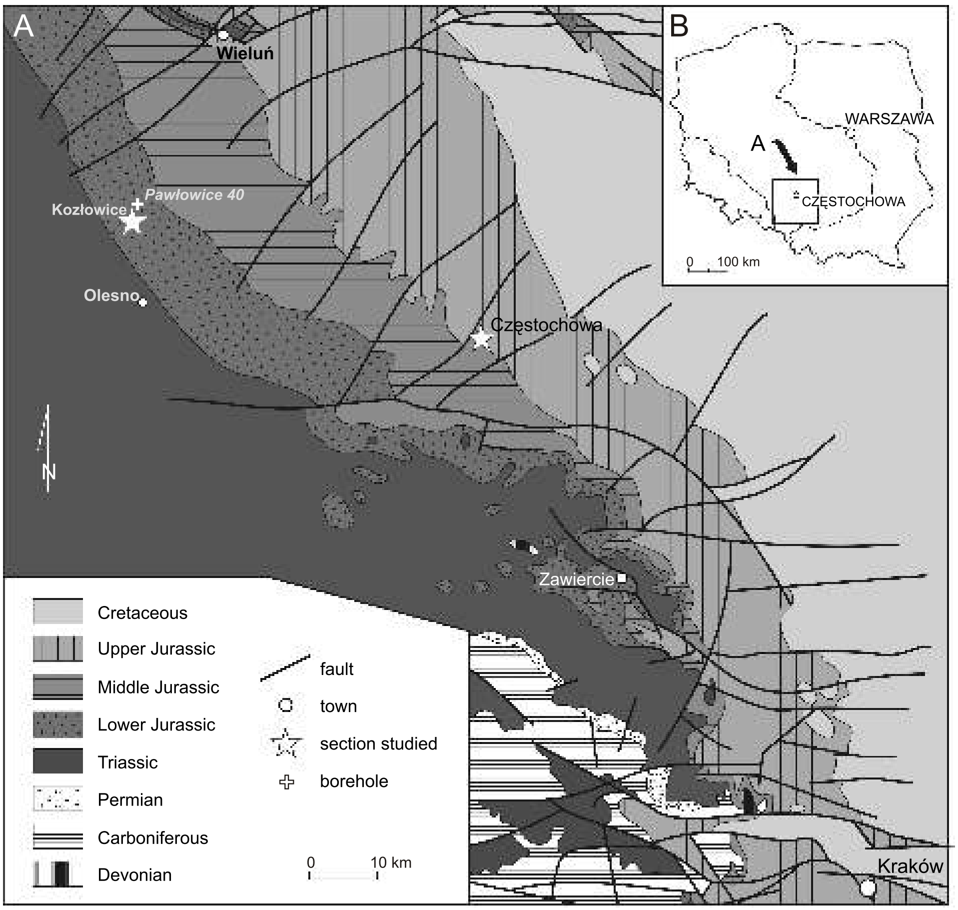

Fig. 1A – geological map of the Silesian-Kraków Upland (after Dadlez et al., 2000, simplified) and location of the successions studied; B – area shown on map A

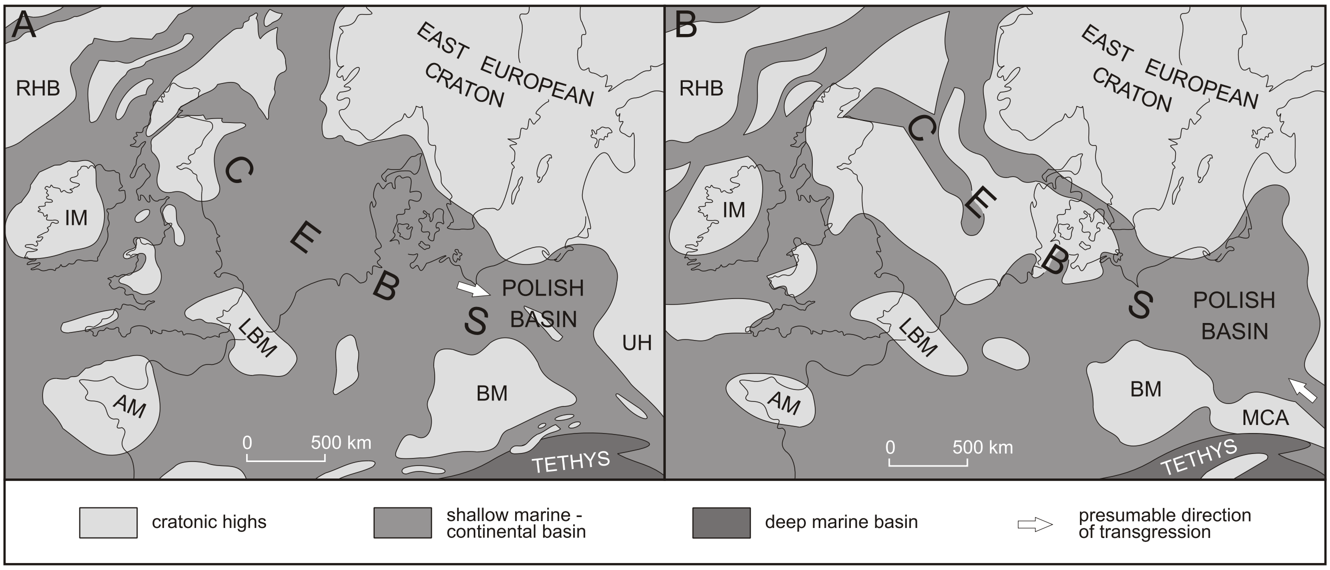

Fig. 2. Palaeogeographical maps of Europe A – in the Early Jurassic, B – in the Middle Jurassic (modified after Ziegler, 1990)

AM – Armorican Massif, BM – Bohemian Massif, CEBS – Central European Basin System, IM – Irish Massif, LBM – London-Brabant Massif, MCA – Meta-Carpathian Arc, RHB – Rockall-Hatton Bank, UH – Ukrainian High

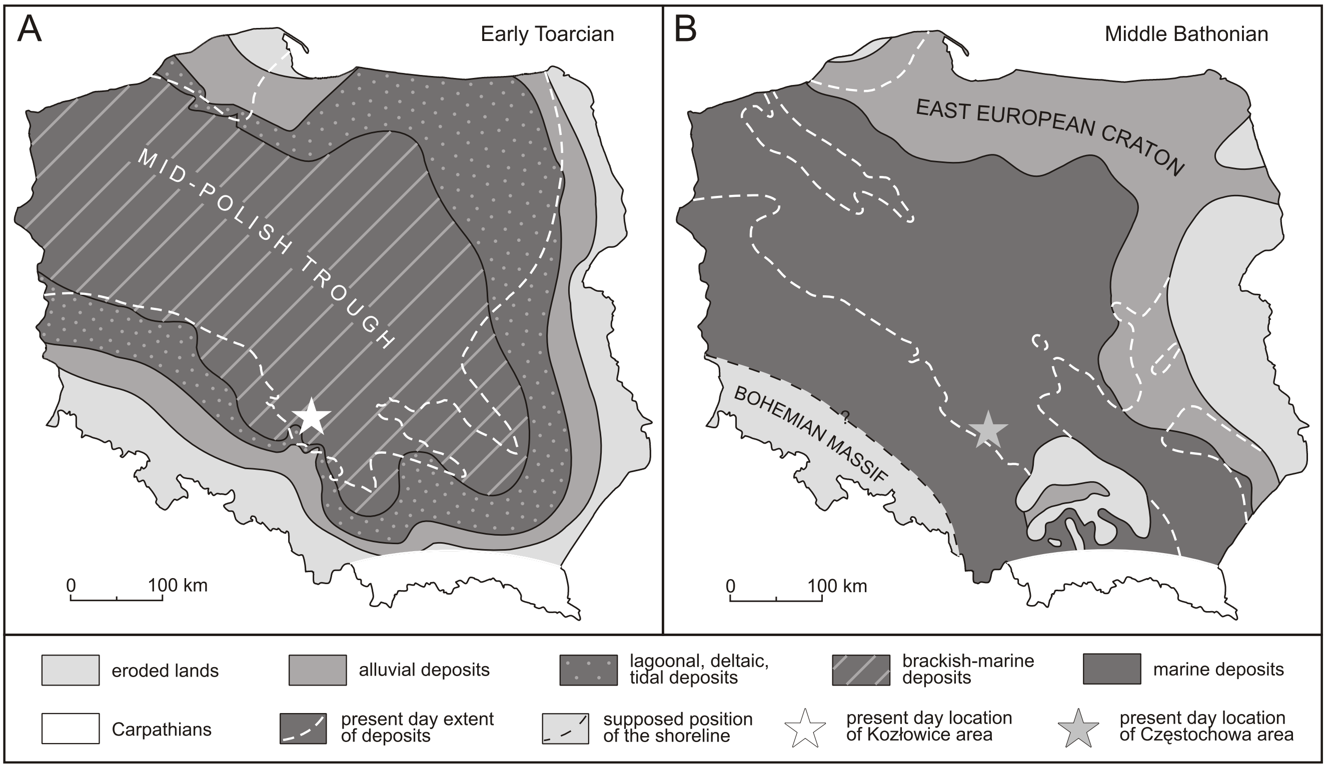

Fig. 3. Polish Basin during the Early and Middle Jurassic and the location of studied exposures

A – Early Toarcian *tenuicostatum* chron (modified after Dadlez, 1973; Pieńkowski, 2004);
B – Middle Bathonian *bremeri* chron (modified after Feldman-Olszewska, 1998)

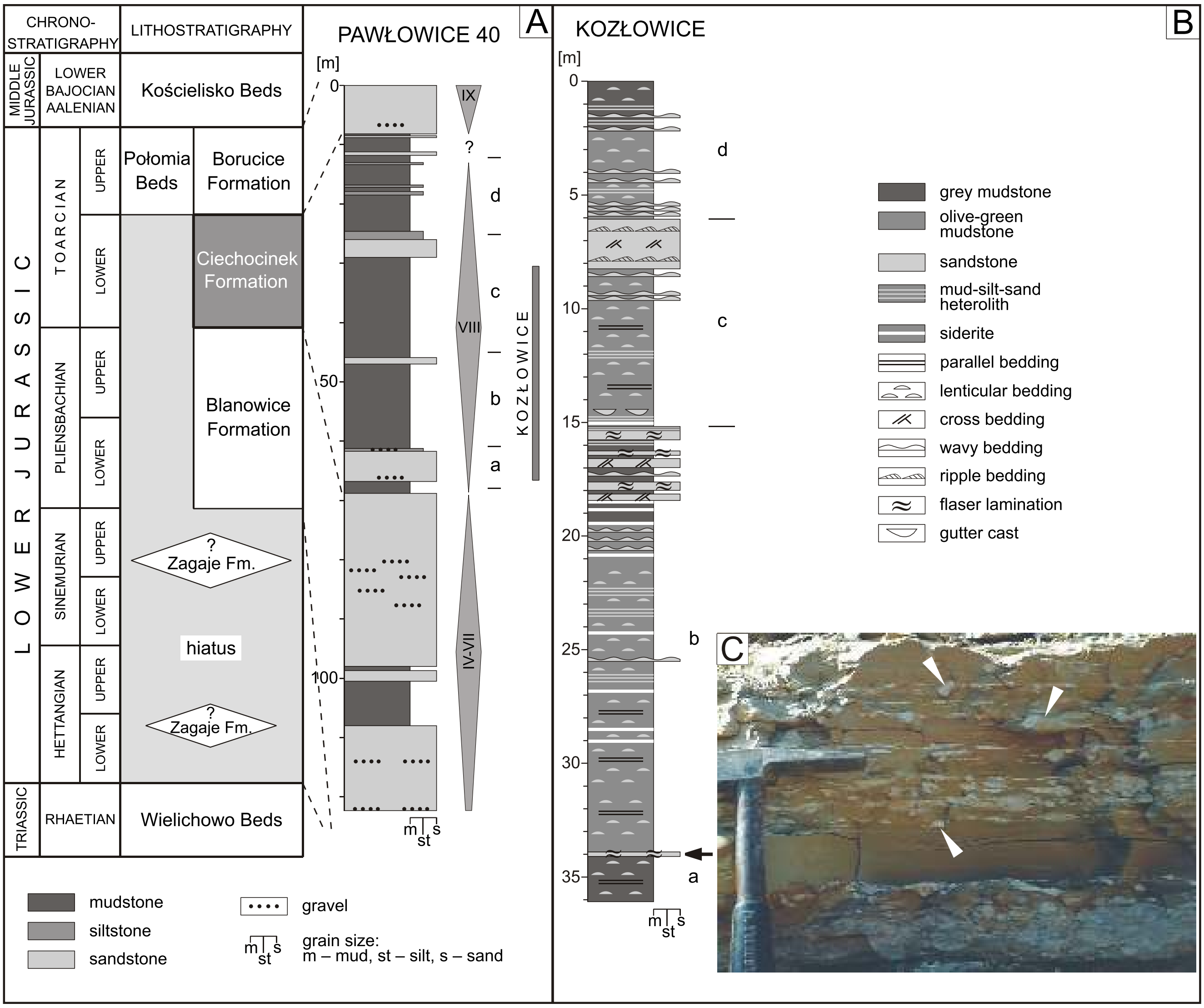

Fig. 4A – lithostratigraphy of the Lower Jurassic in the Silesian-Kraków region (after Kopik, 1998; Pieńkowski, 2004) and representative section of the Pawłowice 40 borehole. Boundaries of depositional sequences (IV–IX) and parasequences (VIIIa, b, c, d) according to Pieńkowski (2004). Interval exposed in Kozłowice is marked to the right; B – lithological log of the Ciechocinek Formation deposits from the Kozłowice section (after Leonowicz, 2011) and the location of horizon with tubular tempestites, shown on C. Boundaries of parasequences VIIIb, c, d according to Hesselbo and Pieńkowski (2011). Boundary between parasequences a and b proposed in this paper coincides with the horizon with tubular tempestites; C – two sandy horizons separating dark grey and olive-green mudstone; the upper one contains tubular tempestites, represented by sand-filled *Spongeliomorpha* tubes (some of them marked by arrows)

mainly in the MPT zone and adjacent areas during Middle Hettangian, Early and Late Sinemurian, Early and Late Pliensbachian and Early Toarcian marine transgressions (Pieńkowski, 2004). The widest extent of the sea was linked with the Early Toarcian transgression (Fig. 3A), dated at the *tenuicostatum* and earliest *falciferum* chrons (Pieńkowski, 2004). This transgression is recorded by the muddy Ciechocinek Formation, widespread in the entire Polish Basin. In the Silesian-Kraków region it is up to 70 m thick (Leonowicz, 2011). It rests on the Pliensbachian sandy Blanowice Formation (Fig. 4A) representing alluvial, lacustrine and deltaic environments, and is overlain by the Upper Toarcian sand-mud Borucice Formation of also alluvial and lacustrine origin (Pieńkowski, 2004).

CHARACTERISTICS OF THE CIECHOCINEK FORMATION

The Ciechocinek Formation is composed of olive-green, grey and willow-green mudstone, claystone and siltstone with lenses and intercalations of fine-grained sandstone and siderite bands (Fig. 4A, B). Sedimentological analyses pointed to deposition in a shallow basin, prevalently <20 m deep, displaying features of a large shallow embayment with deltaic facies developed in marginal parts (Pieńkowski, 2004). Well-preserved sedimentary structures occurring throughout the succession indicate that the deposition was strongly influenced by storms. The quiet background sedimentation was repeatedly interrupted by storm episodes, during which bottom currents transported sand from the nearshore to distal settings (Leonowicz, 2011). The sand was afterwards reworked by waves and redistributed on the sea-floor by wave-drift and wind-driven flows. In distal settings, storm events were recorded by small-scale sedimentary structures observed in mudstone, including:

– graded sand-silt streaks;
– graded sequences: trough cross-laminated silt – parallel-laminated silt – massive mud;
– small sandy lenses;
– interlaid mud-silt-sand heteroliths, sticking in the mud (Leonowicz, 2011).

In proximal settings, tempestites are represented by several centimetre thick sandy layers and several decimetre thick sandy packets, showing various types of sedimentary structures, including wavy-, flaser-, ripple-, parallel- and cross-bedding as well as rare hummocky cross-stratification (HCS). The ripplemarks observed in wavy- and ripple-bedded sandstones commonly reveal features typical of wave origin. In the bypass zone, sandy gutter casts formed (Leonowicz, 2011).

The scarcity of benthic fauna, the impoverished trace fossil association and the geochemical characteristics point to the brackish character of the basin (Pieńkowski, 2004; Leonowicz, 2005, 2007, 2009). The lower part of the Ciechocinek Formation records a progressive transgression and is prevalently developed as dark grey mudstone containing marine dinoflagellate cysts, foraminiferal linings and a relatively diverse trace fossil association, including *Planolites, Palaeophycus, Helminthopsis, Gyrochorte, Protovirgularia, Spongeliomorpha* and *Diplocraterion*, as well as common pyrite mineralisation (Leonowicz, 2009, 2011). The upper part, which is composed of greenish deposits with a strongly impoverished trace fossil association (mainly *Planolites*) and phyllopods *Estheria*, reflects a gradual decline in water salinity during a sea level highstand and regression (Leonowicz, 2011).

TUBULAR TEMPESTITES FROM THE CIECHOCINEK FORMATION

Description: sand-filled tunnels of *Spongeliomorpha* isp. are preserved as endichnia within mudstone (Fig. 4C). The tunnels are up to 2.5 cm thick, horizontal or subhorizontal, and branch at acute angle (Fig. 5A). On the lower and side surfaces of the burrow casts, elongated scratch marks occur (Fig. 5B). The infilling consists of light grey fine quartz sand (Fig. 6A) and is structureless or, rarely, contains thin wavy clay lamina (Fig. 5C), suggesting two stages of burrow filling.

Occurrence: The horizon with *Spongeliomorpha* occurs in the lowermost part of the ca. 36 m thick section exposed in the Kozłowice clay-pit (Fig. 1), which is dated at the *tenuicostatum* zone (Barski and Leonowicz, 2002). Most of this section consists of olive-green claystone and mudstone with several thin (up to 10 cm) intercalations of sandstone and two thick (2.2 and 3.5 m) sandy complexes (Fig. 4B). At the bottom, dark grey mudstone with common framboidal pyrite occurs (Leonowicz, 2011). This dark grey mudstone is separated from the overlying olive-green deposit by two sandy horizons (Fig. 4B, C). The lower one consists of a strongly bioturbated sandstone bed, ca. 5 cm thick. The upper one, ca. 10 cm thick, contains sand-filled tunnels of *Spongeliomorpha* described above, which are accompanied by thin sandy laminae and lenses dispersed in the mudstone. Lower and middle parts of the section contain a relatively diverse trace fossil association and marine dinoflagellate cysts pointing to their marine origin (Leonowicz, 2009, 2011).

MIDDLE JURASSIC

The Middle Jurassic was a time of progressive marine transgression, which began in the Aalenian (Dayczak-Calikowska and Moryc, 1988) and was interrupted by several short-lived regressions and stillstand periods. The succession consists of various siliciclastic rocks with the prevalence of dark grey mudstone. Initially, the sea occupied only the MPT, but from the Early Bajocian it gradually spread outside this zone, extending to the north-east and south-west (Feldman-Olszewska, 1998). In the Silesian-Kraków region the beginning of marine sedimentation is recorded by sandy deposits of the Early Bajocian Kościelisko Beds (Kopik, 1998; Fig. 7A). The development of the transgression (Fig. 3B) led to deposition of a thick (up to 200 m) muddy complex referred to as the Częstochowa Ore-Bearing Clay Formation, spanning the Upper Bajocian to Upper Bathonian (*garantiana–discus* zones; Kopik, 1998; Matyja and Wierzbowski, 2000, 2006; Barski et al., 2004). The Częstochowa Ore-Bearing Clay Formation is overlain by condensed Callovian deposits (Fig. 7A), which in turn pass upwards into Oxfordian limestones recording further expansion of the sea (Kopik, 1997).

CHARACTERISTICS OF THE CZĘSTOCHOWA ORE-BEARING CLAY FORMATION

The Częstochowa Ore-Bearing Clay Formation is composed of dark grey organic-rich calcareous mudstone with horizons of siderite and calcareous concretions and siderite bands (Fig. 7A, B). These deposits, known also as the ore-bearing clay, are developed as two facies varieties. The first one is represented by bioturbated mudstone containing common benthic fauna and a moderately diverse trace fossil association. The second one consists of laminated deposit with rare benthic fauna and an impoverished trace fossil suite (Leonowicz, 2012, 2013). Sedimentological analyses pointed to deposition in a shallow-marine basin, several tens of metres deep, but shallowing to less than 20 m in some periods (Leonowicz, 2015). The sea bottom was mostly below storm wave base, however, sedimentation was strongly influenced by episodic high-energy conditions. Sedimentary structures preserved in laminated deposits include thin silt/sand laminae, bedding-plane accumulations of shell debris, small and medium silt-sand lenses as well as silt-, sand- and shell-debris-rich levels (Leonowicz, 2013, 2015). They record activity of bottom currents that redistributed sediment from shallower areas and intermittently reworked deposited material. Prior to deposition, erosion of the sea-floor often occurred as recorded by common erosional surfaces and occasional pronounced scours. The currents were most probably generated by storms, although an origin linked with tidal processes was also considered (Leonowicz, 2015). The thickness and amount of event laminae depended on the intensity of storms and the distance from the shoreline, which changed with time. Based on the sand, silt and clay content of the mudstone, Leonowicz (2015) distinguished 7 transgressive-regressive cycles within this succession, which fairly well-match the cycles known from central Poland (Pieńkowski et al., 2008).

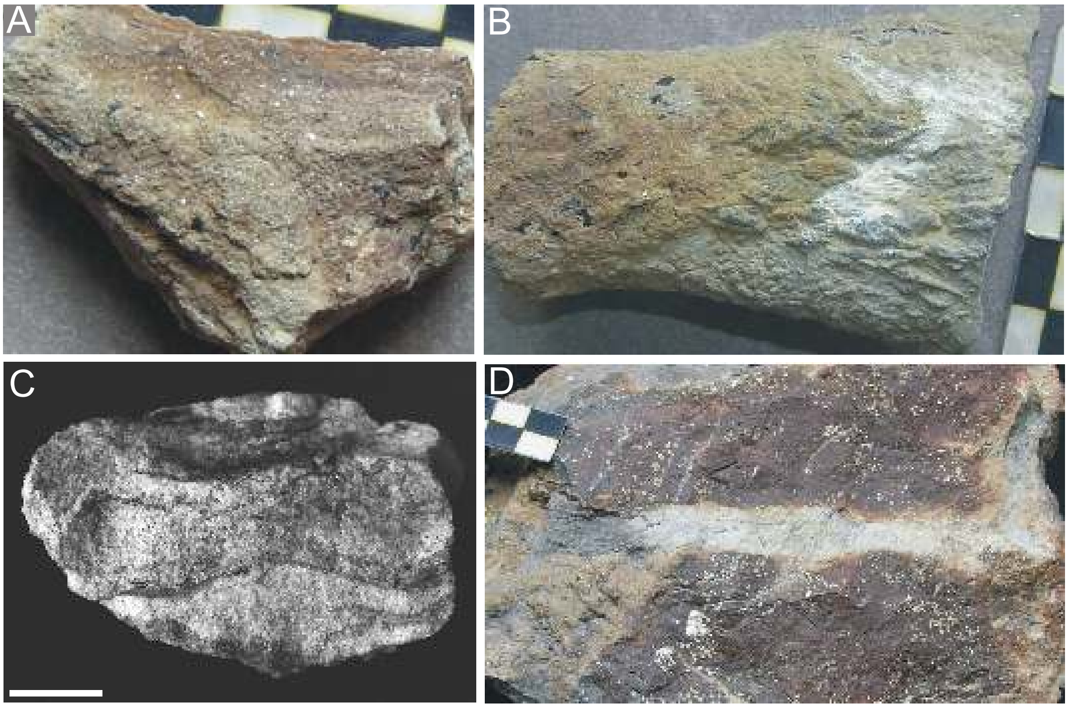

Fig. 5. Tubular tempestites from the Ciechocinek Formation (A–C) and the Częstochowa Ore-Bearing Clay Formation (D)

A – fragment of *Spongeliomorpha* tube with visible Y-shaped branching, view on the upper surface; **B** – lower surface of burrow cast with elongated scratch marks; **C** – cross-section of burrow infilling, thin wavy laminae of clay is visible in the middle; **D** – fine sand-filled *Thalassinoides* tunnel preserved within clayey siderite; branching of tunnel is visible in the upper right; A, B, D – scale bar is in centimetres, C – scale bar is 1 cm

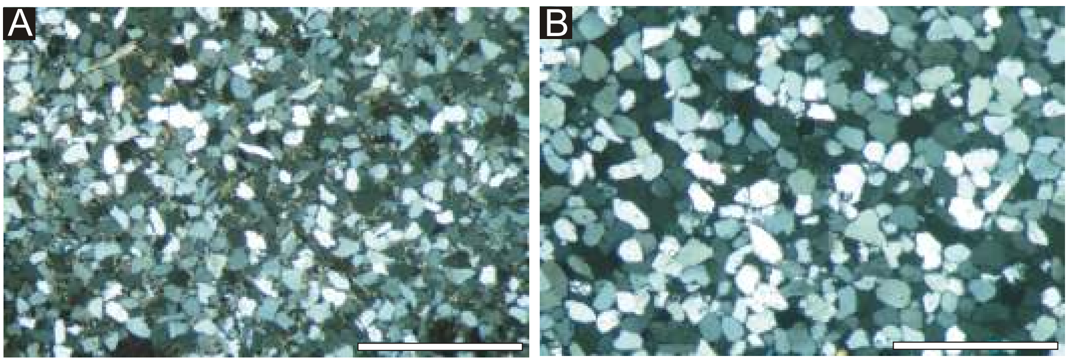

Fig. 6. The filling of *Spongeliomorpha* tube (A) and storm-event sandstone bed (B) in thin section

The grain framework in both samples is dominated by quartz; on A quartz grains are cemented by siderite; Kozłowice outcrop, crossed nicols, scale bar is 1 mm

Bioturbated mudstone is rich in benthic fauna represented by bivalves, gastropods, brachiopods, scaphopods, foraminifers and echinoderms (Gedl et al., 2012). The trace fossil suite includes *Chondrites, Trichichnus, Palaeophycus, Planolites, Protovirgularia, Rosselia?, Schaubcylindrichnus, Taenidium*, cf. *Tasselia* and *Thalassinoides* as well as some undetermined pyritized burrows. Diversity of benthic fauna and trace fossils changes in the vertical succession as well as laterally, showing that the conditions on the sea-floor, such as oxygenation and sedimentation rate, varied significantly.

TUBULAR TEMPESTITES FROM THE CZĘSTOCHOWA ORE-BEARING CLAY FORMATION

Description: sand-filled tunnels of *Thalassinoides* isp. are preserved as endichnia within a clayey siderite band (Fig. 5D, 7C). The tunnels are up to 4 cm thick, slightly flattened, and form a 3-dimensional branching system. They are filled with structureless light grey, very fine quartz sand and silt (Fig. 5D). The tunnels were observed only in cross-section and the relief of burrow walls is unknown, however, they seem to be smooth and devoid of scratch marks.

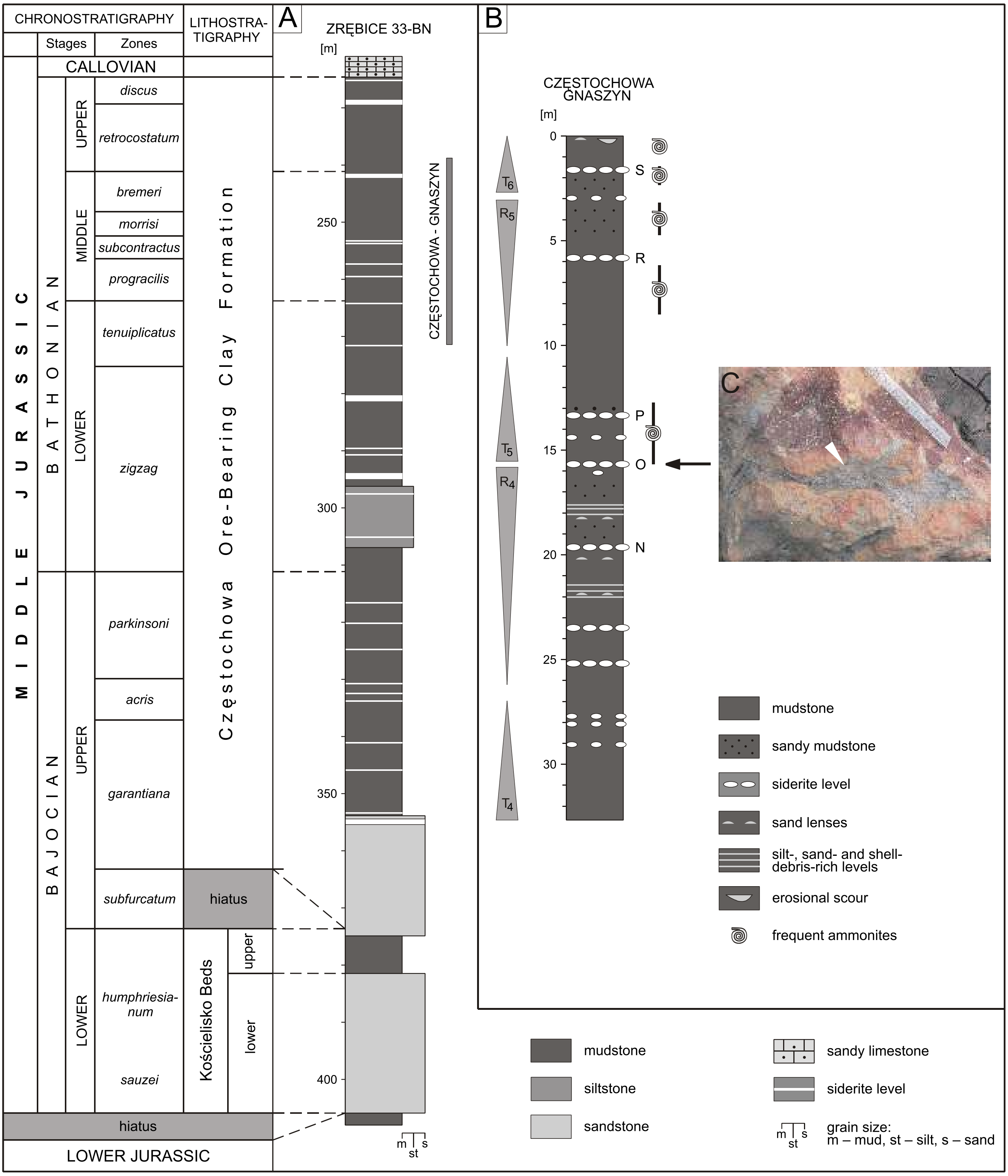

Fig. 7A – stratigraphy of Middle Jurassic deposits from the Silesian-Kraków region (after Kopik, 1998; Matyja and Wierzbowski, 2000, 2006; Barski et al., 2004) and representative section of the Zrębice 33-BN borehole (stratigraphy after Kopik, 1998). B – lithological log of the Częstochowa Ore-Bearing Clay Formation deposits from the Częstochowa-Gnaszyn section (after Leonowicz, 2015) and the location of horizon with tubular tempestites, shown on C. Transgressive-regressive cycles after Leonowicz (2015). Corrected R_4/T_5 boundary falls on the horizon with tubular tempestites; C – tubular tempestite represented by a sand-filled *Thalassinoides* tunnel (arrow), photo by A. Uchman

Occurrence: the horizon with *Thalassinoides* occurs in the middle part of the ca. 32 m thick section exposed in the Ganszyn clay-pit, situated in the western suburb of Częstochowa (Fig. 1). This section consists of dark grey, calcareous mudstone with several horizons of siderite concretions numbered N–S, and one siderite band marked as horizon O (Fig. 7B). The mudstone is strongly bioturbated. Besides a few silt-, sand- and shell-debris-rich levels occurring in the lower half of the succession, it reveals only relics of fine horizontal lamination and rare small sandy lenses. In the middle and upper parts of the section, ammonites commonly occur suggesting a decreased sedimentation rate. Sand-filled tunnels of *Thalassinoides* described above occur in siderite level O (Fig. 7B, C), within the interval dated at the *morrisi* zone (Matyja and Wierzbowski, 2006).

INTERPRETATION AND DISCUSSION

The structures described above were produced in an environment significantly affected by storms. The important share of storm processes in deposition of studied mudstones is confirmed by the common occurrence of sedimentary structures ascribed to storm origin and was already postulated in earlier studies (Pieńkowski, 2004; Leonowicz, 2011, 2013, 2015). In mudstone from Kozłowice, storm deposits are well-preserved and represented by various sand and silt accumulations, ranging from thin laminae formed in a distal location to thick sand accumulations deposited in a proximal setting. Gutter casts, wave ripples, HCS and cross-bedded sandstone beds observed within them record processes typically associated with storms, including syndepositional erosion of the sea-floor, bedload transport of sediment by bottom currents and subsequent wave reworking of deposits (Leonowicz, 2011). Sand-filled *Spongeliomorpha* tubes occur in one horizon with thin sandy laminae and lenses that represent isolated starved ripples carried on the muddy sea-floor by storm-generated traction currents. The material filling the tubes is similar in composition to that forming sandy lenses and storm beds (Fig. 6), and hence it points to their similar origin. Massive structure of the fill indicates its passive character. This suggests that the sand migrating on the sediment surface was simultaneously trapped by abandoned burrows open to the sea-floor. Thus, the fill of *Spongeliomorpha* is interpreted as tubular tempestite. The tube fill represents very likely a single storm event because of its prevalent massive appearance and lack of internal lamination. However, in some cases, it can record also two or more storms, as is suggested by thin clayey lamina observed in the sandy fill.

In the case of mudstone at Częstochowa, the environmental interpretation is impeded by its strong bioturbation, which obliterates the primary fabric. However, the analysis of relics of sedimentary structures and their comparison with well-preserved primary lamination from ore-bearing mudstone from other localities has allowed inferring a significant role of storms during deposition of the succession (Leonowicz, 2012, 2015). This conclusion was supported by the occurrence of few undistorted, relatively thick accumulations of fine sand and shell debris, interpreted as storm event deposits (Leonowicz, 2015). The sand-filled tubes of *Thalassinoides* provide another strong argument for the key importance of storms, contradicting alternative hypotheses referring to tidal processes (Leonowicz, 2015). The structureless character of the fill allows interpreting it as tubular tempestite, similarly as *Spongeliomorpha* described above. Tubular tidalites, in turn, shall exhibit a rhythmically layered fill, reflecting cyclic character of tides (Gingras et al., 2007; Wetzel et al., 2014). The material preserved within the burrows provides valuable information about the presumed composition of storm deposits, supporting the assumption – essential for interpretation of transgressive-regressive cycles – that the sand dispersed within the mudstone mostly came from the storm event accumulations (Leonowicz, 2015).

Tubular tempestites provide also important information about the character of the substrate and the course of sedimentation. In subaqueous environments under normal conditions, the animals construct open tubes in soft sediment and have to reinforce them by particles or mucus to prevent collapse (Bromley, 1996). As a result, burrow margins are accentuated by distinct lining or a thick wall, differing in composition or packing from the surrounding sediment. Abandoned tubes are successively filled with sediment falling in from the bottom and the fill is usually composed of material similar to the host deposit. In deposits studied, the boundaries of the trace fossils are sharp but devoid of lining that indicates emplacement in semi-consolidated substrate (e.g., Wetzel and Uchman, 1998). The exterior of Middle Jurassic *Thalassinoides* was not observed, thus it can be only inferred that the substrate was at least stiff. The Lower Jurassic *Spongeliomorpha* reveals distinct scratch marks on the surface, which implies firm character of the bottom (Wetzel and Uchman, 1998). The sandy infill of these trace fossils differs from the surrounding mud, indicating that they were not continuously filled with the fine-grained material, accumulating throughout the bottom but with the sediment periodically bypassing the depositional site. This feature together with a stiff to firm character of the substrate implies a depositional hiatus or condensation combined with erosion of the sea-floor that led to exposition of consolidated substrate prior to the formation and fill of the tubes. Such character of the trace fossils allows classifying them to substrate controlled *Glossifungites* ichnofacies (cf. Leonowicz, 2009), which is a reliable indicator of a discontinuity in the stratigraphic record.

Discontinuities accentuated by a *Glossifungites* suite of trace fossils can form in different ways (Pemberton et al., 2004; MacEachern et al., 2007), ranging from stratigraphically important allocyclic events (e.g., flooding surfaces, amalgamated sequence boundaries or transgressive surfaces of erosion) to autocyclic discontinuities (e.g., forming in periodically exposed intertidal flats or margins of tidal channels) and differ accordingly. Both studied firmground horizons developed during an early phase of transgressions. The horizon from Kozłowice occurs in the lowermost part of the Ciechocinek Formation succession, recording the beginning of regional transgression pronounced in the entire Polish Basin (depositional sequence VIII, parasequence VIIIb in Pieńkowski, 2004) as well as in other basins of the CEBS (cf. Hallam, 1988, 2001; Pieńkowski et al., 2008). The firmground from Częstochowa formed in the early *morrisi* chron, during the early phase of transgression marked in the entire Polish Basin (T_5 in Silesian-Kraków region – Leonowicz, 2015, T6 in central Poland – Pieńkowski et al., 2008: fig. 14.18) and correlating with the beginning of a long-lasting sea level rise on the eustatic curve of Hallam (1988). Taking into account the position of the studied firmgrounds, both horizons are interpreted as omission surfaces linked with rapid transgressions. Some doubts may arise from the lack of equivalent horizons in other sections from the Silesian-Kraków region (Leonowicz, 2009, 2011 and own unpublished observations concerning Middle Jurassic strata), as discontinuities recording events of a regional extent shall have a wide spatial occurrence. The possible explanation is that the winnowing capacity of bottom currents varied within the basin and only locally it exceeded sedimentation rates, resulting in the development of local firmgrounds. In the case of the Middle Jurassic, such differentiation of the bottom circulation was already postulated to explain the local extent of horizons with hiatus concretions (Leonowicz, 2015) and various thicknesses of deposits (e.g., Dadlez, 1994; Feldman-Olszewska, 1997b; Barski, 1999). It was suggested that this differentiation might be linked with the occurrence of temporal swells and depressions on the sea-floor, resulting from synsedimentary tectonic movements (Leonowicz, 2013, 2015). A morphological differentiation within the CEBS by temporary swells and depressions during the Jurassic has been described also from other areas (e.g., Wetzel and Allia, 2000; Wetzel et al., 2003).

In this context, it is likely that the beginning of transgression T_5 in the Silesian-Kraków region falls on siderite level O, containing tubular tempestites, not 1.5 m below it, as it was placed previously (cf. Leonowicz, 2015). The low net sedimentation rate, which led to the formation of this firmground, was probably linked with recurrent syndepositional erosion of the bottom during the passage of the depositional site through the bypass zone (Leonowicz, 2015). Reduced accumulation prolonged also during the whole *morrisi* chron and, to a lesser degree, during the *bremeri* chron, as is suggested by common ammonite occurrences. The firmground from Kozłowice, which occurs within marine deposits represented by dark grey mudstone with framboidal pyrite and olive-green mudstone with a relatively diverse trace fossil association, probably records the progress of transgression interrupted by a short-lasting regressive episode, marked by an underlying strongly bioturbated sandy horizon. This firmground may constitute the flooding surface of parasequence VIIIb in the scheme proposed by Hesselbo and Pieńkowski (2011).

SUMMARY AND CONCLUSIONS

Tubular tempestites occur in Lower and Middle Jurassic mudstones in southern Poland in two horizons within the Ciechocinek Formation and the Częstochowa Ore-Bearing Clay Formation from the Silesian-Kraków region. They are represented by large sand-filled tubes of *Spongeliomorpha* and *Thalassinoides*. The sediment filling the burrows is similar in composition to storm event beds, implying that it was derived by storm-generated bottom currents. The structures evidence a periodical influence of high-energy processes during mudstone deposition and are especially valuable in environmental interpretation of bioturbated mudstone, the primary fabric of which was obliterated by burrowing animals.

The character of burrow boundaries indicates that they were emplaced in semi-consolidated substrate. The passive nature of the fill shows that tunnels remained open to the sea-floor after the animals left their domiciles. These features are characteristic of *Glossifungites* ichnofacies, which is associated with the firm substrate recording a depositional hiatus combined with erosional exhumation of compacted mud. Both described horizons correlate with initial phases of transgressions pronounced in the entire Polish Basin: the horizon with *Spongeliomorpha* developed in the Early Toarcian *tenuicostatum* chron, whereas the horizon with *Thalassinoides* – in the Middle Bathonian *morrisi* chron. They probably represent transgressive surfaces of erosion, however, their limited extent shows that the erosion exhumed consolidated substrate only locally, whereas in other locations it was shallower and is now undetectable in the rock record.

Acknowledgements. The authoress would like to thank P. Roniewicz and A. Uchman for inspiring discussion during a joint fieldtrip. I also thank A. Wetzel and the anonymous reviewer for their constructive comments and useful remarks, which helped me to improve the final version of the manuscript. The managements of brickyards Cerpol-Kozłowice S.A. and Wienerberger Gnaszyn in Częstochowa are thanked for providing access to their workings. The research was financed by the Institute of Geology, University of Warsaw.

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