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ORIGINAL PAPER

Ichnology of the Middle Jurassic hiatus concretions from Poland: implications for their formation, exhumation, and palaeoenvironment

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Abstract

In the present study, the Middle Jurassic exhumed carbonate concretions (the so-called hiatus concretions) from the Polish Jura (southern Poland) were studied ichnologically (precursor burrows and their tiering and bioerosion patterns) in order to decipher the palaeoenvironmental conditions leading to their formation and exhumation. The ichnological approach to the concretionary bodies used in this study yielded information on the scale of seafloor erosion and its relative timing compared to the burrow-infilling phase. The bioerosion patterns also provided information on proximal-distal trends and the frequency and strength of currents in the environment below storm wave base, a setting recorded in the monotonous, concretion-bearing siliciclastic sections which is studied here. The significance of the stratigraphic sequence is also briefly discussed based on the horizons containing the hiatus concretions.

Keywords Hiatus concretions · Ichnology · Bioerosion pattern · Middle Jurassic · Poland

Introduction

All concretionary bodies, regardless of their composition, form within host sediment (e.g. Coleman 1993; Chan et al. 2004). The position of the redox boundary, the concentration of organic matter within sediment, and the metabolic activity of microbes are all key drivers affecting the growth and mineralogy of concretions (Coleman 1993). This also applies to the so-called hiatus concretions, first described by Voigt (1968) and subsequently reported by many authors from deposits of various ages (e.g. Kaźmierczak 1974; Baird 1976, 1981; Wilson 1985; Hesselbo and Palmer 1992; Brett 1995; Brett et al. 2008; Zatoń et al. 2011; Wilson et al. 2012). According to Voigt (1968), such concretions underwent a complex burial-exhumation process following their formation.

The activity of burrowers can modify the redox boundary position, organic content, and microbial activity within sediment and thus may affect the formation processes of concretions controlled by water geochemistry. Burrows introduce heterogeneity within sediment, as the infilling sediment often differs, e.g. in texture from the host bed (see Braithwaite and Talbot 1972; Bromley 1990; Papaspyrou et al. 2005; Kinoshita et al. 2007; Uchman 2009). This heterogeneity affects cementation paths and therefore affects the growth of the concretions (e.g. Bromley 1967; Gunatilaka et al. 1987; Pemberton and Gingras 2005; Gingras et al. 2012).

In some cases, after concretions nucleated and became cemented, their host sediment must have been removed due to erosion during sedimentary hiatuses. In this way, concretions were exposed at the seafloor, providing hard substrates for various cementing and boring organisms in an otherwise soft-sediment environment (e.g. Kennedy and Klinger 1972; Kaźmierczak 1974; Baird 1976, 1981; Fürsich 1979; Hesselbo and Palmer 1992; Zatoń et al. 2011). However, successful colonisation by hard substrate biotas required concretions to be exposed for some period of time, since rapid reburial might have smothered and subsequently killed the colonisers (e.g. Bromley 1994). Therefore, the signs of colonisation (encrusters and borers) on exposed concretions are taken as evidence of slower sedimentation or a pause in deposition. The period of lowered sedimentation rate or hiatus gives rise to the concretions named as *hiatus concretions*. The bored and encrusted hiatus concretions were finally reburied. Cycles of repeated reburial and exhumation may have occurred many times before final burial (e.g.

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Voigt 1968; Wetzel and Allia 2000). Here it should be noted that the so-called reworked concretions, which are interpreted as having been exhumed but not as having undergone several burial/exhumation episodes (see e.g. Fürsich et al. 1992), may represent only a starting point in the formation of the hiatus concretions sensu Voigt (1968).

Hiatus concretions are important for sedimentological, palaeoenvironmental, and palaeoecologic analyses. Their stratigraphic distribution may highlight horizons of pauses in sedimentation (e.g. Hesselbo and Palmer 1992). Such markers may occur at obvious stratigraphic boundaries (e.g. Wilson et al. 2012). However, they are most important within otherwise homogenous sedimentary units where such pauses may easily be overlooked (cf. Baird 1976, 1981; Hesselbo and Palmer 1992; Zatoń 2010). Concretions may also help to assess the rate of sedimentation within the environment (e.g. Majewski 2000) and hence may provide clues on the relative position of studied concretion assemblages on the proximal-distal trend line. Finally, the hiatus concretions yield information on the composition, succession, and dynamics of communities dwelling on and within the hard substrates provided by the concretions (e.g. Wilson 1987; Zatoń et al. 2006, 2011).

The present paper is focused on hiatus concretions from the Middle Jurassic mudstone-dominated siliciclastic deposits exposed in the Polish Jura area (southern Poland; Fig. 1). Although these concretions were already studied by Zatoń et al. (2011), details of their ichnological characteristics received only general attention. Thus, the present paper concerns ichnological analysis of these concretions (Figs. 2–4). Emphasis is placed on the types of precursor burrows and their tiering and bioerosion patterns, yielding information on the scope and relative timing of the net bottom erosion required to exhume the concretions. The bioerosion patterns are used to enhance our insight into the energy levels of environments represented by otherwise homogenous mud-dominated deposits (see Fig. 6a, b). Finally, potential allocyclic controls on the formation and stratigraphic significance of horizons with hiatus concretions are also discussed.

Geological and palaeoenvironmental background

During the Middle Jurassic, the Polish Basin was an eastern extension of the larger epicontinental sea covering western and central Europe. The basin was bordered on the north, east, and south-west by the Fennoscandian Shield, the Belarusian High with the Ukrainian Shield, and the Bohemian Massif, respectively (e.g. Zatoń et al. 2009; Leonowicz 2013). The pre-Carpathian landmass separated the Polish Basin from the Tethys Ocean, with which communication was sustained through the East Carpathian Gate (Dayczak-Calikowska and Moryc 1988; see also Zatoń et al. 2009, Fig. 1). Feldman-Olszewska (1997) identified several transgressive-regressive (T-R) cycles within the Jurassic Polish Basin and, with a few exceptions, found rather a good correlation with the global records of the sea-level fluctuations. Recently, Leonowicz (2015) analysed grain-size logs for several profiles from various sites in the Częstochowa region (southern part of the Polish Basin and central part of the Polish Jura area) and found that the cycles she had distinguished were also correlated with the eustatic curve of Hallam (1988). However, the number of regressive cycles for the Polish Jura successions does not match those on the eustatic curve; according to Leonowicz (2015), there

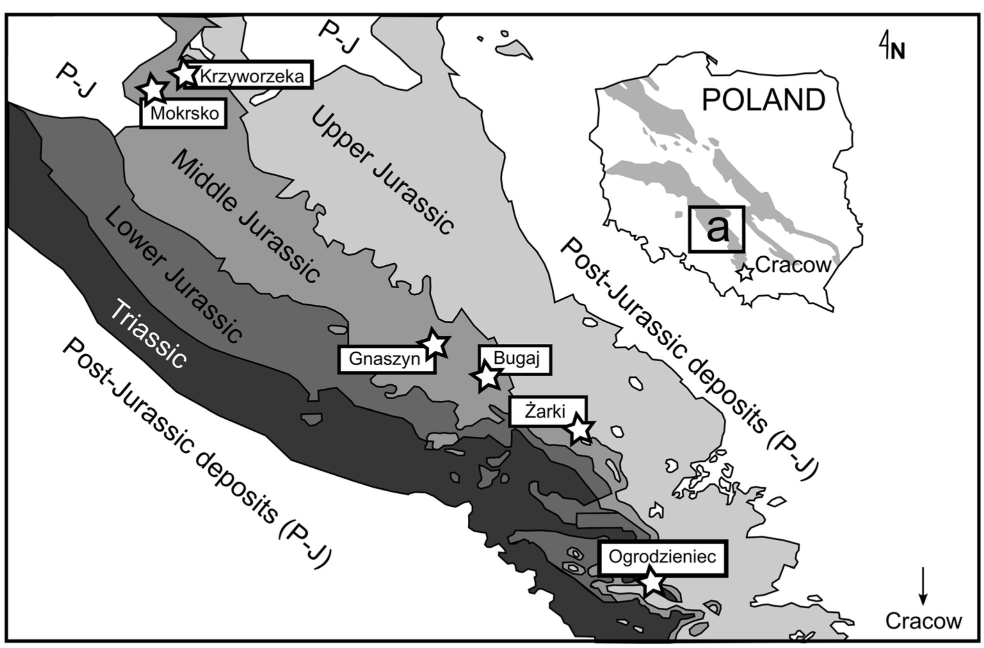

Fig. 1 The geological sketch map of the Polish Jura with outline of Poland (including Jurassic deposits – shaded areas). **a** Position of Polish Jura, the hiatus concretions-bearing localities indicated by stars (slightly modified after Zatoń et al. 2011)

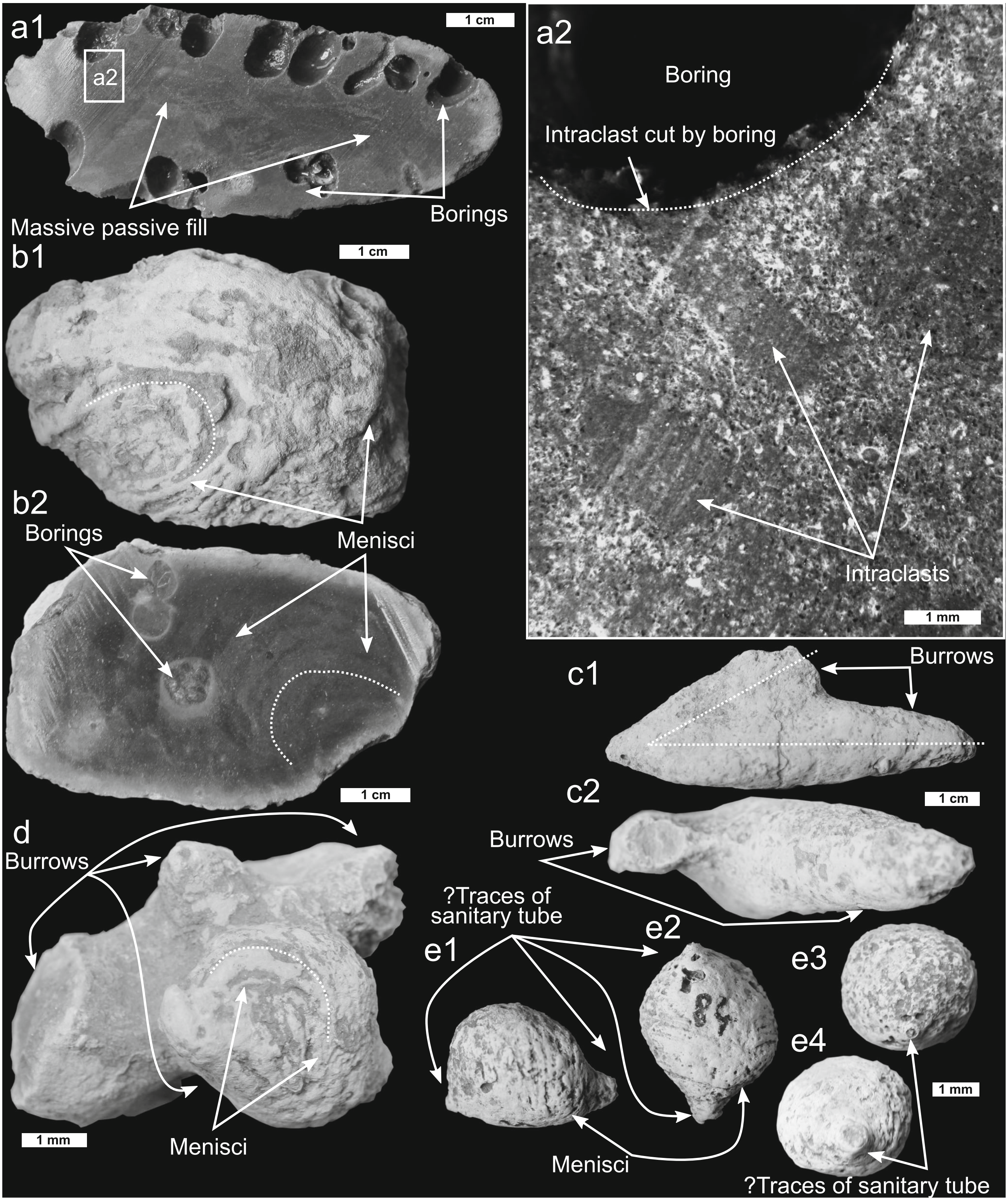

Fig. 2 **a** Hiatus concretions with BP-2 pattern (Krzyworzeka locality): **a1** section, top of concretion shows higher intensity of bioerosion; **a2** magnified part of a1 showing details of infilling sediment with potential intraclasts. **b** Meniscate burrow infill (Bugaj locality), seen in section view **b2** and on the external surface of the burrow infill **b1**. **c** Two branching burrows (likely thalassinoid tunnels; Bugaj locality). **d** Multiple branching burrows (Bugaj locality), including ?spreiten-infilled part (thalassinoid system). **e** Meniscate, back-filled burrow with possible trace of sanitary tube (?echinoid trace fossil; Ogrodzieniec locality)

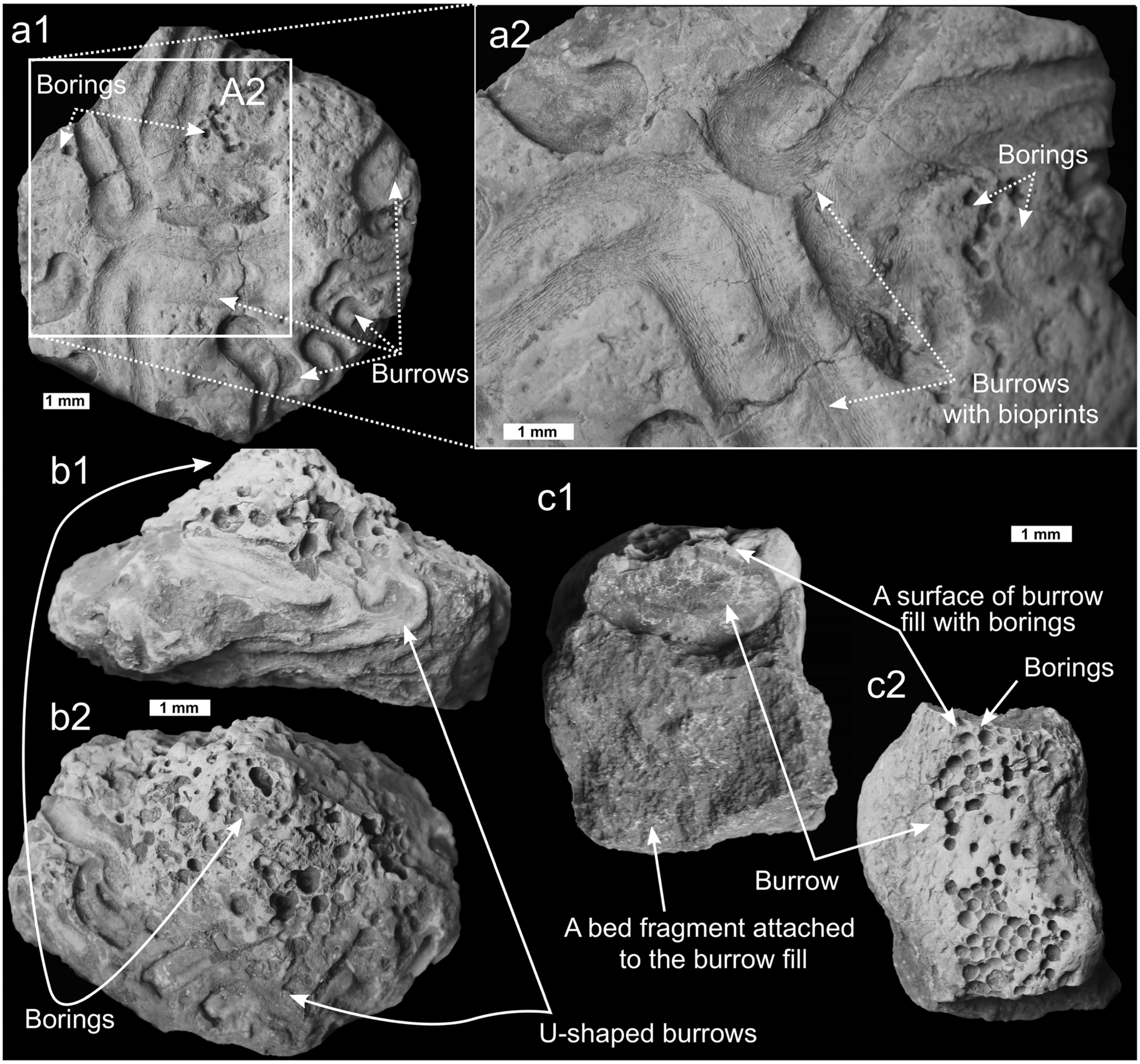

Fig. 3 **a** Lens-like concretion with U-shaped burrows (*Rhizocorallium*; Ogrodzieniec locality). **b** Hiatus concretion with borings and burrows; the borings cover its elevated part and burrows are confined to the lower part (*Rhizocorallium*: **b1** side view, **b2** diagonal view (Ogrodzieniec locality). **c** Hiatus concretion (thalassinoid burrow) with borings and carbonate bed fragment attached (Ogrodzieniec locality)

are extra regressive phases in the Polish Jura sector of the Polish Basin which were local or regional in extent due to tectonic uplifts (cf. Haq et al. 1987). Thus, the T-R cycles distinguished by Leonowicz (2015) did not result from eustatic sea-level changes but rather recorded sea-level changes in the Polish Basin or in the Polish Jura area only.

The studied deposits constitute an informal lithostratigraphic unit referred to as the Ore-Bearing Częstochowa Clay Formation (e.g. Matyja and Wierzbowski 2000). These marine Middle Jurassic (upper Bajocian and Bathonian) sediments are fossiliferous siliciclastics of the mudstone type (e.g. Zatoń et al. 2011; Gedl et al. 2012; Leonowicz 2013), which, apart from the hiatus concretions studied here, also contain fossil-rich carbonate nodules or cemented concretionary horizons (e.g. Majewski 2000). The hiatus concretions occur as discrete and single horizons visible within some of the sections exposed in different sites of the Polish Jura area (see Zatoń et al. 2011, Fig. 1).

Mud – a mixture of silt and clay (see mudrock terminology in Folk et al. 1970) – is the dominant fraction of the unit. Parallel lamination is the dominant physical depositional structure, with colour-highlighted laminae within background muds constituting the most common type of lamination; the preserved lamination suggests low to no sediment mixing by

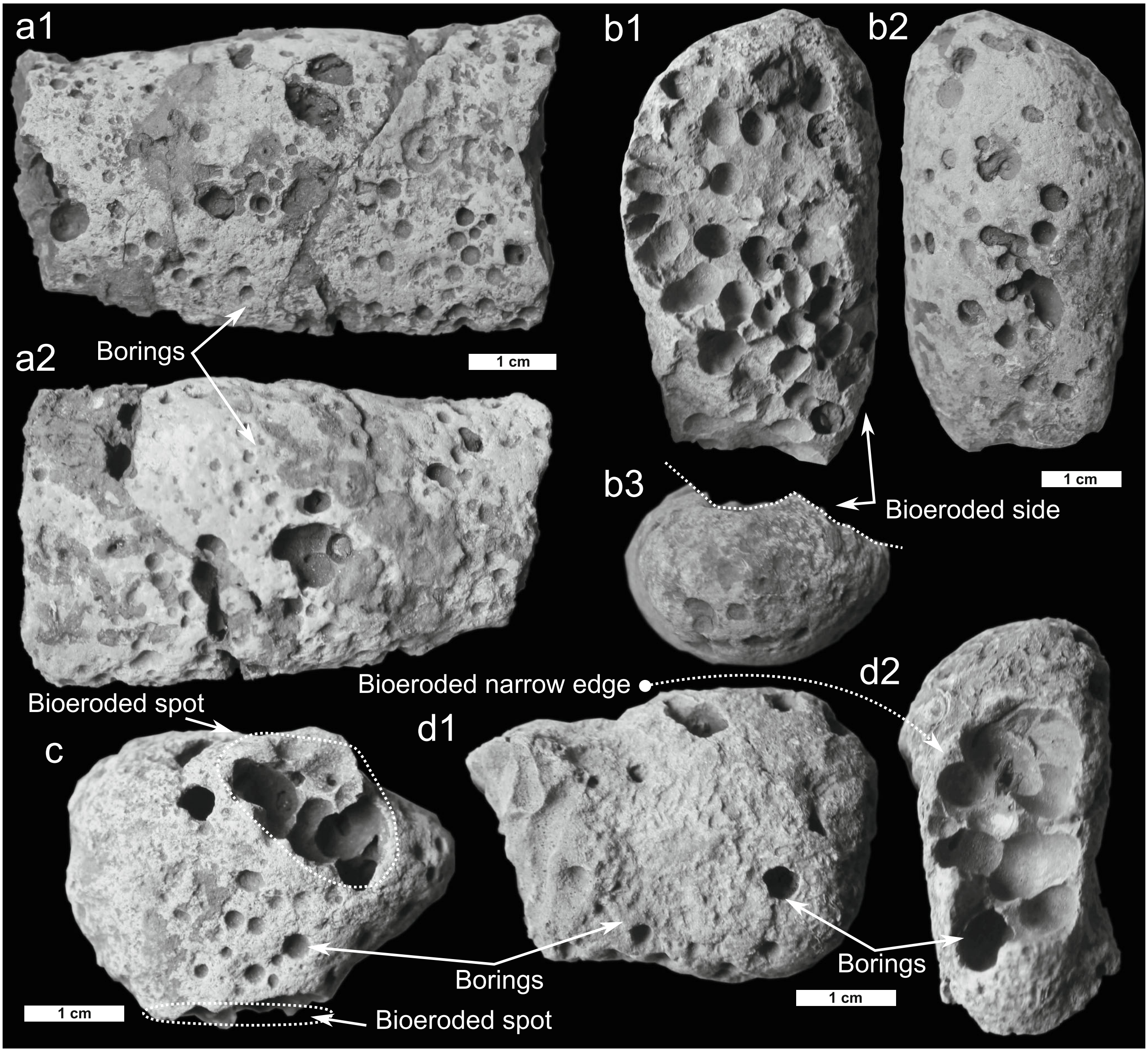

Fig. 4 **a** Hiatus concretion (thalassinoid fragment) with BP-1 pattern (**a1** and **a2** views of opposite sides; Krzyworzeka locality). **b** Hiatus concretion (thalassinoid fragment) with BP-2 pattern (**b1** and **b2** views of opposite sides, Krzyworzeka locality). **c** Hiatus concretion (thalassinoid fragment) with BP-3 pattern (Krzyworzeka locality). **d** Hiatus concretion (thalassinoid fragment) with BP-4 pattern (**d1** side view and **d2** narrow edge view; Krzyworzeka locality)

bioturbators and suggests periods of oxygen deficiency (Leonowicz 2013).

Interpretations of depositional settings by previous authors differed in details (see Leonowicz 2013, 2015, 2016 for reviews). However, the muds were considered mostly as open marine sediments. The fine-grained nature of the deposits and lack of sedimentary structures could be linked with the absence of storm wave influence (see e.g. Duke 1985), suggesting that the deposition took place below the storm wave base (e.g. Feldman-Olszewska 1997; Zatoń et al. 2011; Leonowicz 2013, 2015), under fluctuating oxic to suboxic conditions on the seafloor (e.g. Szczepanik et al. 2007; Marynowski et al. 2007; Zatoń et al. 2009; Leonowicz 2013). Thus, storm waves must have been a negligible agent of erosion and deposition. However, the presence of intercalations of coarser material (sand/silt and bioclasts), erosional surfaces, exhumed burrowing bivalves, and reworked skeletal material and skeletal debris derived from shallower basin zones indicates that storm-induced currents operating in the environment served as the main agents of erosion (Leonowicz 2013, 2015). However, other physical mechanisms of sediment disturbance, e.g. distal influences of tides, cannot be excluded (see, e.g. Gross et al. 1986). Traces of various burrowers occur in the unit (Leonowicz 2016); these burrowers may have increased the erodibility of the bottom sediments through either preparation and conditioning of the sediment for subsequent erosion by currents or direct resuspension of fine particles (cf. Baird 1981; Gross et al. 1988; Hesselbo and Palmer 1992).

The studied deposits generally thin and facies become shallower towards south-east (see, e.g. Deczkowski 1960; Majewski 2000). The studied hiatus concretions are found at single horizons within ~8- to 18-m-thick sections exposed at the sampled sites (Zatoń et al. 2011; see also Fig. 1). In terms of the mineralogy of the concretion-forming sediment, calcite (micrite/microspar cements) is the dominant constituent of the hiatus concretions (Zatoń et al. 2011). The sharp lithological contrast between cemented carbonate, concretion-forming sediment and siliciclastic host mudstone represents a concealed bed junction style of preservation (see Wanless et al. 1988; Jensen 1997). Finally, the studied concretions are encrusted by numerous sabellid/serpulid worms, bryozoans, sponges, and corals – all thoroughly studied earlier by Zatoń et al. (2011) and thus not analysed further in the present work.

Material and methods

Provenance of material

For this paper, Middle Jurassic (Bajocian and Bathonian) hiatus concretions from the mudstones of the Ore-Bearing Częstochowa Clay Formation were analysed. The studied material was collected in six localities of the Polish Jura in southern Poland: Krzyworzeka, Mokrsko, Bugaj, Żarki, Gnaszyn, and Ogrodzieniec (Fig. 1, Table 1, Fig. 7). The analysed concretions totalled 644 specimens. Each sampled site yielded a different number of specimens (Table 1,Fig. 7). The number of concretions was determined by their availability in the field (Zatoń et al. 2011). All of the concretions are housed at the Faculty of Earth Sciences, University of Silesia (Sosnowiec, Poland).

Methods

The collected hiatus concretions were subjected to ichnological analyses. Observations were conducted with the naked eye and with the use of a binocular microscope (light microscope). The morphologies of the concretions were analysed, and the structure and composition of concretion-forming sediment were studied in sectioned specimens. The bioerosion patterns preserved on the surfaces of the concretions were studied and classified according to the schema established in this paper. Each concretion was placed into one of four categories: BP-1, BP-2, BP-3, and BP-4 (see Fig. 6). Finally, selected concretions were photographed and drawn (Figs. 2–4).

Results

Precursor burrows

The preservation style of the trace fossils (abraded surfaces) and reworked character of concretions preclude formal ichnotaxonomic treatment. The morphologies of the concretions range from simply tubular to branched (Figs. 2–4). The sediment that formed the concretions was calcium carbonate (see Zatoń et al. 2011), either massive (Fig. 2a1) or exhibiting a meniscate internal structure (Fig. 2b2). The menisci were visible in a section view as well as traced on external surfaces of some burrows (Fig. 2b). These two types of sediment structure are interpreted here as follows (compare D'Alessandro and Bromley 1987; Bromley 1990):

- Massive structure: passive (gravitational) infill of open burrow systems (e.g. thalassinoid systems)
- Meniscate structure: either active backfill of feeding structures (e.g. echinoid burrows; Fig. 2e) or spreiten infill (e.g. part of thalassinoid systems, Fig. 2d)

Hiatus concretions with massive internal structure were found at all sampled sites (burrows with massive infill). The concretions representing meniscate-filled burrows were found in assemblages from Bugaj and Ogrodzieniec (Fig. 2b, d, e).

Tiering of burrows

Two tiers are present in the studied material. The deeper represents thalassinoid burrowers; the shallower represents U-shaped *Rhizocorallium* burrows (compare Wetzel and Aigner 1986). Traces of the shallower tier are superimposed on concretions, as the U-shaped burrows postdate the thalassinoid burrows. The U-shaped burrows display firmground characteristics and are important evidence of the concretions' hardening stage (see Zatoń et al. 2011).

Bioerosion patterns

The borings occurring on the concretions were classified by Zatoń et al. (2011, fig. 7 therein) into three ichnogenera: *Entobia*, *Trypanites*, and *Gastrochaeonolites*; details of their morphology are obliterated due to abrasion – this precludes detail ichnotaxonomic treatment.

Four different categories of bioerosion patterns (BP) were distinguished during the current study (Fig. 6a):

- Bioerosion pattern 1 (BP-1, Figs. 6a, 4a): Bioerosion intensity exhibits no preferences in terms of distribution in the concretion (two opposite sides are potential resting surfaces). This pattern indicates frequent currents and overturns of the concretion (proximal settings; Fig. 6b).
- Bioerosion pattern 2 (BP-2, Figs. 6a, 4b, 2a): Bioerosion intensity is greater on one side of the concretion (two opposite sides are potential resting surfaces). This pattern indicates infrequent currents and overturns of the concretion (distal settings; Fig. 6b).
- Bioerosion pattern 3 (BP-3, Figs. 6a, 4c): Bioerosion intensity displays patchy distribution and is greater on elevated parts of the concretion surface. This pattern indicates infrequent and weak currents.
- Bioerosion pattern 4 (BP-4, Figs. 6a, 4d): Bioerosion intensity is greatest along a narrow edge or a belt, whereas the opposite side of the concretion is not a stable resting surface (e.g. is too narrow). This pattern indicates infrequent and weak currents.

A summary of the observed frequencies is provided in Table 1 and Fig. 7. All sites except Gnaszyn (excluded due to small sample size; see Table 1) were characterised by 28–70% proportion of concretions with bioerosion patterns classified as BP-2 (Table 1, Fig. 7). The only site with less than 30% of such concretions is Żarki. Patterns BP-3 and BP-4 were typically subordinate components; their abundances ranged from 0 to 11% for BP-3 (with the highest proportion in Bugaj) and 0 to 13% for BP-4 (with the highest proportion again in Bugaj). The abundances of bioerosion patterns on the hiatus concretions are discussed below on a site-by-site basis.

Mokrsko (upper Bajocian)

Hiatus concretions from Mokrsko are typically several centimetres in maximal dimension. However, larger concretions – over 10 cm (e.g. maximum dimension of ~20 cm) – are also present. Their shapes vary from rounded to irregular; their colour is typically grey. Mud-filled burrows are noted on the surfaces of 10% of the concretions. The observed bioerosion patterns were classified as BP-1 (51%) and BP-2 (49%); the patterns BP-3 and BP-4 were not found.

Bugaj (middle Bathonian)

Hiatus concretions from Bugaj are characterised by shapes ranging from rounded to irregular (Fig. 2b–d) and are typically light grey in colour. These concretions nicely preserve the original morphology of precursor burrows. Mud-filled burrows were noted in 1% of concretions (firmground traces). A meniscate structure was observed in 9% of instances. Pattern BP-1 was noted in 24% of the concretions. Patchy bioerosion (BP-3) was found in 11% of cases; preferred bioerosion of narrow edges/belts (BP-4) was seen in 13% of concretions. Bioerosion pattern BP-2 was found in 51% of instances. Thus, 75% of the bioerosion patterns from the assemblage from Bugaj were classified either as BP-2, BP-3, or BP-4.

Gnaszyn (middle Bathonian)

The Gnaszyn site yielded a small sample size consisting of only two large hiatus concretions (patterns: BP-2 and BP-4; Table 1, Fig. 7). Due to the small sample size, the assemblage was ignored in further analyses.

Krzyworzeka (upper Bathonian)

Hiatus concretions from Krzyworzeka are typically several centimetres in maximal dimension and exhibit rounded, generally slightly elongated shapes (Figs. 2a–4) and orange colours (Fe mineralisation). Bioerosion pattern BP-1 occurs in 36% of concretions. Spotty or patchy bioerosion (BP-3) was noted in 6%, bioeroded narrow edges/belts (BP-4) in 3% of concretions. Bioerosion pattern BP-2 was found in 55% of concretions (Table 1, Fig. 7). Thus, patterns BP-2, BP-3, or BP-4 occur in 64% of the whole assemblage.

Ogrodzieniec (upper Bathonian)

Hiatus concretions from Ogrodzieniec range from rounded to flat and are sometimes lenticular in shape (Fig. 3a) and orange to grey in colour. A meniscate structure was noted in 7% of instances. Burrows are frequent in this assemblage (53%). These are U-shaped structures with scratched walls (*Rhizocorallium*; Fig. 3a, b). The borings tend to occur on elevated parts of the concretions (Fig. 3b1). Some of the concretions ranging from flat to lenticular from this site may represent cemented bed fragments rather than burrow fill (in places, relics of lamination). Also, in two examples, it was observed that thalassinoid burrows/concretions were still fused to carbonate bed fragments (Fig. 3c1). Of the specimens from this site, 24% fall into the BP-1 category, whereas 4% of the concretions were allocated to the BP-3 and 2% to the BP-4 patterns. Bioerosion pattern BP-2 was found in 70% of the concretions, with the total contribution of patterns BP-2, BP-3, and BP-4 reaching 76%.

Żarki (upper Bathonian)

Hiatus concretions from Żarki are several centimetres in maximal dimension and rounded and commonly elongated in shape. Their colour is whitish grey. The concretions from this site commonly exhibit burrows, likely firmground structures (66% in total; 8% with scratches, 58% filled with mud). The

Żarki assemblage is dominated by BP-1 pattern (70%), whereas BP-2, BP-3, and BP-4 patterns represent 28, 1, and 1% of the assemblage, respectively.

Discussion

Precursor burrows

Zatoń (2010) and Zatoń et al. (2011) suggested, following other researchers (see, e.g. Fürsich et al. 1992), that burrows (e.g. of the thalassinoid type) might be precursors of the hiatus concretions from the Middle Jurassic deposits of the Polish Jura. This view is supported by the morphologies of the concretions observed in this study. For example, tubular fragments represent sections of burrows and in some instances branching is observed, as well. Additional data are provided below regarding the types of burrows involved and their infilling sediment structure.

In the case of the hiatus concretions with massive structures, the precursors of passive fill were likely thalassinoid-type domicile burrows, representing an ichnomorphology commonly linked with crustaceans (see, e.g. Yanin and Baraboshkin 2013; Carvalho et al. 2007). A proper ichnogeneric assignment is not possible, as only reworked, abraded, and bioeroded fragments are available. For the same reason, the details of the original wall (smooth, pelleted, or scratched) remain unknown. However, based on the mud-dominated host sediment, two ichnogenera are plausible here: *Thalassinoides* and *Spongeliomorpha* (see also Leonowicz 2016). These two would indicate a soft to firm substrate (see, e.g. Bromley 1990). The fine cohesive nature of the sediment, however, excludes the ichnogenus *Ophiomorpha*, which is a trace fossil typical of shifting, sand-grade substrates, characterised by a pellet-enforced wall (see, e.g. Bromley and Frey 1974; Frey and Pemberton 1984; Bromley 1990; D'Alessandro and Bromley 1995; Tchoumatchenco and Uchman 2001; Carvalho et al. 2007; Uchman 2009).

Thalassinoid-type burrow systems may also encompass back-filled and spreiten-infilled burrows (e.g. de Gibert et al. 2012). This also applies to the present material (e.g. Fig. 2d). Finally, some of the apparently back-filled burrows – especially those with trace of sanitary tube (Fig. 2e) – may represent echinoid-produced structures (e.g. Bernardi et al. 2010).

Tiering of burrows

Apparently, various (e.g. passively filled and actively back-filled) burrows contributed to the studied concretion assemblages. The present material does not permit accurate detailed reconstruction of their tiering (see, e.g. Bromley and Ekdale 1986). However, some approximations can be made.

The thalassinoid burrows are characterised by vertical components reaching a depth of ~1 m within the sediment (Uchman 2009; Yanin and Baraboshkin 2013). Therefore, the net erosion that exhumed their infillings and destroyed the thalassinoid horizon would have had to reach at least this depth.

Thalassinoid burrowers likely lived deeper in the sediment than the producers of *Rhizocorallium* (see Wetzel and Aigner 1986; Buatois et al. 2017). In order to superimpose shallower tier traces over deeper ones, the seafloor must have undergone erosion but without exhumation of concretions. Apparently, as consumption of the seafloor progressed, it shifted deeper, approaching the level with abandoned and sediment-infilled, though still not cemented, thalassinoid burrows. Clearly, the sediment infilling thalassinoid burrows hardened over time (Zatoń et al. 2011). The U-shaped burrows bear scratch marks and record the firmground stage of sediment consistency (Fig. 3a, b; *Glossifungites* ichnofacies; see Frey and Pemberton 1984). Therefore, the U-shaped burrows must have formed only after the thalassinoid tunnels, and shafts had been infilled with sediment and after the latter's firming had commenced, yet before hardening had been completed. As a result, the final hardening phase of the concretions bearing U-shaped burrows likely occurred after net erosion of the seafloor. This erosion must have occurred within a relatively short time after the thalassinoid burrows had been filled with sediment, which was apparently not long enough to permit full cementation of thalassinoid burrow-infilling sediment prior to the shift of the thalassinoid zone into the shallower *Rhizocorallium* tier.

Bioerosion patterns

Various borers may attack surfaces of concretions that are exposed on the seafloor (see, e.g. Zatoń et al. 2011). Zatoń et al. (2011, fig. 7 therein) listed three ichnogenera on the hiatus concretions studied here: *Entobia*, *Trypanites*, and *Gastrochaeonolites*. Clavate borings are dominant, but due to abrasion, their accurate ichnotaxonomic assignment is not possible (see, e.g. Kelly and Bromley 1984). Ethologically, borings are typically domicile structures (see Bromley 1994). Therefore, their producers were compelled to attack exposed surfaces, granting them free access to the water column, food, and oxygen. If a concretion rested on the sea bottom, its upward-facing surface is a preferred target for colonisers.

Wave action and/or actions of storm-induced bottom currents may overturn concretions (e.g. Zatoń 2010). The impact of waves on seafloor sediment is reduced towards a basin. Storm-induced currents may operate in more distal settings. The strength of such currents diminishes as they cross the shelf from proximal to distal settings – in other words, the more distal the settings, the less frequent and weaker the storm-induced currents are expected to be (e.g. Elliott 1986; Sherwood et al. 1994; Palanques et al. 2002).

Currents were the dominant agents of erosion within the studied strata and likely caused the overturns of the hiatus concretions (Fig. 5; see Leonowicz 2013, 2015). Over time, repetitive cycles of colonisation and overturns led to specific bioerosion patterns (see Figs 5, 6). These patterns should reflect the frequency of storm-induced currents and thus the relative proximity of the relevant environments (Fig. 6b). The BP-1 pattern may indicate frequent and BP-2 infrequent events (Fig. 6b).

The studied bioerosion patterns can be used to infer not only the frequency (BP-1 vs BP-2) but also the scouring potential of currents (BP-3 and BP-4). Weak flows would lead to shallower erosion than stronger ones. BP-3 and BP-4 patterns might have arisen if currents were relatively weak. However, it should be kept in mind that if erosion by weak currents had continued and prevailed over deposition for a sufficient period of time, the patterns BP-3 and BP-4 would have changed into a BP-2 pattern. Likewise, if currents had become more frequent, the BP-2, BP-3, and BP-4 patterns might have evolved into a BP-1 pattern. As a result, the proportion of BP-3 and BP-4 patterns may have decreased due to the increasing maturity of the assemblage (increasing environmental energy and/or prolonged exposure). A greater proportion of these patterns may indicate that the events were characterised by weak scouring potential and a low level of frequency.

Proximal-distal trends

The high total proportions observed for categories BP-2, BP-3, and BP-4 (Table 1, Fig. 7) indicate the general distal nature of the environments in which the hiatus concretions were formed. The concretion assemblages from both Krzyworzeka and Bugaj are characterised by significant proportions of BP-2 patterns (Table 1). Krzyworzeka is characterised by 55% of BP-2 as compared to 36% of BP-1 and Bugaj by 51% of BP-2 and 24% of BP-1 (Table 1). Krzyworzeka is also characterised by lower frequencies of

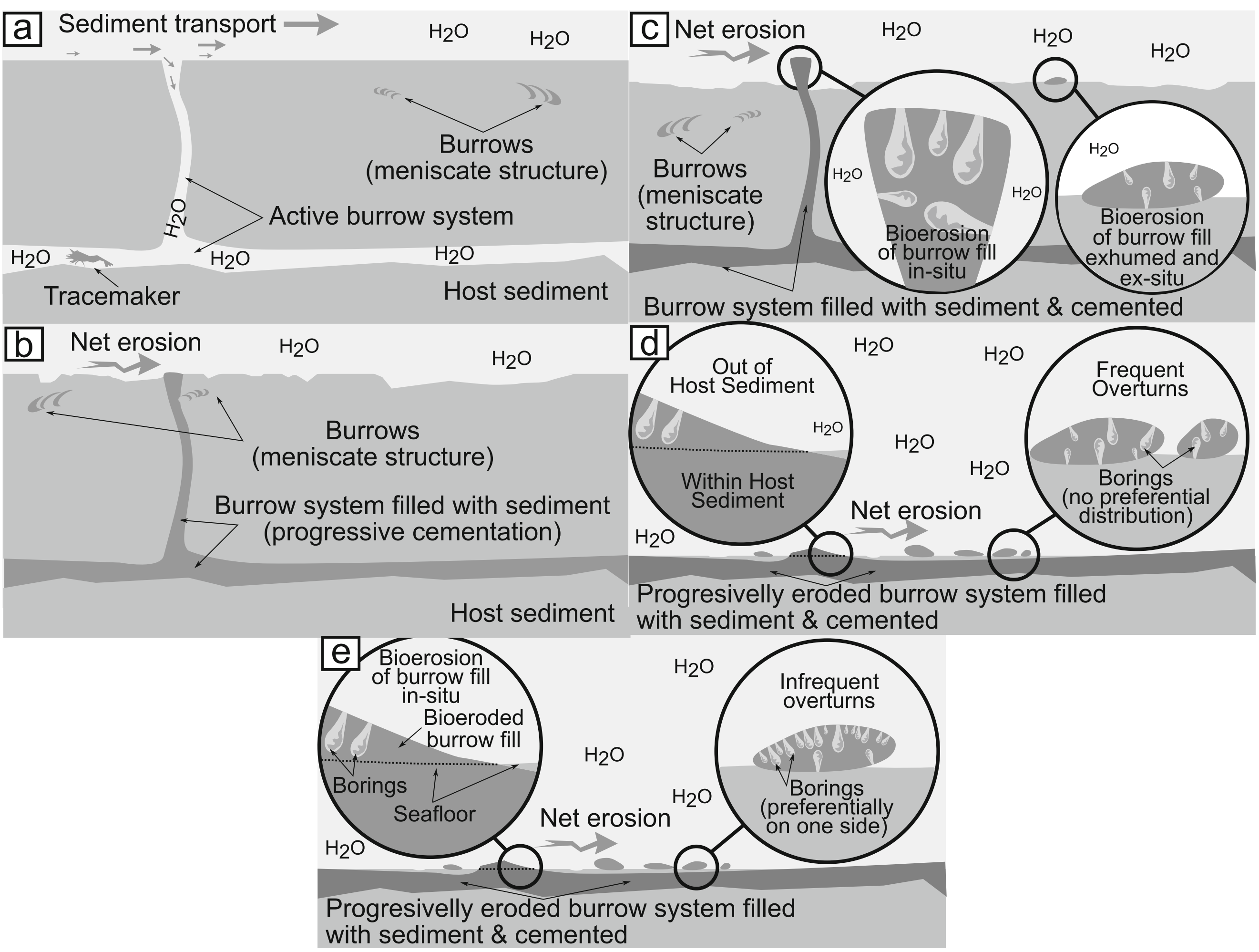

Fig. 5 **a** Schematic illustration of active thalassinoid burrow system. **b** The same system infilled with sediment. **c** Net erosion of seafloor progresses and exhumes the infills – parts of it become concretions resting on the seafloor. **d** Frequent currents overturn the concretions (more proximal settings). **e** Infrequent currents allows the concretions to rest on one side for prolong time (more distal settings)

Table 1 Bioerosion patterns and their abundances (frequencies)

SITE	BP-1 [%]	BP-2 [%]	BP-3 [%]	BP-4 [%]	BURROWS [%]	N
Krzyworzeka	36	55	6	3	0	277
Ogrodzieniec	24	70	4	2	53	135
Bugaj	24	51	11	13	1	98
Żarki	70	28	1	1	66	83
Mokrsko	51	49	0	0	10	49
Gnaszyn*	0	50	0	50	0	2

*The Gnaszyn site has been excluded from further comparisons due to the low number of specimens available for the study.

BP-3 (6%) and BP-4 (3%) than Bugaj, i.e. 11 and 13%, respectively. This means that the Bugaj site likely experienced weaker currents or, alternatively, had less time for transitions from BP-3/BP-4 into BP-2. The Bugaj assemblage is characterised by a higher total proportion of the BP-2, BP-3, and BP-4 patterns (75%) than Krzyworzeka (64%). This, combined with the lower frequency of BP-1 patterns in comparison to Krzyworzeka, suggests that the Bugaj assemblage may have originated in an environment characterised by more distal settings than that in which the Krzyworzeka assemblage was formed.

The Mokrsko assemblage appears to represent a mature stage, as BP-1 and BP-2 patterns occur in similar proportions and no BP-3 and BP-4 patterns were observed. Both may have been transformed into BP-1 or BP-2 patterns (Table 1).

The Ogrodzieniec and Żarki sites clearly stand out, as they are characterised by the highest proportion of firmground burrows. The Żarki assemblage exhibits a high proportion of burrows (66%) coupled with a high proportion of the BP-1 pattern (70%), which is thus more frequent than the BP-2 pattern (28%). The Żarki assemblage is also characterised by a low level of abundance of BP-3 and BP-4 patterns (1% each). In contrast, the Ogrodzieniec concretions show a high proportion of the BP-2 pattern (70%), which dominates over the less frequent BP-1 pattern (24%). The Ogrodzieniec concretions also display a high proportion of burrows (53%). The BP-3 and BP-4 patterns are infrequent (4 and 2%, respectively) but nevertheless more abundant than in the assemblage from Żarki. Ogrodzieniec may appear to have originated in a more distal environment than Żarki. However, the presence of firmground burrows and shapes of some concretions shows that the high proportions of the BP-2 pattern in Ogrodzieniec may be caused by factors other than the distal settings of the environment.

Compared to Krzyworzeka and Bugaj, the Ogrodzieniec site is characterised by a high proportion of burrows and yielded flat/lens-shaped concretions, which may be cemented bed fragments (local relics of lamination). The assemblage also contains rare thalassinoid burrows attached to carbonate beds (Fig. 3c). Apparently in Ogrodzieniec, the carbonate sediments were not only preserved within the burrows but also locally on the seafloor. The presence of carbonate bed fragments in Ogrodzieniec site may suggest its greater proximity to the source area compared to Krzyworzeka and Bugaj (cf. Zatoń et al. 2012). Therefore, the proportion of bioerosion patterns alone may be misleading in this case. It was rather the greater proximity of the site yielding the BP-2 pattern to the carbonate source (e.g. shallow-sea carbonate facies) that led to its high frequency – the cemented carbonate sediment that colonisers were able to attack was likely more resistant to overturns than rounded burrow infills. The Ogrodzieniec example shows the need to combine bioerosion pattern data with other data and observations in order to achieve sound results.

Three upper Bathonian sites – Ogrodzieniec, Żarki, and Krzyworzeka – could be combined here in order to assess their relative proximal-distal positions:

- Ogrodzieniec appears to be the most proximal of all the three sites (despite its high abundance of BP-2 patterns). Low abundances of the BP-3 and BP-4 patterns (4 and 2%, respectively) may suggest frequent and/or relatively strong bottom currents. The assemblage is characterised by a high proportion of concretion-covering firmground burrows (53%), suggesting a relatively short period between the infilling of thalassinoids and the erosion phase that exhumed them. The flat/lenticular shapes of some concretions and carbonate beds attached to thalassinoids may indicate the relative proximity of the source area.
- The Żarki assemblage appears to be more proximal than Krzyworzeka due to a higher proportion of BP-1. Low abundances of the BP-3 and BP-4 patterns (1% each) may also suggest relatively proximal settings with frequent and/or stronger currents leading to rapid complete exhumation. This agrees with the high abundance of firmground burrows (66%), showing that many hiatus concretions from the assemblage were transported into a shallower tier prior to complete hardening (short period between infilling and erosion phase). In contrast to Ogrodzieniec, no carbonate beds associated with thalassinoids are observed in the Żarki assemblage.
- The Krzyworzeka assemblage appears to have originated in an environment characterised by the most distal settings

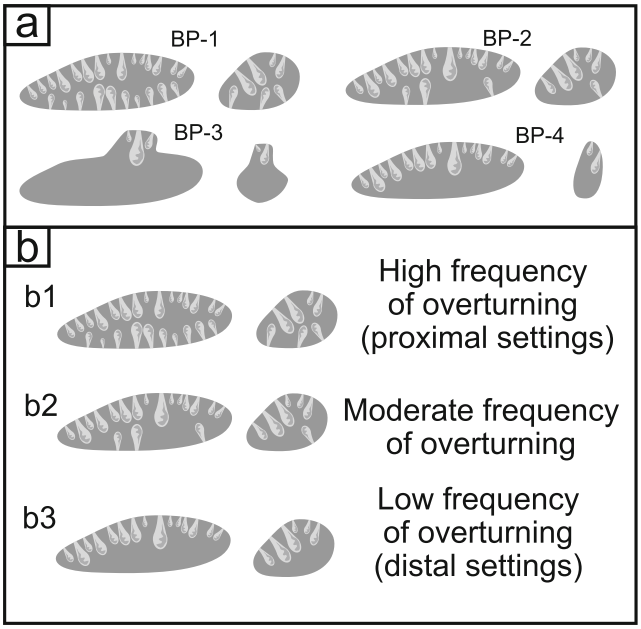

Fig. 6 **a** Graphical definitions of bioerosion patterns recognised in this paper ((left) longitudinal section of the concretions, (right) cross section of the concretion). **b** An illustration of relationship between bioerosion pattern and proximal-distal nature of the environment (frequency of currents and overturns)

of all three sites. Its proportion of BP-2, BP-3, and BP-4 patterns is the highest. Also, unlike the other two sites, the Krzyworzeka assemblage exhibits no firmground burrows. This suggests that thalassinoid infills probably hardened completely before the erosion of the seafloor transported them to shallower tiers, where they were subsequently exhumed completely and exposed to colonisers.

Hiatus concretion horizons and sequence stratigraphy

Thalassinoides and *Rhizocorallium* are two characteristic components of intermediate to distal *Glossifungites* ichnofacies associated with omission surfaces resulting from allocyclic processes (see MacEachern et al. 2007). Leonowicz (2016), who described sand-filled *Thalassinoides* burrows

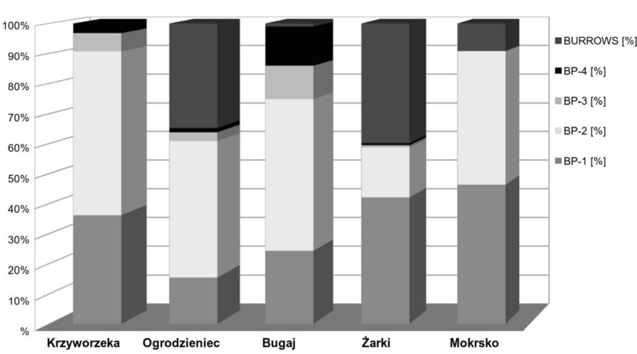

Fig. 7 A graphic illustration of the data shown in Table 1 (Note: Gnaszyn assemblage excluded)

from middle Bathonian deposits of the Ore-Bearing Częstochowa Clay Formation, concluded that the burrowed horizon represents the transgressive ravinement surface and that the thalassinoid-infilling sand was brought from shallower, nearshore zones where the transgressing sea was consuming such facies (for terminology, see Catuneanu 2002; Catuneanu et al. 2011). The stratigraphic distribution of hiatus concretions also indicates allocyclic control over their formation – discrete horizons within the studied sections (one per section; see Zatoń et al. 2011). As the horizons with hiatus concretions represent the former thalassinoid-burrowed zones, their stratigraphic significance may be similar to that of the thalassinoid horizon of Leonowicz (2016). However, the horizons with hiatus concretions were formed not only due to burrowing and infilling of the burrows with tempestites but also to subsequent net erosion of the seafloor. Therefore, any scenario proposed to explain their formation within the framework of sequence stratigraphy should take into account this necessary phase of erosion.

Erosion may be associated with transgressive and regressive phases of sea-level fluctuations (see Baird 1981; Brett 1995; Catuneanu 2002; MacEachern et al. 2007; Catuneanu et al. 2011). During regression, the main wave erosion zone shifts towards the basin, normal and storm wave bases are lowered, and a regressive ravinement surface may form on the shelf. During transgression, waves consume nearshore facies, as the sea encroaches on them, and currents transport the material offshore; thus a transgressive ravinement surface forms (see Fig. 8; see Catuneanu 2002; Catuneanu et al. 2011). However, in a transgressive scenario, shelf facies below storm wave base would not undergo significant net erosion (see Fig. 8) – some erosion could occur on palaeoslopes due to currents winnowing away fine particles (e.g. Baird 1981). The regressive type of erosion may be associated with a facies change, from distal to proximal, across the boundary surface, and highlighted by condensed horizons (see "precursor beds" in Brett 1995). The transgressive scenario (transgressive type of erosion) may be associated with detectable changes, e.g. towards even more distal facies; alternatively, facies' changes may be difficult to detect (e.g. muds on muds in distal settings). The stratigraphic context of the hiatus concretions (see Zatoń et al. 2011), while it matches the transgressive scenario more closely, does not explain the net erosion that exhumed the concretions. In order to fully conform to the transgressvie scenario, thalassinoid burrows infilled with tempestites should have been preserved within the host sediment, in which case no hiatus concretions would have been formed. The evidence points to a combination of the two scenarios.

Feldman-Olszewska (1997) saw the mudstones of the Ore-Bearing Częstochowa Clay Formation as transgressive components of cycles. However, some smaller-scale transgressive-regressive cycles can be distinguished within these deposits

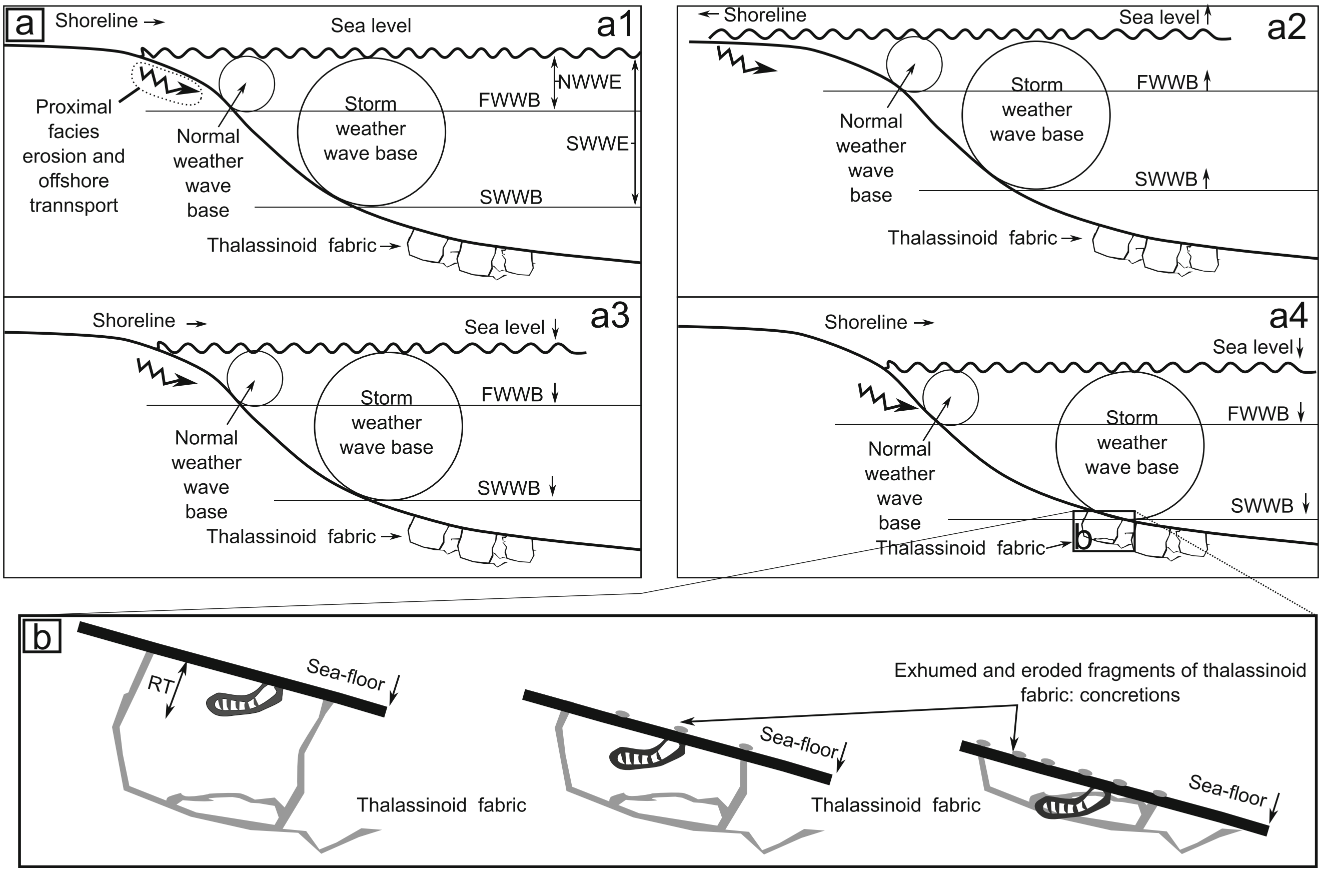

Fig. 8 **a** Relative sea-level fluctuations and associated shifts of erosion zones – impact on thalassinoid fabric and genesis of hiatus concretion horizon, **a1** No sea-level shift; main zones are marked (FWWB, fair/normal weather wave base; SWWB, storm weather wave base; NWWE, normal weather wave erosion; SWWE, storm weather wave erosion). **a2** Transgressive phase, a new erosion zone develops in shallow nearshore facies (see text for more details, **a3**–**a4**; continuous regressive phase, a new erosion zone can develop on shelf that used to be below storm-weather wave base (e.g. **a3** thalassinoid burrows are infilled with distal tempestite as more sediment reaches the zone, **a4** exhumation of thalassinoid infills commenced as the zone moved at or above the storm weather wave base [see (**b**)]). **b** Progressing erosion of sea-floor and associated degradation of thalassinoid fabric – thalassinoid burrows shift progressively into *Rhizocorallium* tier (RT, if thalassinoid burrow infill is firm at this stage; U-shaped, scratched-covered burrows may form)

(e.g. Leonowicz 2015 and references therein). The associated rapid drop in base level may have caused the net erosion that exhumed the hiatus concretions. Contrastingly, the colonisation of the concretions and development of *Entobia* ichnofacies suggest retardation of burial (see Bromley 1994) and hence may suggest a small-scale transgressive episode following erosion. As a result, the fall and subsequent short-term rise in sea-level could explain the exhumation and subsequent colonisation of the concretions. The carbonate sediment-infilling thalassinoids may have been a distal tempestite comprising material derived from the destruction of exposed nearshore carbonate facies and/or from normal and storm wave destruction of carbonate facies, which the sea fall had shifted seaward.

Proximal sites with U-shaped firmground burrows superimposed on concretions show that the span of time between burrow infilling and seafloor erosion was relatively short – not long enough to allow for complete hardening of thalassinoid fills before their incorporation into the *Rhizocorallium* tier. In such cases, the gap between regressive and transgressive phases would be relatively short, confirming that these constituted two phases of one cycle, or successive cycles, rather than components of unrelated cycles separated by a significant gap.

The general proximal-distal trends highlighted by bioerosion patterns agree with the south-eastern direction of the shallowing trend, as is visible in the pinching and thinning of facies (see, e.g. Deczkowski 1960; Majewski 2000). However, the general tendency of these trends is likely complicated by local tectonics and/or variable subsidence overprinted over global sea-level fluctuations (see, e.g. Leonowicz 2013, 2015).

Conclusions

The range of burrow morphologies and their internal structures preserved in the Middle Jurassic hiatus concretions from the Polish Jura indicate that at least two types of precursor burrows were involved during their formation: thalassinoid open systems and back-filled/spreiten burrows. The superposition of tiers and firmground character of U-shaped burrows occurring on some concretions indicates significant net seafloor erosion and a relatively short period of time between phases of thalassinoid infilling with sediment and seafloor erosion. This period must have been short enough to preclude full cementation of thalassinoid infills before they shifted into the *Rhizocorallium* tier.

The bioerosion patterns observed on the concretions were divided into four categories: BP-1, BP-2, BP-3, and BP-4. The BP-1 and BP-2 patterns enabled differentiation between environments of frequent and infrequent concretion overturns (currents), which may indicate relative proximal and distal settings, respectively. The BP-3 and BP-4 patterns were related to the weakness and low scouring potential of currents. The studied hiatus concretions showed that analysis of bioerosion patterns may be used to infer relative proximal-distal trends. However, the data should be also combined with other sedimentological data, e.g. the proximity of the source area in the case of the Ogrodzieniec concretions, in order to achieve the soundest results.

The horizons with hiatus concretions originated due to the infilling of burrows, cementation of infills, and subsequent exhumation of concretions due to erosion (destruction of the thalassinoid fabric). The relevant erosion phase differentiates these horizons and Leonowicz's (2016) thalassinoid-marked transgressive ravinement surface. The horizons with hiatus concretions may be interpreted as a record of the regressive phase (e.g. infilling with carbonates and exhumation) and subsequent transgression (concretions resting on the seafloor, with final reburial delayed). The horizons may thus represent a switch from a regressive to a transgressive regime.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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