Sedimentological implications of an unusual form of the trace fossil *Rhizocorallium* from the Lower Muschelkalk (Middle Triassic), S. Poland

Monika Kowal-Linka · Adam Bodzioch

Received: 8 July 2010 / Accepted: 23 December 2010 / Published online: 19 January 2011
© The Author(s) 2011. This article is published with open access at Springerlink.com

Abstract Specimens of the trace fossil *Rhizocorallium* isp. with retrusive limbs occur in 10–20-cm-thick composite beds: the bottom layers contain abundant *Planolites* and *Thalassinoides* trace fossils, and the top layers are built of horizontally bedded pelitic limestone and contain less bioturbational structures. The first specimens of *Rhizocorallium* isp. occur just 2–3 cm above the lower surfaces of the top layers. The horizontal protrusive sections are 1 cm high and 1 cm wide. At some sites, the horizontal tunnels end, and the limbs become first obliquely retrusive (45°) at a distance of 1.5–2.5 cm, and then vertically retrusive at a distance of 4–6 cm, or at once vertically retrusive at a similar distance. They reach to the upper surfaces of the top layers. The erosional events are recorded as uneven bases and a lack of *Rhizocorallium*, which suggests erosion to approx. 10 cm deep. The lower parts of the top layers record deposition of lime mud from a powerful flow. The protrusive sections of *Rhizocorallium* record relatively quiet periods resulting from significantly decreased sedimentation. The successive retrusive sections provide evidence that the quiet conditions suddenly came to an end, and that sedimentation was reactivated or accelerated. The last retrusive limbs of *Rhizocorallium* isp. mark the border of the storm event and the next erosion event. The composition of the fecal pellets shows that these burrowing animals were deposit-feeders, fast enough to find a sufficient amount of food, and also fast enough to escape being buried.

Keywords Ichnofossil · *Rhizocorallium* · Retrusive structure · Lower Muschelkalk · Upper Silesia

Introduction

In pursuance of the last formal revision of the ichnogenus *Rhizocorallium* Zenker, 1836, proposed by Fürsch (1974), this ichnogenus includes three ichnospecies: *Rhizocorallium jenense* Zenker, 1836, representing straight, short, U-shaped spreiten-burrows commonly oblique to the bedding plane and only rarely horizontal; *Rhizocorallium irregularae* Mayer, 1954, representing long, sinuous, bifurcating or planispiral U-shaped spreiten-burrows, mainly horizontal; and *Rhizocorallium uliarense* Firtion, 1958, representing trochospiral U-shaped spreiten-burrows. Fürsch (1974) regarded *Rhizocorallium commune* Schmid, 1876 as a synonym of *Rhizocorallium jenense*, and included it into this ichnospecies. Knaust (2007) emphasized that *Rhizocorallium commune* and *Rhizocorallium jenense* should be described as two independent ichnospecies, because they represent two different morphologies. According to the original description, *Rhizocorallium commune* is a rather short and straight, horizontally oriented structure showing spreiten, whereas *Rhizocorallium jenense* is oblique to the bedding plane, and the spreiten are poorly developed. Fürsch’s (1974) division is used in this paper.

The most characteristic features of *Rhizocorallium* are the spreiten, which consist of stacked lamellae of reworked sediment, showing that succeeding tunnels were made at
ever deeper levels of an individual bed (protrusive structure of *Rhizocorallium jenense* and *Rhizocorallium uliarense*) or continuously further along the bed top (protrusive structure of *Rhizocorallium irregulare*). According to previous interpretations, the various forms of *Rhizocorallium* result from the different modes of their producers’ lives: *Rhizocorallium jenense* was interpreted as a suspension-feeder’s burrow, whereas *Rhizocorallium irregulare* and *Rhizocorallium uliarense* were thought to record the activity of deposit-feeders (Fürsich 1974; Worsley and Mørk 2001). Modern views emphasize the function of the horizontally developed *Rhizocorallium* tunnel systems as fodinichnia and domicinia of deposit-feeding crustaceans and/or worm-like animals (Knaust 2007; Seilacher 2007).

In addition to the ichnospecies mentioned above, some modified *Rhizocorallium* have been found: (1) specimens with vertically retrusive limbs, known inter alia from the Early Carboniferous (Chisholm 1970), the Middle Triassic (Rodríguez-Tovar and Pérez-Valera 2008), the Late Triassic (Seilacher 2007), the Early Jurassic (Sellwood 1970), and the Late Jurassic (Schlirf 2000; Carvalho et al. 2010, and (2) lobate specimens which penetrate two or more levels in a sediment known from the Early Jurassic (Fürsich 1974; Seilacher 2007). The rarely reported first form is a modification of *Rhizocorallium jenense*, which was created in two stages: the animal initially constructed an inclined protrusive tunnel, and then switched to an upward retrusive position (Seilacher 2007). In the case of the Middle Triassic forms, the values of vertical shifts are approx. 2.0 cm (Rodríguez-Tovar and Pérez-Valera 2008); comparable values of the vertical shift of the Late Jurassic forms lie between 4.3 and 8.0 cm (Schlirf 2000). The retrusive limbs of *Rhizocorallium* are interpreted as an equilibrium structure developed as a response to slow but continuous sedimentation (Fürsich 1974; Schlirf 2000; Rodríguez-Tovar and Pérez-Valera 2008). The common Middle Triassic *Rhizocorallium* (without retrusive sections) known from the German Basin were always formed after deposition of a bed, starting at the top, and were developed during quiet conditions as a result of the sea floor colonization after storm activity (Aigner 1985; Worsley and Mørk 2001). The horizontally developed *Rhizocorallium* were formed just 1–3 cm beneath the bottom surface (Wetzel and Aigner 1986).

The present contribution reports for the first time the occurrence of *Rhizocorallium* isp. with retrusive limbs in the Gogolin Formation (Lower Muschelkalk, Upper Silesia, S. Poland). Such forms of *Rhizocorallium* isp. have to date not been reported from the other Muschelkalk formations in Poland. The specific position and the unusual form of the *Rhizocorallium* isp. with retrusive limbs provide new insight into the rate of development of the retrusive limbs in relation to the storm depositional processes.

The present observations of *Rhizocorallium* isp. and its relationship to other trace fossils make it possible to distinguish between the successive minor sedimentological processes during individual storm events, which are known from analogous carbonate formations.

**Geological setting**

The specimens of *Rhizocorallium* isp. were collected in small active quarries located in the vicinity of Żyglin (northern edge of Upper Silesia, S. Poland), where the lower part of the Gogolin Formation is exposed (Fig. 1). The 45-m-thick Gogolin Formation is the lowermost lithostratigraphical unit of the Lower Muschelkalk (Middle Triassic) in Upper Silesia. From the Late Olenekian/Early Anisian to the Early Pelsonian, the sediments of the Gogolin Formation were deposited on a carbonate ramp situated in the southern part of a shallow epicontinental sea (the German Basin) at about 25°N (Nawrocki and Szulc 2000; Szulc 2000), which was affected by severe storms and hurricanes (Parrish 1999; Szulc 2008).

The two lowermost units represent transgressive sediments. The lower part of the limestone with *Pecten* and *Dadocrinus* consists predominantly of thick- and medium-bedded, cross-bedded bioclastic limestones (calcarenites and calcirudites, packstones, and grainstones; Fig. 2), interpreted as skeletal shoals deposited on the inner ramp, which alternate with thin marl laminae (Bodzioch and Szulc 1991; Szulc and Głuchowski 1991; Szulc 1993; Kowal 1998). The upper part of this unit is built mainly of composite beds consisting in their lower part of pelitic limestones, usually bioturbated, with erosionally truncated tops, which are covered by bioclastic limestones containing numerous crinoid stem ossicles and molluscs (Fig. 2). These bioclastic limestone beds are interpreted as proximal tempestites deposited on autochthonous lime mud beds in the inner ramp zone, in front of the skeletal shoals. The uppermost part of the limestones with *Pecten* and *Dadocrinus* is built of non-bioturbated pelitic limestone and marl alternations with some debris-flow deposits (Kowal 1998).

The first horizon of the wavy-bedded limestone consists of several rocks types. The most characteristic are the approx. 40-cm-thick beds of crumpled, highly bioturbated pelitic limestones that contain *Rhizocorallium* *jenense*, *Rhizocorallium* *irregulare*, *Planolites*, and *Thalassinoides*, all preserved in full relief, enclosed in a more marly deposit (Fig. 2). The horizon also contains: (1) thin, platy pelitic limestone beds of approx. 1–3 cm thick with bioturbated tops, which are interbedded with marl laminae; (2) up to
40-cm-thick sets of wavy-bedded pelitic limestone laminae intercalated with very thin marls; and (3) composite beds consisting in their lower part of bioturbated pelitic limestone with erosionally truncated tops and in the upper part consisting of thin and medium-bedded bioclastic limestones, containing mainly crinoid ossicles and mollusks, or sandy limestones comprising mainly quartz and muscovite grains. The highly bioturbated pelitic limestones are interpreted as autochthonous sediments deposited in the mid-ramp zone, whereas the weakly bioturbated pelitic limestones, bioclastic limestones, and sandy limestones are interpreted as distal tempestites deposited on the autochthonous, semi-consolidated, usually bioturbated lime muds (Szulc and Głuchowski 1991; Kowal 1998).

Materials

The specimens of *Rhizocorallium* isp. occur in hard rocks, so isolation of individuals was not possible. Specimens have been cut to examine their three-dimensional forms. Most of the collected specimens are incomplete or show combined structures of two or more burrow systems. We present here the most complete and clear examples. According to the Fursich’s division (1974), the collected specimens show features characteristic of *Rhizocorallium jenense*, but their protrusive tunnels are developed horizontally, which is rare. The long, horizontally developed *Rhizocorallium irregulare* are not known to have horizontally retrusive sections. We therefore use the name *Rhizocorallium* isp. to avoid incorrect identification of the specimens. Thin sections were prepared to examine the texture of the host rock and the composition of the fecal pellets. The specimens are deposited at the Institute of Geology, Adam Mickiewicz University, with catalogue numbers UAMIG-Zg-42-51.

Description of the *Rhizocorallium* burrows

The specimens of *Rhizocorallium* isp., with retrusive limbs occur in 10–20-cm-thick composite beds, which consist distinctly of two layers (Fig. 3a). The top layers are up to 4 cm thick and consist of abundant *Planolites* and minor *Thalassinoides* pelitic limestone burrow-fillings preserved in full relief, which are enclosed in more marly limestone (Fig. 3a, b). The bottom layers do not contain any species of *Rhizocorallium*. The lower surfaces of the bottom layers are horizontal and uneven, with swellings and depressions. The upper surfaces are also very uneven, horizontal to oblique (up to 40°), and with a maximum difference of 3 cm in level (Fig. 3c). Some burrow-fillings occurring in the uppermost part of the bottom layers have been truncated.

The top layers are built of homogenous gray pelitic limestone and contain less bioturbational structures (Fig. 3a). The limestones are horizontally to low-angle cross-bedded; the bedding is very fine and occurs only on weathered flank surfaces. The first specimens of *Rhizocorallium* isp. occur just 2–3 cm above the lower surfaces of the top layers (Fig. 3a, c). The horizontally developed protrusive tunnels are approx. 1 cm high and also approx. 1 cm wide, and contain numerous beige-colored rod-like fecal pellets, which are up to 1 mm long, and more pale than the background (Fig. 3d). The fecal pellets consist of homogeneous micrite, and do not show any internal structure. At some sites, the horizontal tunnels end and the limbs become initially obliquely retrusive (approx. 45°) at a distance of 1.5–2.5 cm, then vertically retrusive at a distance of 4–6 cm (Figs. 3a, 4a), or at once vertically retrusive at a similar distance. The retrusive tunnels are slightly wider (up to 1.8 cm), and filled with numerous fecal pellets showing the same composition and structureless character as the pellets in the protrusive tunnels. Calcite crystals, interpreted as pseudomorphs after gypsum, and scattered pyrite frambooids are present in the
filling of the retrusive tunnels (Bodzioch and Kowal 2001). The retrusive limbs reach to the upper surfaces of the top layers (Fig. 4b, c). No scratches were found. The boundaries between the host rock and the protrusive tunnels are indistinct and marked only by the occurrence of fecal pellets. In the retrusive sections, the tunnel walls are darker than the host rock and the tunnel-fillings, and the “aureole” of the darker sediment (lining) is even 2 mm thick (Fig. 4d, e). The *Rhizocorallium* isp. burrow systems are perpendicular to the bedding surfaces or lopsided (Fig. 4f, g).

A few escape burrows (fugichnia) leading from the bottom layers to the top layers have been found. They end 2–3 cm above the lower surfaces of the top layers and are cut by the protrusive sections of *Rhizocorallium* isp. (Figs. 3c, 4a).
Discussion

The composite beds containing *Rhizocorallium* with re-
trusive limbs show sedimentary structures characteristic of
distal calcareous tempestites. Such tempestites were iden-
tified and described in detail from, inter alia, the Upper
Muschelkalk carbonate ramp of S. Germany, which was
affected by storms and hurricanes (Aigner 1985). The
“ideal” distal calcareous tempestite bed is 1–10 cm thick,
shows an erosional base often with tool marks, consists of a
thin skeletal lag at the base, and homogenous pelitic lime
mud (calcisiltite to calcilutite), which shows horizontal
bedding and low-angle cross-bedding in the upper part, and
wave ripples on the top. These structures reflect changes in
depositional processes during the one storm event. Deposi-
tion is followed by colonization on the bed tops. Animal
activity manifested by bioturbations always starts at the
bed tops (Aigner 1985; Wetzel and Aigner 1986).

The uneven, oblique upper surfaces of the completely
bioturbated bottom layers of the composite beds, and the
cut burrow-fillings record erosional truncation resulting
from bottom current action (e.g., Myrow and Southard
1991). Lack of any *Rhizocorallium* in these bottom layers,
which consist of numerous *Planolites* and *Thalassinoides*,
allows estimation of the depth of erosion. According to
infaunal tiering (the characteristic vertical zonation of the
ichnofossils associations), *Rhizocorallium* is characteris-
tic of the upper parts of bioturbated beds, thus the occurrence
of *Planolites* and *Thalassinoides* on bed top records the
erosion of more than 10 cm (Aigner 1985; Wetzel and
Aigner 1986), as in this case. The oblique surfaces of the
truncated bottom layers, which mark differences in levels of
approx. 3 cm, additionally support deeper erosion.

The lowermost 2–3 cm of the top layers, without biotur-
bourational structures other than the escape burrows, show
that the first portion of the lime mud of the top layers was

---

**Fig. 3** Features of composite beds with unusual *Rhizocorallium* isp. (UAMIG-Zg-49). a Composite bed consisting of a strongly biotur-
ated bottom layer and a very fine horizontally laminated top layer. Cross-section of the right retractive limbs is visible. b Bottom view of
the bottom layer containing *Planolites* (Pl) and *Thalassinoides* (Th) preserved in full relief. c Uneven and oblique upper surface of the
bottom layer. The difference of 3 cm in levels of the bottom surface of
the top layer is shown. The first protrusive tunnels of *Rhizocorallium*
isp. are developed just 2 cm above the lower surface of the top layer.
The position of the last retractive limbs on the bed’s top is marked
with dashed lines. The escape structure leading from the bottom layer
to the top layer is visible. For further details, see Fig. 4. d Close-up of
the cross section of the protrusive section; pale rod-like fecal pellets
are visible (UAMIG-Zg-50)
Fig. 4 Macroscopic features of *Rhizocorallium* isp. (UAMIG-Zg-49) and models. 

**a** Fragment of protrusive section and right vertically retrusive limbs of a *Rhizocorallium* isp. An escape burrow (fugichnion) leading from the bottom layer to the top layer, cut by protrusive section, is visible. 

**b** The last vertically retrusive limbs on the bed’s top. The relation of the last right retrusive limb to the other right vertically retrusive tunnels is visible. 

**c** Top view of the whole last vertical retrusive limbs on the bed’s top. 

**d** Cross section of the whole burrow system: the right vertically retrusive limbs, the uppermost part of the left vertically retrusive limbs, and a part of the horizontal protrusive section are visible. The indistinct walls of the protrusive tunnels and the distinctly darker walls of the retrusive limbs are visible (UAMIG-Zg-49/1, 2). 

**e** Cross section of the whole vertically retrusive right limbs. The uneven upper surface of the bottom layer is visible. The indistinct walls of protrusive tunnels, darker walls of the vertically retrusive limbs, and pale fecal pellets are clearly visible (UAMIG-Zg-49/3). 

**f–g** Models of *Rhizocorallium* isp. from the Gogolin Formation. The first model (f) shows the specimen in the right position, and the second (g) shows the lopsided specimen.
deposited relatively quickly, and just after the first horizontal *Rhizocorallium* isp. were formed. The sudden deposition is also evidenced by the escape structures leading from the bottom layers to the top layers. These observations suggest that the lime muds constituting the lower part of the top layers were deposited from the powerful flow resulting from storm activity (e.g., Walker et al. 1983; Myrow and Southard 1991). Because benthic animals start their burrowing activity after deposition at the tops of the beds (Aigner 1985), the horizontal protrusive sections of *Rhizocorallium* indicate that the deposition from the powerful flow had decreased significantly, and that a period of relatively quiet conditions had begun. The escape burrows mentioned above occur only to the level where the first horizontal *Rhizocorallium* systems are present, which also supports temporally decelerated deposition. Newly deposited lime mud a few centimeters thick, supplied from the shallower part of the carbonate ramp, must have been rich in organic matter, which made it very attractive for deposit-feeders; these started their activity at the top of the new bed, which contained abundant nourishment. The beige color of the fecal pellets in the protrusive tunnels, paler than the surrounding sediment, supports the hypothesis that the burrowing animals were deposit-feeders (e.g., Dworschak et al. 2006). The subsequent shift in direction of *Rhizocorallium* from horizontal to oblique and vertically retrusive indicate that the sedimentation of distal tempestite bed was reactivated or accelerated, although this fact is not recorded either in the sediment texture, or in sedimentary structures. The lowermost parts of the top layers continue into successive parts without any visible sedimentological boundary or other evidence of an interruption in sedimentation. This could mean that the whole tunnel systems (protrusive and retrusive sections) were created relatively quickly. This is not surprising, as research into modern mud shrimps shows that these animals can dig tunnels of tens of centimeters long in just a few hours, and a whole burrow system in only 1 week (Dworschak 2004). The shift in direction from horizontal to oblique and vertical was a response to the deposition from suspension (e.g., Walker et al. 1983), which started after deceleration or short cessation of sedimentation from the powerful flow. The animals had to protect themselves from burial, and therefore created vertically retrusive limbs. The composition and pale color of the fecal pellets in the tunnels, showing the same features regardless of whether they are placed in protrusive or retrusive sections, indicates that the whole *Rhizocorallium* systems occurring in the Gogolin Formation were made by deposit-feeders. These need to dig long tunnels to find sufficient food. Research into modern burrowing animals shows that they spend most of their time on burrowing activity, and that their tunnel systems are dynamic and change shape continuously for the purpose of obtaining food (Nickell and Atkinson 1995; Dworschak et al. 2006).

Had sedimentation during the final stage of deposition been slow, the fast-digging deposit-feeders would have created an extensive horizontal burrow system in order to find enough food instead of vertically retrusive tunnels. The current hypothesis that vertical retrusive limbs reflect slight but continuous sedimentation, should therefore, in our opinion, be re-evaluated. This has been suggested earlier by Fürsch (1974) for *Rhizocorallium jenense*, and later, inter alia, by Schlirf (2000), who suggested that retrusive limbs were formed as a response to slow but continuous sedimentation, or in order to achieve sufficient nutrient exploitation of the sediment (the latter interpretation presumes that *Rhizocorallium jenense* burrows were also created by deposit-feeders, not suspension-feeders), and Rodríguez-Tovar and Pérez-Valera (2008), who also thought that the retrusive limbs were a response to slow but constant sedimentation. We postulate, in contrast, that the vertically retrusive limbs are a result of a relatively fast sedimentation rate, and that the animals continued burrowing for feeding, but also needed to avoid burial. Slow sedimentation is not a satisfactory explanation, because deposit-feeders digging only short vertically retrusive tunnels during slow sedimentation would not find sufficient food.

This hypothesis is also supported by differences in the wall structure of the tunnels. The protrusive sections have indistinct wall boundaries, not consolidated by mucus, which shows that the horizontal section was created during relatively quiet conditions, and that the tunnels did not need to be protected against compaction. The retrusive sections have distinctly darker walls, consolidated by mucus, which suggests that the tunnels were made in loose, unstable and continuously falling sediment, and that they needed to be protected against compaction by the overlying sediment.

**Conclusions**

Detailed observations on the development of trace fossils, especially of those with unique features, are useful for the identification of relatively small events and the successive stages of single events of storm-induced sediment remobilization and deposition. In the case presented here, these stages of erosion, sedimentation from the powerful flow, relatively quiet condition, and renewed sedimentation from the suspension can be identified thanks to the trace fossils.

The erosion events are recorded as uneven tops of completely bioturbated bottom layers, with differences in levels up to 3 cm, and as a lack of *Rhizocorallium*, which indicates erosion to approx. 10 cm deep. The sudden deposition of the first amounts of the lime mud,
remobilized in the inner ramp and transported to the middle ramp by the powerful flow, is manifested by escape burrows leading from the bottom layers to the top layers, and by lack of any other burrows in these parts of the beds.

The protrusive sections of *Rhizocorallium* isp. that occur approx. 2–3 cm above the bases of the top layers record the relatively quiet periods resulting from temporally decelerated sedimentation or even temporal cessation of sedimentation as the powerful flow waned. This is also supported by the length of the escape burrows, which end in the top layers and are cut by protrusive tunnels of *Rhizocorallium* isp. The succeeding vertically retrusive tunnels of *Rhizocorallium* isp. indicate that the relatively quiet conditions came suddenly to an end. The shift in direction from horizontal to oblique and vertical was a response to the deposition from suspension, which started after the deposition from the powerful flow of the same bed during the same storm event. Eventually, the last retrusive limbs of *Rhizocorallium* isp. occurring on the top of the beds mark the end of the storm event and the next erosion event (the last limb should occur 1–3 cm beneath the bed top, and the last tempestite division with ripples is not preserved).

The composition and color of the fecal pellets (which are the same in both the protrusive and retrusive sections of *Rhizocorallium*) show that the burrowing animals were deposit-feeders, which presumably needed to dig relatively long tunnels to find enough food. We consequently propose that vertically retrusive limbs created by deposit-feeders record relatively fast sedimentation. Slow sedimentation is not a satisfactory explanation, because deposit-feeders digging only short vertically retrusive tunnels during slow sedimentation would not find sufficient food. The retrusive limbs must have been made by deposit-feeders fast enough to find sufficient food and also fast enough to avoid being buried.

**Acknowledgments** We would like to thank Michał Jankowiak for preparing the rock slabs and thin-sections. The detailed and constructive comments by Eduardo Jesus Mayoral (University) and Prof. Alfred Uchman (Jagiellonian University, Poland) are highly appreciated. Prof. Antonius J. van Loon (Adam Mickiewicz University, Poland) and Stephen Mulraney are thanked for language editing. The research was financed by Adam Mickiewicz University.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

**References**

Aigner T (1985) Storm depositional systems: Dynamic stratigraphy in modern and ancient shallow-marine sequences. Lect Notes Earth Sci 3. Springer, Berlin Heidelberg New York

Bodzioch A, Kowal M (2001) Occurrence and origin of calcite pseudomorphs after sulphates from the Lower Muschelkalk in Poland (Upper Silesia). Z Geol Wiss 29:109–118

Bodzioch A, Szulc J (1991) The Röt/Muschelkalk boundary. In: Hagdorn H (ed) Muschelkalk. A Field Guide. Goldschnecken-Verlag Werner K. Weidert, Stuttgart, pp 62–64

Carvalho CN, Rodrigues NPC, Viegas PA, Bauton A, Santos VF (2010) Patterns of occurrence and distribution of crustacean ichnofossils in the Lower Jurassic–Upper Cretaceous of Atlantic occidental margin basins, Portugal. Acta Geol Pol 60:19–28

Chisholm JI (1970) *Teichichnus* and related trace-fossils in the Lower Carboniferous at St Monance, Scotland. Bull Geol Surv Great Brit 32:21–51

Dadlez R, Marek S, Pokorski J (eds) (2000) Mapa geologiczna Polski bez utworów kenozoiku w skali 1 : 1,000,000. Państwowy Instytut Geologiczny, Warszawa

Dworschak PC (2004) Biology of Mediterranean and Caribbean Thalassinidea (Decapoda). In: Tamaki A (ed) Proceedings of the symposium on ecology of large bioturbators in tidal flats and shallow sublittoral sediments—from individual behaviour to their role as ecosystem. Nagasaki University, Nagasaki, pp 15–22

Dworschak PC, Knolleer H, Abed-Navandi D (2006) Burrow structure, burrowing and feeding behaviour of *Corallinasp. ass. longiventris* and *Pestarella tyryhena* (Crustacea, Thalassinidea, Callianassidae). Mar Biol 148:1369–1382

Firtion F (1958) Sur la présence d’ichnites dans le Portlandien de l’Île d’Oléron (Charente maritime). Ann Univ Saraviens 7:107–112

Fürsich FT (1974) Ichnogenus *Rhizocorallium*. Paläontol Z 48:16–28

Knaust D (2007) Invertebrate trace fossils and ichnodiversity in shallow-marine carbonates of the German Middle Triassic (Muschelkalk). In: Bromley RG, Bauton LS, Mañongo MG, Genise JF, Melchor RN (eds) Sediment–organism interactions: a multifaceted ichnology. SEPM Spec Publ 88, pp 221–238

Kowal M (1998) Charakterystyka warstw gołoglińskich okolic Żyg-line. M.S. Thesis, Adam Mickiewicz University

Mayer G (1954) Ein neues *Rhizocorallium* aus dem mittleren Hauptmuschelkalk von Bruchsal. Beitr Naturkundl Forsch in Südwestdeutschl 13:80–83

Myrow PM, Southard JB (1991) Combined-flow model for vertical stratification sequences in shallow marine storm-deposited beds. J Sediment Petrol 61:202–210

Nawrocki J, Szulc J (2000) The Middle Triassic magnetosтратigraphy from the Peri-Tethys basin in Poland. Earth Planet Sci Lett 182:77–92

Nickell LA, Atkinson RJA (1995) Functional morphology of burrows and trophic modes of three thalassinidean shrimp species, and a new approach to the classification of thalassinidean burrow morphology. Mar Ecol Prog Ser 128:181–197

Parrish JT (1999) Pangaea und das Klima der Trias. In: Hauschke N, Sellwood BW (eds) Pangaea und das Klima der Trias. In: Hauschke N, Sellwood BW (eds) Trias: Eine ganz andere Welt. Mitteleuropa im frühen Erdmittelalter, Verlag Dr. Friedrich Pfeil, München, pp 37–42

Rodriguez-Tovar FJ, Pérez-Valera F (2008) Trace fossil *Rhizocorallium* from the Middle Triassic of the Betic Cordillera, southern Spain: characterization and environmental implications. Palaios 23:78–86

Schlirf M (2000) Upper Jurassic trace fossils from the Boulonnais (northern France). Geol Palaeontol 34:145–213

Schmid EE (1876) Der Muschelkalk des östlichen Thüringens. Jena

Sellwood BW (1970) The relation of trace fossils to small-scale sedimentary cycles in the British Lias. In: Crimes TP, Harper JC (eds) Trace fossils. Geol J Spec Iss 3:489–504

Szulc J (1993) Early Alpine tectonic and lithofacies succession in the Silesian part of the Muschelkalk Basin. A synopsis. In: Hagdorn
Szulc J (2000) Middle Triassic evolution of the northern Peri-Tethys area as influenced by early opening of the Tethys Ocean. Ann Soc Geol Pol 70:1–48
Szulc J (2008) Climate evolution in the Tethys area and its control. In: McCann T (ed) The geology of Central Europe, Volume 2: Mesozoic and Cenozoic. Geol Soc Lond, pp 751–752
Szulc J, Głuchowski E (1991) Stop B15. Żyglin. In: Hagdorn H (ed) Muschelkalk. A field guide, Goldschneck-Verlag Werner K. Weidert, Stuttgart, pp 71–72
Walker RG, Duke WL, Leckie DA (1983) Hummocky stratification: significance of its variable bedding sequences: discussion and reply. Bull Geol Soc Am 94:1245–1251
Wetzel A, Aigner T (1986) Stratigraphic completeness: Tiered trace fossils provide a measuring stick. Geology 14:234–237
Worsley D, Mørk A (2001) The environmental significance of the trace fossil *Rhizocorallium jenense* in the Lower Triassic of western Spitsbergen. Polar Res 20:37–48
Zenker JC (1836) Historisch-topographisches Taschenbuch von Jena und seiner Umgebung besonders in naturwissenschaftlicher und medicinischer Beziehung, Jena, 338 pp