Ichnological record of deep-sea palaeoenvironmental changes around the Oceanic Anoxic Event 2 (Cenomanian–Turonian boundary): An example from the Barnasiówka section, Polish Outer Carpathians

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A B S T R A C T
Trace fossil assemblages including Planolites, Thalassinoides, Palaeophycus, Taenidium, Chondrites and Trichichnus have been determined in the Upper Cenomanian turbiditic deep-water succession, corresponding to the pre-OAE-2 interval in the Barnasiówka–Ostra Góra section, the Skole Nappe, Polish Outer Carpathians. These assemblages indicate that oxygenation within sediment fluctuated from oxic to dysoxic zone. The overlying uppermost Cenomanian organic-rich facies (Bonarelli-equivalent horizon), corresponding to the main interval of the OAE-2 contains black shale layers, devoid of trace fossils representing anoxic (euxinic) events, and green shales that include Chondrites, Planolites and Thalassinoides, recording dysoxic intervals. Three subintervals (phases) within the OAE-2 sediments have been distinguished in the Barnasiówka section, based on trace fossil diversity, ichnofabrics and chemical redox indices. These phases correspond to intervals with various intensity of sea floor oxygenation. Ichnofabrics within the OAE-2 succession was also controlled by consistency of sediment. Post-OAE-2 interval recorded by the earliest Turonian red and green siliceous–manganiferous shales and two Fe–Mn layers represent sediments deposited in well oxygenated conditions under extremely low sedimentation rate. Most of the shales are parallel-laminated, and they do not include any benthic microfossils and trace fossils, however some of the red and green layers display cryptic bioturbation. These features are related to food scarcity, cessation of gravity flows, unfavorable characteristics of bottom water, and a low consistency of substrate.

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1. Introduction

Commonly, trace fossils are the only evidence of in situ macrofaunal life in clastic sediments. Especially if combined with ichnofabric analysis, they can provide information on many palaeoenvironmental parameters, which are difficult to obtain by means of other tools. Therefore, ichnological methods are very useful in studies of biotic events in Phanerozoic history, for instance in the studies on the Permian–Triassic (e.g., Twitchett and Barras, 2004) or the Cretaceous–Palaeogene boundary events (e.g., Ekdale and Bromley, 1984; Ekdale and Stinnesbeck, 1998; Rodríguez-Tovar and Uchman, 2006). So far, less attention is paid to ichnology of the Oceanic Anoxic Event 2 (OAE-2) during Cenomanian–Turonian transition, especially in deep-sea clastics (but see Olivero and Gaillard, 1996); however, at least oxygenation changes related to this event represent a potentially good topic for such studies. The only ichnological data related to the OAE-2 come from the facies deposited on shelves and continental slopes (Mortimore and Pomerol, 1991; Hilbrecht and Dahmer, 1994). In this paper, we discuss the distribution of trace fossils and ichnofabric in relation to the Eh conditions at the sea floor around the OAE-2 in the deep-water basin below the calcium compensation depth (CCD). Lately, the occurrence of such assemblages, dominated by Chondrites isp. and Thalassinoides isp. was reported from the pre-OAE-2 turbidite and calciturbidite successions and the OAE-2 organic-rich facies in the Silesian, Subsilesian and Skole Nappes of the Outer Carpathians (Bąk, 2006, 2007a,b). However, no detailed observations of these assemblages have been described. The present study was carried out in the Barnasiówka–Ostra Góra section, the Silesian Nappe of the Polish Outer Carpathians. The Cenomanian–Turonian boundary interval (CTBI) sediments in this section have been earlier studied by Bąk (2007a) using microfossils, microfossils, and chemical data.

Trace fossils are good indicators of oxygenation in sediments. Their diversity, composition and even size change with oxygenation changes. In many fine-grained more or less continuously deposited sediments, Chondrites is the first trace fossil occurring in dysoxic condition after oxygenation improvement. Appearance of the larger

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Zoophycos, Thalassinoides and than other trace fossils indicates further improvement of oxygenation (e.g., Bromley and Ekdale, 1984). Also other trace fossils can occur in poorly oxygenated environments (e.g., Leszczyński, 1991; Martin, 2004), for instance Trichichnus (Uchman, 1995, 1999). Changes of these trace fossils allow reconstruct oxygenation curves and modeling their shape, which show common fluctuation of oxygen content in sediment pore waters (e.g., Savrda and Bottjer, 1986; Savrda, 2007). In deep-sea environments, incidental turbiditic flows can bring oxygenated waters and improve the oxygenation, which decreases gradually with time and control succession of trace fossils (e.g., Wetzel and Uchman, 2001). Further, discussion of this general topic is beyond scope of this paper.

1.1. Trace fossils in the OAE-2 successions

Poorly-diversified assemblages of trace fossils are known from the calcareous and siliciclastic sediments deposited during the OAE-2. Most of them include abundant Chondrites and Thalassinoides. Such examples have been described from the uppermost Cenomanian Pecínov Member and the Lower Turonian Bílá Hora Formation in the Bohemian Cretaceous Basin, a relatively shallow, narrow seaway connecting the Boreal and Tethyan realms across the Bohemian Massif (Uličny et al., 1997). In other sections from this area, the Upper Cenomanian shallow-marine siltstones (the Peruc–Korycany Formation; offshore succession), includes Chondrites, which occurs irregularly throughout these facies (Uličny et al., 1993). The Upper Cenomanian Plenus Marl Member, a clay-rich interval of grey marls, includes numerous burrows (Paul et al., 1999). Chondrites and Thalassinoides were described also from omission surfaces directly below the Plenus Marl Member in the Dover–Eastbourne region of England (Keller et al., 2001).

Two thin beds with Chondrites were also reported from the Upper Cenomanian epicontinental sediments, near the base of the Plenus Bank in North Germany (e.g., Ernst et al., 1983; Lehman, 1999). They have been used there for stratigraphy (Hilbrecht and Dahmer, 1994) but their isochronous position is not clear (Lehman, 1999). These two Chondrites events have been also recognized in the very shallow water marly–calcareous–silty facies of the Dölzschen Formation in the Elbe Valley Geosuture, which separates the Erzgebirge block (mid European island during Cretaceous) from the Lusatian block (West Sudetic Island) (Tröger, 2003). These two Chondrites events, occurring directly below the organic-rich facies of the OAE-2 (the second one is close to the base of the δ13C excursion) are also present in the NW Münsterland Basin, Westphalia. Besides Chondrites, the “fucoidal burrows” of uncertain taxonomy and Zoophycos have been recognized in the Upper Cenomanian marls (Lehman, 1999).

Olivero and Gaillard (1996) presented a section from the Vocontian Trough (SE France) with black shales (Thomel level) at the Cenomanian–Turonian boundary interval (CTBI), which is characterized by a decrease of bioturbation intensity and a presence of some levels with Chondrites, which indicates dysoxic conditions in the generally anoxic black shale. Below and above the shale, intensity of bioturbation is higher and the trace fossil Teichichnus is common. This is related to good oxygenation and increased rate of sedimentation.

Fig. 1. (A) Palaeogeographical map of the northern part of the Western Tethys during the Turonian (adapted from Golonka et al., 2000; simplified) showing the position of the studied section within the Outer Carpathian Basin. Abbreviations of basin names: Mg — Magura Basin, Si — Silesian Basin, Sk — Skole–Tarçau Basin; (B, C) Position of the studied sections (star) in relation to the main geological units in the Alpine orogens (B) and the Outer Carpathians (C); IC. — Inner Carpathians, CF. — Carpathian Foredeep, PKB — Pieniny Klippen Belt (geological map of the Outer Carpathians adapted from Poprawa and Nemčok, 1998).
2. Geological setting

The Barnasiówka section (called also Barnasiówka–Ostra Góra section) is located in the Silesian Nappe, one of the largest tectonic units of the Outer Carpathians, Poland (Fig. 1B and C). During Cretaceous–Palaeogene times, this area was an independent sedimentary basin located close to the passive margin of the West European Platform (Fig. 1). Since the Berriasian, deposition in the Silesian Basin (mainly siliciclastic turbidites) took place below the CCD (Książkiewicz, 1975; Uchman et al., 2006), with relatively low sedimentation rate, from 1 to 6 cm/kyr (Słomka et al., 2006). The Early Cretaceous interval of sedimentation took place during the post-rifting thermal stage in extensional conditions.

The Upper Cenomanian–Lower Turonian sediments in the Silesian Nappe belong to the Barnasiówka Radiolarian Shale Formation (BRSF) and to the lowermost part of the Variegated Shale (Bąk et al., 2001). The trace fossils and ichnofabrics of this formation were studied in the quarry on the Barnasiówka Ridge (Fig. 1C). The detailed location of the studied section and its relationship to the regional geology was presented by Bąk et al. (2001). The BRSF in this section consists of three parts (Fig. 2): (1) a lower one, 10 m thick, with a succession of thin-bedded silty and sandy turbidites (partly calcareous) interbedded with non-calcareous green and subordinate black shales, (2) a middle part, 2.2 m thick, an equivalent of the Bonarelli horizon, with organic-rich black shales intercalated with green shales and bentonites, and an upper part (3), 1.2 m thick, with green and red siliceous–manganiferous shales, including two horizons of Fe–Mn layer and a single organic-rich black shale. The lowermost part of the Variegated Shale, 2 m thick, consists of green and red shales with intercalations of thin-bedded silty turbidites. The detailed description of the studied sediments, based on microfacies, microfossils and chemical analyses was presented by Bąk (2007a).

The stratigraphy of the BRSF was proposed by Bąk et al. (2001, 2005) and Bąk (2007a), based on foraminifers, radiolarians and carbon isotope data. Following these studies, the whole studied succession belongs to the Whiteinella archaecretacea Zone. The turbidite succession represents interval below the carbon stable isotope excursion (except for its topmost part, 1.5 m thick), the organic-rich facies (an equivalent of the Bonarelli horizon) corresponds to the δ13C excursion, and the green and red siliceous–manganiferous shale succession with two horizons of the Fe–Mn layer belong to the earliest Turonian post-excision interval (Fig. 2). The Cenomanian–Turonian boundary is placed within the 0.9 m thick interval from a base of the first Fe–Mn layer to a base of thin organic-rich shale, directly underlying the second Fe–Mn layer (Bąk, 2007a).

3. Materials and methods

Samples for trace fossil and ichnofabric analyses have been collected bed by bed from two parts of the Barnasiówka (sections A and B; Fig. 2): a first one from a 1 m thick interval of the turbidite succession (Fig. 3A), and the second one, from a 4.7 m thick succession
including organic-rich facies followed by green and red siliceous–manganiferous shales. Trace fossils and ichnofabrics have been observed in variably oriented polished surfaces. The surfaces were oiled in order to improve colour contrast. Selected samples of shales have been analyzed using SEM in order to check the clay minerals fabric.

The trace fossils (collection 174P) are housed in the Institute of Geological Sciences, Jagiellonian University.

4. Results

4.1. Synopsis of trace fossils

*Chondrites* isp. (Figs. 4A–C, 5D and E) is observed mostly in cross-section. It appears as patches of circular to elliptical spots and short bars, which are 0.4–1.1 mm wide and display occasional branches. Probably, they belong to *Chondrites intricatus* (Brongniart, 1823; smaller forms) and *Chondrites targionii* (Brongniart, 1828; larger forms) (cf. Uchman, 1999). Their filling is black or dark-grey.

*Palaeophycus heberti* (Saporta, 1872) (Fig. 4B and C) is an oblique tube with a thick wall. The tube, filled with dark clayey material, is from 1 to 2.2 mm in diameter. The wall is pale-coloured and is 0.7–1.1 mm thick. *Palaeophycus* is interpreted as an open tube produced by carnivorous or omnivorous invertebrates, mostly polychaetes (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

*Planolites* isp. (Fig. 4A–C) is represented by horizontal to oblique, straight to slightly winding, simple flattened cylinders, which are 3–4 mm wide. They are filled with dark-grey fine-grained material. *Planolites* is an actively filled burrow (pascichnion) that occurs in many environments and is probably produced by a number of different organisms (Pemberton and Frey, 1982; Keighley and Pickerill, 1995). An observed specimen (Fig. 4E) displays branches and a slightly lobate margin, which suggests a peletal filling. Affinity of this specimen to *Planolites* is tentative (?*Planolites* isp.).

*Thalassinoides* isp. (Figs. 4B and C, 6A–D) occurs as straight or slightly winding, horizontal to oblique, flattened cylinders, 4–10 mm, rarely up to 18 mm wide, showing Y- or less commonly T-shaped branches. They are filled with homogenous dark clayey material. The cylinders are swollen at the branching points up to 15 mm. *Thalassinoides* Ehrenberg, 1944 is a domicinial and fodinichnial structure produced by crustaceans, mostly decapods (Frey et al., 1984). It occurs in a great variety of marine environments, yet is most typical for the shelf *Cruziana* ichnofacies. For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992) and Schlirf (2000).

*Trichichnus linearis* Frey, 1970 (Fig. 4B) is a lined, straight, vertical to steeply oblique, thin, thread-like, occasionally branched cylinder filled with ferruginous substance, with or without a yellowish halo around
the cylinder. The cylinder is from 0.1 to 1.0 mm in diameter. *Trichichnus* Frey, 1970 is a eurybathic marine trace fossil that is common in fine-grained sediments. Its filling displays a strong tendency to pyritization (e.g., Werner and Wetzel, 1981; McBride and Picard, 1991). *Trichichnus* is regarded as domichnial burrows of marine meiofaunal deposit feeders (Frey, 1970). Possibly, the producer of *Trichichnus* was a chemosymbiont (Uchman, 1995), as in the case of the *Chondrites* producer (Seilacher, 1990; Fu, 1991). McBride and Picard (1991) suggest that *Trichichnus* had a more opportunistic character than *Chondrites* because it occurs more deeply in very poorly oxygenated sediments. For taxonomic discussion — see Uchman (1999).

*Taenidium* isp. (Fig. 4D) is a horizontal to oblique, tubular structure without a wall, 3–4 mm in diameter. It displays a meniscate structure. *Taenidium* is a common facies-crossing trace fossil produced probably by deposit feeders, but Locklair and Savrda (1998) suggested that at least some *Taenidium* were produced by a non-vagile worm maintaining a connection to the sediment surface or shallow subsurface and keeping pace with sediment accumulation. For discussion of this ichnogenus — see D’Alessandro and Bromley (1987) and Keighley and Pickerill (1994).

4.2. Ichnofabrics in pre-OAE-2 interval

The ichnofabric in the pre-OAE-2 interval can be observed in the upper part of the BRSF. They are exemplified in section A (Fig. 7) and are similar in general features of ichnofabrics to the underlying Albian–Lower Cenomanian Lgota Beds, as shown by Uchman (2004).

The beds of section A are turbiditic–hemipelagic couplets, which at the base contain fine-grained calcareous–siliceous turbiditic sandstone with primary lamination (mostly Tb and Tc Bouma intervals). They are followed by greenish or dark-grey siltstone–mudstone, which is calcareous in the lower part and non-calcareous in the upper part. In many beds, the couplets are capped with a thin layer (up to 1 cm) of non-calcareous, dark-grey or black mudstones. In other beds, dark-grey mudstones are overlain with a thin layer of non-calcareous greenish mudstones.

In the most complex ichnofabrics, the top, dark or black layer is homogenous or displays a spotty mottling, seen in very thin diffusive zone in the transition to the underlying greenish mudstone. The greenish mudstone shows a homogenous to inindistinctly mottled background, against which cross-sections of dark-filled trace fossils *Planolites*, *Thalassinoides*, *Palaeophycus*, *Taenidium*, *Chondrites* and ferruginized *Trichichnus* are visible (Fig. 4). *Thalassinoides* and *Planolites* are cut by *Palaeophycus*. *Chondrites* has cross cut *Thalassinoides*, *Planolites* and *Taenidium*. All of them are cut by *Trichichnus*. *Chondrites* and *Trichichnus* penetrate into the calcareous siltstones and sandstones up to the Tc interval. In other beds, some trace fossils are missing and limited to *Thalassinoides*, *Planolites*, *Chondrites* and *Trichichnus* or to *Chondrites* only.

4.3. Ichnofabrics in the OAE-2 interval

The OAE-2 interval in the studied section contains the uppermost part of the turbiditic succession, 1.5-m thick, and the Bonarelli-equivalent horizon (Fig. 2). The termination of the OAE-2 is here not determined, because of the lack of the carbon isotope data from the sediments overlying the organic-rich facies, which are carbon-free,
and the occurrence of hiatuses, recorded by precipitation of the Fe–Mn sediments (Bąk, 2007a). Most probably the top of the OAE-2 corresponds to the first horizon of the Fe–Mn layer.

The Bonarelli-equivalent horizon is composed of alternating black and greenish mudstone layers. Only three very thin laminae of siltstones or very fine sandstones are present in the first quarter of the horizon. The black layers display primary lamination and no sign of macrobioturbation except for two layers, where Chondrites penetrates at the top from the overlying greenish layer. The SEM observations of the arrangement of clay minerals in the black shales show that the lower part of a black layer at the base of the siliceous part of the Bonarelli-equivalent horizon displays a not fully parallel arrangement of clay minerals typical of non-bioturbated laminated shales (cf. O’Brien, 1987). Instead, some disorder in arrangement of clay minerals (Fig. 8A) is present, which suggests a weak bioturbation (probably cryptobioturbation) of this sediment. More chaotic arrangement of clay minerals is typical of the greenish shale layers (Fig. 8B), which additionally display mostly diffusive mottling or rarely Planolites, Thalassinoides and Chondrites, seen against the massive or mottled background (Fig. 6). In most of the greenish shale layers, the trace fossil diversity is reduced to Planolites and Chondrites or to Chondrites only. In rare cases, only Thalassinoides is recognizable against the mottled background. The reduced diversity is very distinct in the upper part of the Bonarelli-equivalent horizon. Commonly, the trace fossils display jagged or diffusive margins.

4.4. Ichnofabrics in the post-OAE-2 interval

The red and variegated shales between the two Fe–Mn layers are massive and do not display any sign of mottling. However, the clay minerals arrangement points to bioturbation (mostly cryptobioturbation) of this sediment (Fig. 8C). Similarly, the greenish shales at the base of the Variegated Shale (the top of studied section B) display chaotic arrangement of clay minerals (Fig. 8D), but macroscopically, these shales are massive, without any bioturbational structures. Two ferromanganese layers are strongly impregnated with Fe–Mn oxide-

Fig. 7. Log of section A with the distribution of trace fossils, interpreted oxygenation curve, tiering patterns from selected set of beds, and their relationship to the life conditions of the ichnofossil tracemakers. Grain size: cl - clay; s - silt; vf - very fine sand; f - fine sand; m - medium sand, c - coarse sand.
hydroxides and any bioturbational structures or primary fabric cannot be seen.

5. Discussion

5.1. Interpretation of the pre-OAE-2 trace fossils and ichnofabric

Section A contains foremost turbiditic sediments, which continue from down the section for at least 300 m. However in sense of time, background sedimentation prevailed and was interrupted incidentally by turbiditic currents. Average frequency for the Albian–Lower Cenomanian turbidites in the Middle Lgota Beds is 1 per 5 kyr (Uchman, 2004). Very few trace fossils penetrate to the base of turbiditic sandstones. Thus, tracermaker activity was concentrated mostly in turbiditic mud, as is a norm in flysch deposits (Kern, 1980). The turbidites transported calcareous sands and muds from outer shelf – upper slope environments to the sea floor below CCD (Bąk et al., 2001, 2005; Bąk, 2007a) as indicated by calcareous free mudstones at the top of turbidite–hemipelagite couplets (cf. Hesse, 1975).

Changes of trace fossil diversity during the pre-OAE-2 interval (section A) have a primary cause. Their occurrence can be arranged in a succession that indicates deterioration of life conditions (Fig. 7). The cross-cutting relationships of trace fossils in turbiditic sediments record a successive colonization (Wetzel and Uchman, 2001) rather than a vertical shift of tiers in a steady stationary community typical of continuously deposited pelagites or hemipelagites (e.g., Ekdale and Bromley, 1991). The assemblage Planolites, Thalassinoides, Palaeophycus, Taenidium, Chondrites and Trichichnus contains trace fossils produced by deposit feeders having no permanent connection to the sea floor (Planolites, Taenidium). Their presence, together with totally bioturbated top of the turbiditic mudstones indicates relatively good oxygenation of pore waters and food obtained from reworked particles, which was supplied by turbiditic currents. They represent the first stage of colonization of the turbiditic sediment rich in food and oxygen transported from shallower waters. The other trace fossils represent burrow systems having a permanent connection to the sea floor and their trace maker can use oxygen from the water column. They are related to the later stages of colonization, when oxygenation in the sediment deteriorated. The latest stage of colonization is recorded by Chondrites and Trichichnus, which represents stationary, deep burrows produced by probably chemosymbiotic organisms in dysoxic sediment, when searching for food by sediment reworking was impossible.

Elimination of the first colonizers and a tendency toward the presence of the last colonizers can indicate a problem with either oxygen or food that was available by reworking, or both. The dark colour of sediments including only Chondrites (e.g., bed Br21C; Fig. 7) suggests high organic matter content and high content of potential food. Also common darkening toward the top of beds points to a high organic productivity (cf. Wetzel and Uchman, 1998). In consequence, the deterioration of oxygenation is considered as the primary cause of the reduced ichnodiversity. Chondrites is commonly known as the indicator of poor oxygenation where it occurs alone (e.g., Bromley and Ekdale, 1984). In beds with higher ichnodiversity, Chondrites penetrated deeper up to the sandstones. In the beds with lower diversity, it is confined to mudstones. Nevertheless, in the beds in which Chondrites occurs alone, the top of mudstones is totally bioturbated as indicated by the mottling and lack of primary lamination. Total bioturbation can be a product of even very shallow and very slow reworking of the background pelagic and hemipelagic sediments during long inter-turbidite periods, when the sediment grains have long time residence on the sea floor and a high chance to be reworked (Uchman, 2004).

The pelagic or hemipelagic mudstones are totally bioturbated together with the upper part of the turbiditic mudstones. Distinction
between them is not always easy but the colour change is the macroscopic feature. They are also free of calcium carbonate. The colour change is not sharp but diffusive in a zone up to a few mm thick. This suggests that the vertical displacement of sediment particles in the totally bioturbated sediment was not large. The bioturbation did not lead to production of trace fossils because of low shear strength of sediment saturated by water. Trace fossils were formed deeper or later in the sediment, which was more cohesive (cf. Bromley, 1996).

5.2. Interpretation of the OAE-2 trace fossils and ichnofabrics

The event sediments are almost solely non-calcareous mudstones with a few very thin layers of siltsstones or very fine-grained mudstones at the base of this succession. Thus, a pelagic and hemipelagic environment below the CCD is interpreted in the lower part of the Bonarelli-equivalent horizon, with only very rare and weak current action (Bak, 2007a).

The black, organic-rich layers in the Bonarelli-equivalent horizon, with TOC content varying from 3.2 to 6.3%, represent dysoxic events with the redox boundary above the sea floor (Bak, 2007a). Chemical indices such as U/Th and V/(V+Ni) recorded from these sediments (Fig. 9; Bak, 2007a) are indicative of decreasing amount of oxygen in bottom waters during the whole Bonarelli-equivalent horizon. The highest values of these indices, interpreted as the maximum of oxygen deficiency in pore- and bottom water, are characteristic of the sediments corresponding to an interval with the highest δ13C values (topmost 120 cm of the organic-rich facies). The V/(V+Ni) profile displays values exceeding 0.80 in this part of the section, the range indicative of euxinic conditions (Hatch and Leventhal, 1992). Such values are characteristic here both of the black and green shales. Chondrites that exceptionally penetrates in the dark layers represents the environment of the overlying greenish layer, when colonization by the trace makers was possible. The common layers with no recognizable trace fossils, where only mottling is present, point to sediments of low consistency (soup ground). Probably, burrowing was confined to a shallow zone, saturated with water, comparable to the mixed layer in the recent pelagic sediments (e.g., Ekdale et al., 1984b). The dysoxic zone was very shallow which limited deeper colonization, but the absence of Chondrites or Trichichnus is not clear. The sediment grains had long time residence at the sea floor, and therefore were easily reworked. When the redox boundary was deeper, colonization by Chondrites, Planolites or even Thalassinoideas was possible. The jagged and diffusive margins of these trace fossils suggest a low consistency of the sediment. These features are rare in section A. Thus, the sediments of the greenish layers in the Bonarelli-equivalent horizon were less cohesive than sediments of section A. Trace fossils below the CCD commonly display fuzzy margins (Ekdale et al., 1984a, p. 251). This can be caused by the fact that calcareous sediments display higher shear strength than non-calcareous sediments, which favor trace fossil preservation (Berger et al., 1979; Ekdale, 1985). The dark filling of trace fossils can derive from the overlying black sediments, but in such a case, only a passive filling is possible for open burrows. This is hardly applicable to Planolites, which is basically an actively filled burrow. It is most probably that the filling derived from very short dysoxic periods, when black laminae were deposited on the sea floor; subsequent improvement of oxygenation would lead to total bioturbation of the black laminae, which sediments are preserved only in burrow fillings. Such short-term deterioration of oxygenation can cause an environmental instability, preventing the formation of a more stable community of deep burrowers.

5.3. Interpretation of the post-OAE-2 trace fossils and ichnofabric

Most of the green and red layers are parallel-laminated, marked by thin radiolarian laminae, do not display any macrobioturbation. These sediments also do not include benthic foraminifers. According to Bak (2007a), a few factors could restrict the micro- and macrofossil population at the sea floor during this interval: the extremely low sedimentation rate (lack of the land-derived organic matter), the food scarcity related to a decrease of primary productivity, unfavorable characteristics of bottom water (mainly its high temperature) and type of substrate (soup ground).

Nevertheless, some layers of the red and variegated siliceous–manganiferous shales between two Fe–Mn layers are massive and do not display any sign of motting. The lack of primary lamination in these layers and grain-size change suggest a homogenization, which can be caused by cryptobioturbation, which effects are not seen as trace fossils or bioturbational structures but are indicated by random orientation of clay minerals (Fig. 8). The chemical redox indices in this succession clearly point to well oxygenated conditions at the sea floor (Fig. 9). Furthermore, the low values of chemical indices of detrital flux variations and the occurrence of ferrous incrustations, as evidence of hiatuses, suggest extremely low sedimentation rate during this interval, correlated with the earliest Turonian highstand (Bak, 2007a). In such conditions, the shallow semifluid layer of the sediment should be totally reworked, and a lack of lithological contrast between trace fossil fillings and the host rock deteriorate trace fossil preservation (cf. Berger et al., 1979).

6. Concluding remarks

Changes in trace fossil diversity, their frequency and ichnofabrics around the OAE-2 in the deep-water sediments of the Outer Carpathian Basin record the changes in oxygenation of bottom and pore water, food availability and substrate consistency.

During the advent of the OAE-2 trace fossils and ichnofabrics point to moderately oxidized sediments on the sea floor. However, the oxygenation fluctuated in time irrespective of possible second-order oxygenation changes caused by gravity flows, which transported oxygenated waters and improved oxygenation for a while. The trace fossils community of the pre-OAE-2 has a low diverse in comparison to other Cretaceous flysch formations (cf. Uchman, 2004).

Trace fossil assemblages during the OAE-2 show an alternation of long-lasting periods of euxinic conditions and intervals with the poor oxygenation of the uppermost part of the sediment. Bed by bed observations of trace fossils and ichnofabric, compared with the chemical proxies of redox conditions within the Bonarelli-equivalent horizon show that three phases of Eh fluctuations at the sea floor could be distinguished during the OAE-2 (Fig. 9).

The first phase, recorded by the topmost part of the turbidite succession and the lowermost part of organic-rich facies (0–140 cm from the base of section B; Fig. 9), characterized by relatively long-lasting periods with oxic–dysoxic conditions, which enabled a shallow colonization of poorly diversified macrofossils. Chondrites, Planolites and even Thalassinoideas represent the trace fossil community of this phase. Opportunistic and poorly diversified assemblages of deep-water agglutinated foraminifers also inhabited the sea floor during this phase (Bak, 2007a).

During the second phase of the OAE-2, corresponding to the interval of the highest δ13C values (Bak, 2007a) and represented by the middle part of the organic-rich facies (110–225 cm from the base of section B; Fig. 9), long-lasting periods of euxinic conditions prevailed. These periods have alternated with probably short-term intervals of dysoxic conditions. This may be interpreted by comparison of the chemical redox proxies and trace fossil occurrences. The high values of redox index V/(V+Ni) in the green shales suggest anoxic or even euxinic conditions in the sediment. In turn, this sediment displays distinctly lower trace fossil diversity than in the first phase, restricted mostly to Chondrites. This may show that the content of oxygen was restricted to the shallowest part of the sediment, and additionally, that the periods of better oxygenation, probably related to bottom current activity, lasted relatively briefly. The jagged and diffusive margins of
Trace fossils and occurrence of mottling in the green shales suggest a low consistency of the sediment, saturated with water (soupground).

The third phase of the OAE-2, represented by the topmost part of the organic-rich facies (225–265 cm from the base of section B; Fig. 9) was again (as during the first phase) characterized by longer intervals with oxic–dysoxic conditions, which favored shallow colonization of Chondrites, Planolites and Thalassinoides during sedimentation of green layers. Opportunistic deep-water agglutinated foraminifers (Lazarus taxa) also appeared in these layers (Bąk, 2007a). Short-termed improvement of oxygenation at the sea floor could also have taken place during the sedimentation of black shales as confirmed by the occurrence of limited cryptobioturbation in this sediment.

The post-OAE-2 interval recorded by red and green siliceous–manganiferous shales and two Fe–Mn layers represent sediments deposited in well oxygenated conditions under extremely low sedimentation rate. Most red and green shales are parallel-laminated,

Fig. 9. Log of section B with indicated trace fossils distribution, interpreted oxygenation curve, tiering patterns from selected set of beds with their relations to life conditions of ichnofossils, and chemical indices of redox conditions (chemical indices after Bąk, 2007a).
and they do not include any benthic microfossils and trace fossils. This may be related to several factors, such as food scarcity, lack of gravity flows, unfavorable characteristics of bottom water, and type of substrate (soupground). Some layers in this succession are homogenized, which can be caused by cryptobioturbation, which effects are not seen as trace fossils or bioturbational structures but it is indicated by random orientation of clay minerals.

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