ICHNOLOGICAL ANALYSIS OF LATERAL ENVIRONMENTAL HETEROGENEITY WITHIN THE BONARELLI LEVEL (UPPERMOST CENOMANIAN) IN THE CLASSICAL LOCALITIES NEAR GUBBIO, CENTRAL APENNINES, ITALY

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ABSTRACT

Dark, pelagic sediments of the uppermost Cenomanian Bonarelli Level (OAE2 event) interval, in two classical sections Contessa and Bottaccione in the Central Apennines, contain unbioturbated and bioturbated beds suggesting fluctuations in pore water oxygenation from anoxic to oxy or dysoxic conditions. The oxic and dysoxic improvement events prior to, during, and after the event are marked by biogenic structures showing an increase in the diversity of the trace fossils (Chondrites, Planolites, Thalassinoides, Trichichnus, and Zoophycos) from none to five ichnogenera in individual beds. The number of anoxic events differs in the Contessa and Bottaccione sections, even though they are only 2.5 km apart. Comparison with sections from the Carpathians (Poland) and the Betic Cordillera (Spain), reveals that minor anoxic events below and above the Bonarelli Level are absent in the studied Apennine sections. Moreover, the diversity and density of trace fossils in the Apennine sections are lower than those from other studied sections in the Tethys, most likely indicating a comparatively lower availability of food in the Gubbio area as a result of its paleogeographic location. The preservation of trace fossils, controlled by the consistency of sediments and diagenetic processes, can mask diversity and density in some beds.

INTRODUCTION

The Cenomanian-Turonian boundary interval yields a record of a global faunal extinction and turnovers associated with significant environmental perturbations (Schlanger and Jenkyns, 1976; Jenkyns, 1980; Arthur et al., 1990; Tsikos et al., 2004; Mort et al., 2007 and references therein). These biotic changes are related mostly to the Oceanic Anoxic Event 2 (OAE2) recorded in the sedimentary record as a package of dark anoxic shales, called the Bonarelli Level (il livello Bonarelli) in honor of Guido Bonarelli (1871–1951), who described them from the Contessa and Bottaccione sections in the Gubbio area of central Italy as a result of its paleogeographic location. The preservation of trace fossils, controlled by the consistency of sediments and diagenetic processes, can mask diversity and density in some beds.

Many researchers have assigned the Bonarelli Level to different positions with respect to the Cenomanian-Turonian boundary. In the classic locality of the Gubbio gorge, the Bonarelli Level is located 5–6 m below the first occurrence of Helvetoglobotruncana helvetica (following Premoli-Silva and Sliter, 1994, 1999), and is therefore considered part of the Cenomanian stage. Tsikos et al. (2004) demonstrated that the OAE2 associated with the Bonarelli Level in the study area is largely (if not completely) confined to the latest part of the Cenomanian stage. This interpretation agrees with the biostratigraphic data available for the Bottaccione section (Ciocci and Luciani, 2004) and has been adopted in our study. However, age data available from other nearby areas are divergent. In the Furlo area (Umbria, Apennines), Mort et al.
(2007) marked the Cenomanian-Turonian boundary in the upper part of the Bonarelli Level, at the base of the *Helvetoglobotruncana helvetica* Zone. These authors tentatively identified the *Whiteinella archeocretacea* Zone between the *Rotalipora cushmani* and *Helvetoglobotruncana helvetica* zones, showing important variations in the \( \delta^{13}C \) isotopic composition at the Cenomanian-Turonian boundary. The position of the Cenomanian-Turonian boundary relative to the Bonarelli Level in the Umbria-Marchean Apennines is still uncertain and beyond the scope of the present study.

In the Bottaccione section, several events and biotic changes have been analyzed, including the acmes and crises of different planktonic foraminifera genera of the latest Cenomanian (Coccioni and Luciani, 2004). Coccioni and Luciani (2004) applied high-resolution approaches and quantitative methods for studies of planktonic foraminifer and radiolarian assemblages of the Bonarelli Level.

**METHODS**

Ichnological analyses of the Bonarelli interval in the Gubbio area consisted of bed-by-bed analysis of 109 beds; 52 (with samples) from the Bottaccione section and 57 from Contessa, respectively (Fig. 3). All samples are housed in the repository of the Earth Science Department of Perugia University (collection labeled GbB for the Bottaccione and CB for Contessa sections, respectively, numbers as in Fig. 3, and see Supplementary Data1). Hard lithotypes (mainly calcareous mudstones, siltstones, silicified radiolarite deposits, chert, and a tuffite layer) were cut in different orientations, while soft marls and shales were hardened mainly by epoxic resin cast. Variably oriented cut surfaces (and occasionally rough surfaces) were dampened and photographed to enhance trace fossil preservation. The bed-by-bed spatial arrangement of biogenic structure was assessed to define ichnofabrics (Savrda, 2007).

**SUPPLEMENTARY DATA**

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**SYNOPSIS OF TRACE FOSSILS**

Five ichnotaxa were recognized on surfaces of vertical, horizontal, and oblique sections of beds or on parting surfaces: *Chondrites* isp., *Planolites* isp., *Thalassinoides* isp., *Trichichnus linearis*, and *Zoophycos* isp. (Fig. 4). Trace fossil preservation is generally very poor due to diagenetic obliteration, thus, their determination in some beds was problematic.

*Chondrites* isp. (Figs. 4A, C, E–G) appears as patches of circular to elliptical trace cross sections and short segments with occasional branches, 0.5–1.5 mm wide. They occur as cross sections of a downward-branching tunnel system infilled with sediment darker or lighter than the host rock, depending on the lithology of the overlying bed. *Chondrites* is a deep-tier trace fossil probably produced by surface ingestors (Kotake, 1991a) that most likely lived in dysoaerobic conditions as chemosymbiotic organisms (Seilacher, 1990; Fu, 1991).

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FIGURE 3—Ichnological features of the Bottaccione and Contessa sections, interpretation of oxygenation changes and their correlation. The gray shading in the ichnotaxa columns means reserved determinations, e.g., ?Thalassinoides isp. Total bioturbation means that 100% volume of sediment was bioturbated. Micropaleontological zones according to Coccioni and Luciani (2004, 2005).
Planolites isp. (Fig. 4G) is represented by horizontal to oblique, straight, simple or occasionally branched (i.e., not simultaneous branching sensu D’Alessandro and Bromley, 1987), flattened cylinders, 2–3 mm wide. These structures are filled with dark-gray, fine-grained material, and are commonly observed as ovate in cross section. Planolites is a facies-crossing form. Pemberton and Frey (1982) and Keighley and Pickerill (1995) interpreted Planolites as a pascichnion (i.e., grazing trace), produced by a number of different soft-bodied invertebrates.

Thalassinoides isp. (Figs. 4A, C–E, H) occurs as straight or slightly winding, horizontal to oblique, branched, flattened cylinders, 6–11 mm wide. Within the study interval it is commonly ovate in cross section. Thalassinoides is mostly a domichnial (i.e., dwelling) and fodinichnial (i.e., feeding) structure produced by arthropods, most commonly decapod crustaceans (Frey et al., 1984). Thalassinoides occurs in a great variety of marine environments, from the intertidal to the deep sea. For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992), and Schlirf (2000).

Within the study area, Trichichnus linearis Frey, 1970 is a vertical to oblique, lined, straight to undulose, thin, thread-like, occasionally branched cylinder filled with a ferruginous substance, with a yellowish, diagenetic halo around the cylinder. The cylinder is ≤ 1.0 mm in diameter. The halo is up to 1.5 mm in diameter. Trichichnus is a eurybathic marine trace fossil, and is common in fine-grained deposits (e.g., Fillion and Pickerill, 1990). The filling displays a strong tendency towards pyritization (e.g., Werner and Wetzel, 1982; McBride and Picard, 1991). The ferruginous filling in this material likely resulted from the oxidation of pyrite. Trichichnus is regarded as domichnial burrows of marine meiofaunal deposit feeders (Frey, 1970). The producer of Trichichnus has also been suggested as a chemosymbiont (Uchman, 1995), as has been interpreted for the Chondrites producer (Seilacher, 1990; Fu, 1991). McBride and Picard (1991) suggest that Trichichnus indicates a more opportunistic character than Chondrites because Trichichnus occurs more deeply in sediments that have been interpreted as very poorly oxygenated. For taxonomic discussion see Uchman (1999).

Zoophycos isp. is observed in cross section as horizontal or sub-horizontal spreitenate stripes, 2–3 mm thick. In general, Zoophycos consists of planar spreitenate lobes surrounded by a marginal tunnel and arranged in helical whors. In cross section appear as stacked menisci-filled stripes. The apparent menisci, however, may be obliterated and the stripes then appear uniform (see Voigt and Hántzschel, 1956), as is the material described here. Zoophycos has been interpreted as a feeding structure (fodinichnia; Seilacher, 1967; Wetzel and Werner, 1981;
Ekdale and Lewis, 1991; Olivero and Gaillard, 1996). Other ethological interpretations, however, consider Zoophycos to have been produced by surface ingesters of organic detritus that accumulate fecal pellets in a subsurface structure (Kotake, 1989, 1991b; Löwemark et al., 2007). Bromley and Hanken (2003) suggested that the upper helical part of a large Pliocene Zoophycos from Rhodes, Greece, was a deposit-feeding structure, and lateral lobes developing from its lower part were sulphide wells for chemosymbiotic bacteria.

**DISCUSSION**

**Reconstruction of Oxygenation Changes**

In pelagic, slowly deposited sediments, such as the Bonarelli Level (Fig. 3), discriminating bioturbated from unbioturbated beds is crucial for differentiating between oxic and anoxic sediments; for a wider discussion of ichnological proxies of oxygenation in the studies of OAE2, see Uchman et al. (2008). Beds within the Bonarelli Level showing primary fine lamination (Fig. 3), usually within black, bituminous, non-calcareous shale, indicate an absence of macrobenthic sediment reworking and are interpreted to have been deposited under anoxic conditions. The anoxic conditions are confirmed by multivariate geochemical studies in the Bottaccione section (Scopelli et al., 2004, 2006). Nonlaminated strata characterized by motting but without trace fossils are interpreted as totally (100%) bioturbated, where bioturbation took place in a soupground consisting of shallow, water-saturated sediment. The soupground is manifested by irregular, poorly contrasted spots with vague margins suggesting semi-fluid medium. Trace fossils having smeared margins likely occurred in more cohesive sediments (i.e., more softground than soupground). In better-oxygenated environments, deeper, more cohesive softground layers of sediments were bioturbated, resulting in enhanced preservation of discrete trace fossils. As a result of increased sediment cohesion, trace fossils in these deposits have sharp, well-preserved margins, which are visible on the totally bioturbated background (i.e., mottilled or homogenized) that is herein referred to the mixed layer (Bromley, 1996). Deeply burrowed sediments, deposited under well-oxygenated conditions, contain higher diversity of tracemakers penetrating at different levels (tiers) and, as a consequence, have higher trace fossil diversity. In some beds such interpretations can be difficult or impossible to make due to diagenetic obliteration of primary lamination and ichnofabrics. Such obliteration is complete in some chert beds, which were not interpreted.

Using these interpretations, oxygenation changes can be assessed from the ichnological record through the Gubbio sections (Fig. 3). Nonbioturbated, laminated beds are referred to anoxic conditions (grade 0); bioturbated beds without distinct trace fossils indicate dysoxerobic conditions (grade 1). They refer to a situation in which only the soupy surface layer of sediment was colonized. The deeper tiers, in which discrete trace fossils would be preserved in more cohesive sediment, were still not available due to anoxic pore water. Those bioturbated and containing distinct trace fossils are referred to better oxygenation, from dysoxerobic to aerobic conditions (grades 2–6; one grade per taxon). The successive appearance of trace fossils from the Trichichnus-Chondrites-Zoophycos-Planolites-Thalassinoides suite in more diverse assemblages having increasingly complex tiering patterns indicates improved oxygenation of the burrowing medium (compare Bromley and Ekdale, 1984; Savrda and Bottjer, 1986, 1989a; Savrda, 2007). Details of ORI, such as tiering patterns or the relationship of ichnobarf between adjacent beds, are hardly visible when (1) sedimentation rate is low and/or (2) the oxygenation changes are quick (Savrda and Bottjer, 1989b), or (3) trace fossils are not dense, i.e., very few in a rock volume. All of these factors influenced the trace fossil record in the Bonarelli Level. Thus, reconstruction of tiering pattern is fragmentary for many beds. Also, application of ichnobarf indices illustrating the degree of bioturbation would not be informative in the study interval because the beds are totally bioturbated or not bioturbated (Fig. 3), with transitions in the scale of less than a few millimeters, thus rendering them difficult to study. In successions like this, differentiation between the nonbioturbated and bioturbated beds and recognition of trace fossil types and abundances within the bioturbated beds are fundamental for reconstruction of oxygenation changes. In practice, the degree of oxygenation is closely related to the number of ichnotaxa in an assemblage (Uchman, 2004; Uchman et al., 2008; Rodríguez-Tovar et al., 2009a, 2009b), in which every taxon occupies different tiers. The order of tiers in the study interval is as follows: Trichichnus, which occupies the deepest tier, and Chondrites, Zoophycos, Planolites, and Thalassinoides in successively shallower tiers, similarly to other Cretaceous pelagic and hemipelagic sediments (e.g., Ekdale and Bromley, 1991). The bed-by-bed oxygenation grades for the study interval provide the basis for the oxygenation curve presented in Figure 3.

**Oxygenation and Other Paleoenvironmental Changes in the Studied Sections**

Below the Bonarelli Level (samples GbB1a-15a in the Bottaccione section; Cb1-15 in the Contessa section; Fig. 3), the limestone, silicified limestone and marlstone contain Chondrites, Planolites, Thalassinoides, Zoophycos and Trichichnus, all occurring on totally bioturbated (mottilled or homogenized) background. Values of the curve in both sections fluctuate between grades 5 and 1, pointing to changing oxygenation between aerobic and slightly dysoxerobic conditions, but without anoxic periods.

Within the Bonarelli Level (samples GbB16-51 in the Bottaccione section; Cb16-52 in the Contessa section; Fig. 3), several layers with primary lamination, mostly in black shale successions, but also in radiolarian shale beds, are recognized. These are separated by bioturbated horizons, which are represented by radiolaritile shale, green shale, radiolaritile chert, marlstone, or limestone. Some beds in the upper part of the Bonarelli Level contain Chondrites, Planolites, and Thalassinoides. Others do not contain trace fossils but are totally bioturbated. The resultant oxygenation curve (Fig. 3) illustrates dramatic oxygenation changes from anoxic (grade 0) to dysoxerobic (grade 1 or 2) or aerobic levels (up to grade 4) in the upper part of the section. Neither the lithology nor the oxygenation events are the same in both of the sections (Fig. 3), which are 2.5 km apart. The Contessa section shows 11 (possibly 12) anoxic horizons, whereas the Bottaccione section displays eight such events. The events differ in thickness, and some of them coalesce, being split in the other section. The lithological changes suggest lateral facies variations. Such quick lateral facies changes over a distance of 2.5 km are unexpected in a pelagic environment; therefore, local conditions influenced the fluctuation of oxygenation on the sea floor during the OAE2 event.

Above the Bonarelli Level (samples GbB52-56 in the Bottaccione section; Cb53-62D in the Contessa section; Fig. 3), the trace fossil content and ichnofabrics are very similar to those below the level, but some minor differences can be seen; the absence of some ichnotaxa (Zoophycos in the Contessa section and Chondrites infilled with light-colored material in both sections), and a comparatively lower abundance of trace fossils. The relative oxygenation grade fluctuates between 1 and 3, but usually attains only grade 1. A return to similar ichnofabrics suggests the environment partly recovered after the anoxic events, at least for infaunal animals, but with decreased oxygenation or diminished food resources in the deeper levels of the sediment compared to conditions prior to deposition of the Bonarelli Level. If food was concentrated near the seafloor, deeper burrows—those having higher preservational potential—are less common. Consequently, a lower diversity of trace fossils is very probable. The influence of diagenetic processes below and above the Bonarelli Level is rather comparable, taking into account that the lithology of these intervals of the sections is very similar.
Comparisons to Other Sections

A similar situation has previously been seen in the Betic Cordillera (Rodríguez-Tovar et al., 2009a, 2009b). There, a high-resolution ichnological analysis of the OAE2 event reveals significant differences between the Hidionda and El Chorro sections, which are paleogeographically 70 km apart. In an interval dominated by anoxia, dysoaerobic or aerobic subevents during the OAE2 are less common in the distal section (Hidionda) than in the proximal section (El Chorro). This was interpreted to reflect a higher tendency toward anoxia in the more distal zone (Hidionda) than toward the inner area (El Chorro). Thus, it was suggested that the event was diachronous, starting earlier in the distal zone and was favored by a prior influence of upwelling in this location. Taking into account the analogous occurrence in the Betic Cordillera, the Contessa section could be interpreted to reflect deeper, more open marine conditions, strongly influenced by anoxia, but at a much smaller distance between the sections (in a paleogeographic sense) compared to the Betic Cordillera. This suggests significant paleoecological and possible morphological differences within the basin, which have thus far not been recognized by other methods.

Minor differences have been recognized between trace fossil assemblages in the study area and those from the Bnamentsiówka section in the Carpathians and in the Hidionda and El Chorro sections in the Betic Cordillera (cf., Rodríguez-Tovar et al., 2009a, 2009b). In general, density and diversity of trace fossils in the study interval appear to be lower than those from the Carpathians and the Betic Cordillera. For example, Palaeophycus is absent in the study area. Likely, the differences in trace fossil density and the minor differences in diversity are caused by a comparatively lower availability of food in the Gubbio area. This can be suggested by the paleogeographic location. The Bicipantsiówka section is located in a basin with turbiditic sedimentation in a slope-proximal setting (Bak, 2007; Ulchman et al., 2008). The Betic Cordillera sections are located on a submarine high between the Atlantic and Mediterranean Tethys (Rodríguez-Tovar et al., 2009a, 2009b), while the Gubbio area sections are located in a deep-sea setting without turbiditic deposition (e.g., Scopelliti et al., 2006). Moreover, based on the analysis of agglutinated benthic foraminiferal assemblages, Kaminski et al. (in press) interpret the Turonian member of the Scaglia Bianca Formation in Contessa to represent an oligotrophic environment comparable to that of the North Atlantic abyssal plains. In such conditions, even small changes of food availability and oxygenation can influence the ichnofauna. These changes could be related to a variety of environmental parameters including organic matter productivity, water circulation, or lateral changes of sediments (e.g., differences in porosity, organic matter burial). The lower preservation potential of trace fossils in the Gubbio section compared to the Bicipantsiówka, Hidionda, and El Chorro sections must be taken into account, however. Strong diagenetic obliteration of primary fabric, mostly by silicification in the limestones and radiolarian shales, has likely led to underestimation of the trace fossil record in some beds. For instance, Thalassinoides shows concretionary silica overgrowth in some beds (Fig. 4D). Nevertheless, trace fossils in most beds in the Gubbio area are sufficiently discernable for proper determination of general diversity in the studied sections.

In the studied section, anoxic layers below and above the Bonarelli Level are absent. These are present in the Carpathians and in the Betic Cordillera, mostly below the Bonarelli Level. The absence of those anoxic layers in the studied sections indicates better-oxygenated conditions (and by inference possible oligotrophy) prior to and subsequent to the Bonarelli Level in the Gubbio area.

CONCLUSIONS

The trace fossils Chondrites, Planolites, Thalassinoides, Trichichnus, and Zoophycos are present in some layers within the dark, pelagic sediments of the uppermost Cenomanian Bonarelli Level (OAE2 event) interval, in two classical sections, Contessa and Bottaccione, in the Central Apennines. The layers containing these trace fossils, and bioturbated layers without discernable trace fossils, alternate with unbioturbated layers. These alternations suggest fluctuations in oxygenation of pore waters from anoxic to dysoxic or oxic conditions. The layers characterized by total bioturbation and higher ichnodiversity are related to better oxic conditions than those that display lower ichnodiversity or only biogenic mottling. The number of anoxic events differs in the two sections, even though they are only 2.5 km apart, providing evidence for strong paleoenvironmental lateral heterogeneity in the pelagic environment. Minor anoxic events below and above the Bonarelli Level, known from the Carpathians (Poland) and the Betic Cordillera (Spain) sections, are absent. Also, the diversity and density of trace fossils are lower in the Central Apennines than those from sections in the Tethys region (Poland, Spain). This is probably caused by a lower availability of food in the Central Apennines area, which is paleogeographically restricted.

ACKNOWLEDGMENTS

Research of F.R.-T. was supported by projects CGL2008-03007/CLI (Spanish Government) and RNM-3715 (Junta de Andalucia, Spain), and the research group RNM-178 (Junta de Andalucia, Spain). Additional support for A.U. was provided by the Jagiellonian University (DS funds) and by RicBas 2009–2010 (P. Monaco) of Perugia University. Michal A. Kaminski (Dhahran) improved the text and provided helpful suggestions. The paper benefited from critical reviews by Nicola Tonkin (St John’s) and an anonymous reviewer. John-Paul Zonneveld (Edmonton) and Stephen Hasiotis (Lawrence) provided further editorial comments.

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