

ICHTNOLOGICAL 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 oxic 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 ichnotaxa 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 the Central Apennines, Italy (Bonarelli, 1891). High-resolution ichnological analysis of the Bonarelli Level in the Carpathians, Poland (Uchman et al., 2008) and Betic Cordillera, Spain (Rodríguez-Tovar et al., 2009a, 2009b) has enabled deeper insight into oxygenation changes and other paleoenvironmental parameters. Detailed ichnological studies, however, have never been completed in the classical sections of the Gubbio area.

The aim of this paper is to fill this gap by investigating the ichnological record of the latest Cenomanian interval in the Contessa and Bottaccione sections, and comparing it to sections from the Betic Cordillera and the Carpathians, which were studied using the same methodology (see discussion).

Samples for trace fossil and ichnofabric analyses were collected bed-by-bed from the Bonarelli Level and from the underlying and overlying sediments in both of the studied sections. Trace fossils and ichnofabrics

were observed in variably oriented, cut (and occasionally rough) surfaces, which were dampened and photographed.

GEOLOGICAL SETTING

The studied sections are located in the Gubbio area of the Umbrian Apennines, Central Italy (Fig. 1). The Bottaccione section is located in the Bottaccione gorge (on the slope west of the GPS point: N43°21.701'; E012°34.309'; ±11 m). The Contessa section (Fig. 2) is located near the Contessa quarry (GPS coordinates: N43°22.535'; E012°33.646'; ±13 m). The Bonarelli Level in these sections consists of a regional marker bedset (Scisti ittoliolici of Bonarelli, 1891), approximately 1 m thick, which contains non-calcareous black shale, silicified radiolaritic black shale, dark, varicolored siltstone and mudstone, orange radiolaritic shale, dark marlstone and a tuffite layer, which enables correlation of the two studied sections. The package occurs near the top of the uppermost Albian-basal Turonian Scisti a Fucoidi and Scaglia Bianca Formation of the Umbria-Marche Basin in the grayish Member W4 (Coccioni, 1996). It is sandwiched between two distinct cherty layers, and is considered to be an entirely pelagic limestone interval (Coccioni and Luciani, 2004). The grayish Member W4 of the Scaglia Bianca Formation consists of interbedded light-gray pelagic limestones, thin black shale levels and gray to black nodular to bedded cherts that are rhythmically arranged (Mitchell et al., 2008). Spectral analyses of these rhythmic beds in the Scaglia Bianca of the Umbria-Marche area have been made in previous studies documenting Milankovitch cyclicity and thickness variations of bedded cherts and other lithologies (Schwarzacher, 1994; Grippo et al., 2004; Mitchell et al., 2008). Throughout the Umbria-Marche Basin, the Scaglia Bianca is interpreted to have been deposited at water depths above the carbonate compensation depth, but far below storm wave base, (~depth of 1500–2000 m; Arthur and Premoli-Silva, 1982; Kuhnt, 1990). The Umbria-Marche Basin formed on the thinned continental margin of Adria, which appears to have been tectonically inactive from the Aptian through the Turonian. Evidence of tectonic quiescence includes the tabular bedding and basin-wide uniformity in the thickness of the Scaglia Bianca Formation and the absence of syndimentary slumping, faulting, and turbidites (Montanari et al., 1989).

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 (Coccioni 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.

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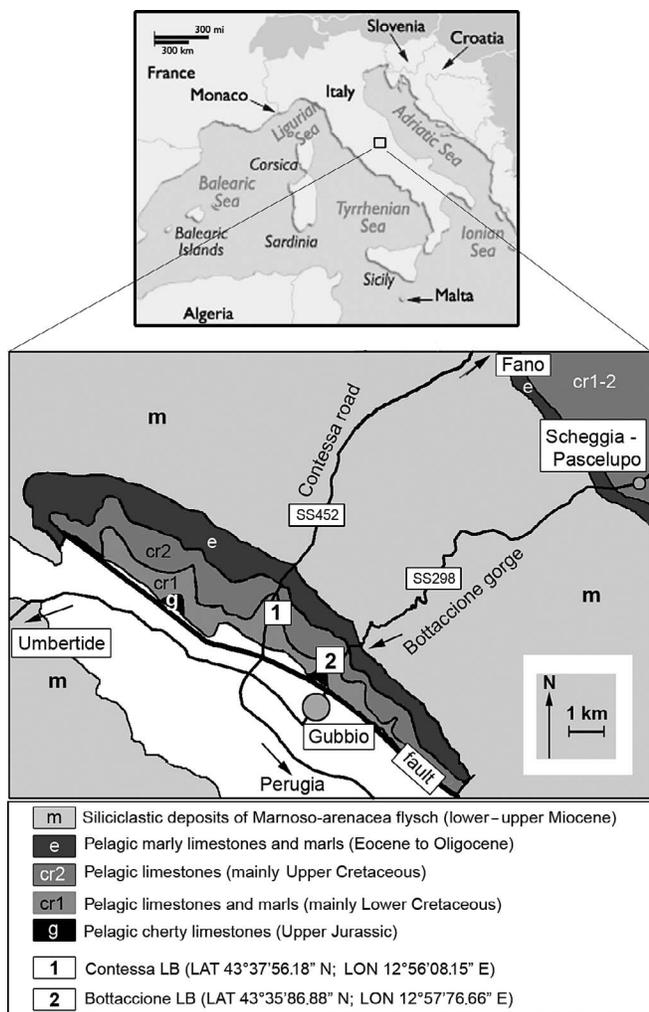


FIGURE 1—Location map. Based on the Geological Map of Italy (“Foglio 116 Gubbio,” ISPRA).

(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 $\delta^{13}\text{C}$ 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



FIGURE 2—The Contessa section with the Bonarelli Level at the level of the stick, which is 1 m long.

Supplementary Data¹). Hard lithotypes (mainly calcareous mudstones, siltstones, silicified radiolaritic 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). Distribution of primary lamination was observed on black shale, varicolored siltstone-mudstone, orange radiolaritic shale, and dark marlstone. Thin-section analysis aided in establishing the micro-fabric, mainly in radiolaritic deposits. The distribution of ichnogenera (*Zoophycos*, *Trichichnus*, *Thalassinoides*, *Planolites*, light and dark *Chondrites*) allowed definition of an oxygenation curve expressed in relative grades (0 to 6; Fig. 3). The assemblages correspond to the oxygen-related ichnocoenoses (ORI) by Savrda and Bottjer (1986). Non-bioturbated, laminated beds are referred to anoxic conditions (grade 0), while bioturbated beds without discernable trace fossils were taken to indicate dysaerobic conditions (grade 1). Oxygenation changes were plotted following the principles of ichnological record, such as trace fossil content and assemblages as outlined, e.g., by Savrda and Bottjer (1986, 1989a) and Savrda (2007). The sharpness of burrows was considered as a proxy defining the consistency of the burrowed media (=substrate). The Bonarelli Level in the Contessa and Bottaccione sections is then compared to other sections from the Betic Cordillera and the Carpathians, which were studied using this same methodology, in order to find common trends in environmental changes and to show differences.

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 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 dysaerobic conditions as chemosymbiotic organisms (Seilacher, 1990; Fu, 1991).

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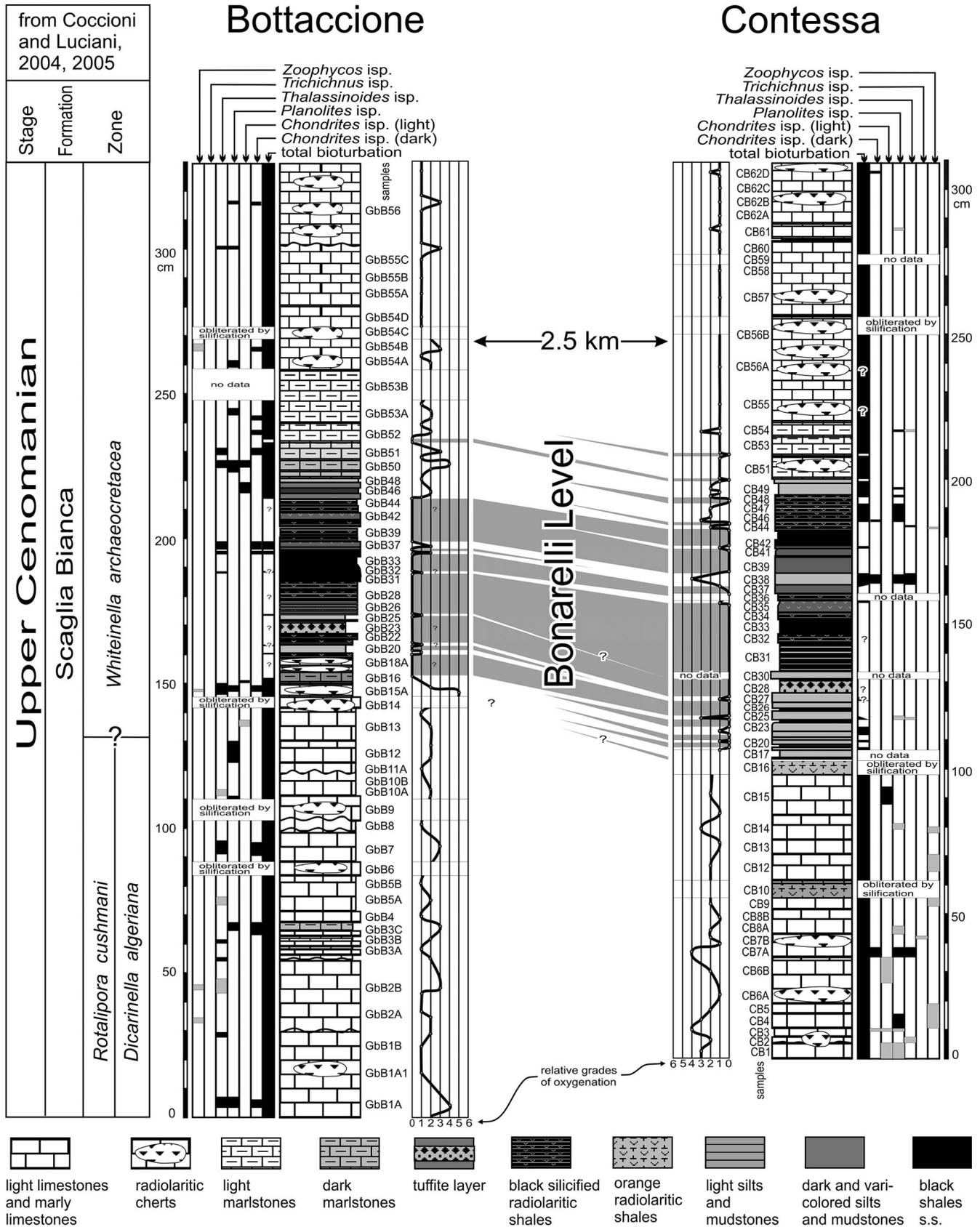


FIGURE 3—Ichnological features of the Bottaccione and Contessa sections, interpretation of oxygenation changes and their correlation. The gray shading in the ichnotaxa columns means reserved determinations, e.g., ?Thalassinoides isp. Total bioturbation means that 100% volume of sediment was bioturbated. Micropaleontological zones according to Coccioni and Luciani (2004, 2005).

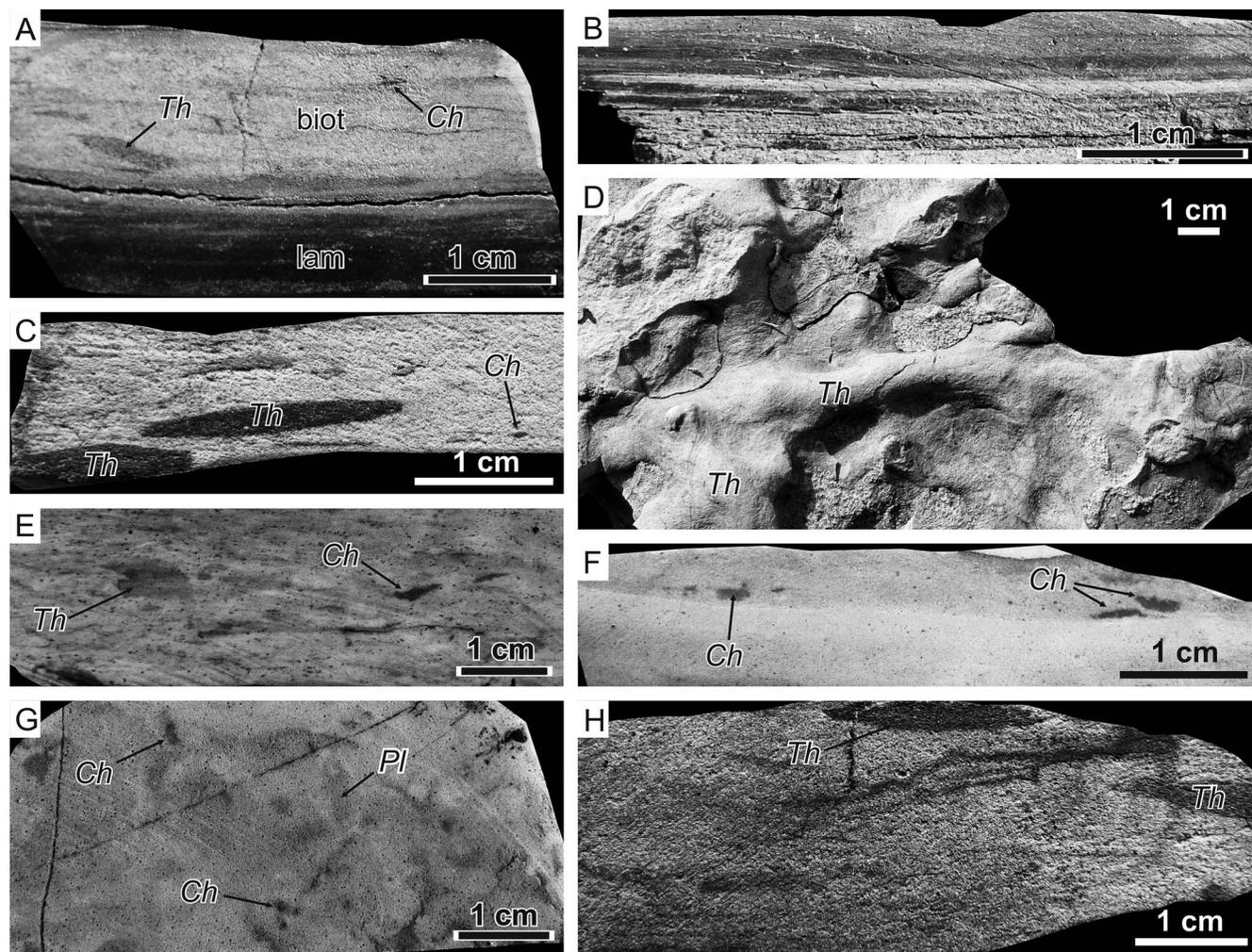


FIGURE 4—Selected examples of fabrics and trace fossils from the Bottaccione and Contessa sections. Total bioturbation in C–H. A) Vertical section of bed GbB34 showing the laminated lower part (=lam) and bioturbated upper part (=biot). *Th* = *Thalassinoides* isp., *Ch* = *Chondrites* isp. B) Primary lamination in the bed Cb26. C) Vertical section of bed Cb38B, *Th* = *Thalassinoides* isp., *Ch* = *Chondrites* isp. D) Silica concretionary growth on *Thalassinoides* isp. (=Th), bed GbB1B. E) Vertical section of bed GbB7A, *Th* = *Thalassinoides* isp., *Ch* = *Chondrites* isp. Contours of trace fossils are poorly outlined because of low sediment cohesion. F) Vertical section of bed GbB56, *Ch* = *Chondrites* isp. Contours of trace fossils are poorly outlined because of low sediment cohesion. G) Horizontal section of bed Cb49, *Ch* = ?*Chondrites* isp., *Pl* = *Planolites* isp. H) Vertical section of bed GbB37, *Th* = *Thalassinoides* isp.

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 domicichnial (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 domicichnial 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 whorls, which 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 Häntzschel, 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 ingestors 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 (Scopelliti et al., 2004, 2006). Nonlaminated strata characterized by mottling 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., mottled 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). Non-bioturbated, laminated beds are referred to anoxic conditions (grade 0); bioturbated beds without distinct trace fossils indicate dysaerobic 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 dysaerobic 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 ichnofabric 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 ichnofabric 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 (mottled or homogenized) background. Values of the curve in both sections fluctuate between grades 5 and 1, pointing to changing oxygenation between aerobic and slightly dysaerobic 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 radiolaritic shale, green shale, radiolaritic 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 dysaerobic (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 Hedionda and El Chorro sections, which are paleogeographically 70 km apart. In an interval dominated by anoxia, dysaerobic or aerobic subevents during the OAE2 are less common in the distal section (Hedionda) than in the proximal section (El Chorro). This was interpreted to reflect a higher tendency toward anoxia in the more distal zone (Hedionda) 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) compare to the Betic Cordillera. This suggests significant paleoceanographic 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 Barnasiówka section in the Carpathians and in the Hedionda 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 Barnasiówka section is located in a basin with turbiditic sedimentation in a slope-proximal setting (Bak, 2007; Uchman 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 Barnasiówka, Hedionda, 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 lead 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*, *Trichichmus*, 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.

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REFERENCES

- ARTHUR, M.A., and PREMOLI-SILVA, I., 1982. Development of widespread organic carbon-rich strata in the Mediterranean Tethys, in Schlanger, S.O., and Cita, M.B., eds., *Nature and Origin of Cretaceous Carbon-Rich Facies*: Academic Press, London, p. 7–54.
- ARTHUR, M.A., BRUMSACK, H.J., JENKINS, H.C., and SCHLANGER, S.O., 1990. Stratigraphy, geochemistry, and paleoceanography of organic carbon-rich Cretaceous sequences, in Ginsburg, R.N., and Beaudoin, B., eds., *Cretaceous Resources, Events and Rhythms*: Kluwer Academic Publishing, Dordrecht, p. 75–119.
- BAK, K., 2007. Deep-water facies succession around the Cenomanian–Turonian boundary in the Outer Carpathian Basin: sedimentary, biotic and chemical records in the Silesian Nappe, Poland: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 248, p. 255–290.
- BONARELLI, G., 1891. Il territorio di Gubbio. *Notizie geologiche*: Tipografia economica, Roma, p. 1–38.
- BROMLEY, R.G., 1996. *Trace Fossils: Biology, Taphonomy and Applications*: Chapman and Hall, London, 361 p.
- BROMLEY, R.G., and EKDALE, A.A., 1984. *Chondrites*: A trace fossil indicator of anoxia in sediments: *Science*, v. 224, p. 872–874.
- BROMLEY, R.G., and HANKEN, N.-M., 2003. Structure and function of large, lobed *Zoophycos*, Pliocene of Rhodes, Greece: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 192, p. 79–100.
- COCCIONI, R., 1996. The Cretaceous of the Umbria-Marche Apennines (Central Italy), in Wiedmann, J., ed., *Cretaceous Stratigraphy, Paleobiology and Paleobiogeography*, Tübingen, 7–10 March 1996, Abstracts: *Berichte aus dem Sonderforschungsbereich 313*, p. 129–136.
- COCCIONI, R., and LUCIANI, V., 2004. Planktonic foraminifera and environmental changes across the Bonarelli event (OAE-2, latest Cenomanian) in its type area: A high-resolution study from the Tethyan reference Bottaccione section (Gubbio, central Italy): *Journal of Foraminiferal Research*, v. 34, p. 109–129.
- COCCIONI, R., and LUCIANI, V., 2005. Planktonic foraminifera across the Bonarelli Event (OAE2, latest Cenomanian): The Italian record: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 224, p. 167–185.
- D'ALESSANDRO, A., and BROMLEY, R.G., 1987. Meniscate trace fossils and the *Muensteria-Taenidium* problem: *Palaeontology*, v. 30, p. 743–763.
- EKDALE, A.A., 1992. Muckraking and mudslinging: The joys of deposit-feeding, in Maples, C.G., and West, R.R., eds., *Trace Fossils*: Paleontological Society, Short Courses in Paleontology, v. 5, p. 45–171.

- EKDALE, A.A., and BROMLEY, R.G., 1991, Analysis of composite ichnofabrics: An example in uppermost Cretaceous chalk of Denmark: *PALAIOS*, v. 6, p. 232–249.
- EKDALE, A.A., and LEWIS, D.W., 1991, The New Zealand *Zoophycos* revisited: *Ichnos*, v. 1, p. 183–194.
- FILLION, D., and PICKERILL, R.K., 1990, Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada: *Palaeontographica Canadiana* (Toronto), v. 7, p. 1–119.
- FREY, R.W., 1970, Trace fossils of Fort Hays Limestone Member of Niobrara Chalk (Upper Cretaceous), West-Central Kansas: University of Kansas Paleontological Contributions, v. 53, p. 1–41.
- FREY, R.W., CURRAN, A., and PEMBERTON, S.G., 1984, Tracemaking activities of crabs and their environmental significance: The ichnogenus *Psilonichmus*: *Journal of Paleontology*, v. 58, p. 333–350.
- FU, S., 1991, Funktion, Verhalten und Einteilung fucoider und lophoctenoider Lebensspuren: *Courier Forschungs, Institut Senckenberg*, v. 135, p. 1–79.
- FÜRSICH, F.T., 1973, A revision of the trace fossils *Spongeliomorpha*, *Ophiomorpha* and *Thalassinoides*: *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, v. 12, p. 719–735.
- GRIPPO, A., FISCHER, A.G., HINNOV, L.A., HERBERT, T.D., and PREMOLI SILVA, I., 2004, Cyclostratigraphy and chronology of the Albian stage (Piobbico core, Italy), in D'Argenio, B., Fischer, A.G., Premoli Silva, I., Weissert, H., and Ferreri, V., eds., *Cyclostratigraphy: Approaches and Case Histories: SEPM (Society for Sedimentary Geology) Special Publication 81*, p. 57–81.
- JENKYN, H.C., 1980, Cretaceous anoxic events from continents to oceans: *Journal of the Geological Society London*, v. 137, p. 171–188.
- KAMINSKI, M.A., CETEAN, C.G., BALC, R. & COCCIONI, R., 2011, Upper Cretaceous Deep-Water Agglutinated Foraminifera from the Contessa Highway Section, Umbria-Marche Basin, Italy: Taxonomy and Biostratigraphy, in Kaminski, M.A., and Filipescu, S., eds, *Proceedings of the Eighth International Workshop on Agglutinated Foraminifera*. Grzybowski Foundation Special Publication, v. 16, p. 71–106.
- KEIGHLEY, G.D., and PICKERILL, R.K., 1995, The ichnotaxa *Palaeophycus* and *Planolites* in historical perspectives and recommendations: *Ichnos*, v. 3, p. 301–310.
- KOTAKE, N., 1989, Paleoecology of the *Zoophycos* producers: *Lethaia*, v. 22, p. 327–341.
- KOTAKE, N., 1991a, Packing process for filling material in *Chondrites*: *Ichnos*, v. 1, p. 277–285.
- KOTAKE, N., 1991b, Non-selective surface deposit feeding by the *Zoophycos* producers: *Lethaia*, v. 24, p. 379–385.
- KUHNT, W., 1990, Agglutinated foraminifera of western Mediterranean Upper Cretaceous pelagic limestones (Umbrian Apennines, Italy, and Betic Cordillera, southern Spain): *Micropaleontology*, v. 36, p. 297–330.
- LÖWEMARK, L., LIN, I.-T., WANG, C.-H., and SCHÖNFELD, J., 2007, A test of the gardening hypothesis for the trace fossil *Zoophycos*, in Bromley, R.G., Buatois, L.A., Mángano, M.G., Genise, J.F., and Melchor, R.N., eds., *Sediment–organism interactions: A multifaceted ichnology: SEPM (Society for Sedimentary Geology) Special Publication*, no. 88, p. 79–86.
- MCBRIDE, E.F., and PICARD, D.M., 1991, Facies implications of *Trichichnus* and *Chondrites* in turbidites and hemipelagites, Marnoso-arenacea Formation (Miocene), Northern Apennines, Italy: *PALAIOS*, v. 6, p. 281–290.
- MITCHELL, R.N., BICE, D.M., MONTANARI, A., CLEAVELAND, L.C., CHRISTIANSON, K.T., COCCIONI, R., and HINNOV, L.A., 2008, Oceanic anoxic cycles? Orbital prelude to the Bonarelli Level (OAE 2): *Earth and Planetary Science Letters*, v. 267, p. 1–16.
- MONTANARI, A., CHAN, L.S., and ALVAREZ, W., 1989, Synsedimentary tectonics in the Late Cretaceous–Early Tertiary pelagic basin of the Northern Apennines, in Crevello, P., Wilson, J.L., Sarg, R., and Reed, F., eds., *Controls on Carbonate Platform and Basin Development: SEPM (Society for Sedimentary Geology) Special Publication 44*, p. 379–399.
- MORT, H., JACQUAT, O., ADATTE, T., STEINMANN, P., FÖLLMI, K., MATERA, V., BERNER, Z., and STÜBEN, D., 2007, The Cenomanian/Turonian anoxic event at the Bonarelli Level in Italy and Spain: Enhanced productivity and/or better preservation?: *Cretaceous Research*, v. 28, p. 597–612.
- OLIVERO, D., and GAILLARD, C., 1996, Paleoecology of Jurassic *Zoophycos* from south-eastern France: *Ichnos*, v. 4, p. 249–260.
- PEMBERTON, S.G., and FREY, R.W., 1982, Trace fossil nomenclature and the *Planolites*–*Palaeophycus* dilemma: *Journal of Paleontology*, v. 56, p. 843–871.
- PREMOLI-SILVA, I., and SLITER, W.V., 1994, Cretaceous planktonic foraminiferal biostratigraphy and evolutionary trends from the Bottaccione section, Gubbio (Italy): *Palaeontographia Italica*, v. 82, p. 1–89.
- PREMOLI-SILVA, I., and SLITER, W.V., 1999, Cretaceous paleoceanography: Evidence from planktonic foraminiferal evolution, in Barrera, E., and Johnson, C.C., eds., *Evolution of the Cretaceous Ocean-Climate System: Geological Society of America, Boulder, Colorado*, p. 301–328.
- RODRIGUEZ-TOVAR, F.J., UCHMAN, A., and MARTIN-ALGARRA, A., 2009a, Oceanic Anoxic Event at the Cenomanian–Turonian boundary interval (OAE-2): Ichnological approach from the Betic Cordillera, southern Spain: *Lethaia*, v. 42, p. 407–417.
- RODRIGUEZ-TOVAR, F.J., UCHMAN, A., MARTIN-ALGARRA, A., and O'DOHERTY, L., 2009b, Nutrient spatial variation during intrabasinal upwelling at the Cenomanian–Turonian oceanic anoxic event in the westernmost Tethys: An ichnological and facies approach: *Sedimentary Geology*, v. 215, p. 83–93.
- SAVRDA, C.E., 2007, Trace fossils and marine benthic oxygenation, in Miller, W., III, ed., *Trace Fossils Concepts, Problems, Prospects: Elsevier, Amsterdam*, p. 149–158.
- SAVRDA, C.E., and BOTTJER, D.J., 1986, Trace-fossil model for reconstruction of paleo-oxygenation in bottom waters: *Geology*, v. 14, p. 3–6.
- SAVRDA, C.E., and BOTTJER, D.J., 1989a, Anatomy and implications of bed in “Black Shale” sequences: Examples from the Jurassic Posidonienschiefer (southern Germany): *PALAIOS*, v. 4, p. 330–342.
- SAVRDA, C.E., and BOTTJER, D.J., 1989b, Trace-fossil model for reconstructing oxygenation histories of ancient marine bottom waters: Application to Upper Cretaceous Niobrara Formation, Colorado: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 74, p. 49–74.
- SCHLANGER, S.O., and JENKYN, H.C., 1976, Cretaceous oceanic anoxic events: Causes and consequences: *Geologie en Mijnbouw*, v. 55, p. 179–184.
- SCHLIRF, M., 2000, Upper Jurassic trace fossils from the Boulonnais (northern France): *Geologica et Palaeontologica*, v. 34, p. 145–213.
- SCHWARZACHER, W., 1994, Cyclostratigraphy of the Cenomanian in the Gubbio District, Italy; a field study: *Special Publication of the International Association of Sedimentologists*, v. 19, p. 87–97.
- SCOPELLITI, G., BELLANCA, A., COCCIONI, R., LUCIANI, V., NERI, R., BAUDIN, F., CHIARI, M., and MARCUCCI, M., 2004, High-resolution geochemical and biotic records of the Tethyan “Bonarelli Level” (OAE2, latest Cenomanian) from the Calabianca–Guidaloca composite section, northwestern Sicily, Italy: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 208, p. 293–317.
- SCOPELLITI, G., BELLANCA, A., NERI, R., BAUDIN, F., and COCCIONI, R., 2006, Comparative high-resolution chemostratigraphy of the Bonarelli Level from the reference Bottaccione section (Umbria–Marche Apennines) and from an equivalent section in NW Sicily: Consistent and contrasting responses to the OAE2: *Chemical Geology*, v. 228, p. 266–285.
- SEILACHER, A., 1967, Bathymetry of trace fossils: *Marine Geology*, v. 5, p. 413–428.
- SEILACHER, A., 1990, Aberration in bivalve evolution related to photo- and chemosymbiosis: *Historical Biology*, v. 3, p. 289–311.
- TSIKOS, H., JENKYN, H.C., WALSWORTH-BELL, B., PETRIZZO, M.R., FORSTER, A., KOLONIC, S., ERBA, E., PREMOLI SILVA, I., BAAS, M., WAGNER, T., and SINNINGHE DAMSTE, J.S., 2004, Carbon-isotope stratigraphy recorded by the Cenomanian–Turonian Oceanic Anoxic Event: Correlation and implications based on three key localities: *Journal of the Geological Society London*, v. 161, p. 711–719.
- UCHMAN, A., 1995, Taxonomy and palaeoecology of flysch trace fossils: The Marnoso-arenacea Formation and associated facies (Miocene, Northern Apennines, Italy): *Beringeria*, v. 15, p. 3–115.
- UCHMAN, A., 1999, Ichnology of the Rhenodanubian flysch (Lower Cretaceous–Eocene) in Austria and Germany: *Beringeria*, v. 25, p. 65–171.
- UCHMAN, A., 2004, Deep-sea trace fossils controlled by palaeo-oxygenation and deposition: An example from the Lower Cretaceous dark flysch deposits of the Silesian Unit, Carpathians, Poland: *Fossils and Strata*, v. 51, p. 39–57.
- UCHMAN, A., BAK, K., and RODRIGUEZ-TOVAR, F.J., 2008, 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: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 262, p. 61–71.
- VOIGT, E. and HÄNTZSCHEL, W., 1956, Die grauen Bänder in der Schreibkreide Nordwest-Deutschlands und ihre Deutung als Lebensspuren: *Mitteilungen aus dem Geologischen Staatsinstitut Hamburg*, v. 25, p. 104–122.
- WERNER, F., and WETZEL, W., 1982, Interpretation of biogenic structures in oceanic sediments: *Bulletin de l'Institut de Géologie du Bassin d'Aquitaine*, v. 31, p. 275–288.
- WETZEL, A., and WERNER, F., 1981, Morphology and ecological significance of *Zoophycos* in deep-sea sediments off NW Africa: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 32, p. 185–212.