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SPECTRAL ANALYSIS OF TOARCIAN SEDIMENTS FROM THE VALDORBIA SECTION (UMBRIA-MARCHE APENNINES): THE ASTRONOMICAL INPUT IN THE FORAMINIFERAL RECORD

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Abstract. Toarcian sections studied mainly in Europe have revealed the incidence of Milankovitch forcing with a well-developed, highly stable, 405 ky component of eccentricity, a short-term eccentricity of ~100 kyr, the cycle of obliquity ~36 kyr, and the precession signal at ~21 kyr. Cyclostratigraphic analysis of the Toarcian succession at the Valdorbia section (Umbria-Marche Apennines) was conducted based on time-series of foraminiferal assemblages. Well-developed cyclic patterns were obtained, with several significant cycles corresponding to thicknesses of 3.8-4.1 m / 5.8-6.3 m / 8.2 m / 10.4 m. Comparison with previous studies at the Valdorbia section led us to interpret the cycle of ~4 m as directly related with the short-term eccentricity (95-105 kyr). The rest of the cycles could be assigned to a periodicity of ~140-160 kyr, ~200 kyr and ~250 kyr, and interpreted as indirect signals of the long-term eccentricity, obliquity and precession, whose record would be impeded by the incompleteness of the studied succession and the sampling interval. Studied components in the foraminiferal assemblage show variable cyclostratigraphic patterns, allowing for a differentiation of groups based on similar registered cycles. These groups reveal different responses by the foraminiferal assemblage, associated with particular requirements, to the palaeoenvironmental changes of Milankovitch origin.

Introduction

Lower Toarcian sediments have been profusely studied in recent years, mainly due to the involvement of the Toarcian Oceanic Anoxic Event (T-OAE) and associated palaeoenvironmental changes. The T-OAE is one of the largest perturbations in the carbon cycle in the past 250 Ma, characterized by a significant negative carbon-isotope excursion (CIE) (Jenkyns & Clayton 1997; Hesselbo et al. 2000). Multidisciplinary analyses are very useful for interpreting the origin of this phenomenon, which induced severe global warming and a generalized oceanic anoxia, although locally the influence of the widespread anoxia could be reduced (i.e., Braga et al. 1981; Rodríguez-Tovar & Uchman 2010). Of the different approaches, integrative geochemical and palaeontological studies prove to be especially informative (i.e., Rodríguez-Tovar & Reolid 2013; Reolid et al. 2014a); the analysis of foraminiferal assemblages and the characterization of morphogroups indicative of particular palaeoenvironmental conditions were used to shed light on the T-OAE (i.e., Bartolini et al. 1992; Reolid et al. 2012a, b, 2013b, 2014b).

Recently, astronomical forcing during the Toarcian has been addressed, at times focusing on the T-OAE (i.e., Huang & Hesselbo 2014), and occasionally involving the Early Toarcian or even the entire Toarcian Stage (Boulila et al. 2014; Ruebsam et al. 2014). On this basis, astronomical calibrations of the T-OAE, the different zones of the Toarcian, and the entire Toarcian Stage have been conducted (i.e., Suan et al. 2008; Ogg & Hinnov 2012; Boulila et al. 2014; Huag & Hesselbo 2014; Ruebsam et al. 2014). The Valdorbia section (Umbria-Marche Apennines) presents a well-exposed Lower Jurassic formation, with a detailed biostratigraphic characterization, allowing for detailed sedimentological, palaeontological and geochemical studies (i.e., Bar-

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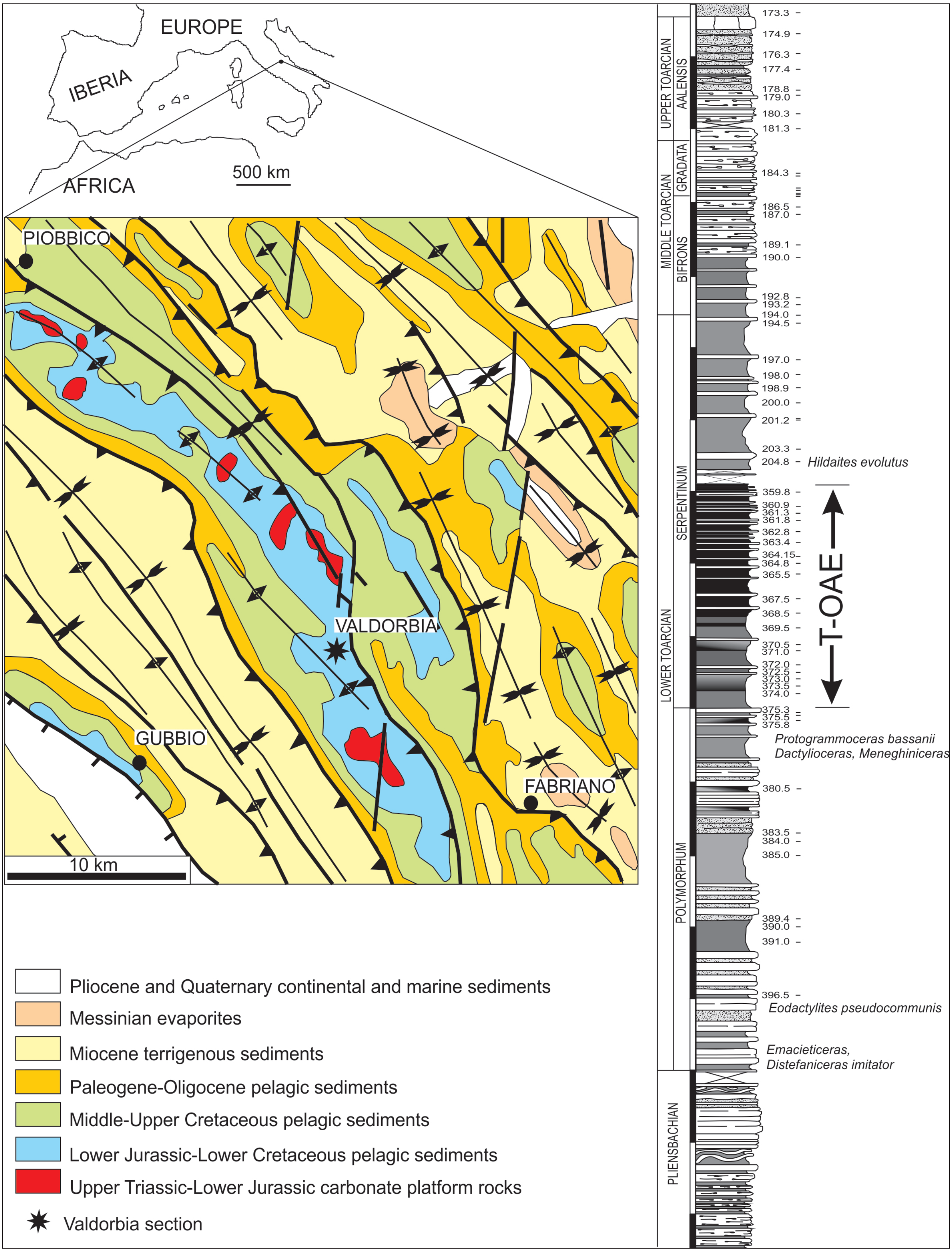

Fig. 1 - Location and lithological column of the Valdorbia section (Umbria-Marche Apennines). Position of the samples is indicated in the column.

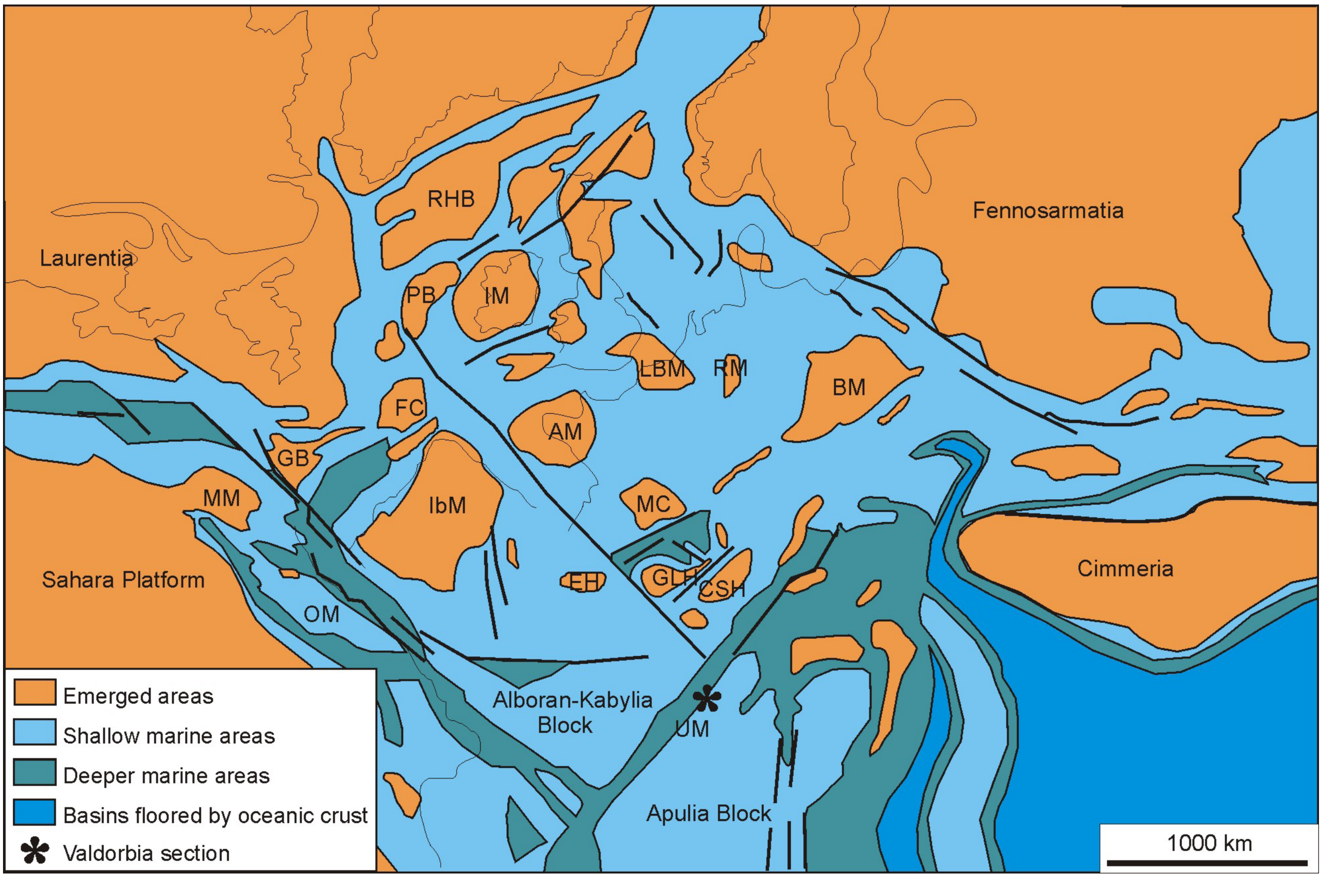

Fig. 2 - Palaeogeographic reconstruction for the Toarcian in the westernmost Tethys based on Ziegler (1988), with location of the Umbria Marche Basin (Note: AM, Armorican Massif; BM, Bohemian Massif; CSH, Corsica-Sardinia High; EH, Ebro High; FC, Felmish Cap; GB, Gran Banks; GLH, Golf de Lyon High; IbM, Iberian Massif; IM, Irish Massif; LBM, London-Brabant Massif; MC, Massif Central; MM, Moroccan Massif; OM, Oran Massif; PB, Porcupine Bank; RHB, Rockall-Hatton Bank; UM, Umbria Marche Basin).

tolini et al. 1992; Monaco et al. 1994; Nocchi & Bartolini 1994; Sabatino et al. 2009). However, cyclostratigraphic analysis was scarce and focused on the T-OAE (Sabatino et al. 2009; Huang & Hesselbo 2014). This study presents a novel cyclostratigraphic analysis of the Toarcian succession of the Valdorbia section based on the spectral analysis of foraminiferal time-series. The aim of this research is to evaluate the incidence of the different-scale Milankovitch forcing during deposition of Toarcian sediments at the Valdorbia section, and the response of foraminifera to the involved palaeoenvironmental changes.

Geological setting. The Valdorbia section

The Valdorbia section is a typical locality for the Lower Jurassic record of the Umbria Marche Apennine fold-and-thrust belt (Figs 1-2). The abundance of ammonoids provides for good stratigraphic resolution (see Cresta et al. 1989; Monaco et al. 1994; Venturi & Ferri 2001; Venturi et al. 2010). Besides the ammonite biostratigraphy, calcareous nannofossils have been analysed by Reale et al. (1991), and more recently for the lower Toarcian interval by Mattioli et al. (2013). The Valdorbia section, which crops out in the Inner Ridge of the Umbria Marche Apennine fold-and-thrust, consists of three NW-SE anticlines that involve Mesozoic and Paleogene pelagic formations made up mainly of marls and limestones. The Valdorbia section is located along Road N-360 (43°25'N, 12°42'E) between the villages of Scheggia and Sassoferrato.

The studied interval is located over the Corniola Unit, comprising well-bedded hard limestones with chert nodules and, locally, brown nodular marly limestones and calcisiltitic turbidites. The lower part of the studied interval corresponds to the Marne del Monte Serrone Formation; it is composed by 49 m of dark shales and grey marlstones with calcarenitic-calcisiltitic turbidites (up to 1.5 m thick in the lower part). The T-OAE has been well identified by the negative

CIE and by the increase of organic carbon (Sabatino et al. 2009). It is characterized by organic-rich horizons intercalated in the lower part of interval with calcisiltitic turbidites (Jenkyns & Clayton 1986; Baudin et al. 1990; Monaco et al. 1994; Sabatino et al. 2009). The onset of the CIE in Valdorbia section (at ~ 22 m in Sabatino et al. 2009, corresponding approximately with the interval around 375 m in the log of Fig. 1) is just above the *Protogrammoceras bassanii* ammonite horizon, characterizing the "Livello Lecceti" in the Apennines, and correlated with the uppermost part of the Tenuicostatum Zone (= Polymorphum Zone) (Venturi & Ferri 2001; Venturi et al. 2010). An interval of 10-12 m follows, devoid of ammonites, corresponding with the black-slale occurrence (Fig. 1). The ammonite *Hildaites* was found in the sediments just underlying the bed 204 (Fig. 1). This *Hildaites* horizon is correlated with maximum positive values of $\delta^{13}C$ (45.70 m in Sabatino et al. 2009), and it has been used to place the base of the Serpentinum Zone = Falciferum Zone (see for example Cresta et al. 1989). However, because of the large gap of ammonite record in Valdorbia section, such *Hildaites* occurrence should not be considered as a "first occurrence", and the boundary between the Tenuicostatum (Polymorphum) and Serpentinum (Falciferum) Zone is actually floating in a large interval of incertitude, corresponding with the T-OAE interval (Fig. 1). Then, the paroxymal phase of the T-OAE (negative CIE and increase of organic matter) in Valdorbia, is framed by the "Livello Lecceti" (uppermost Tenuicostatum) below and the occurrence of *Hildaites* above. It is therefore compatibly synchronous with the lower Toarcian negative CIE, recorded worldwide in the lowermost Serpentinum (Falciferum) Zone (exaratum subzone) (Sandoval et al. 2012; Sell et al. 2014). At Valdorbia, over the organic-rich interval, 14 m of marls and clays of progressively brownish colour do occur (Serpentinum Zone and lower part of Bifrons Zone). The contact with the overlying Rosso Ammonitico Umbro-Marchigiano Unit is identified by the record of a first nodular layer where the colour turns red. This formation has about 27 m of red nodular marly limestones, calcareous nodular marlstones and red shales (Monaco et al. 1994), ammonite rich horizons being characteristic of the top of the Bifrons Zone (Middle Toarcian) to the Opalinum Zone (Aalenian) (Cresta et al. 1989; Cecca et al. 1990). Above the ammonitico rosso facies there are

		Boreal	Subboreal	Submediterranean	Mediterranean
TOARCIAN	Upper	*falcodiscus*	*aalensis*		
			pseudoradiosa	*meneghini*	
			dispansum	*speciosum*	
		wuerttenbergeri	*thouarsense*	*thouarsense*	*bonarelli*
	Middle	*compactile*	*variabilis*	*gradata*	
		braunianus	*bifrons*		
		commune			
	Early	*falciferum*	*serpentinum*		*levisoni*
		antiquum	*tenuicostatum*		*polymorphum*

Fig. 3 - Toarcian subdivisions and correlation of ammonite zones for Boreal, Subboreal Submediterranean and Mediterranean domains based on Elmi et al. (1997), Zakharov et al. (1997) and Page (2003).

white limestone beds known as the Calcari a Posidonia Unit.

Material and methods

Toarcian subdivisions (zones and subzones) and correlations between the Boreal, Subboreal, Submediterranean and Mediterranean provinces are illustrated in Fig. 3. Throughout the text we maintain the biostratigraphic zonation presented in the original papers; for correlation see Fig. 3.

Studied variables. The foraminiferal assemblage

A total of 59 sampling stations were studied along the Toarcian succession of the Valdorbia section. According to the Toarcian subdivisions for the Submediterranean/Mediterranean province (Elmi et al. 1997; Page 2003), the number of studied samples is: 39 samples from Polymorphum and Serpentinum chronozones (Lower Toarcian substage), 6 from Bifrons (Middle Toarcian substage), 7 from Gradata (Middle Toarcian substage) and 7 from Aalensis (Upper Toarcian substage).

Foraminifera were obtained from residues of sieved samples. A total of 400 g of dried sample was washed in a column of standard stainless steel sieves with mesh openings of 500, 200, 100 and 63 μm. No special chemical treatment of the samples was required prior to the washing procedure. Less than 3 g of washed residue was usually obtained. Specimens of foraminifera were hand-picked with a hair paintbrush on a standard black picking grid-tray under stereoscopic microscope (see Bartolini et al. 1992; Nocchi & Bartolini 1994). One gram of

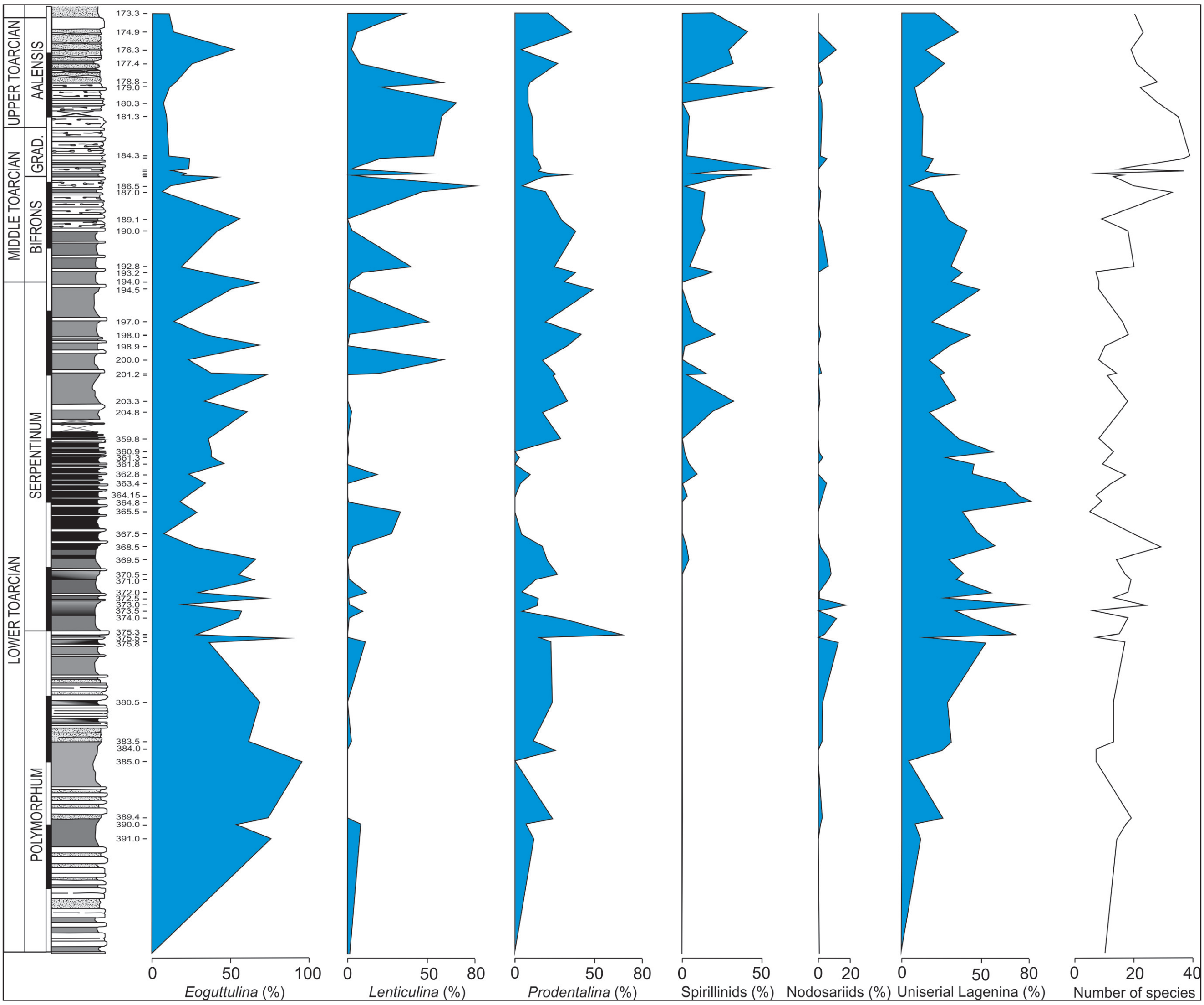

Fig. 4 - Stratigraphic distribution of the proportions of selected genera (*Eoguttulina, Lenticulina* and *Prodentalina*), spirillinids, nodosariids, uniserial forms of suborder Lagenina and the diversity (number of species). Original data from Bartolini et al. (1992).

residue was examined from each sample and between 200 and 400 individuals were counted when possible.

The recorded foraminiferal taxa are exclusively benthic, belonging to the suborders Textulariina, Lagenina, Miliolina, Spirillinina and Robertinina. The benthic assemblage consists predominantly of calcareous forms and scarce agglutinated shell-type forms. The calcareous group includes forms with three wall types: calcitic perforated, represented by Lagenina and Spirillinina, porcelaneous Milionina, and aragonitic Robertinina. The foraminifera belonging to suborder Lagenina are dominant during the Toarcian in Umbria Marche sections (Bartolini et al. 1992; Monaco et al. 1994; Nocchi & Bartolini 1994).

Seven variables were studied (Fig. 4): proportions of spirillinids, nodosariids, uniserial forms of Lagenina, *Prodentalina*, *Lenticulina*, and *Eoguttulina* in the foraminiferal assemblages, and finally number of species. Original data of foraminifera comes from Bartolini et al. (1992). Spirillinids correspond mainly to genus *Spirillina*, and secondarily *Conicospirillina* and *Turrispirillina*. The nodosariids include genera *Lingulonodosaria*, *Nodosaria* and *Pseudonodosaria*. Within uniserial forms of the order Lagenina a wide number of genera are included, most notably *Lingulonodosaria*, *Nodosaria*, *Paralingulina*, *Prodentalina*, *Pseudonodosaria*, and scarce *Citharina*, *Ichthyolaria*, *Marginulina* and *Tristix*. Moreover, *Prodentalina*, *Lenticulina* and *Eoguttulina* were analysed separately given the nearly continuous record in the samples studied from the Toarcian of Valdorbia as well as their palaeoenvironmental role in the foraminiferal assemblages.

Cyclostratigraphic methodology

Several methodologies of spectral estimation may be applied in cyclostratigraphic analysis, largely depending on the type of data and the sampling interval (Pardo-Igúzquiza et al. 1994; Pardo-Igúzquiza & Rodríguez-Tovar 2006). As in the case study, one important practical problem lies in the spectral analysis of sequences with uneven sampling. The Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) has been shown to be a very useful spectral methodology when working with uneven sampling data (Jiménez-Moreno et al. 2007; Rodríguez-Tovar et al. 2010, 2013; Pardo-Igúzquiza & Rodríguez-Tovar 2011, 2012, 2013, 2014; Pardo-Igúzquiza et al. 2014; Rodrigo-Gámiz et al. 2014). It may be shown that the alternative of obtaining an even time series by interpolation, or considering the uneven time series as even with an average sampling interval equal to the mean interdistance between data, introduces artifacts in the estimated power spectrum. When the number of experimental data is small, the uncertainty of the estimated power spectrum is large. In order to attenuate this effect there is the possibility of using a larger smoothing in the estimated power spectrum. In the case study we have used a moving triangular filter which length is 10% the length of the examined frequency interval. By using this approach we obtain a consistent estimate of the power spectrum. Anyway, to evaluate the significance of the peaks registered in the spectral analysis, one appropriate method is the achieved confidence level using the permutation test, implemented for the Lomb-Scargle periodogram (see Pardo-Igúzquiza & Rodríguez-Tovar 2000, 2005, 2011, 2012 for a detailed description). Spectral peaks with confidence levels larger than 90% are of interest and even confidence levels larger than 80% may be considered if they represent cycles with cyclostratigraphic interest.

Even sampling interval is not constant; according to the total of 59 sampling stations along the studied interval at the Toarcian succession, corresponding to around 63 m thick, an averaged sampling interval of approximately 1 m could be estimated. With ~1 sample per metre and with ~63 m of section, the periods in the interval 2 m to 15 m is the one that can be examined with some certainty. Two m will be the minimum wavelength in relation to the frequency of Nyquist and 15 m is much larger than the frequency of Rayleigh which is the minimum frequency that can be studied. Thus, following the usually applied conservative procedure (i.e., Jiménez-Espejo et al. 2014), we consider only those cycles in the frequency range with more possibilities of being registered, discarding those on the edge of the low frequencies close to the vertical axe in the achieved confidence level, as well as those corresponding to a thickness close to the sampling interval.

Results

Cyclostratigraphic analyses for the entire Toarcian succession reveal the presence of variable cyclostratigraphic patterns in the Lomb-Scargle periodogram on the analyzed time-series corresponding to the seven studied variables (*Lenticulina*, spirillinids, nodosariids, uniserial forms of Lagenina, *Prodentalina* and *Eoguttulina*, and finally, number of species). In order to be as conservative as possible, out of all the peaks recorded by means of the Lomb-Scargle procedure, only those having higher significance within the achieved significance level (Confidence Level >80%, in cases between 90-100%) were considered. Analysis of these significant peaks reveals a clear distribution according to the studied variables (Fig. 5):

a) at the higher frequency band, cycles between 3.8-4.1 m are registered in nodosariids, Lagenina and *Prodentalina*;

b) in the middle frequency band, two groups of cycles are well differentiated; the first between 5.8 m and 6.3 m, and the second around 8.2 m. Both of them are registered in nodosariids, spirillinids, and number of species. To note, that a cycle in between these cycles, at 6.7-7 m are observed in *Lenticulina* and *Eoguttulina*;

c) in the middle-lower frequency band, a constant cycle at 10.4 m is common in *Prodentalina*, *Euguttulina*, uniserial Lagenina and number of species;

d) no peak at the lower frequency band was observed, except for punctual record at 20.8 m that could be associated to a trend, as reflected in the achieved confidence level diagram.

Discussion

According to Bucefalo-Palliani & Mattioli (1994), Monaco et al. (1994), Parisi et al. (1996, 1998), Nini et al. (1997), and Parisi & Morettini (1999) among others, the T-OAE black-shale facies in the Umbria-Marche area must be located in

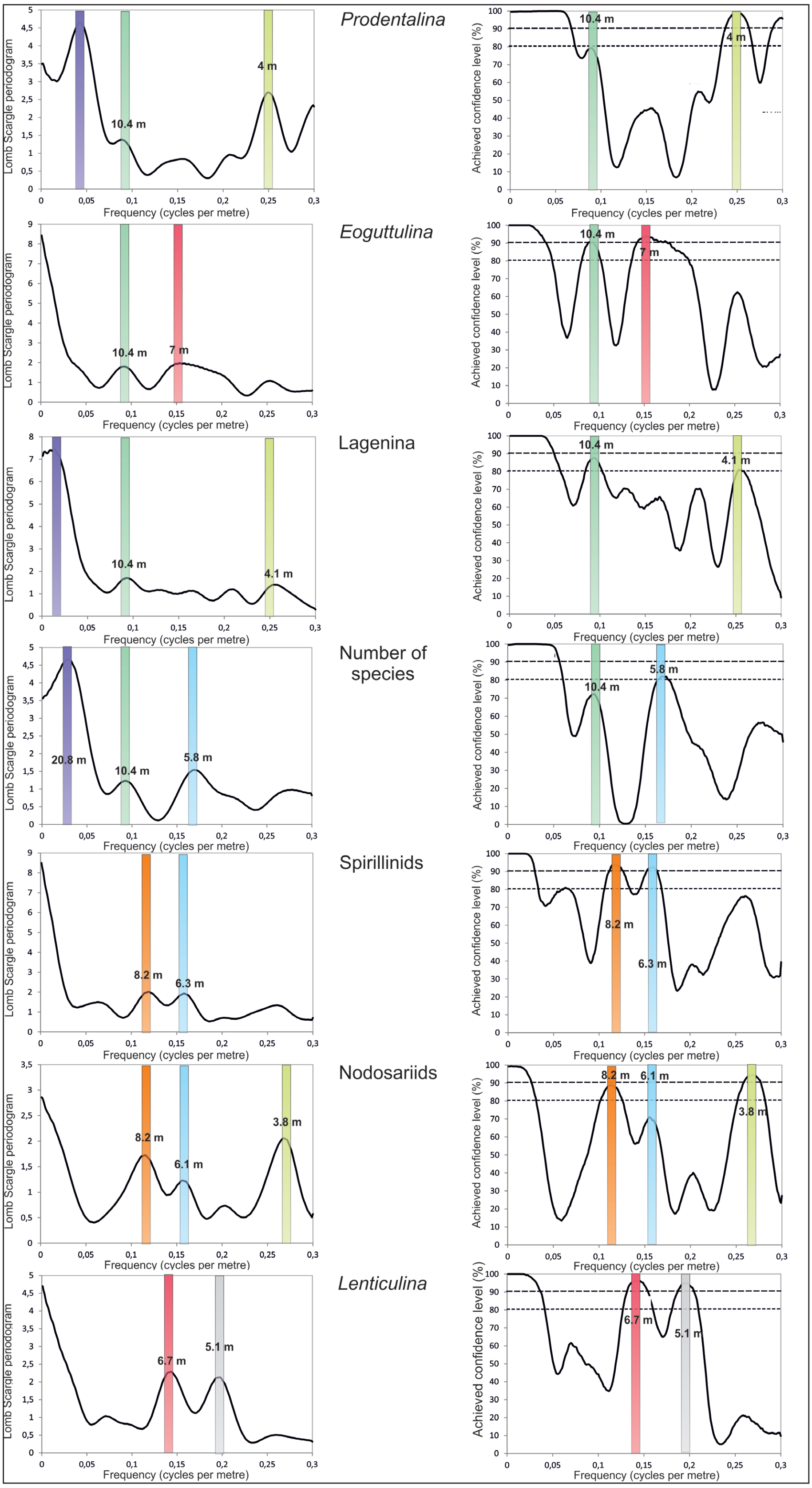

Fig. 5 - Lomb-Scargle periodogram and Achieved confidence level (discontinuous lines for 80% and 90% CL) for the seven studied variables (proportions of spirillinids, nodosariids, uniserial forms of Lagenina, *Prodentalina, Lenticulina*, and *Eoguttulina* in the foraminiferal assemblages, and number of species). Note cycles in meters and same color of vertical columns for similar cycles.

the first ammonite zone of the Toarcian. However, other authors (e.g., Jenkyns & Clayton 1986; Jenkyns 1988; Farrimond et al. 1994; Hesselbo et al. 2000) agree in locating the black shales in the lower part of the Serpentinum/Falciferum Zone. For a detailed discussion thereof see Macchioni (2002) and Mailliot et al. (2006).

The record of the T-OAE in the Valdorbia section, as identified by the maximum values of total organic carbon and negative CIE (Sabatino et al. 2009), and the decrease of foraminiferal diversity, is situated in the lower part of the Serpentinum Zone; hence, it coincides with other localities where the CIE and a drop in the diversity or presence of benthic barren intervals are found at the beginning of the second biozone (levisoni/serpentinum/falciferum) of the Lower Toarcian. This finding has been reported from the Betic Cordillera (Reolid et al. 2013a, 2014a), Lusitanian Basin (Hesselbo et al. 2007), Saharan Atlas (Reolid et al. 2012a, b), Tlemcen Domain (Reolid et al. 2013b, 2014b), East Midlands Shelf (Caswell & Coe 2012), Cardigan Bay Basin (Jenkyns & Clayton 1997), NW German Basin (Röhl et al. 2001), Paris Basin (Hermoso et al. 2009) and Northern Siberia (Suan et al. 2011; Nikitenko et al. 2013), among others.

Astronomical input during Toarcian and the role on calibration of the Toarcian Stage

There is no consensus regarding the predominant Milankovitch cycles during the Toarcian. This uncertainty refers not only to the Oceanic Anoxic Event deposits, but also to the remainder of the Early Toarcian (Ogg & Hinnov 2012). Several studies document the input of the three main Milankovitch cycles - precession, obliquity, and eccentricity - but with variable significance. Special attention has been placed on the T-OAE, and the pre-, syn-, and post-orbital incidence. Thus, Kemp et al. (2005) analyzing $\delta^{13}C_{org}$ and $CaCO_3$ data from Yorkshire (UK) consider the astronomical precession as the main phenomena. Most researches, however, points to a combination of the three Milankovitch components yet with strong changes throughout the Early Toarcian. An evolution of orbital forcing with a change from precession and eccentricity during the earliest Early Toarcian (Tenuicostatum Zone) is evoked, followed by appearance of the obliquity component and maintenance of precession and eccentricity associated to the Toarcian black shales, then pure obliquity during Serpentinum Zone, after deposition of the Lower Toarcian black shale. Finally, pure obliquity would have been replaced by the precession signal at the Bifrons Zone, as is interpreted for the Colle di Sogno section of the Lombardy Basin (Italy), based on thickness analysis (Hinnov & Park 1999; Hinnov et al. 2000). Changes in the relative influence of the different orbital parameters were also recognized by Suan et al. (2008) in terms of the $CaCO_3$ abundance in two sections from Peniche (Portugal) and Dotternhausen (SW Germany): the upper part of the Polymorphum Zone and the base of the Levisoni Zone (base of the negative carbon-isotope excursion, CIE) showed a dominance of the eccentricity signal (~100 kyr), and a lesser influence of precession (~21 kyr) and obliquity (~36 kyr), then incidence of obliquity and eccentricity in the interval of the lowest values of $\delta^{13}C$, and re-occurrence of the precession signal at the end and above the T-OAE when $\delta^{13}C$ returned to higher values. Latterly, Kemp et al. (2011) re-evaluated previous cyclostratigraphic studies in Yorkshire (Kemp et al. 2005) and compared them with those in Peniche (Suan et al. 2008), confirming a change in astronomical forcing during the Early Toarcian in association with the T-OAE and the $\delta^{13}C_{org}$ excursion. Sabatino et al. (2009) hold that eccentricity forcing controlled cyclicity in $\delta^{13}C_{org}$ and $CaCO_3$, as seen through the OAE interval in sections in the Apennines (including the one studied here, the Valdorbia section) and the Alps. Over the last year several papers have dealt with this topic:

a) the analysis of high-resolution magnetic susceptibility data from the southern Paris Basin involving the entire Toarcian Stage (Boulila et al. 2014) revealed a stable 405 kyr cyclicity, as well as significant periodicities representing short term eccentricity, obliquity and precession, emphasizing the strong expression of the obliquity-scale signal (30 to 34 kyr) in the T-OAE interval;

b) likewise, Huang and Hesselbo (2014) analyzed the sections of Peniche, Yorkshire, Dotternhausen and Valdorbia, confirming that pre- and post-CIE intervals show a strong precession-eccentricity-forced climate change, whereas the CIE interval is dominated by obliquity forcing; and finally

c) Ruebsam et al. (2014), at the Lorraine Sub-Basin (NE Paris Basin), on magnetic susceptibility and sediment color data, confirm the presence of eccentricity, obliquity and precession in the Tenuicostatum Zone, then eccentricity and obliquity in the black shale interval (*sensu lato*), at the base of the Serpentinum Zone (base of the Elegantulum Subzone), obliquity and precession for the rest of the Elegantulum Subzone, and again eccentricity, obliquity and precession during the Falciferum Subzone (upper part of the Serpentinum Zone).

According to the different cyclostratigraphic proposals, disagreement also surrounds the estimated duration of the T-OAE, and the different zones of the Toarcian Stage. Thus, the duration of the Toarcian OAE has been estimated from 120 kyr to 900 kyr based on cyclostratigraphic approaches (see Huang and Hesselbo 2014 for a recent review). Similarly, the duration of zones involved in this study is uncertain; i.e., the Tenuicostatum/Polymorphum ammonite Zone has been estimated as 0.04-0.09 kyr (Boulila et al. 2014), >555 kyr (Ruebsam et al. 2014), ~860 kyr (Huang and Hesselbo 2014), or at least 1 Myr (Ogg & Hinnov 2012); the Serpentinum Zone may have a minimum duration of 1.08 Myr (Ogg & Hinnov 2012), ~1.31 Myr (Ruebsam et al. 2014), or 1.50-1.62 Myr (Boulila et al. 2014); estimations for the Bifrons Zone are 2.12 Myr (Ogg & Hinnov 2012) and 2.15-2.17 Myr (Boulila et al. 2014), and for the Aalensis Zone from 0-13 Myr (Ogg & Hinnov 2012) to 0.44-0.51 Myr (Boulila et al. 2014). For the entire Toarcian, a similar duration around 8.3 to 8.6 Myr has been estimated based on astronomical calibration (Huang et al. 2010; Ogg & Hinnov 2012; Boulila et al. 2014).

Previous cyclostratigraphic analyses at the Valdorbia section

In the Valdorbia section, cyclostratigraphic analyses and characterizations of the involved Milankovitch phenomena are very scarce. A first spectral analysis was conducted on the roughly 18.50 m-thick black shale Toarcian interval (Sabatino et al. 2009); power spectra of $CaCO_3$ revealed the presence of regular cyclicity characterized by a single peak with a mean wavelength of 3.2 m, mainly registered in the lower 6.90 m, and less well defined in the overlying interval. This peak was interpreted to correspond to the ca 100 kyr eccentricity signal based on the associated sedimentation rate (of 3.2 cm/kyr); interpreting the cycle as eccentricity in origin is more plausible than with 15 cm/kyr, if the cycle were assumed as controlled by the 21 kyr precession cycle. Moreover, the sedimentation rate of 3.2 cm/kyr is in line with others estimated for cyclically bedded black shales in Peniche (Portugal) and Belluno (Italy) (Sabatino et al. 2009). Power spectra analysis of the $\delta^{13}C_{carb}$ at the T-OAE negative CIE interval at the Valdorbia section recently confirmed the presence of a well-developed cyclicity - cycles of 3.0 m, 1.2 m and 0.5 m, associated to periods of 100 kyr (eccentricity), 36 kyr (obliquity) and 18 kyr (precession) - suggesting a duration of 620 kyr for the main negative CIE and ~860 kyr for the Polymorphum Zone (Huang & Hesselbo 2014).

Milankovitch cyclicity at the Valdorbia section

The time-series analysis conducted here revealed variable cyclostratigraphic patterns in the Lomb-Scargle periodogram corresponding to the seven studied variables of foraminiferal assemblages (Fig. 5). The peaks of higher significance (CL >80%, in cases between 90-100%) registered by means of the Lomb-Scargle procedure represent cycles (in meters) corresponding to thicknesses of: 3.8-4.1 m / 5.8-6.3 m / 8.2 m / 10.4 m.

Interpretation of the registered cycles is not easy, as no evident pattern emerges, above all when taking into account the particular features of the studied Valdorbia section (see below). To this end, a tentative approach is based on the ratios (relationships) between the registered cycles, as previously successfully applied (i.e., Jiménez-Moreno et al. 2005): 1 (3.8 m)-1.08 (4.1 m) / 1.5 (5.8 m)-1.66 (6.3 m) / 2.16 (8.2 m) / 2.7 (10.4 m). As it is well known, values of the main astronomical periods involving obliquity and precession show variations from pre-Quaternary times (Berger et al. 1989, 1992). According to Hinnov & Hilgen (2012), periodicities of obliquity and precession for the Toarcian (included in the range of 200-205 Ma ago) were around 42.7 kyr, 34.2 kyr, and 33.3 kyr (for the actual obliquity values of 54 kyr, 41 kyr, and 39 kyr), and around 21.3 kyr, 20.2 kyr, and 17.5 kyr, (actual precession of 24 kyr, 22 kyr, and 19 kyr). Considering a more or less constant value for eccentricity of 95-105 kyr, then the ratios between the main astronomical phenomena of precession (17.5 kyr, 20.2 kyr, 21.3 kyr), obliquity (33.3 kyr, 34.2 kyr, 42.7 kyr), and eccentricity (95 kyr, 105 kyr) for the Toarcian would be 1 (17.5 kyr) / 1.15 (20.2 kyr) / 1.22 (21.3 kyr) / 1.9 (33.3 kyr) / 1.95 (42.7 kyr) / 5.4 (95 kyr) / 6 (105 kyr).

A comparison of the relationships derived from the registered cycles in the Valdorbia section (1-1.08 / 1.5-1.66 / 2.16 / 2.7), and those calculated for precession, obliquity, and eccentricity during the Toarcian (1 / 1.15 / 1.22 / 1.9 / 1.95 / 5.4 /6) shows no clear correlation. This might indicate that the cycles observed in Valdorbia do not correspond to the three Milankovitch terms, but only to some of them. To appraise which Milankovitch components could correspond to the registered cycles, we assumed the previous data for the Valdorbia section, with a significant cycle of 3.2-3 m associated to the eccentricity of around 100 kyr (Sabatino et al. 2009; Huang & Hesselbo 2014). Thus, one possibility is that the observed cycle of 3.8-4.1 m in our cyclostratigraphic analysis could be correlated with this eccentricity signal. A way to support this interpretation would be to estimate the duration of the Tenuicostatum/Polymorphum Zone at the Valdorbia section, taking into account its relative completeness, considering that our highest frequency cycle at ~4 m is that of 95-100 kyr. For the Tenuicostatum Zone, a thickness of around 39 m is assigned by Cresta et al. (1989) and Monaco et al. (1994), then followed by Sabatino et al. (2009); according to our cycle of ~4 m/100 kyr, the duration of the Polymorphum Zone could correspond to around 980 kyr. However, this evaluation must be taken with caution because, at the Valdorbia section, the boundary between the Polymorphum and Serpentinum Zones is not well definite, and then a precise thickness assignation is difficult. In a recent study of the Valdorbia section, Bilotta et al. (2010) offer a detailed biostratigraphy of the ammonite faunas of the Pliensbachian-Toarcian, which present a Mirabilis Chronozone (correlated to Polymorphum Choronozone in fig. 1) of around 45.7 m that could correspond to a duration of around 1.1 Ma. Finally, a thickness of around 33 m is indicated in Huang & Hesselbo (2014; fig. 2) for the Valdorbia section from the base of Mirabilis Zone to the base of Serpentinum Zone, that could represent, according to our cycle of ~4 m/100 kyr, a duration of 825 kyr. In light of the different proposals, considering that the registered cycle of ~4 m corresponds to the short-term eccentricity signal of 100 kyr, a duration of around 800 kyr-1.1 Ma could be assigned to the Polymorphum Zone; this value is within the duration range usually proposed for the Tenuicostatum/Polymorphum ammonite Zone (see above). This fact supports the assignation of around 100 ky for our registered cycle at ~4 m, and then a short eccentricity origin.

A similar approach could be conducted for the entire Toarcian. However, as illustrated in several papers from the Valdorbia section (Cresta et al. 1989; Bartolini et al. 1992; Monaco et al. 1994; Sabatino et al. 2009; Bilotta et al. 2010; Huang & Hesselbo 2014), the entire Toarcian at the Valdorbia section is integrated by four partial sections, meaning there are real uncertainties about its completeness.

Assuming that the cycle at around 3.8-4.1 m could correspond to the eccentricity cycle of 95-105 kyr, then the rest of cycles could correspond to a periodicity of ~140-160 kyr (5.8-6.3 m), ~200 kyr (8.2 m) and ~250 kyr (10.4 m). As indicated above, cyclostratigraphic studies in Toarcian sections worldwide revealed a well-developed, highly stable, 405 kyr component of eccentricity (a long-term cycle used as a basic calibration period for cyclostratigraphy; see Laskar et al. 2004, 2011; Hinnov & Hilgen 2012; Boulila et al. 2012; Ikeda & Tada 2013; and Huang & Hesselbo 2014, for recent reviews), while also reflecting the incidence of short-term eccentricity, obliquity, and precession (see cites above). Previously, in the Valdorbia section, cycles of 1.2 m and 50 cm have been interpreted as indicative of cycles of 36 kyr (obliquity) and 18 kyr (precession) (Huang & Hesselbo 2014). In the case study, however, neither the cycle of long-term eccentricity, nor those of obliquity and precession are registered. The absence of these cycles could be a consequence of the section's incompleteness and the sampling interval (number of samples). In the range of the lowermost frequencies, those associated with the 405 kyr cycle, the absence of a continuous record of the Toarcian succession, and incompleteness (Gradata Zone, Middle Toarcian, and Fallaciosum and Reynesi zones, Late Toarcian are not recorded in Valdorbia section) impede recognition of those cycles. On the other hand, in the range of the higher frequencies, the variable sampling interval (in most cases > 1 m between consecutive samples) complicates recognition of those higher frequency cycles, lower than 1 m, associated with the obliquity and precession signals. Although a direct record of the Milankovitch terms was not obtained, the other recognized cycles at 140-160 kyr (5.8-6.3 m), ~200 kyr (8.2 m) and ~250 kyr (10.4 m) are in the range of those related to the precession and the obliquity amplitude and frequency modulation signals (i.e., Hinnov 2000), or in the range of those registered in spectral and wavelet analysis of the 405 kyr tuned time series (Wu et al. 2013). In other words, they may indirectly support the incidence of these phenomena.

Palaeoenvironmental changes, the response of the foraminiferal assemblage

Foraminiferal analysis is a very useful tool in palaeoenvironmental interpretations, based on the characterization of major controlling factors affecting foraminiferal assemblages, such as food supply, oxygenation, substrate and salinity (Olóriz et al. 2006, 2012; Nagy et al. 2009; Reolid et al. 2010, 2012c). This approach has been applied in assessing the T-OAE phenomena (i.e., Bartolini et al. 1992; Reolid et al. 2012a, b, 2013b, 2014b). Changes in these palaeoenvironmental conditions can be induced by Milankovitch forcing, being foraminiferal analysis a proxy to evaluate the involved cyclicity.

Analysis of the registered cycles shows no similar pattern regarding the studied variables; significant differences observed in the foraminiferal assemblage can be interpreted as evidence of a variable response to palaeoenvironmental changes induced by the Milankovitch forcing. Thus, several groups are discerned:

a) a first group involving nodosariids and spirillinids shows a well-developed, nearly exclusive cyclicity, associated with the cycles of 6.1-6.3 m and 8.2 m. *Nodosaria*, *Lingulonodosaria* and *Pseudonodosaria* are active deposit feeders and bacterial scavengers having a shallow infaunal lifestyle (e.g., Koutsoukos et al. 1990; Reolid et al. 2013b). Rey et al. (1994) suggested that the elongated shells of nodosariids during the Early Jurassic would indicate adaptation to confined environments. In the case of *Spirillina*, the main epifaunal genus in the foraminiferal assemblages of Valdorbia section (see Bartolini et al. 1992; Monaco et al. 1994; Nochi & Bartolini 1994), this epifaunal-phytal form (Morris 1982; Kitazato 1988; Reolid et al. 2008a, b) has been interpreted as related to the abundance of trophic resources of photosynthetic origin (Bouhamdi et al. 2001; Olóriz et al. 2003). Yet according to Reolid & Martínez-Ruiz (2012), *Spirillina* presents low tolerance to oxygen-depleted conditions, regardless of food availability;

b) a second group consisting of uniserial forms of the Suborder Lagenina, and separately *Prodentalina* and *Eoguttulina*, is characterized by a single, constant, significant cycle of 10.4 m. Both the uniserial Lagenina group and *Prodentalina* are shallow infaunal forms. *Prodentalina* is interpreted in the Valdorbia section as a relatively unspecialized form that proliferates in oxygenated environments (Bartolini et al. 1992; Nocchi & Bartolini 1994). *Eoguttulina* is a spiral-sigmoidal elongated form with asymmetrical alternating chambers interpreted as inhabiting shallow to deep infaunal microhabitats, as active deposit feeders and grazing omnivores (Reolid et al. 2013). *Eoguttulina* was an opportunist during the Early Jurassic, and proliferates under oxygen restricted conditions (Nocchi & Bartolini 1994; Reolid et al. 2012a, 2013b, 2014b);

c) cycles at the higher frequency band of 3.8-4.1 m are registered in forms of both groups; nodosariids (first group) and uniserial Lagenina plus *Prodentalina* (second group);

d) the number of species appears to have a cyclostratigraphic pattern involving cycles from the two differentiated groups: 5.8 m (first group) and 10.4 m (second group);

e) *Lenticulina* shows a particular cyclostratigraphic pattern with nearly exclusive cycles at 6.7 m and 5.1 m, the latter also registered in *Eoguttulina*. The genus *Lenticulina* corresponds to planispiral biconvex forms with life habit ranging from epifaunal to deep infaunal microhabitats (e.g., Tyszka 1994; Reolid et al. 2012b; Reolid 2014). It has been interpreted as opportunist during the Jurassic (Rey et al. 1994; Tyszka 1994; Reolid et al. 2012a, b; Reolid 2014).

Conclusions

Cyclostratigraphic analysis of foraminiferal data from the Toarcian succession at the Valdorbia section (Umbria-Marche Apennines) confirms the Milankovitch orbital input during deposition. Different order cycles are registered, the main one of ~4 m interpreted as directly related with short-term eccentricity (95-105 kyr). The rest of the cycles, in the range of 5.8 m to 10.4 m, could be indirect signals associated with the long-term eccentricity, obliquity and precession, difficult to register due to the incompleteness of the studied succession and sampling interval. Variable cyclostratigraphic patterns within the studied foraminiferal assemblage reveal different responses of the components to palaeoenvironmental changes of Milankovitch origin, according to their particular requirements.

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