CALCAREOUS NANNOFOSIL BIOSTRATIGRAPHY AND PALEOCEANOGRAPHY
OF THE TOARCIAN OCEANIC ANOXIC EVENT AT COLLE DI SOGNO
(SOUTHERN ALPS, NORTHERN ITALY)

CRISTINA EMANUELA CASELLATO & ELISABETTA ERBA

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Abstract. We present calcareous nannofossil biostratigraphy and abundances for the Upper Pliensbachian-Lower Toarcian interval, including the Toarcian Oceanic Anoxic Event (T-OAE), represented by the Fish Level at Colle di Sogno (N Italy). In addition to biohorizons identifying NJT 5 and NJT 6 nannofossil zones, the first occurrences of C. superbus and D. strigatus constrain the onset and the end of the T-OAE, respectively. We propose the last occurrence of M. janae as additional event to approximate the end of the T-OAE at lower latitudes. Quantitative data highlight the “Schizosphereella decline” marking the Pliensbachian/Toarcian boundary and the “Schizosphereella crisis” at the onset of the T-OAE as supplementary biohorizons. S. punctulata and M. janae constitute most of the micrite in the interval below the Fish Level, which is marked by an increase in abundance of small coccoliths remaining abundant in the overlying interval, with limited contributions of S. punctulata, while M. janae disappears.

Principal Component Analysis implemented nannofossil paleoecological and paleoenvironmental reconstructions. The latest Pliensbachian was characterized by stable oligotrophic conditions favourable to calcification at low pCO2 levels promoting the proliferation of deep-dwelling and highly-calciﬁed S. punctulata. During the earliest Toarcian an initial pulse of continental run-off introduced terrigenous material favouring the intermediate-dweller M. janae and the low-salinity adapted Calcycula. Higher nutrient concentrations and ocean acidification magniﬁed during the T-OAE, stimulating mesotrophic low-calciﬁed coccolith-producers and suppressing k-strategist deep- to intermediate-dwellers. After the T-OAE, partial recovery of calcareous nannoplankton indicates still perturbed conditions. Ecosystem modiﬁcations anticipated the T-OAE of ~1 million years with species origination and major changes in assemblages.

Introduction

In the last thirty years, much attention has been devoted to Jurassic calcareous nannofossils to explore their potential as stratigraphic tool for correlations at regional to global scale. During the Early Jurassic, the Late Pliensbachian-Early Toarcian interval was a crucial time for calcareous nannoplankton evolution as a major speciation episode took place and some of the most common Jurassic and Cretaceous genera (Biscutum, Lotharingius, Discorhabdus and Watznaueria) appeared and rapidly evolved (Bown 1987; Mattioli & Erba 1999; Bown et al. 2004; Erba 2004, 2006) providing a number of biostratigraphic events. The Early Jurassic world was characterized by nannoplankton paleoprovincialism (Bown 1987, 1992; Baldanza et al. 1995) and, therefore, two different biostratigraphic schemes were proposed: a Boreal biozonation based on Northern Europe sections (UK, Germany, The Netherlands) (Bown 1987; Bown et al. 1988; Bown & Cooper 1998) and a Tethyan biozonation based on lower latitude sections (Italy, W Portugal, Central Hungary, SW Germany, S France, Greece) (Mattioli & Erba 1999).

The latest Pliensbachian to Early Toarcian time interval was marked by paleoclimatic and paleoceanographic perturbations, associated to transient and long-lasting C isotope anomalies, including the Toarcian Oceanic Anoxic Event (T-OAE) (Jenkyns 1988, 2003, 2010; Hesselbo et al. 2000).
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horizons characterizing the Late Pliensbachian-Early
Toarcian time interval offers the opportunity to biostra-
tigraphically constrain the T-OAE. We investigated
calcareous nanofossil assemblages of the Colle di Sog-
gno section (Upper Pliensbachian-Lower Toarcian inter-
val), located in the Lombardy Basin within the Southern
Alps. This section was previously studied for lithostra-
tigraphy (Gaetani & Poliani 1978) and nanofossil con-
tent (Erba 2004). Jenkyns & Clayton (1986) document-
ed low-resolution carbon and oxygen isotopic profiles
for the uppermost Pliensbachian-lowermost Toarcian
interval, including the T-OAE organic-rich sediments.

The objectives of this study are: A) nanofossil biostratigraphy for dating the Colle di Sogno section and making comparisons with available data to assess biohorizon reproducibility at regional to global scales; B) nanofossil quantitative abundances and statistical analyses for reconstruction of paleoecological affinities and paleoceanographic conditions preceding, during and following the T-OAE perturbation.

Geological Setting and Lithostratigraphy

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can prontmonitory, the Adriatic plate (Fig. 2). During
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phase further differentiated deep basins and pelagic struc-
tural highs, bounded by synsedimentary faults that
ruled facies distribution (Winterer & Bosellini 1981;
Baumgartner et al. 2001). In the deeper parts sedimen-
tary successions are thick, continuous and temporarily
characterized by a pelagic turbiditic regime, whereas
condensed and partially discontinuous sedimentation
characterizes the pelagic highs.

This study was conducted on the Colle di Sogno
section located in the depocentre of the Albenza Plateau
(Fig. 1B), where a continuous Jurassic sequence is ex-
posed (Muttoni et al. 2005). In particular, we focus on
the Upper Pliensbachian-Lower Toarcian interval (Fig.
3), previously characterized for lithostratigraphy, bio-
stratigraphy and chemostatigraphy (Gaetani & Poliani
1978; Jenkyns & Clayton 1986; Lozar 1995; Mattioli &
Erba 1999; Erba 2004), therefore providing an inte-
grated stratigraphic framework for calibration of nan-


cased fossil biohorizons and zones. The ammonites (Da-
tyloceras simplex Fucini and Partschyceras anonymum
Haas) from the top of Domarò Limestone (Lmst.) cor-
respond to the tenisostatum ammonite Zone (AZ)
(Gaetani & Poliani 1978). A few ammonite specimens
(Dactyloceras polymorphum Fucini and Hildaites sp.
ind.) found approximately one meter above the top of
the Fish Level (Gaetani & Poliani 1978) suggest the fal-
terum AZ as discussed by Jenkyns et al. (1985),
who interpreted Dactyloceras specimens as reworked.

Low-resolution 613C data of Jenkyns & Clayton
(1986) document a negative shift at the Domarò Lmst./
Sogno Formation (Fm.) boundary. Such an anomaly
was recognized in different stratigraphic settings and
dated as Pliensbachian/Toarcian boundary in recent pa-
pers (Hesselson et al. 2007; Suan et al. 2008, 2010), and thus reinforces the age assignment based on ammonites of the topmost layer of the Domaro Lmst. Another negative excursion grossly correlates with the Fish Level: this is the widely recognized carbon isotope excursion associated with the T-OAE, and suggests that the Fish Level is the local sedimentary expression of this event.

The studied ~30 m-thick interval, spanning the uppermost part of the Domaro Lmst. and the lowermost part of the Sogno Fm. (Fig. 3) is located along the road SP 179 leading northward from the village of Sogno to Colle di Sogno, on the northern slope of Mt. Brughetto (45°47'29" N, 9°28'44" E). The Domaro Lmst. consists of light grey marly limestone and lime stone in 25-15 cm-thick beds, with greenish marly claystone interbeds, which sometimes reach a thickness up to 5 cm. Rare grey cherts nodules and lists, 1-2 cm-thick, are present. The lithostratigraphic boundary with the Sogno Fm. is sharp and marked by the occurrence of a 27 cm-thick interval of greenish marly claystone. The lower 8.27 m of the Sogno Fm. consists of greenish and reddish marlstone and limy marlstone in 25 to 5 cm-thick beds. A slumped interval is present between 2.90 m and 4.75 m. A carbonate-poor interval named Fish Level, corresponding to the sedimentary expression of the T-OAE, consists of dark greenish-grey marly claystone in the lower portion (8.27-10.73 m) and dark brown marly claystone to fissile black shale in the upper part (10.73-12.98 m). The interval above the Fish Level comprises light brownish grey marlstone and limy marlstone organized in 20 to 40 cm-thick strata.

As far as microfacies are concerned, the Domaro Lmst. consist of light brown mudstone-wackestone with pelagic bivalves, radiolarians and echinoderm fragments. The lithostratigraphic boundary between the Domaro Lmst. and Sogno Fm. is marked by an increase of extracasts (especially quartz and mica). Light brown mudstone passing upward to reddish brown mudstone characterizes the lower portion of the Sogno Fm. Pelagic bivalves, radiolarians and echinoderm fragments are the dominant bioclasts. Just below the Fish Level base, the microfacies consists of light brown wackestone with abundant isorotated pelagic bivalves. Mudstone with high organic matter, clay and dark mineral contents are observed through the Fish Level. Two portions are distinguished on the basis of micrite color and allochem content: the lower part corresponds to dark reddish brown micrite, while the upper part consists of very dark brown micrite with relatively frequent radiolarians, echinoderm fragments and dark minerals. Above
Fig. 3 - Lithostratigraphy and calcareous nanofossil biostratigraphy of the Colle di Sogno section. The main events of Mattioli & Erba (1999) are in bold. @ = ammonite findings after Gaetani & Polliani (1978) are discussed in the text. The C isotope curve is after Jenkyns & Clayton (1986). Microfacies were defined according to Dunham (1962) classification, employing the tables of Baccelli & Bossellini (1965) for percentage estimation of allochems.
the Fish Level mudstone consists of light brown micrite with an allochemical content decreasing upwards.

**Materials & Methods**

Calcareous nannofossil biostratigraphy was performed on a total of 163 samples (Fig. 3). Average sampling rate is ~20 cm through the section, with exceptions of the lowermost 6 m, having much wider sample spacing, and the interval across the Domaro Lmst./Sogno Fm. boundary and the Fish Level both sampled every 10 cm. Samples were prepared from muddy limestones and limestones of the Domaro Lmst. and marlstones, limy marlstones, marly claystones and black shales of the Sogno Fm.

Biostratigraphic analyses were performed on smear slides prepared as follows: a small amount of rock material was powdered adding few drops of bi-distillate water, without centrifuging, ultrasonic cleaning or settling the sediment in order to retain the original composition. The obtained suspension was mounted onto a slide, covered with a cover slide and fixed with Norland Optical Adhesive. Smear slides were investigated using a light polarizing microscope, at 120X magnification. Calcareous nannofossil preservation and semi-quantitative abundances were evaluated by examining at least 400 fields of view in each smear slide. The biostratigraphic scheme adopted is that of Mattioli & Erba (1999). Calcareous nannofossil taxa recognized are listed in Appendix 1. The range chart is reported in Appendix 2.

Calcareous nannofossil quantitative analyses were performed on 49 samples, selected every 40-80 cm, with exception of the Fish Level analyzed every 40 cm. Absolute abundances were obtained counting all specimens in 1 mm² of ultrathin sections (7 µm thick), following the methodology of Erba & Tremolada (2004). For quantitative analyses calcareous nannofossil taxa were counted at the generic level, because the use of ultrathin section partly constrain the identification at specific level. While this type of investigation is ideal for large-sized and highly calcified taxa (e.g. *Mitrilithus, Schizopherella*), that result to be unequivocally detectable and quantifiable, small and medium size coccoliths (e.g. *Biscutum, Lotharingium*) are often covered. Moreover, the delicate structure of smaller coccoliths is frequently incomplete due to slicing and thinning of ultrathin sections.

Within genus *Biscutum, B. finchii* is the dominant species while *B. novum*, *B. duttoni* and *B. grande* are rare to absent in a few samples. *Lotharingium haussii* is dominating the *Lotharingium* spp. group, while other species (*L. horoz*, *L. crucicentrata*, *L. froidi*, *L. sigillatus*, *L. umbriensis*, *L. velatum*) are rare. Concerning *Carnottolitus*, *C. poulnabrone* and *C. superbus* are equally abundant, while *C. cantabropu* gives a very little or no contribution. *Crepidolithus crassus* largely dominates the genus *Crepidolithus* since *C. conus* and *C. granulatus* are sparse. Counting and statistical treatment at generic level were previously adopted by Bour et al. (2007). Also, some datasets of individual species abundances were grouped at generic level for statistical analyses to overcome very low percentages (Tremolada et al. 2004; Agüedo et al. 2008; Mattioli et al. 2009; Fraguas et al. 2012; Clémence et al. 2015).

Principal component analysis (PCA) was performed on calcareous nannofossil abundances with the free statistical software Past v1.94b (Hammer et al. 2001). The method to extract factors was eigenvalues. The PCA method facilitates interpretations of complex data sets, reducing large data matrix composed of several variables to a small number of factors representing the main modes of variations (Fukunaga 1992; Beaufort & Heusner 2001). As *Schizopherella punctulata* is considered a dinoflagellate cyst (Kalin & Bennouli 1984), two datasets were used in including and excluding this taxon. For both datasets, absolute abundances and percentages (the latter calculated from the total absolute abundances) of all taxa were introduced in the analysis. Furthermore, PCA was performed on both the entire studied interval, and on the interval bounded by the first occurrence (FO) of genus *Carnottolitus* and the last occurrence (LO) of *Mitrilithus janseii* in order to consider the real absence or presence within the stratigraphic range of taxa. Carbonate content analyses were performed on a total of 156 samples. Bulk rock samples were reduced to fine powder in agate mortar. Carbonate content was obtained using a Dietrich-Frühling calcimeter, measuring the CO₂ volume produced by the complete dissolution of pre-weighted samples in 37% vol. HCl. Standards of pure calcium carbonate were measured every five samples to ensure proper calibration.

Microfacies were analyzed on the same 49 thin sections used to achieve calcareous nannofossil absolute abundances (Fig. 3).

**Taxonomic notes**

In this paragraph, remarks concerning morphological and/or dimensional features of a few taxa (*B. finchii, C. crassus, M. janseii, and S. punctulata*) observed under the light polarizing microscope are reported, alphabetically ordered per genus. Furthermore the descriptions of *Rucmolithus* sp. and *Watznaurina* sp. 1 are reported.

**Genus Biscutum** Black in Black & Barnes, 1959

**Biscutum finchii** (Crux, 1984) Bown, 1987

**Remarks**. In the studied section rare to frequent specimens of *B. finchii* with dimensions smaller than the holotype (5.6 µm length - 4.7 µm width) were observed. The specimens with length < 5.5 µm are here reported as "small *B. finchii*" (Pl. 1, figs 6-7), while specimens with length = 5.5 µm are reported as *B. finchii* (Pl. 1, figs 8-9) (Appendix 2). The “small *B. finchii*” specimens are characterized by a subcircular outline and prominent distal shield. They partially correspond to the morphotypes named as *B. all. *B. finchii* by Cobianchi (1992, 1992) and as "small *B. finchii*" by Picotti & Cobianchi (1996), who separated specimens with length < 6 µm.

**Stratigraphic observations**. "Small *B. finchii*” is present from the lowermost studied sample, below the FO of *B. finchii*. Similarly, Cobianchi (1992) and Picotti & Cobianchi (1996) documented "small *B. finchii*" in the interval preceding the FO of *B. finchii*, before the FO of *L. haussii*. In the studied section, *B. finchii* is observed from the uppermost part of the NTJ 5a Subzone, between the FOs of genus *Calycalis* and *L. sigillatus*, at a similar stratigraphic level to that reported by Cobianchi (1992).

**Genus Crepidolithus** Noël, 1965

**Crepidolithus crassus** (Deflandre in Deflandre & Fert, 1954) Noël, 1965

**Remarks**. The holotype of *Discolithus crassus* has dimensions of 8.2 µm length and 5.5 µm width. Later,
Noël (1965) moved this species in the *Crepidolithus* genus, and pointed out the co-occurrence of specimens with smaller dimensions (3.7–4.4 μm length and 2.3–3.2 μm width). Bown (1987) reported specimens with size ranges of 5.0–9.0 μm for length and 3.5–5.5 μm for width. In this study, specimens displaying length = 5 μm and width = 3.5 μm are attributed to *C. crassus* (Pl. 1, figs 18–19), while specimens with length < 5 μm and width < 3.5 μm are reported as “small *C. crassus*” (Pl. 1, fig. 20) (Appendix 2).

**Stratigraphic observations.** “Small *C. crassus*” and *C. crassus* co-occur through the studied interval, although the small one presents a discontinuous occurrence and is rarer than the latter.

**Genus Mitrolithus** De Bellandre, 1954 in De Bellandre & Fort, 1954

*Mitrolithus jansae* (Wiegand, 1984) Bown in Young et al., 1986

**Remarks.** This species was described as *Calcivascularis jansae* by Wiegand (1984), a nannolith of 2.4–5.6 μm length (height) and 3.2–5.6 μm maximum width (holotype: 2.3 μm length – 3.5 μm maximum width). Later, Bown (in Young et al. 1986) moved this species in the *Mitrolithus* genus, pointing out a considerable variation in dimensions and reporting a comprehensive size of 4–8 μm, without specify length or width. Bown (1987) also remarked a great size variation, describing ranges of 3.0–4.6 μm for maximum width, and 2.3–5.3 μm for rim height. Later Bown & Cooper (1989) specified a height variability of 2.3–5.6 μm. A notable variation of murolith height was reported by previous Authors (plate 1, Mailliot et al. 2006; plate 1, fig. 5, Fraguas et al. 2008; fig. 5a–c, Bodin et al. 2010; plate 1, figs 9–12, Reggiani et al. 2010b; figs 56–60, Sandoval et al. 2012). Specimens observed in the studied samples show height variability from 3 to 8 μm. Moreover, we noticed that the thickness of outer elements of the murolith varies from 0.5 to 2 μm. Specimens characterized by very thin outer elements (<1 μm) and displaying grey to whitish colours under crossed nicols are distinguished here as “*thin *M. jansae*” (Pl. 1, figs 26–27), while specimens with thicker outer elements, displaying bright white to yellow colours, are attributed to *M. jansae* (Pl. 1, fig. 28) (Appendix 2). The structure of the central spine is identical in both morphotypes.

**Stratigraphic observations.** Specimens of *M. jansae* and “*thin *M. jansae*” co-occur in the Domaro Lmst. and in the lower portion of the Sogno Fm. below the Fish Level. “*Thin *M. jansae*” is the only morphgroup present through the Fish Level where no regular *M. jansae* specimens were observed. “*Thin *M. jansae*” disappears one meter above the top of the black shale interval.

In the studied section, the rim height variability has no stratigraphic significance: tall and short specimens co-occur with comparable abundances through the Domaro Lmst. and the Sogno Fm., displaying similar trends.

**Genus Rucinolithus** Stover, 1966

*Rucinolithus* sp. ind.

**Description.** Polyccololith specimens consisting of 7–9 imbricated elements, with radial symmetry, and showing high birefringence colours. The elements are arranged slightly irregularly and have a petaloid shape with rounded ends. The outline is sub-circular, display-

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**PLATE 1**

Scale bars represent 2 μm.

Figs. 1-2 - *B. dubium*, 1) cross-polarized light, 2) quartz lamina, sample 72B (2.8 m).

Figs. 3-4 - *B. grande*, 3) cross-polarized light, 4) quartz lamina, sample 71A (0.2 m).

Fig. 5 - *B. prinssi*, cross-polarized, sample 71B (0.3 m).

Figs. 6-7 - “*small B. finschi*”, 6) cross-polarized light, 7) quartz lamina, sample 84BB (14.5 m).

Figs. 8-9 - *B. finschi*, 8) cross-polarized light, 9) quartz lamina, sample CS-L1-78 (4.80 m).

Fig. 10 - *B. lescunensis*, cross-polarized, sample 73A (1.05 m).

Fig. 11-13 - *Calyculus sp.* aude view, cross-polarized light, 11) sample 84Z (11.45 m), 12) sample 84D (9.45 m), 13) sample 3A (~0.15 m).

Fig. 14-15 - *C. poulnabronrei*, aude view, cross-polarized light, 14) sample 84P (10.75 m), 15) sample 84U (11.25 m).

Figs. 16-17 - *C. superbus*, 16) cross-polarized light, 17) quartz lamina, sample 84C (9.35 m).

Figs. 18-19 - *C. crassus*, cross-polarized light, 18) sample 3Q (~3.6 m), 19) sample CS-L1-75 (2.6 m).

Fig. 20 - “*small C. crassus*”, cross-polarized light, sample TS 38.00 (~9.6 m).

Fig. 21 - *C. crasso*, cross-polarized light, sample 71A (0.2 m).

Fig. 22 - *C. granulatus*, cross-polarized light, sample 71A (0.2 m).

Figs. 23-24 - *D. constans*, 23) cross-polarized, 24) quartz lamina, sample 85B (15.15 m).

Fig. 25 - *M. lenticularis*, cross-polarized, sample 71A (0.2 m).

Figs. 26-27 - “*thin M. jansae*”, cross-polarized, 26) sample 73B (1.1 m), 27) sample 3K (~2.3 m).

Fig. 28 - *M. jansae*, cross-polarized, sample 72D (1.0 m).

Figs. 29-30 - *D. ignotus*, 29) cross-polarized, 30) quartz lamina, sample 84AA (11.55 m).
ing a diameter comprised between 6 and 8 µm (Pl. 2, figs 16-17).

**Remarks.** The observed specimens are very similar to *R. terebrodentium* (Covington & Wise 1987; Tremolada & Erba 2002). *Rubiolithus* specimens are common in Cretaceous sequences (Stover 1966; Covington & Wise 1987; Erba 1994, 2004; Burnett 1998; Tremolada & Erba 2002) and were recently described from the Middle Jurassic (Tiraboschi & Erba 2010). This is the first time that *Rubiolithus* is reported from the Lower Jurassic. Specimens observed in this study generally belong to the “small *Rubiolithus*” category of Tiraboschi & Erba (2010, fig. 6 pictures 1-8).

**Stratigraphic observations.** These nannoliths were observed in the lower part of the studied section up to the base of the Fish Level. They are rare within the NJT 5a Subzone and become extremely rare in the NJT 5b Subzone.

Genus *Schizophaerella* Deflandre & Dangeard, 1938

*Schizophaerella punctulata*  
Deflandre & Dangeard, 1938

**Remarks.** This species was described as a nannolith composed by two interlocked valves with a diameter of 12-30 µm (Deflandre & Dangeard 1938). Later, other Authors pointed out specimens with smaller dimensions: Bown (1987) and Cobianchi (1992) reported a diameter of 8-12 µm, while Mattioli & Pittet (2002) gave a range of 7-13.5 µm. In the studied section specimens displaying dimensions of 4-7 µm are separated as “small *S. punctulata*” (Pl. 2, figs 15, 20) while specimens with diameter = 7 µm are reported as *S. punctulata* (Pl. 2, figs 21-22; Fig. 4A) (Appendix 2). Additionally, specimens surrounded by fringing crust of radiating prismatic crystals were also observed, and grouped as “encrusted *S. punctulata*” (Pl. 2, figs 23-25; Fig. 4B-C-D) (Appendix 2). The thickness of fringes varies from 2 to 5 µm. It is to be pointed out that crusts affect only specimens with a diameter > 7 µm.

**Stratigraphic observations.** “Small *S. punctulata*” and *S. punctulata* occur together through the studied interval, both showing a drastic decrease in abundance within the Fish Level. “Small *S. punctulata*” is less abundant above the black shale interval. “Encrusted *S. punctulata*” is present in the Domaro L.mst. and in the lower part of the Sogno Fm., prior to the base of the Fish Level.

**Discussion.** Kälin (1980) described specimens of *S. punctulata* with fringes of radial crystals in samples from the Southern Alps, Tuscany and Umbrian sequences (Kälin 1980, fig. 14), and demonstrated their early diagenetic origin, with formation of neomorphic calcite, possibly controlled by a low Mg/Ca ratio of oceanic waters (Kälin & Bernoulli 1984). Although a diagenetic origin of such crusts is not questioned, we point out that diagenetic processes should affect all *S. punctulata* specimens with a diameter > 7 µm, therefore it is difficult to explain why encrusted morphotype occur together with non-encrusted ones of similar dimensions.

Genus *Watznaueria* Reinhardt, 1964

*Watznaueria* sp. 1 Cobianchi et al., 1992

**Remarks.** *Watznaueria* coccoliths 3-5 µm length and 2-4 µm width with a small open central area. At crossed nicols they show white birefringence colours (Pl. 2, figs 18-19).

**Discussion.** Comparable specimens were reported as *W. aperta* by Erba & Cobianchi (1989). Cobianchi et al. (1992) and Gardin & Manivit (1994) described analogous coccoliths as *Watznaueria* sp. 1, whereas Reale et al. (1992) and Baldanza & Mattioli (1992) reported similar specimens as *W. burnesiae*. Mattioli (1996) revised the latter attribution, ascribing the specimens to *Watznaueria* sp. 1. Mattioli & Erba (1999)
used the name *W. fossacincta* for *Watznueria* coccoliths with a small open central area (fig. 10, Mattioli & Erba 1999).

The specimens observed in this study have shield dimensions (both length and width) smaller than *W. fossacincta*, and display a proportionally smaller central opening than *W. fossacincta*. Therefore, we maintain the name *Watznueria* sp. 1 in analogy with Cobianchi et al. (1992) and Mattioli (1996).

**Stratigraphic observations.** The FO of *Watznueria* sp. 1 is the youngest biohorizon detected in the studied section (above the Fish Level) and, as reported by previous Authors (Cobianchi et al. 1992; Mattioli 1996), marks the appearance of genus *Watznueria* in the Early Toarcian.

**Results**

Calcereous nanofossil preservation and abundance vary through the studied section, generally increasing from the Domaro Lmst. to the Sogno Fm. Nanofossil preservation seems to be lithology-dependent, improving from limestone to marlstone. Nanofossils from the Domaro Lmst. display a preservation ranging from poor to moderate and a total abundance varying from rare to frequent/common. The marly lithologies of the Sogno Fm. show a slightly better nanofossil preservation (from poor/moderate to moderate) and abundance (frequent/common). In the Fish Level and in the overlying interval abundances fluctuate from rare to common, while preservation is still poor/moderate to moderate. Although the preservation of
calcareous nannofossils ranges from poor to moderate, primary signals are present. In fact, the continuous occurrence of small and delicate taxa, prone to dissolution such as Biscutum and delicate species of genus Lotharingius (L. barozii, L. velatus) ensures that diagnosis has not been pervasive. Moreover, these dissolution-prone taxa increase in abundance when robust and dissolution-resistant genera (e.g. Schizosphaerella and Mitro lithus) show a major decrease that, thus, cannot be ascribed to diagnosis.

Biostratigraphy

The biostratigraphic scheme adopted in this study is that of Mattioli & Erba (1999). Seventeen calcareous nannofossil biohorizons were recognized (Fig. 3), including 9 main and 3 rare biohorizons. Based on the main ones we identified the Lotharingius haussii Zone (NJT 5), divided into Biscutum finchii (NJT 5a) and Lotharingius sigillatus (NJT 5b) Subzones, and the Carinolithus superbus (NJT 6) Zone (Mattioli & Erba 1999).

The oldest investigated sample is assigned to the latest Pliensbachian NJT 5a nannofossil Subzone, based on the presence of L. haussii and L. barozii in the lowest sample (~11.97 m). Within the NJT 5a Subzone few biohorizons were identified: the FOs of Calyculus, B. grande and Bussumius primiti (~6.4 m), followed by the FOs of L. fredoii (-5.0 m) and Bussumius leuconensis (~4.55 m). The FO of L. sigillatus (0.4 m) defines the NJT 5a/NJT 5b subzonal boundary: this biohorizon approximates in the Tethyan area the Pliensbachian/Toarcian boundary (Mattioli & Erba 1999), that at Colle di Sogno corresponds to the Domaro Lmst./Sogno Fm. lithostratigraphic boundary (Gaetani & Poliani 1978).

In the Early Toarcian NJT 5b Subzone, the following biohorizons were detected: FOs of C. poulnabronei (0.5 m), L. crucicentrals (1.05 m) and C. cantaluppu (1.2 m). Near the NJT 5b top, the FO of Diductus constans was observed (~8.3 m). The FO of C. superbus (8.75 m) defines NJT 5/NJT 6 zonal boundary. The top of NJT 6 Zone was not detected due to the absence of Discorhabdus strinus in the studied interval. In the NJT 6 Zone, the FOs of L. velatus (10.1 m) and Discorhabdus ignotus (11.55 m), followed by the LOs of Similiscutum cruci culus (11.65 m), M. jansae (14.05 m) and Mitro lithus leuconensis (15.3 m) were recognized. The youngest biohorizon detected is the appearance of genus Watznauresi, with the FO of Watznauresi sp.1 (15.6 m).

The calcareous nannofossil assemblage characterizing the NJT 5a Subzone is dominated by S. punctulata and M. jansae (both frequent to common) and L. haussii (rare/frequent to frequent/common), while genera Crepidolithus, Biscutum and Calyculus are rare. Within Schizosphaerella, S. punctulata is dominant (rare/frequent to frequent/common), while “small S. punctulata” and “encrusted S. punctulata” are subordinated (rare to rare/frequent). Within the M. jansae group, “thin M. jansae” is dominating (rare/frequent to common), while M. jansae is subordinated (rare to rare/frequent).

Assemblage of the NJT 5b Subzone is dominated by L. haussii (frequent to common), S. punctulata and M. jansae (rare/frequent to frequent/common). Among schizosphaerellids, S. punctulata is the dominant form, showing an increase in abundance upwards: in the Sogno Fm. portion below the slumped interval, it is rare to frequent, and becomes frequent to frequent/common between the slumped interval and the Fish Level. “Small S. punctulata” is rare to frequent, decreasing upwards. “Encrusted S. punctulata” is rare and observed only below the Fish Level. Within the NJT 5b Subzone “thin M. jansae” is more abundant (rare/frequent to common) than M. jansae (rare to frequent/common); the latter is observed only below the Fish Level. Genera Carinolithus and Biscutum are rare/frequent to frequent, while genera Calyculus and Crepidolithus are rare. Through the NJT 5 Zone, extremely rare specimens of Rucinolithus sp. were observed.

The taxa dominating the assemblage of NJT 6 Zone belong to the genus Lotharingius (L. haussii frequent/common to common/abundant; L. fredoii and L. sigillatus frequent; L. velatus, L. crucicentrals and L. umbriensis rare to frequent). The assemblage of the lower part of NJT 6 Zone (corresponding to the Fish Level) is also characterized by genera Biscutum, Calyculus and Carinolithus, which are frequent, while genera Schizosphaerella, Mitro lithus and Crepidolithus are very rare. The assemblage of the uppermost part of NJT 6 Zone (above the Fish Level) is characterized by rare to frequent S. punctulata (both S. punctulata and “small S. punctulata”), Biscutum and Carinolithus.

Comparison with previous works

The biohorizons recognized at Colle di Sogno (Fig. 5B) are compared to the events of Mattioli & Erba (1999) to discuss analogies and/or differences. In the latest Pliensbachian-Early Toarcian interval (spinatum serpentinitis Ammonite Zones - AZs) Mattioli & Erba (1999) identified twenty-one calcareous nannofossil events (i.e. fourteen main events, five rare and two subjected to further investigations) and defined four zones (Fig. 5A). In the studied section all biohorizons of Mattioli & Erba (1999) were recognized with the exception of FOs of Similiscutum lovei and Watznauresia colacchi. The succession of main and rare biohorizons of latest Pliensbachian age at Colle di Sogno shows minor differences with Mattioli & Erba (1999). In fact, the FO of C. cantaluppu is detected slightly after the FO of L. crucicentrals, most probably due to the rarity of C. cantaluppu in the studied material. At Colle di Sogno, the FO of L. fredoii is observed after the FO of genus Calyculus, possibly because this species is rare in its
lower range. Our results confirm the LO of *M. jansae* (thin specimens) between the FOs of *D. ignotus* and *Watznaueria* sp. 1 (*W. fossacincta* of Mattioli & Erba 1999), thus this biohorizon appears to be reliable and that it can be considered a main one, at least for low-latitude Tethyan sites. The FO of *D. constans*, an event not reported by Mattioli & Erba (1999), was detected below the FO of *C. superbus*, within the NJT 5b Subzone at Colle di Sogno. Gardin & Manivit (1994) reported this biohorizon from the Early Toarcian, below the FO of *Watznaueria* sp. 1; De Kaenel et al. (1996) reported it above the FO of *C. superbus*, while Bown & Cooper (1998) only reported a questionable appearance datum from the earliest Toarcian tentucostatum AZ. Recently, the lowest occurrence of *D. constans* was reported from Southern Spain and Germany, below the FO of *C. superbus* (Mattioli et al. 2004; Sandoval et al. 2012). Our result supports the consistency of the FO of *D. constans* and we put this biohorizon in the group of the rare ones (Fig. 5B). The LO of *S. cruciulus* is observed in the NJT 6 Zone, within the Fish Level. It is bracketed between the FO of *D. ignotus* and the LO of *M. jansae*. Mattioli & Erba (1999) considered this event among the ones subject to further investigations and suggested a LO in latest Aalenian. However, in their literature overview, the LO of *S. cruciulus* is reported in the Early Toarcian (De Kaenel & Bergen 1993; Bown & Cooper 1998). Later this biohorizon was attributed to the Early Toarcian in Greece (Kafousia et al. 2014) and Germany (Mattioli et al. 2004). While Perilli et al. (2004) and Perilli & Duarte (2006) reported this species as discontinuously present until the end of the Toarcian in N Spain and Portugal.

Using the zonation of Mattioli & Erba (1999), in Figure 6 we compare nanofossil biohorizons comprised between the FOs of genera *Calyculus* and *Watznaueria* against ammonite biozons (latest Plenianbian to Early Toarcian) as documented for sections in Germany, France, Spain, Portugal, Italy and Greece (see Tab. 1 for references). The chronostratigraphy of each calcareous nanofossil event is discussed below in stratigraphic order.

- The FO of *Calyculus* is reported from the middle-upper *emiaeatum* AZ in Italy and from the upper *spinatum* AZ in Argentina (Al-Suwaidi et al. 2010). This species is present since the base of the Dotternhausen (Germany) and Sancerre-Couy (France) sections, which are assigned to the upper *spinatum* AZ. In two sections from N Spain (Camino and San Andrés) this genus is reported as rare and discontinuous since the *ibex* and *davei* AZs, while in one section form Portugal (Peniche) it is present since the *jamesoni* AZ.

- The FO of *L. sigillatus* correlates with the *emiaeatum/polyomorphum* AZs boundary interval in Portugal, the *emiaeatum/tentucostatum* AZs boundary interval in Italy and lowermost *tentucostatum* AZ in some Spanish sections. Older first occurrences are reported from N Spanish sections, where this biohorizon falls within the *spinatum* AZ. The FO of *L. sigillatus* correlates with younger levels in Argentina, within the uppermost *tentucostatum* AZ (Al-Suwaidi et al. 2010). This species is present since the base of the sections in Germany and France, in samples assigned to the upper *spinatum* AZ. The rareness of *L. sigillatus* potentially weakens the reproducibility of its FO, however, Figure 6 evidences, as pointed out by previous Authors (Mattioli & Erba 1999; Mattioli et al. 2013), that this event can be useful to approximate the Plenianbian/Toarcian boundary only at lower latitudes (Italy, Portugal and S Spain), while at higher latitudes this event is older and
Fig. 6 - A) Main calcareous nanofossil biohorizons plotted against Ammonite Zones from higher and lower latitude sections as synthesized in Tab. 1. Solid symbols identify data derived from published range charts; empty ones refer to works without range charts; B) Diachronity and reproducibility of individual biohorizons based on ammonite dating.
Tab. 1 - Sections considered in Figs 6 and 7. For each section the papers describing calcareous nanofossil distribution are reported. The presence of ammonite zones and/or chemotaxonomy is also included. Number after each section name corresponds to the paleogeographic position reported in Fig. 2.

- The FO of *L. crucentralis* is reported from the *tenuscostatum AZ*, although at different levels, in Italy and Greece. An older occurrence is reported from Germany, Spain and Portugal where it correlates with the uppermost *spinatum*-lowermost *tenuscostatum AZs*, or with the uppermost *emacatatum*-lowermost polymorpham AZs.
- The FO of *C. poulhaboronei* is reported from the lower *tenuscostatum AZ* in Spain and Italy, whereas in Germany and Portugal this taxon has a younger FO in the lowermost *falci sermon* and *levisoni AZs*, respectively.
- The FO of *C. superbus* is reported from the lower-middle *tenuscostatum* and middle polymorpham AZs to the lower-middle *falci sermon* and *levisoni AZs*. While in most Italian sections the FO of *C. superbus* is dated as lower-middle *tenuscostatum AZ*, in most Spanish and Portugal sections it correlates with the middle *serpentinus* and middle *levisoni AZs*, respectively.
- The FO of *L. velatus* is reported from the lower *tenuscostatum AZ* to the middle *serpentinus AZ* in Germany, Spain and Italy. This biohorizon correlates with two different levels in Portugal: uppermost *emacatum AZ* and middle *levisoni AZ*.
- The FO of *D. ignotus* is reported from Italy and one Spanish section (Castillo de Pedrero) in the interval across the *tenuscostatum/serpentinus AZs* boundary, while in Germany it is from the base of the *falci sermon AZ*. In the other Spanish sections and in Greece, this biohorizon correlates...
with the interval across the serpentinus/bifrons AZs boundary. In Portugal it is reported from the middle levisoni to the base of bifrons AZs.

- The LO of *M. jansae* ranges from the uppermost teniocrasatum to the lower falciferum and lower serpentinus AZs in Germany, France, Spain, Italy and Greece. In Portugal this biohorizon is younger, as it is reported from the middle levisoni AZ. In most sections from Spain (La Almunia, Rambla del Salto), Portugal (Rabacal, Peniche) and Italy (Pozzale, M.te Serrone) and in one section from higher latitudes (West Rodiles, N Spain) it is possible to separate the “last common occurrence” (LCO) from the LO of *M. jansae* based on its abundance and range continuity (Fig. 6). At lower latitudes, the LCO of *M. jansae* correlates with the middle-upper teniocrasatum AZ (Italy and Spain), while in Portugal this biohorizon correlates with the polymorphum/levisoni AZ boundary interval. At higher latitudes, in the West Rodiles section, the LCO corresponds to the upper teniocrasatum AZ.

- The FO of *Watznaueria* sp. 1 was documented with certainty only from France and Italy, where it correlates with the top of falciferum and the base of the bifrons AZs, respectively. It might be that the FO of *W. fossacincta* reported from Germany and Spain corresponds to the FO of *Watznaueria* sp. 1 (see taxonomic notes); if so, then the event is dated as latest teniocrasatum and earliest bifrons AZs in Spain and Germany, respectively.

The critical evaluation of nannofossil biohorizons calibrated to ammonite zones (Fig. 6B) evidences that the succession of nannofossil events is consistent with the scheme of Mattioli & Erba (1999) and reproducible, with the only exception of older FOs of *L. velatus* when the revisions of the Valdoria and Peniche sections (Mattioli et al. 2013) are taken into account. Nevertheless, time discrepancy of various extents is derived for all nannofossil biohorizons. In some cases diachronity seems justifiable by the rareness of taxa, especially in their initial ranges, and in part with very poor preservation of nannofossil assemblages (e.g. Greek sections, Baldanza & Mattioli 1992); the delicate structures of some species (e.g. *L. velatus*) and taxonomic uncertainties (e.g. *W. fossacincta* versus *Watznaueria* sp. 1) may also contribute to the documented diachronity. Even if the available dataset is limited, latitudinal time-differences of some biohorizons are recognized. This is the case for the FOs of *L. sigillatus* and *L. crucidentalis*, which are older at higher latitudes, while the FO of *L. velatus* is older at lower latitudes (Fig. 6B). Data from Portugal are different relative to both higher and lower latitudes and no systematic patterns are recognizable. For *M. jansae*, both the LCO and the LO appear to be coeval at lower and higher latitudes. However, in Portugal both biohorizons are younger. Figure 6 suggests that the generalized diachronity of nannofossil events could also result from the calibration to ammonite biozones, known to be controlled regionally (Jenkyns et al. 2002). Mattioli & Erba (1999) demonstrated that their Tethyan nannofossil scheme is largely correlatable with the Boreal one (Bown et al. 1988; Bown & Cooper 1998) (Mattioli & Erba 1999, fig. 12), overcoming the paleoprovincialism shown by ammonites (Elmi et al. 1993).

As suggested by Hesselbo et al. (2007), chemosratigraphy is probably a best framework to test the synchrony of biohorizons and, consequently, in Fig. 7 we consider nannofossil events against the C isotopic anomaly associated to the TOAE for sections where these datasets are available (Tab. 1), expanding the previous calibration of the FOs of *C. superbus* and *D. striatus* done by Mattioli et al. (2004). Since the C isotope curves available for most of the considered sections have low resolution, we used a generalized curve following Hesselbo et al. (2007, fig. 1) and subdivided the analysed interval in five sub-intervals: pre-anomaly (sub-interval a), rapid decrease (sub-interval b), minimum (sub-interval c), recovery (sub-interval d) and post-anomaly (sub-interval e) phases. Individual calcareous nannofossil events are discussed below in stratigraphic order.

- The FO of *L. velatus* show diachronity among different sections: in Italy this biohorizon correlates with C isotopic sub-intervals a to e, while it was found in sub-interval a in sections from Portugal, N Spain and Germany.

- The FO of *D. ignotus* is correlatable to C isotopic sub-intervals a to e in Italian sections; while this biohorizon correlates with sub-intervals a and d in Portugal and Greece, respectively. In sections from N Spain and Germany the FO of *D. ignotus* falls within C isotopic sub-interval b.

- The FO of *C. poulabronae* correlates with isotopic sub-interval a in Italy and N Spain, with sub-interval b in Portugal, and with sub-interval c in Germany.

- The FO of *C. superbus* correlates with C isotopic sub-interval a in Portugal and Germany, with sub-intervals a to b in N Spain and Italy, while this biohorizon falls within sub-interval b in S Spain and within sub-interval c in France.

- The LO of *M. jansae* correlates with sub-intervals b, c and d in France, Germany and Portugal, respectively. In sections from Italy and N Spain this biohorizon spans sub-intervals d and e. When the LCO of *M. jansae* is considered, it correlates with sub-intervals a and c in Italy, a in N Spain and c in Portugal. This datum is not distinguishable in sections from France, Germany, S Spain and Greece.

- The FO of *D. striatus* is correlatable to C isotopic sub-interval e in all analysed sections.

- The FO of *Watznaueria* sp. 1 is correlatable with C isotopic sub-interval e at Colle di Sogno, while
this biohorizon was not unequivocally documented in sections with C isotopic chemostratigraphy. However, if the FO of W. fossacincta reported from Germany, N Spain and Greece corresponds to the FO of Watznaueria sp. I (see taxonomic notes) then this event spans the C isotopic sub-intervals d to e.

The evaluation of nannofossil biohorizons calibrated against the C isotope generalized curve (Fig. 7B) evidences some differences in the sequence of events relative to the one reported in Figure 6B and the scheme of Mattioli & Erba (1999). We notice that the only discrepancies derive from recent re-examination of the Valdorbia and Peniche sections (Mattioli et al. 2013) that resulted in older FOS of L. velatus and D. ignotus (Fig. 6B).

When the C isotopic anomaly is taken as reference, the nannofossil biohorizons show some diachronity, although much reduced relative to the calibration against ammonite zones. This reinforces the problematic use of ammonite zonation as stratigraphic framework (Jenkyns et al. 2002; Mattioli et al. 2004; Hesselbo et al. 2007). Possible reasons for some of the diachronous events might reside in the common presence of a few species, especially in their early range (e.g. L. velatus and D. ignotus) and taxonomic uncertainties (e.g. W. fossacincta versus Watznaueria sp. I). In Figure 7B, latitudinal time-differences of some biohorizons are recognized: in fact, C. polynabronci first appears at higher latitudes, while the FO of C. superbus is older at lower latitudes. When the C isotopic curve is taken as reference, the dataset from Portugal is consistent with lower latitude records.

In sections from France and Germany, it is not possible to separate the LCO from the LO of M. jansae: here the LO of this taxon is older than in the other areas. In most sections from N Spain, Portugal and Italy, instead, the LCO of M. jansae is distinguished from its LO (Fig. 7). We underline that the LCO of M. jansae at lower latitudes correlates with the LO at higher latitudes (Fig. 7B). Indeed, the record from N Spain (West Rodiles section) shows that M. jansae experienced first a LCO at stratigraphic levels comparable to the LCO at lower latitude and LO at higher latitudes, and later the COeval with the LO at lower latitudes. The LCO of M. jansae is evidenced by the drop in abundance of M. jansae and the disappearance level of the normal morphotypes, as documented in this study (Fig. 8).

Our results, complementing previous data, show that few nannofossil events constrain the T-OAE C isotopic anomaly and are traceable among different regions. Specifically, although C. superbus is discontinuous at higher latitudes, its FO correlates with the onset of T-OAE at supraregional scale, as also pointed out by Mattioli et al. (2004) and illustrated by Hesselbo et al. (2007). Our analyses confirm that the FO of D. stratus is useful to approximate the end of the T-OAE C isotopic anomaly (Mattioli et al. 2004; Hesselbo et al. 2007). The critical evaluation of M. jansae
disappearance level allowed the separation of its LCO preceding the LO. These biohorizons are more evident at lower latitudes, where *M. jansae* is a common component of Pliensbachian-lowermost Toarcian assemblages and shows a marked decrease in abundance in the early phase of the C isotopic anomaly (sub-intervals b and c). At similar stratigraphic levels, the LO of *M. jansae* is reported at higher latitudes. Taking into account latitudinal differences, the LO of *M. jansae* is here proposed as additional event to approximate the end of the T-OAE at lower latitudes, where the LCO is very close to the FO of *C. superbus*. The record from N Spain (West Rodiles section documented by Fraguas et al. 2015) suggests that the LCO and LO can be separated also at relatively higher latitudes where both events are coeval with those documented at lower latitudes.

**Fig. 8** - Calcareous nannofossil absolute abundances and carbonate content (% *CaCO₃*) of the Colle di Sogno section. For lithology and microfacies legend see Fig. 3.

**Absolute abundances**

The quantitative investigation of ultrathin sections revealed that the nannofossils total abundance is highest in the Domaro Lmst. and the lower part of the Sogno Fm. (~1000 specimens/mm²), without significant changes at the sharp lithostatigraphic boundary between the two formations (Fig. 8). At the base of the Fish Level total abundance is halved remaining at similar values across the black shales and overlying interval (Fig. 8).

The carbonate content mostly trace the fluctuations in nannofossil absolute abundances, with the exception of the interval above the Fish Level where *CaCO₃* values of ~60-80% correlate with low abundances around 500 specimens/mm². The *S. punctulata* and *M. jansae* morphgroups constitute most of the micrite through the Domaro Lmst. and Sogno Fm. below the Fish Level. In the black shale interval both *S.
punctulata and M. jansae drop in abundance while an increase in abundance is observed for small coccoliths that, however, do not contribute much to calcite, justifying the low carbonate content. In the interval above the Fish Level, nanofossils are mostly represented by small taxa with some contribution by S. punctulata; this is possibly the reason for a relatively high CaCO3 content. As previously discussed for other intervals (Erba & Tremolada 2004), it is clear that the number of specimens per se does not reflect the amount of biogenic calcite since the volume mass of individual taxa play a crucial role for micrite production.

Total S. punctulata abundance (S. punctulata + “small S. punctulata” + “encrusted S. punctulata”) shows the highest values within the Domaro Lmst. (~750 specimens/mm2). In the Sogno Fm., after an initial decrease to a minimum of ~170 specimens/mm2, the S. punctulata mean abundance fluctuates around ~400 specimens/mm2 up to 7.5 m. The interval below the base of the Fish Level displays an increase up to ~750 specimens/mm2. Across the Fish Level the abundance of S. punctulata drop to ~100 specimens/mm2. In the interval above the Fish Level a slight recovery is underlined by an increase of S. punctulata to ~230 specimens/mm2. Within the S. punctulata group, “encrusted S. punctulata” is dominating in the Domaro Lmst. (~370 specimens/mm2), drops in abundance across the Domaro Lmst./Sogno Fm. boundary, and corresponding to the Pliensbachian/Toarcian boundary. Furthermore, the “Schizophasiella crisis” is spectacularly well expressed at Colle di Sogno, where at the base of the Fish Level (corresponding to the onset of the T-OAE) S. punctulata abundances dramatically drop, accompanied by a contemporaneous major decrease of M. jansae and paralleled by an increase of placolith genera, as highlighted by Tremolada et al. (2005). Considering these data, it is evident that the “Schizophasiella decline” and the “Schizophasiella crisis” are biohorizons traceable at supragenetic scale and they are here used and proposed as additional biohorizons (Fig. 5B) to approximate the Pliensbachian/Toarcian boundary and the T-OAE onset, respectively.

Contrary to S. punctulata, the abundance of the M. jansae group shows an increase across the Pliensbachian-Toarcian boundary: in the Domaro Lmst. the total abundance varies from values of 165 specimens/mm2 (at the base) to ~420 specimens/mm2 (at the top), and “thin M. jansae” is dominating over M. jansae. A further increase to ~850 specimens/mm2 is observed in the Sogno Fm. up to 5.5 m: in this interval M. jansae displays a marked increase in abundance while the thin morphotypes remain rather constant. A decrease to ~150 specimens/mm2 due to a major drop of both thin and normal M. jansae nanoliths precedes an abundance peak of “thin M. jansae” of ~585 specimens/mm2 just below the Fish Level. Notably, only “thin M. jansae” specimens are observed in the black shale interval,
where their abundance drops to ~40 specimens/mm² up to ~14 m, where this taxon disappears.

Genus *Lotharingia* is the only coccolith-genus with abundances comparable to highly calcified nannoliths (*S. punctulata* and *M. jansae*). It shows very low abundances in the Domaro Lmst. and lower portion of the Sogno Fm. (a mean of ~35 specimens/mm²), although a slight increase is observed across the Pliensbachian/Toarcian boundary. An increase in abundance is observed from 7 m upwards, reaching the highest abundance within the Fish Level (up to 460 specimens/mm²). In the interval above the black shales *Lotharingia* abundance decreases to values higher than those recorded below the Fish Level (a median of ~100 specimens/mm²).

The biostratigraphic investigation of smear slides shows that genus *Biscutum* is present from the base of the analysed interval (see Appendix 2). However, the rarity and tiny sizes of *Biscutum* coccoliths prevent their identification in ultrathin sections if abundance is very low. Therefore, *Biscutum* is observed only above 8.3 m, where mean abundances of ~30 specimens/mm² are recorded across the Fish Level. In the interval above, abundances are very low (a mean of ~3 specimens/mm²). Genus *Carinolithus* appears in the earliest Toarcian, and therefore is absent throughout the Domaro Lmst. and the lowermost part of the Sogno Fm. In the first part of its record this genus shows very low abundance (a mean of ~20 specimens/mm²) and an increase across the Fish Level, reaching values up to ~110 specimens/mm². In the portion above the black shale interval *Carinolithus* abundance decreases to values slightly higher than those recorded below the Fish Level (a mean of ~30 specimens/mm²).

Genus *Calculus* shows the lowest abundance within the Domaro Lmst. (mean of ~20 specimens/mm²) and a significant increase from the base of the Sogno Fm. reaching its highest values at 6.0 m (up to 150 specimens/mm²). *Calculus* abundance decreases before the Fish Level (a mean of ~50 specimens/mm²) and displays ample fluctuations across the black shale.
interval (0-120 specimens/mm²). Above the Fish Level, abundance decreases to a mean of ~30 specimens/mm².

Genus *Crepidolithus* shows minor fluctuations in abundance with average values of ~45 specimens/mm² in the Domaro Lmst. and the lower part of the Sogno Fm. In the Fish Level and the overlying interval *Crepidolithus* abundance decreases to a mean value of ~20 specimens/mm².

Principal Component Analyses

The results of PCA applied to both absolute abundances and percentages of the entire studied interval and of the restricted interval (see Materials and Methods for details) are synthesized in Tab. 2 and Fig. 9. The PCA conducted on assemblages without *S. punctulata* extracted three factors, identical for absolute abundances and percentages as well as for the total and restricted stratigraphic intervals. Factor 1 explains the highest variance (60.9-80.7 %) and has the highest positive loading for *M. jansae*, while the lowest negative loading for *Biscutum* and *Lotharingius* (Tab. 2A).

Factor 2 explains 17.4-35.2 % of the variance and displays highest loading for *Lotharingius* opposite to *Crepidolithus*. Factors 1 and 2 together explain ~95-98% of the variance, while Factor 3 corresponds only to 1-2% of the total variance. The latter factor marks the opposition of genus *Calyculus* (highest) to genus *Biscutum* (lowest).

PCA performed on the datasets including *S. punctulata* extracted three factors consistent for absolute abundances and percentages as well as for the total and restricted stratigraphic intervals (Tab. 2B). Factor 1 (54.3-80.9 % of the total variance) displays the highest positive loading for *S. punctulata* and *M. jansae* in opposition to *Biscutum* and *Lotharingius*. We notice that when the total interval is considered, Factor 1 shows highest positive loading for *S. punctulata* opposed to *Biscutum*. Factor 2 of the restricted interval (13-32.8 % of the total variance) corresponds to Factor 3 of the total interval (6.6-11.1 % of the total variance): they have the highest loading for *Lotharingius* and lowest loading for *Crepidolithus*. Factor 3 of the restricted interval (9.2-10.8 % of the total variance) corresponds to Factor 2 of the total interval (11.8-23.3 % of the total variance): their loadings are opposite for *S. punctulata* and *M. jansae*.

### Paleocology of Early Jurassic calcareous nanofossil plankton

The paleoecological affinities of Early Jurassic calcareous nanofossil plankton are still not well understood
and the different interpretations proposed are summarized in Tab. 3 that includes taxa considered in our counts and statistics. On the basis of its size and mass, *S. punctulata* was considered a deep-dweller associated to a deep chlorophyll maximum, like the Cretaceous *Nannoconus* (Erba 2004) in analogy with the extant coccolithophore *Flaemopra profunda* (Molino & McIntyre 1990), that flourishes in oceanic stable conditions, when the nutrientic is deep and, therefore, surface waters are characterized by enhanced oligotrophy. Other Authors interpreted *S. punctulata* a shallow-dweller preferring relatively high nutrients in unstable surface waters, especially in proximal settings. The temperature affinity of this taxon is still controversial, being interpreted as a warmer or colder water form.

*Genus* *Crepidolithus* was considered a deep-dweller taxon with oligotrophic affinity. In one case *Crepidolithus* spp. (C. caesi and C. aff. C. ocellatus) was interpreted as preferring higher latitudes. Different paleoecological interpretations were proposed for *C. crassus*: most Authors indicate this taxon as oligotrophic and deep-dweller. Some Authors reconstructed preferences for distal or proximal settings, perhaps with affinity for higher latitudes. A single paper considers *C. crassus* as an opportunistic taxon proliferating under unstable fertile conditions.

Most Authors (Tab. 3) interpreted *M. jansae* as a deep to intermediate-dweller. Other paleoecological reconstructions proposed affinity for oligotrophic areas, lower latitudes or colder temperatures.

The Early Jurassic genus *Biscutum* was interpreted similarly to the Cretaceous species *Biscutum constans* (Roth & Krumbach 1986; Erba 1992; Herrle et al. 2003; Mutterlose et al. 2005), considered a higher fertility indicator. The suggested paleotemperature affinities are questionable, because opposed interpretations were forwarded. As far as single species are concerned, a common preference for mesotrophic conditions was derived, for *B. novum*, *B. finchii*, *B. dubium* and *B. intermedius*. In addition some control by surface water temperature was pointed out for *B. novum*, although affinity for both warmer and colder conditions were proposed. Some preference for colder water was suggested for *B. finchii*. Recently, *B. novum* was interpreted as stress tolerant to anoxia and low salinities.

*Genus* *Lotharingius* was interpreted as a shallow-dweller and higher fertility taxon, usually asso-
associated to Biscutum. Both L. hauffii and L. sigillatus were found to be favored by mesotrophic conditions, while L. sigillatus and L. crucenrectalis were associated to warmer temperature.

Genus Calcarius was considered a shallow, intermediate or deep-dweller, with preference for higher nutrient concentrations, and possibly adapted to lower salinity. Only in one case the genus Calcarius was associated to warmer temperature. In a recent study by Clémence et al. (2015) genera Calcarius and Caninolithus were considered tolerant to anoxia and low salinities.

As a general remark, the screening of previous literature on the paleoecology of Early Jurassic calcareous nanofossil assemblages (Tremolada et al. 2006; Bour et al. 2007; Aguado et al. 2008; Mattioli et al. 2008; Reggiani et al. 2010b; Fraguas et al. 2012; Clémence et al. 2015) extracted factors very similar to those obtained in this study, and interpreted as related to fertility (nutricline depth and intensity), position of nanoplankton groups in the photic zone, or salinity of surface water masses.

When S. punctulata is excluded from the assemblages, our Factors 1 and 2 seem both associated to fertility, although with some degree of differentiation. Specifically, Factor 1 extracts the mesotrophic shallow-dwellers Biscutum and Lotharingius opposite to the intermediate-dweller M. jansae. As discussed above, the paleoecological affinities of individual species within Lotharingius and Biscutum are mostly consistent with the reconstructed preference of the genera. Therefore, our interpretations are largely in agreement with previous works (Mattioli et al. 2008; Fraguas et al. 2012; Clémence et al. 2015). We interpret our Factor 2 opposing Lotharingius to Crepidolithus as related to a more specific control by nutrients on surface (Lotharingius) versus intermediate (Crepidolithus) dwellers, similarly to previous reconstructions (Aguado et al. 2008; Mattioli et al. 2008). However, we notice that in previous PCA analyses (Mattioli et al. 2008; Clémence et al. 2015) L. hauffii was also extracted together with C. crusculus and interpreted as related to a stratified ocean with the nutricline at intermediate depth within the photic zone.

In the Colle di Sogno section, we also detected a Factor 3 opposing Calcarius and Biscutum as previously found by Bour et al. (2007), who provided an interpretation of nutricline position. However, following the reconstructions of Mattioli et al. (2008) and Clémence et al. (2015) suggesting that Calcarius might be favoured by lower salinity we interpret our Factor 3 as indicative of changing run-off and therefore salinity of surface waters.

The factors obtained from the dataset including S. punctulata, partly overlap those extracted excluding S. punctulata. In fact, Factor 1 opposing S. punctulata and M. jansae to Biscutum and Lotharingius is interpreted as deriving from nutricline position and intensity, with M. jansae and S. punctulata taking advantage of a deep nutricline in the intermediate to lower part of the photic zone, respectively. Other Authors found Schizosphærella opposed to Biscutum: Aguado et al. (2008) interpreted this opposition reflecting nutricline depth, whereas Tremolada et al. (2006) highlighted a possible influence of colder temperature or higher salinity on Biscutum.

Our factor 2 is identical for the datasets excluding and including S. punctulata (Fig. 9, Tab. 2). We speculate that Factor 3, opposing M. jansae and S. punctulata records the competition between these two taxa in the middle to lower part of the photic zone. Specifically, S. punctulata occupied a deeper position profiting of a deeper nutricline, while M. jansae was an intermediate-dweller flourishing with a relatively shallower nutricline.

Figure 9 illustrates the factors and their scores obtained for the total investigated interval as well as for the interval comprised between the FO of Caninolithus and the LO of M. jansae, pointing out identical results. The factor scores highlight trends and changes primarily associated to the Fish Level interval that is distinguished from the underlying and overlying portions of the section. After conditions of relative stability and oligotrophy (Factors 1 and 2), a rapid shift to higher nutrient content (Factors 1 and 2) and perhaps lower salinity (Factor 3 excluding S. punctulata) marks the deposition of dysoxic to anoxic sediments. Above the Fish Level, a return to a deeper nutricline (Factors 1 and 2) remains apparently associated to lower salinity (Factor 3 excluding S. punctulata) of surface waters.

Paleoceanographic reconstruction of the Late Pliensbachian-Early Toarcian time interval at local, regional and global scale

Our results confirm and partly implement the paleoecological affinities of some Early Jurassic nanoplankton taxa. As expected, a large influence was exerted by fertility of surface waters and in Fig. 10 we synthesize the possible distribution of Lotharingius, Biscutum, Calcarius, Caninolithus, Crepidolithus, M. jansae and S. punctulata relative to their depth within the photic zone in areas of stability (thermocline and deep nutricline) and instability (surface nutricline). Concurrent paleoecological factors were presumably
temperature and salinity, but limited support is available for Early Jurassic times. *M. jansae* might have preferred colder waters, while *Calyculus*, *B. finchu*, *L. crucen\_tralis* and *L. sigillatus* seem more adapted to warmer temperature (Tab. 3). Another factor controlling abundance and type of nannoplankton is CO₂ concentration in the atmosphere-ocean system that influences calcification rates. Heavily calcified *S. punctulata* and *M. jansae* were conceivably disadvantaged under higher CO₂ (and relative ocean acidification), while taxa producing smaller and less calcified coccoliths were favoured (e.g. Erba 2004, 2006; Mattioli et al. 2004; Tremolada et al. 2005; Suan et al. 2008, Fraguas & Young 2011).

The paleoceanographic conditions in the Late Pliensbachian–Early Toarcian time interval at Colle di Sogno are here reconstructed using changes in nannofossil absolute abundances and scores of PCA factors (Figs 8–9). In the Lombardy Basin, during the latest Pliensbachian stable oligotrophic conditions promoted the proliferation of deep-dwelling and highly calcified *S. punctulata* and *M. jansae*. At the beginning of the Toarcian enhanced continental run-off is evidenced by a significant increase of terrigenous input with, presumably, twofold effects. A decreased light penetration penalized the deep-dweller *S. punctulata*, favouring the intermediate-dweller *M. jansae*. At the same time, accelerated run-off induced lower salinity and an increase of *Calyculus*.

In the studied area, the onset of the T-OAE corresponds to higher concentration of nutrients, apparently associated with lower salinity and perhaps warmer waters stimulating the proliferation of shallow, mesotrophic coccolith-producers (particularly *Biscutum* and *Lotharingius*) and favoring *Calyculus*, but hampering deep- to intermediate-dwelling, oligotrophic forms (*S. punctulata*, *M. jansae* and *Crepidolithus*). The slight increase in abundance of *Crepidolithus* within the Fish Level (Fig. 8) suggests two hypotheses: this taxon preferred higher nutrient concentrations, or was adapted to lower salinity.

We notice that paleoenvironmental changes shortly preceded the onset of the major perturbation, as evidenced by a relative increase in *Lotharingius* abundance and Factor 2 scores below the δ¹³C anomaly (Figs 8–9). However, some condensation is observed in the interval preceding the Fish Level and nannofossil abundances might derive from differential dissolution.

After the deposition of black shales in the Lombardy Basin, calcareous nannoplankton only partly recovered in abundance and diversity, possibly suggesting residual perturbed conditions. In fact, scores of PCA Factors 2 and 3 remain relatively high for the fertility-related *Lotharingius* and *Biscutum* and for the lower-salinity *Calyculus*, suggesting that stable conditions and a deep nutricline were not restored.

Our data are mostly consistent with nannofossil abundance, diversity and dominance documented in central Tethys (Claps et al. 1995; Erba 2004; Mattioli et al. 2004, 2008, 2009), in the westernmost Tethys (Mattioli et al. 2008, 2009; Suan et al. 2008, 2010; Reolid et al. 2014), in Portugal and N Spain (Tremolada et al. 2005; Mattioli et al. 2008, 2009; Fraguas & Young 2011; Fraguas et al. 2012), and partly in the Boral/SubBoreal region (Bucefalo Palliani et al. 2002; Mattioli et al. 2004, 2008, 2009; Hermoso et al. 2009a; Mailliot et al. 2009; Clémence et al. 2015). Although some specific patterns characterize individual sections as a result of local paleoceanographic changes, at supra-regional scale the latest Pliensbachian was characterized by the dominance of *S. punctulata* and *M. jansae* suggesting stable, oligotrophic, relatively cool conditions (Claps et al. 1995; Tremolada et al. 2005; Suan et al. 2010; Fraguas et al. 2012; Reolid et al. 2014). At the beginning of the Toarcian a decrease in abundance of *S. punctulata* and locally of *M. jansae* is registered together with an increase of *Biscutum* and *Lotharingius* (Tremolada et al. 2005; Mattioli et al. 2008, 2009; Fraguas et al. 2012; Reolid et al. 2014). There is a general consensus for an initial relative increase in nutrient availability, possibly introduced by higher run-off, and warming.
The "Schizosphaerella decline" at the Pliensbachian/Toarcian boundary recorded at supraregional scale (Erba 2004; Tremolada et al. 2005; Mattioli et al. 2008; Suan et al. 2008) suggests a global cause. Although higher fertility might have induced a reduction of oligotrophic forms, calcification failure under increased atmospheric pCO2 and some ocean acidification were proposed as main triggering mechanism (Erba 2004, 2006; Tremolada et al. 2005; Mattioli et al. 2008; Suan et al. 2008). In this study, at the Pliensbachian/Toarcian boundary we also notice a decrease of the "encrusted S. punctulata" that, as it is the most calcified form, might have been the morphotype most sensitive to acidification. At the same level a decrease in size of S. punctulata is reported from various basins (Mattioli et al. 2004, 2009; Suan et al. 2008, 2010).

The nanoplankton patterns indicate a significant paleoenvironmental change just before the onset of the T-FAE recorded by the most dramatic shift in assemblage composition reaching a climax during the anoxic interval. The extreme paleoenvironmental conditions produced by fertilization, fresh water input, warming and relative acidification contributed to the establishment and maintenance of very stressing surface waters with overwhelming opportunistic taxa. Ocean acidification might have reached threshold values at the onset of the T-FAE inducing the "Schizosphaerella crisis", the exclusion of "encrusted S. punctulata" and the survival of exclusively "thin M. jansae" (Figs 8-9). The size reduction in Schizosphaerella (Mattioli et al. 2004, 2009; Suan et al. 2008, 2010; Clémence et al. 2015) and Lotharingius (Fraguas & Young 2011) were also argued to be a result of unfavourable condition for biomineralization under ocean acidification.

Although our dataset does not allow reconstructions of paleotemperature trends, previous works documented a significant warming across the T-FAE (e.g. Jenkyns 2010) presumably induced by the emplacement of the Karoo-Ferrar province at ~183 Ma (e.g. Ikeda & Hori 2014), that might have introduced excess CO2 causing a climate change as speculated by previous Authors (Erba 2004; Mattioli et al. 2004, 2009; Tremolada et al. 2005; Suan et al. 2008; Fraguas et al. 2012; Hermoso et al. 2009b; Clémence et al. 2015). Data from the Colle di Sogno section confirm that the T-FAE was a weathering-induced nutrification episode combined with ocean acidification due to excess CO2 exerting a direct control on phytoplankton type and abundance.

Environmental stress started to affect the ocean structure, fertility and chemistry at least 1 million years before the T-FAE, close to the Pliensbachian/Toarcian boundary, and was marked by precursor steps of perturbation culminating into a biological-chemical-physical crisis (Wignall et al. 2005; Suan et al. 2010). The nanoplankton speciation episode, the most important one for calcareous nanoplankton within the Mesozoic (Bown et al. 2004; Erba 2006), is testified by accelerated rates in nanoplankton origination (mainly placoliths) in the latest Pliensbachian-Early Toarcian interval. Although dramatic transient changes in nanofloral communities are recorded worldwide, the environmental perturbations preceding and accompanying the T-FAE had also some positive effects on calcareous nanoplankton evolution by stimulating calcification of new coccolith morphologies.

After the T-FAE, paleoceanographic conditions only partly and gradually returned to the pre-perturbation state, at least as far as the photic zone is concerned. All available data testify nanoplankton assemblages with relatively abundant Crepidolithus, Biscutum and Lotharingius and a minor recovery of Schizosphaerella and total nanofloral abundance suggesting that the deepening of the nutricline and stratification of calcareous phytoplankton through the photic zone required a long period after anoxia terminated (Tremolada et al. 2005; Mattioli et al. 2008, 2009; Fraguas et al. 2012; Maillot et al. 2009; Clémence et al. 2015; Reolid et al. 2014; this study).

Conclusions

The calcareous nanofossil biostratigraphy of the Colle di Sogno section allowed the identification of seventeen biohorizons spanning the latest Pliensbachian-Early Toarcian interval. The zonation proposed for the Tethyan realm (Mattioli & Erba 1999) was successfully applied and NJT 5 and NJT 6 zones were identified. The sequence of nanofossil biohorizons is mostly consistent with data available from different areas at lower and higher latitudes, although only few of them can be used for inter-regional correlations. The apparent discrepancies obtained through calibration of the nanofossil events against ammonite zones are in part overcome by the correlation to the C isotope chemostratigraphy of the Early Toarcian. Few nanofossil events constrain the T-FAE C isotopic anomaly and are traceable among different regions. The appearance of C. superbus correlates with the onset of the T-FAE, while the FO of D. striatus postdates the end of the C isotopic anomaly. The dataset regarding the disappearance level of M. jansae allowed the separation of its LCO preceding the LO. The LCO of M. jansae is more evident at lower latitudes where a major abundance decrease marks the onset of T-FAE C isotopic anomaly. At similar stratigraphic levels, the LO of M. jansae is reported at higher latitudes. We propose here the LO of M. jansae as additional event to approximate the end of the T-FAE at lower latitudes. Quantitative investigation of ultrathin sections revealed major changes in ab-
solute abundances of total nannofloras and individual taxa; in particular, the "Schizophaerella decline" and "Schizophaerella crisis" are here suggested as additional biohorizons to approximate the Pliensbachian/Toarcian boundary and the T-OAE onset, respectively.

The PCA, performed on assemblages including and excluding *S. punctulata*, extracted three factors attributed to surface water stability/instability, fertility and salinity. Our results confirm and partly implement previous reconstructions of nannoplankton paleoecology that are used to trace the environmental evolution across the T-OAE at local, regional and global scales.

During the latest Pliensbachian stable oligotrophic conditions promoted the proliferation of deep-dwelling and highly calcified *S. punctulata* and *M. jancsae* in the Lombardy Basin and in general at lower latitudes. Ecosystem perturbations started in the earliest Toarcian with generally enhanced nutrient availability and possibly lower salinity, evidenced by a significant increase in terrigenous input in the Lombardy Basin. The "Schizophaerella decline" at the Pliensbachian/Toarcian boundary recorded at supraregional scale is inferred to be related also to partial calcification failure under CO$_2$-induced ocean acidification. At global scale, paleoenvironmental stress due to a combination of nutrification, disruption of surface water stability, lower salinity and excess CO$_2$ reached threshold values inducing a rapid turnover of assemblages just before the beginning of the T-OAE. During this event, prolonged meso- to eutrophic conditions associated to lower salinity and possibly warmer waters favoured *Lotharingius*, *Biscutum* and *Calyculus* while ocean acidification arguably hampered calcification of *S. punctulata* and *M. jancsae* at local to supraregional scales. Available data indicate that after the T-OAE, the recovery of k-selected deep- and intermediate-dwellers required a long period after anoxia terminated.

Data from the Colle di Sogno section confirm that the T-OAE was a nutrification episode combined with some ocean acidification exerting a direct control on phytoplankton type and abundance. A general consensus indicates the emplacement of the Karoo-Ferrar province as crucial for the Early Toarcian palaeoclimatic and paleoceanographic changes. Stressing conditions started in the latest Pliensbachian and triggered subsequent changes in nannofloral composition and structure recorded worldwide, associated to accelerated rates in nannoplankton origination suggesting that the environmental perturbations preceding and accompanying the T-OAE possibly stimulated biomineralization of new coccolith morphologies.

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### Appendix 1

- *Biscutum dubium* (Noël 1965) Grün in Grün et al. 1974
- *B. finchii* (Crux 1984) Bown 1987
- *B. grande* Bown 1987
- *B. novum* (Goy 1979) Bown 1987
- *Bussonisus leuuenensis* Bown & Kielbowicz 1987
- *B. prinsii* (Noël 1973) Goy 1979
- *Calyculus Noël 1973*
- *Carinolithus cantaluppii* Cobianchi 1990
- *C. polnabranoi* Mattioli 1996
- *C. superbus* (Deflandre 1954) Prins in Grün et al. 1974
- *Crepidolithus cavus* Rood, Hay & Barnard 1973
- *C. crassus* (Deflandre in Deflandre & Fert 1954) Noël 1965
- *C. granulatus* Bown 1987
- *Diductus constans* Goy 1979
- *Discocharadus ignotus* (Gorka 1957) Perch-Nielsen 1968
- *D. striatus* Moskhovitz & Ehrlich 1976
- *Lotharingius barozii* Noël 1973
- *L. fadola* Mattioli 1996
- *L. hauffii* Grün & Zweili in Grün et al. 1974
- *L. sigillatus* (Stradner 1961) Prins in Grün et al. 1974
- *L. umbriensis* Mattioli 1996
- *L. velatus* Bown & Cooper 1989
- *Milorolithus elegans* Deflandre 1954
- *M. jansae* (Wiegand 1984) Bown in Young et al. 1986
- *M. lenticularis* Bown 1987
- *Parhabdolithus lieavicis* Deflandre 1952
- *Rucinolithus Stover 1966*
- *Schizosphaerella punctulata* Deflandre & Dangeard 1938
- *Similiscutum crucius* De Kaenel & Bergen 1993
- *Tubirhabdus palitus* Rood et al. 1973
- *Watznaueria* sp.1 Cobianchi et al. 1992

Taxonomic index of the calcareous nannofossil taxa reported in this study. Genera, species and subspecies are listed in alphabetic order. Authors and date of the original description and, when necessary, emendations are provided. See Bown (1987), Perch-Nielsen (1988), Bown & Cooper (1998), Mattioli & Erba (1999) and references therein for further information regarding taxonomy and authorship.
Appendix 2
Calcarenite nanofossil range chart of the Colle di Sogno section. The chart reports the distribution and semi-quantitative abundance of all taxa observed, as well as total abundance and preservation of each investigated sample. "F" corresponds to badly preserved specimens that cannot be unequivocally classified but are tentatively assigned to a taxon. "Firm" means fragment; "DV" means distal view; "SV" means side view. Total and semi-quantitative abundances obtained as follows:

Total abundance:
- C/A (common to abundant): more than 11 specimens per field of view.
- C (common): 6-10 specimens per field of view.
- F/C (few/common): 1-5 specimens per field of view.
- F (few): 1 specimen in 1-5 fields of view.
- R/F (rare/frequent): 1 specimen in 6-10 fields of view.
- R (rare): 1 specimen in 11-50 fields of view.
- RR (very rare): 1 specimen in 51-100 fields of view.
- VB (virtually barren): 1 specimen in more than 100 fields of view.

Abundance of individual taxa:
- C/A (common/abundant): >30 specimens in 50 fields of view.
- C (common): >30 specimens in 100 fields of view.
- F/C (few/common): >30 specimens in 200 fields of view.
- F (few): 11-30 specimens in 200 fields of view.
- R/F (rare/frequent): 6-10 specimens in 200 fields of view.
- R (rare): 1-5 specimens in 200 fields of view.
- RR (extremely rare): 1 specimen in 400 fields of view.

Preservation of calcarenite nanofossils was characterized adopting the codes described by Roth (1983): E1 (slight etching); E2 (moderate etching); E3 (strong dissolution); O1 (slight overgrowth); O2 (moderate overgrowth); O3 (strong overgrowth). Moreover, preservation was also coded as follows:
- G (good): no evidence of dissolution and/or overgrowth; primary morphological characteristics are preserved.
- MG (moderate/good): very little evidence of dissolution and/or overgrowth; primary morphological characteristics are usually preserved.
- M (moderate): little evidence of dissolution and/or overgrowth; primary morphological characteristics are sometimes altered.
- MP (moderate/poor): evidence of dissolution and/or overgrowth; primary morphological characteristics are often altered.
- P (poor): most specimens exhibit dissolution or overgrowth; primary morphological characteristics are often destroyed.