Rivista Italiana di Paleontologia e Stratigrafia
(*Research in Paleontology and Stratigraphy*)
vol. 125(1): 219-230. **March 2019**

THE LOWER BAJOCIAN GAETANI LEVEL: LITHOSTRATIGRAPHIC MARKER OF A POTENTIAL OCEANIC ANOXIC EVENT

ELISABETTA ERBA[1*], GABRIELE GAMBACORTA[1] & MASSIMO TIEPOLO[1]

[1*]Corresponding author. Dipartimento di Science della Terra, Università degli Studi di Milano, Via Mangiagalli 34, 20133 Milano, Italy.
E-mail: elisabetta.erba@unimi.it

To cite this article: Erba E., Gambacorta G. & Tiepolo M. (2019) - The lower Bajocian Gaetani Level: lithostratigraphic marker of a potential Oceanic Anoxic Event. *Riv. It. Paleontol. Strat.*, 125(1): 219-230.

Keywords: Gaetani Level; Oceanic Anoxic Event; early Bajocian; stable isotopes.

Abstract. In this paper we document in detail the transition from the Rosso Ammonitico Lombardo to the Radiolarites outcropping at Alpe Turati (Albavilla, Como) in the Lombardy Basin of the Southern Alps. At this location, the Jurassic succession was deposited on a flank of the Corni di Canzo paleohigh: as found on other structural shallow areas, the upper Pliensbachian–Toarcian–Aalenian interval is represented by pseudonodular to nodular marly limestones of the Morbio Limestone and Rosso Ammonitico Lombardo units. In the early Bajocian deposition of biosiliceous sediments is ubiquitously testified by the Radiolarites (Bajocian–Callovian). At Alpe Turati, the interval immediately below the basal green member of the latter unit, consists of a 10 cm thick black shale, pointing to oxygen-depleted bottom waters. Dysoxia persisted during the Bajocian–Callovian as evidenced by dark green stratified cherts. Calcareous nannofossil biostratigraphy indicate an early Bajocian age for the black shale that correlates with the core of a distinct C isotopic negative anomaly also known in various basins outside the Southern Alps.

Very dark grey to black lithologies of early Bajocian age have been documented in a few sections from Poland, Corsica and Morocco. We name Gaetani Level the black shale interval in recognition of Maurizio Gaetani's pioneering and extensive work on Jurassic sedimentary successions of the Lombardy Basin. The association of the Gaetani black shale with a C isotopic anomaly suggests that it could be the sedimentary record of an Oceanic Anoxic Event whose regional to global extension must be ascertained.

Introduction

Some of the best exposures of Jurassic pelagic sedimentary rocks are located in the Southern Alps, where reference-sections have been extensively investigated for stratigraphy, sedimentology, paleontology, paleomagnetism and geochemistry (Bernoulli & Jenkyns 2009). In fact, the Southern Alps constitute a well-preserved and relatively undeformed portion of Adria interpreted as an African "promontory" or as a microplate. They represent a portion of the passive margin of the Tethys Ocean, with original patterns and geometries maintained along a 300 km-long W-E transect.

Received: October 4, 2018; accepted: March 4, 2019

In the latest Triassic-earliest Jurassic a rifting phase caused the fragmentation of carbonate platforms of the southern Tethyan margin into a series of "horst and graben", limited by listric faults, which constituted the physiographic control of facies distribution throughout the Jurassic (Bernoulli & Jenkyns 1974; Santantonio & Carminati 2011; Bertotti et al. 1993). In fact, facies evolution reflects increasing water depth during syn-rift and post-rift thermal subsidence of the passive continental margin: basinal areas formed where drowned carbonate platform segments subsided rapidly and structural highs evolved at sites of initially less subsident blocks of drowned carbonate platform (Bernoulli & Jenkyns 2009; Gaetani 2010). The earliest Jurassic tectonic phase controlled a wide area on the passive margin of the western Tethys (Bosence et al. 2009), and in the Southern Alps determined a large-scale

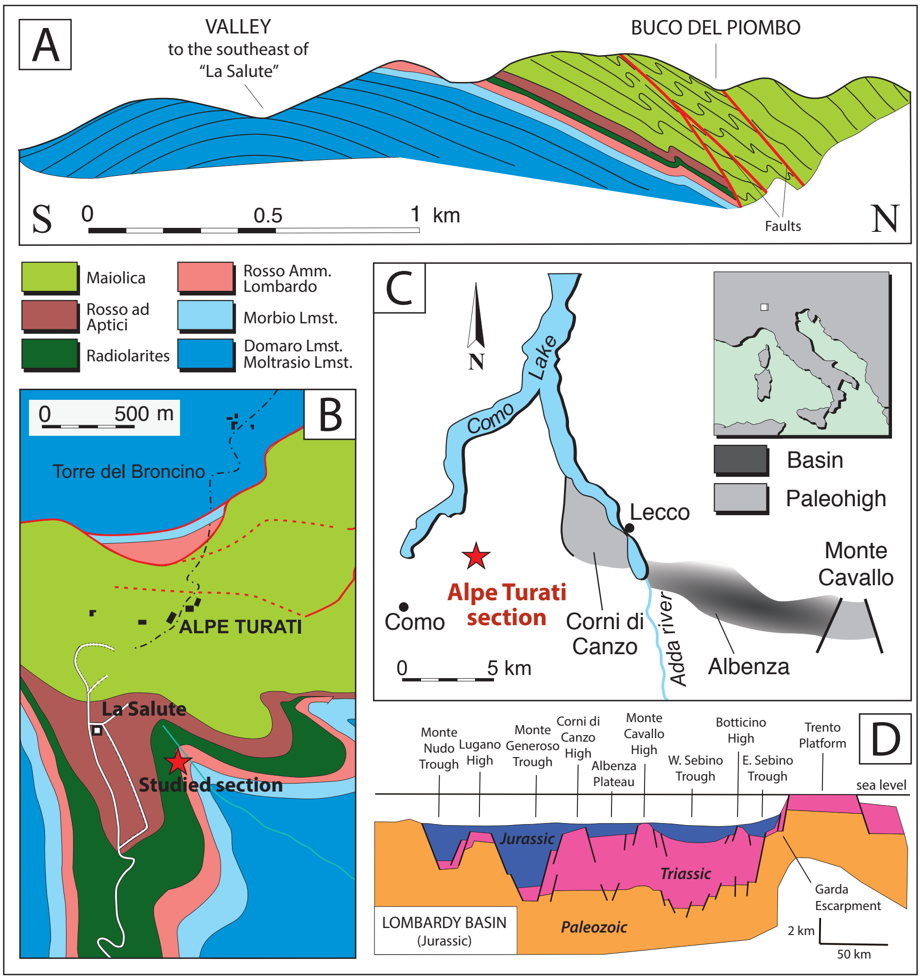

Fig. 1 - A and B) Simplified geological map and cross section modified after Pinna (1963). C) Location of the Alpe Turati section. D) Schematic cross section of the Lombardy Basin as part of the Southern Alps continental passive margin in the Jurassic (modified after Gaetani & Erba 1990).

subdivision into, from W to E, the Lombardy Basin, the Trento Plateau, the Belluno Basin and the Friuli Platform. During the Jurassic, their structural and sedimentary evolution was directly controlled by extensional tectonics at regional scale associated with opening of the central Atlantic and the Ligurian Oceans. The Early Jurassic rifting phase related to the beginning of oceanic spreading in the Atlantic-Tethyan domain (Winterer & Bosellini 1981; Bertotti et al. 1993) caused the break-up of the Triassic and Lower Jurassic carbonate platforms into structural highs and troughs, bounded by syn-sedimentary faults. Sedimentation was markedly different between elevated areas and depressions: very condensed sequences were deposited on structural highs and their flanks, whereas basinal areas were characterized by thick and continuous sedimentary successions (Winterer & Bosellini 1981).

Within the Lombardy Basin, the latest Triassic-earliest Jurassic rifting produced a number of troughs and paleohighs that are, from W to E: M. Nudo Trough, Lugano High, M. Generoso Trough, Corni di Canzo High, Albenza Plateau, M. Cavallo High, W Sebino Trough, Botticino High, E Sebino Trough (Gaetani 1975, 2010) (Fig. 1D). Troughs are some 20-30 km wide and paleohighs are a few km in width. In the troughs, Jurassic sedimentary sequences may reach a non-decompacted thickness of 3000 m, as in the Generoso Trough, suggesting extraordinary sedimentation rates up to 250 m/My (Gaetani 2010). Conversely, condensation and hiatuses characterize the sedimentation on paleohighs, with peculiar reddish nodular facies (Rosso Ammonitico Lombardo). Sedimentation of paleohigh slopes was marked by fluidal textures, slumps, resedimented bodies, and locally megabreccias (Gaetani & Erba 1990; Gaetani 2010). As synthetized by Gaetani (2010) biogenic calcareous sediment accumulated in the Hettangian-Aalenian and Kimmeridgian-Tithonian intervals, but during the Bajocian-Oxfordian carbonate deposition was substituted by red claystones and cherts (Gaetani 1975; Winterer & Bosellini 1981; Muttoni et al. 2005). Siliceous sedimentation dominated for about 20 My

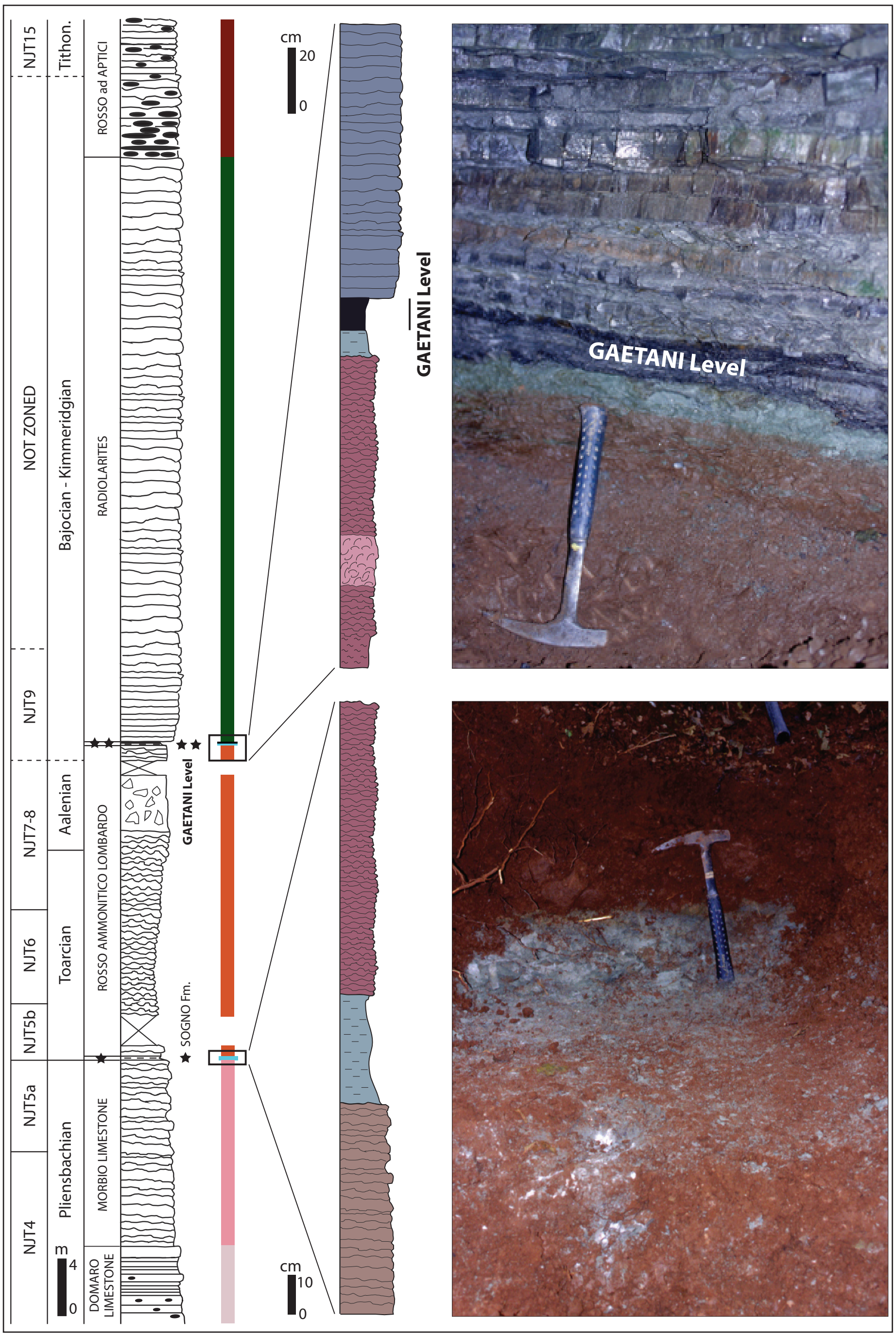

Fig. 2 - Lithostratigraphy and nannofossil biostratigraphy of the Alpe Turati section. The two close-ups document in detail from bottom to top: the Sogno Formation between the Morbio Limestone and the Rosso Ammonitico Lombardo, and the transition between the Rosso Ammonitico Lombardo and the Radiolarites.

(Baumgartner 1987, 2013; Baumgartner et al. 1995), possibly due to a southwards motion of Adria from ~30 to ~10° N latitude into the northern upwelling belt promoting siliceous bio-productivity (Muttoni et al. 2005). Carbonate sedimentation resumed in the Kimmeridgian and progressively increased with the deposition of the Rosso ad Aptici Fm. and then Maiolica Limestone as a result of the calcite compensation depth (CCD) deepening (Gaetani 1975; Winterer & Bosellini 1981) or motion of Adria - linked to the African counterclock rotation - to higher latitudes into stable and oligotrophic waters, favoring calcareous rather than siliceous plankton (Muttoni et al. 2005).

Multi- and interdisciplinary studies have demonstrated that Jurassic pelagic successions of the Lombardy Basin represent 'type-sections' of the Tethyan southern margin and preserve a long history of oceanic sedimentation and biota evolution. In this paper, we describe the Pliensbachian-Tithonian section outcropping at Alpe Turati (Figs 1 and 2) that has been previously investigated for lithostratigraphy (Gaetani & Fantini Sestini 1978; Gaetani & Erba 1990), ammonite paleontology (Venzo 1952;

Pinna 1963, 1968; Pelosio 1968; Fantini Sestini 1977), and nannofossil biostratigraphy (Gaetani & Erba 1990; Cobianchi 1992). Here, we focus on the Rosso Ammonitico Lombardo-Radiolarites transition documenting detailed lithostratigraphy and stable isotope chemostratigraphy during the early Bajocian as dated by calcareous nannofossil biostratigraphy. This lithostratigraphic interval is represented by a peculiar facies, unique in the Lombardy Basin and more generally in the Southern Alps. Integrated lithostratigraphy, nannofossil biostratigraphy and chemostratigraphy is used to detail the chronostratigraphic age and depositional conditions across the Aalenian/Bajocian boundary interval at Alpe Turati. Data will be compared to coeval sections to derive local, regional and global patterns.

Material and Methods

We investigated 28 samples from the Rosso Ammonito Lombardo-Radiolarites transition and the lowermost part of the latter formation (Fig. 3). The outcrop was carefully excavated so as to expose fresh rocks in order to log the detailed section with a cm resolution. The same samples were used for both calcareous nannofossil investigation and geochemistry. In particular, 8 samples were recovered from the Rosso Ammonitico Lombardo Fm. with an average sampling rate of 5 cm, the topmost one lying in correspondence of the turquoise marly claystone layer. Three samples were collected from a black shale and the remaining 17 samples belong to the lower part of the Radiolarites, taken from mm to cm thick marly clayey interbeds (Fig. 3). Sampling was carefully undertaken on fresh surfaces in order to minimize potential effects of weathering, and veins.

Nannofossil biostratigraphic analyses were performed on simple smear slides prepared following the standard technique: 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 fixed with Norland Optical Adhesive. Smear slides were investigated using a light polarizing microscope, at 1250X magnification; at least 400 fields of view were scrutinized in each smear slide. The biostratigraphic scheme adopted is that of Mattioli & Erba (1999).

The same samples were measured for carbonate content and C and O stable isotopes. The $CaCO_3$ content was detected using the Dietrich-Frühling gas volumetric method by measuring evolved CO_2 after acidification of the bulk sample with HCl. For carbon and oxygen stable isotopes powdered samples were analysed by continuous-flow mass spectrometry using a GasBench II connected to a ThermoFisher Delta V Advantage mass spectrometer. In the instrument, they were reacted with purified phosphoric acid (H_3PO_4) at 70°C. Samples with a carbonate content lower than 1% were not analysed because the low signals do not allow the determination of isotope ratios with the required precision and accuracy. Reproducibility of replicated standards is usually better than 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$. Stable-isotope ratios are reported using the conventional δ notation to indicate per mil (‰) deviation from the VPDB standard. Total organic-carbon (TOC in % weight) was measured on the three samples from the Gaetani Level. Samples were reduced to a fine powder and TOC determination was conducted according to the Walkley-Black method (Walkley & Black 1934; Walkley 1947), consisting of an oxidation with dichromate solution and sulfuric acid and a titration with ferrous sulphate.

The Alpe Turati section

The Alpe Turati section is placed in locality Parravicini (Albavilla, Como), in a small valley to the south-east of the ruins of the "Albergo La Salute" at 45°49'17" N 9°11'07" E (Fig. 1). The studied section is located on the northern flank of an anticline with axis oriented East-West (Pinna 1963). The pelagic succession is sub-horizontal, dips very gently south-westwards with an inclination of about 5°, and is ~110 m thick, as estimated from the upper part of the Domaro Limestone to the uppermost part of the Rosso ad Aptici (Fig. 2). Lithostratigraphy of the Alpe Turati section (Gaetani & Erba 1990) comprises, from bottom to top:

Domaro Limestone. Light gray-hazel calcilutites in 20 to 30 cm-thick beds, and light green marlstones as minor lithology. Black chert nodules are rare in the upper part. Thickness from the beginning of the measured section 3.5 m.

Coverage 2 m.

Morbio Limestone. Pinkish pseudonodular to nodular limestones in 5 to 40 cm-thick layers, occasionally amalgamated. Nodules consist of light colored limestones surrounded by a reddish marly matrix, rich in micas. The upper part of the Morbio Limestone becomes more markedly nodular and reddish. The top bed of this lithostratigraphic unit consists of recrystallized gray-green limestone (0.55 m). Total thickness 12.5 m.

Sogno Formation. Between the Morbio Limestone and the Rosso Ammonitico Lombardo, a peculiar interval consisting of turquoise marly claystones, rich in muscovite, is attributed to the Sogno Formation (0.28 m).

Rosso Ammonitico Lombardo. Nodular marly limestone with abundant clay matrix, dark brick red in color (0.75 m). After a 2 m thick covered interval, the Rosso Ammonitico Lombardo crops out continuously and undisturbed for a total thickness of 15 m. It consists of red, intensively bioturbated, nodular limestone in 3 to 15 cm thick layers (max 10 cm thick). Nodules are well developed and the marly matrix is subordinated. The upper part of this formation is characterized by a slump and brec-

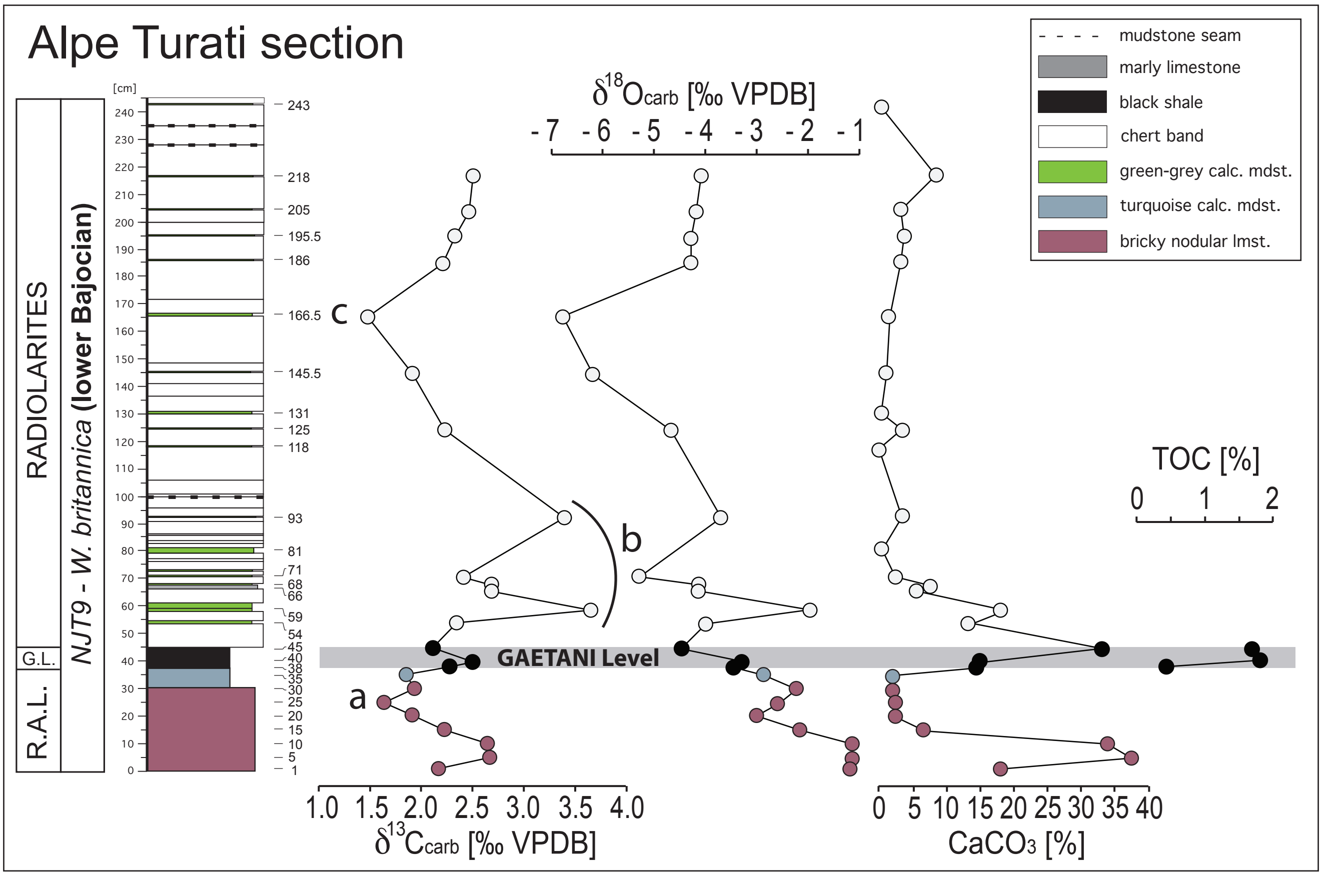

Fig. 3 - Lithostratigraphy, nannofossil biostratigraphy, isotopic composition ($\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$) calcium carbonate content and TOC of the Alpe Turati section. The positions of peaks in the $\delta^{13}C_{carb}$ for the lower Bajocian CIE are reported (see text for explanation). The grey band marks the position of the Gaetani Level.

cia (5 m). After a ~2 m thick covered interval, the topmost part of the Rosso Ammonitico Lombardo is undisturbed and consists of brick red marly claystone (0.10 m), brick red nodular marlstones (0.15 m), pinkish limestone corresponding to the "Lumachella a *Posidonia alpina*" (0.16 m), dark red pseudonodular marlstones (0.55 m).

Between the Rosso Ammonitico Lombardo *sensu stricto* and the Radiolarites a peculiar interval comprises: 7.5 cm of light-green to turquoise marly claystones followed by 10 cm of black shales.

Radiolarites. Dark green, regularly bedded cherts separated by mm thick joints of dark green marly claystones (7 m), followed by progressively thicker layers of brown to red stratified chert. An increase in carbonate content is detected in the upper part of the Radiolarites where interbeds become red in color and marly. The transition to the overlying Rosso ad Aptici is gradual and consists of marly limestone and siliceous marlstones of pink color with abundant nodules of red chert. The total thickness of the Radiolarites is ~40 m.

Rosso ad Aptici. Rhythmic alternations of marly limestone and marlstones with frequent chert nodules. The dominant color is red, with abundant diffuse light green mottles. Chert nodules are dark red-brown in color (30 m). This unit is characterized by locally abundant Aptichus on bedding surfaces. The transition to the Maiolica Limestones is covered.

Maiolica. The lower part of this formation crops out close to the former "La Salute" hotel. It consists of whitish calcilutites with frequent stylolites, organized in decimetric layers, with rare nodules of light grey chert.

Calcareous nannofossils of the Alpe Turati section were investigated by Gaetani & Erba (1990) and Cobianchi (1992). Here previous data are integrated and the nannofossil zones of the Tethyan zonation (Mattioli & Erba 1999) are reported in Figure 2. The nannofossil zones NJT4 to NJT9 were identified in the interval spanning the top of the Domaro Limestone (Pliensbachian) to the low-

Tab. 1 - Results of geochemical investigations carried out on the Alpe Turati section.

Samples	Formation	Depth (cm)	% $CaCO_3$	Mean value $\delta^{13}C$ (per mil)	Mean value $\delta^{18}O$ (per mil)	% TOC
AT243	Radiolarites	243	0.38	/	/	
AT217	Radiolarites	218	8.46	2.51	- 4.09	
AT205	Radiolarites	205	3.24	2.46	- 4.19	
AT195,5	Radiolarites	195.5	3.70	2.32	- 4.25	
AT186	Radiolarites	186	3.36	2.21	- 4.28	
AT166,5	Radiolarites	166,5	1.64	1.46	- 6.80	
AT145,5	Radiolarites	145.5	1.24	1.90	- 6.21	
AT131	Radiolarites	131	0.39	/	/	
AT125	Radiolarites	125	3.39	2.23	- 4.66	
AT118	Radiolarites	118	0.12	/	/	
AT93	Radiolarites	93	3.51	3.40	- 3.66	
AT81	Radiolarites	81	0.52	/	/	
AT71	Radiolarites	71	2.40	2.41	- 5.24	
AT68	Radiolarites	68	7.68	2.68	- 4.13	
AT66	Radiolarites	66	5.56	2.68	- 4.13	
AT59	Radiolarites	59	18.74	3.65	- 1.96	
AT54	Radiolarites	54	14.01	2.34	- 3.96	
AT45	Gaetani Level	45	33.00	2.12	- 4.49	1.7
AT40	Gaetani Level	40	14.87	2.51	- 3.30	1.8
AT38	Gaetani Level	38	14.53	2.29	- 3.44	0.4
AT35	R.A.L. (turquoise calc. mdst.)	35	2.04	1.84	- 2.84	
AT30	Rosso Ammonitico Lombardo	30	2.13	1.93	- 2.21	
AT25	Rosso Ammonitico Lombardo	25	2.69	1.63	- 2.53	
AT20	Rosso Ammonitico Lombardo	20	2.41	1.90	- 3.00	
AT15	Rosso Ammonitico Lombardo	15	6.79	2.22	- 2.16	
AT10	Rosso Ammonitico Lombardo	10	33.87	2.64	- 1.13	
AT5	Rosso Ammonitico Lombardo	5	37.42	2.66	- 1.10	
AT1	Rosso Ammonitico Lombardo	1	18.09	2.17	- 1.17	

ermost part of the Radiolarites (Bajocian). Biogenic stratified cherts of the Radiolarites and siliceous limestones with abundant chert nodules and layers of the lower part of the Rosso ad Aptici are barren or extremely impoverished of calcareous nannofossils. Only the upper part of the latter formation was attributed to the nannofossil NJT15 Zone of Tithonian age (Casellato 2010).

Results

$CaCO_3$ content and TOC

The $CaCO_3$ content (Tab. 1) of the Alpe Turati section is presented in Figure 3. Samples show a calcium carbonate content from about 0.1% up to about 37.4%. The lowermost part (0 to 10 cm) of the analysed Rosso Ammonitico Lombardo interval shows a relatively high $CaCO_3$ content, with an average value of about 30%. A sharp decrease in $CaCO_3$ content is then observed in the uppermost part of the formation and in the turquoise marly claystones, with values of about 2.5%. In the black shale level right above, $CaCO_3$ content spans from 14% to about 33%. The samples from the bottom 71 cm of the Radiolarites have a $CaCO_3$ content progressively decreasing to the average value of about 7%. From sample AT 81 upwards the studied succession is characterized by a $CaCO_3$ content of about 2.5% on average.

The TOC values (Tab. 1) measured in the Gaetani Level are between 0.4 and 1.8%: they increase passing from very dark grey (bottom sample AT38) to black (middle sample AT40 and top sample 45) marly claystones (Fig. 3).

$\delta^{13}C$ and $\delta^{18}O$ data

A cross-plot of $\delta^{13}C_{carb}$ data against the $\delta^{18}O_{carb}$ (Tab. 1) values for all the analysed samples is reported in Fig. 4. In the presence of variable quantities of isotopically homogeneous cements a correlation between the two isotopic ratios is generally observed (e.g. Marshall 1992; Blanchet et al. 2012). While no significant correlation (R^2=0.08) can be inferred when considering all the Alpe Turati samples together, a good correlation can be instead observed grouping the data according to formation. In fact, samples from the Rosso Ammonitico Lombardo Fm. and the Radiolarites Fm. show a R^2 value of 0.70 and 0.79, respectively. These generally good correlations suggest that a moderate diagenesis affected the studied samples, acting probably differently on the two formations.

The chemostratigraphy of the Alpe Turati section is synthesized in Figure 3. The $\delta^{13}C_{carb}$ values fall in the range of ~1.5‰ to ~3.7‰. The

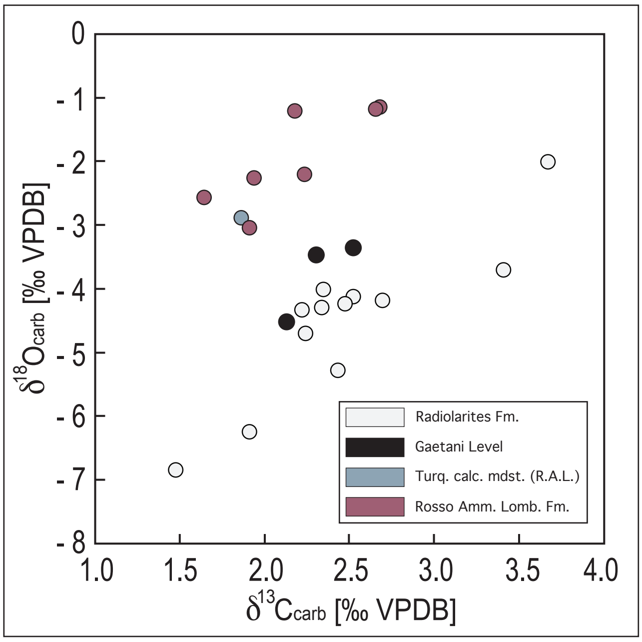

Fig. 4 - Cross-plot of carbonate carbon- and oxygen-isotope ratios for samples analysed from the Alpe Turati section.

lowermost part of the section, from 0 to 10 cm, shows average $\delta^{13}C_{carb}$ values of 2.5‰. From 10 cm to 25 cm, carbon isotopes display a decreasing trend reaching a minimum value of 1.5‰. After this relative decrease, an overall rise in $\delta^{13}C_{carb}$ is present up to 59 cm. Two prominent peaks mark the highest values in carbon isotopes with values of about 3.5‰, in the interval that goes from 59 cm up to 93 cm. Above this portion, a general reduction is observed up to 166.5 cm, with a $\delta^{13}C_{carb}$ value of about 1.5‰. Finally, the carbon isotope-ratio rises back to a background value of 2.5‰ in the uppermost part of the record.

Along the section, $\delta^{18}O_{carb}$ shows an overall decreasing trend. In fact, a progressive change in the oxygen-isotope ratio from about -1.1‰ at the base of the section to a value of about -6.8‰ is observed. A possible relatively small rise in $\delta^{18}O_{carb}$ values can be further observed in correspondence of the interval from 59 cm to 93 cm. In the uppermost part of the analysed section, from 166.5 cm upwards, $\delta^{18}O_{carb}$ values rise back to higher values of about -4‰.

Discussion

Lower Bajocian Carbon Isotopic Excursion (LB-CIE)

In the Alpe Turati section, the lower Bajocian negative carbon isotope excursion (CIE) is characterized by a M-shaped pattern. In particular, two negative peaks, here named 'a' (about 1.6‰) and 'c' (about 1.5‰), are separated by a relatively positive excursion, named 'b' (about 3.5‰; Figs 3 and 5). A similar pattern, with a generally negative excursion of about 1.5-2.0‰ in $\delta^{13}C_{carb}$ can be observed in the carbon isotope data presented by other authors for the same time interval, prior to the early-middle Bajocian $\delta^{13}C$ positive excursion (Bartolini et al. 1996, 1999; Zempolich & Erba 1999; Baumgartner 2013). In fact, a shift toward light C isotopic values in lowermost Bajocian terrestrial and marine successions was discussed by Hesselbo et al (2003) pointing to a complex perturbation of the C cycle starting with a negative CIE followed by a positive anomaly (Hesselbo et al. 2003; Aguado et al. 2008, 2017; Gómez et al. 2009; Suchéras-Marx et al. 2015). More specifically, the $\delta^{13}C$ negative excursion close to the Aalenian/Bajocian boundary was recorded in sections from the Iberian Paleomargin (O'Dogherty et al. 2006; Gómez et al. 2009), in the Umbria-Marche Basin (Bartolini et al. 1999), in the Digne area (Suchéras-Marx et al. 2015), Yorkshire (Hesselbo et al. 2003), Portugal (Suchéras-Marx et al. 2015) and the Hebrides Basin (Jenkyns et al. 2002).

In a similar way to our results from the Alpe Turati section (Fig. 5), the record produced by Bartolini et al. (1999) highlights a M-shaped negative excursion of about 1‰ in the pelagic limestones of the Calcari a Posidonia Fm., also deposited in the southern continental margin of the western part of the Tethys. Even if at low-resolution, also the record in the Scottish section of Bearreraig Burn analysed by Jenkyns et al. (2002) shows a single negative excursion in correspondence of the lower Bajocian. Hesselbo et al. (2003) described a major negative carbon isotope excursion in the Aalenian/Bajocian boundary interval analysed in fluvio-deltaic deposits of the Yorkshire. This record clearly displays a two-peaks negative trend quite similar to that observed in the Alpe Turati section. An analogous trend is also documented in the pelagic successions deposited in the Hispanic Corridor, that constituted a narrow seaway connecting the western Tethys with the eastern Pacific (O'Dogherty et al. 2006; Molina et al. 2018). In particular, La Losilla section described by Molina et al. (2018) is characterized by a $\delta^{13}C_{carb}$ with a clear M-shaped pattern (peaks "a", "b" and "c") closely resembling the Alpe Turati re-

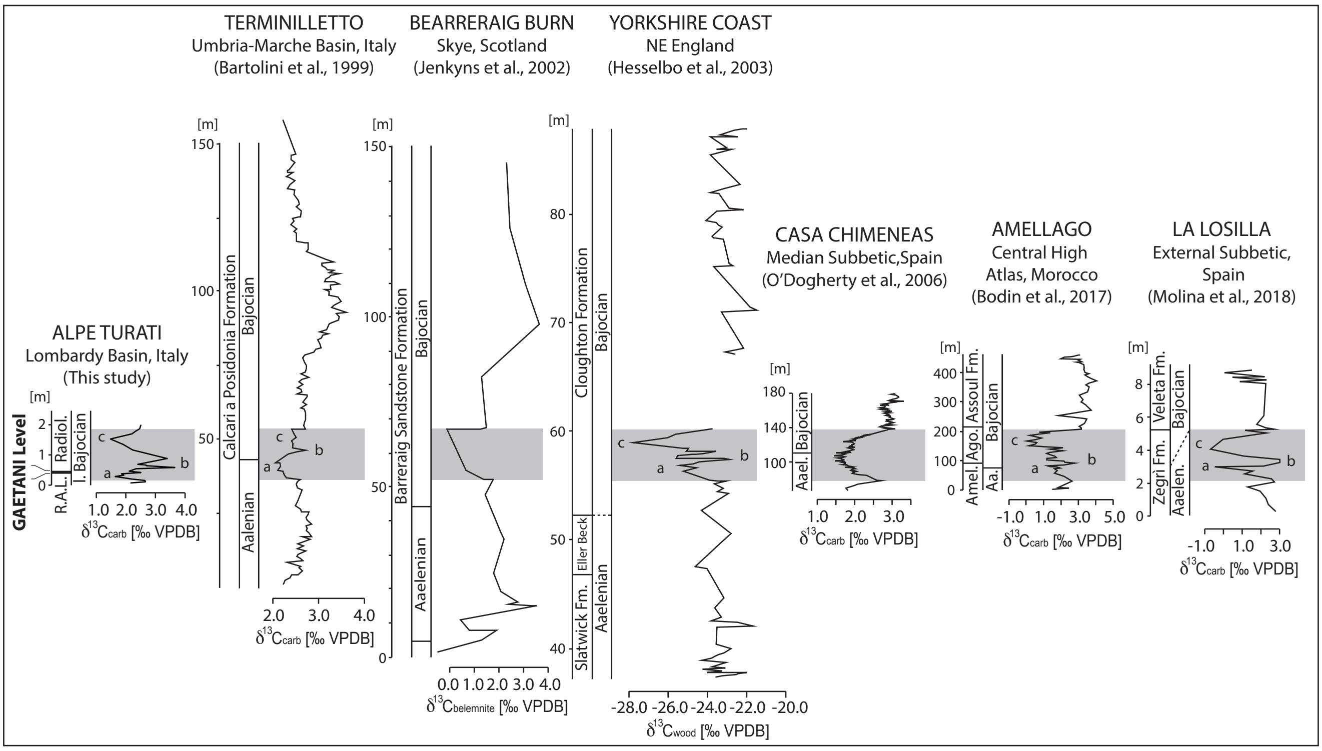

Fig. 5 - Chemostratigraphic correlation of the Alpe Turati section with Terminilletto (Bartolini et al. 1999), Bearreraig (Jenkyns et al. 2002), Yorkshire Coast (Hesselbo et al. 2003), Casa Chimeneas (O'Dogherty et al. 2006), Amellago (Bodin et al. 2017), La Losilla (Molina et al. 2018) sections. The grey band marks the position of the lower Bajocian carbon isotope excursion (CIE). The positions of peaks in the $\delta^{13}C_{carb}$ are reported (see text for explanation).

cord. A similar M-shaped trend was also observed in the $\delta^{13}C_{carb}$ profile recorded in the offshore marine deposits of the Amellago section in the Central High Atlas (Bodin et al. 2017). It must be stressed that in some sections the carbon isotope excursion is limited to less than 0.5‰, a value that can be affected by diverse factors, such as for example the large variation in the $CaCO_3$ abundance. However, the identification of common carbon isotope patterns in sedimentary sections coming from continental and marine shallow-water to pelagic settings, suggests a global extent of the negative CIE in the earliest Bajocian as previously postulated by Hesselbo et al. (2003). Furthermore, we point out that the similarity of the Alpe Turati carbon isotope record with those measured on sections from other basins suggests that the measured $\delta^{13}C_{carb}$ profile in the studied section still preserves a useful chemostratigraphic signal, despite the isotopic values are potentially modified by diagenesis to some degree.

The correlation of the chemostratigraphic curved across the Aalenian/Bajocian boundary and in the early Bajocian (Fig. 5) shows a diachroneity of the C isotopic anomaly. Since a supra-regional CIE cannot be time-transgressive, we infer that discrepancies are, at least partially, due to the stage/age attribution based on different (micro)paleontological groups with variable degree of resolution and calibration to standard chronostratigraphy. Certainly, the age of the $\delta^{13}C$ negative shift merits further investigation.

While diagenesis did not apparently influence the structure of the $\delta^{13}C_{carb}$ curve, contrasting burial diagenetic conditions presumably affected $\delta^{18}O_{carb}$ values that are, therefore, interpreted cautiously. The observed $\delta^{18}O_{carb}$ negative excursion of about 5‰ in amplitude implies a warming of about 25°C (using the equation of Anderson & Arthur (1983) and assuming a $\delta^{18}O_{smow}=-1$‰), which seems unrealistic. However, we speculate that the observed $\delta^{18}O_{carb}$ trend is representative of a general warming, even though the diagenetic imprint probably biases absolute values. An increase in paleotemperature corresponds to the onset of the first negative excursion (peak 'a') and the warming trend associated with the earliest Bajocian CIE persisted up to the end of the negative C isotopic anomaly. The relatively small rise in $\delta^{18}O_{carb}$, in correspondence of the peak 'b', might possibly represent an interlude of relative cooling.

The Gaetani Level

The interval across the Rosso Ammonitico Lombardo/Radiolarites boundary contains common and moderately preserved calcareous nannofossil assemblages including *W. britannica, W. communis* and *Cyclogelospahera margerelii* indicating the NJT 9 Zone of Mattioli & Erba (1999). The base of this zone is calibrated with the latest Aalenian, but the occurrence of *W. communis* in the lowermost sample above the 2 m thick covered interval (Fig. 2) indicates an earliest Bajocian age for the topmost part of the Rosso Ammonitico Lombardo (Figs 2 and 3).

The occurrence of a black shale immediately below the Radiolarites in the Alpe Turati section is a unique finding for both the Lombardy Basin and the Southern Alps. This dark interval suggests oxygen-depletion of bottom waters, perhaps as the result of purely local conditions. However, in continuous Tethyan sections the basal member of the Radiolarites is very dark green to black in color during the early Bajocian (Baumgartmer 2013), suggesting dysoxic to anoxic conditions at regional scale. Outside the Southern Alps, very dark grey-black lithotypes of early Bajocian age occur W and N of the Tethys Ocean. Black chert, shale and quartz-bearing siltstones of Bajocian age were documented just above pillow basalts of ophiolite sequences in the Double Barre section of the Balagne Nappes, San Colombano Pass, in NW Corsica (Baumgartner 2013). Krobicki & Golonka (2008) documented very dark grey to black sediments within the Skrzypny Shale Formation of early Bajocian age in the Pieniny Klippen Belt in the Carpathian (Poland). Also, Barski et al. (2012) describe the "black flysch" (Szlachtowa Formation at Podubocze, Poland) deposited in a relatively deep basin bordering the Czorsztyn Ridge. Lower Bajocian black marly shales with spherosiderite concretions are reported in the Czorsztyn succession, in the Polish sector of the Pieniny Klippen Belt (Carpathian) (Bak et al 2005). Lower Bajocian black marlstones are also observed in Morocco (Bodin et al. 2017). Although a black shale interval is not present, trace element geochemistry suggests anoxic condition in the lowermost Bajocian negative $\delta^{13}C$ spike (peak "a") at La Losilla section (S Spain), which was situated at the eastern end of the Hispanic Corridor (Molina et al. 2018).

Here, we name Gaetani Level the black shale layer just below the Radiolarites (Figs 2 and 3) in recognition of Maurizio Gaetani's pioneering and extensive work on Jurassic sedimentary successions of the Lombardy Basin. The Gaetani Level follows the first negative spike (peak "a") of the early Bajocian CIE (lowermost part of nannofossil NJT9 Zone). We speculate that the Gaetani Level is the local sedimentary expression of a supraregional to global perturbation of the C cycle associated to profound paleoceanographic changes to dysoxic-anoxic bottom waters (e.g. Baumgrtner 2013) and more humid climate (Hesselbo et al. 2003).

The occurrence of the black shale within the C isotopic anomaly suggests that the Gaetani Level could be the sedimentary record of an early Bajocian Oceanic Anoxic Event (OAE). As for other Jurassic and Cretaceous OAEs (Erba 2004; Jenkyns 2010), we speculate that the Gaetani Event might be the result of major igneous-tectonic episodes, singularly or concomitantly. In fact, previous authors (Bjerrum & Dorsey 1995; Bartolini & Larson 2001; Muttoni et al. 2005) dated to the early Middle Jurassic oceanic spreading in the Alpine Tethys and in the Pacific, a pulse of subduction-related magmatism in the Pacific, and continental deformation around the margins of Pangea. The paleoenvironmental perturbations documented in lowermost Bajocian sequences might be directly or indirectly related to tectonically-associated volcanism. Some support come from the paper by Hesselbo et al. (2003) presented preliminary leaf stomatal data with some evidence of raised pCO_2 relative to background values at about the level of the earliest Bajocian C isotopic negative excursion. Moreover, our $\delta^{18}O_{carb}$ results from the Alpe Turati section suggest a warming phase coeval with the negative CIE that might have triggered multiple processes, including a climate change and higher fertility, oxygen consumption due to enhanced primary productivity and onset of dysoxic-anoxic bottom waters (Baumgartner 2013). TOC values in the middle and upper part of the Gaetani Level (1.8 and 1.7%) support relatively higher productivity and better preservation of organic matter under increasingly anoxic conditions.

An intriguing aspect of the Gaetani Level/OAE interval is related to the evolution of coccolithophores. Indeed, the Aalenian/Bajocian boundary interval was marked by the spectacular diversification of genus *Watznaueria* (Cobianchi et al. 1992;

Mattioli & Erba 1999; Bown et al. 2004; Erba 2006; Sucheras-Marx et al. 2012) that became dominant for the rest of the Mesozoic. As documented in specific works (Sucheras-Marx et al. 2012; Molina et al. 2018) origination of new *Watznaueria* species and their rapid increase in abundance clearly predate the early Bajocian perturbation and was not interrupted or affected by global changes of the C cycle either during the first negative CIE or the subsequent positive anomaly. This evolutionary pattern is very similar to origination pulses occurred in the Pliensbachian/Toarcian and Barremian/Aptian boundary intervals prior to the Toarcian OAE (T-OAE) and OAE 1a, respectively (Erba 2004). Intriguingly, palaeoceanographic and paleoclimatic changes associated to the T-OAE and OAE 1a are, although much more pronounced, are quite similar to those reconstructed for the Gaetani OAE: increased fertility, higher pCO_2, warming, oceanic anoxia, reduced marine plankton calcification (Erba 2004). A rapid nannofloral speciation predates deposition of black shales associated to the T-OAE, the Gaetani OAE and OAE 1a whose perturbations did not trigger extinctions among coccolithophores.

Acknowledgements: This paper is the result of fascinating and exciting discussions with Maurizio Gaetani: he introduced me (EE) into the world of Jurassic stratigraphy of the Lombardy Basin and I feel lucky and honored to have been able to spend many days with him in the field. We thank G. Bonacina for lab preparation and analyses of C and O isotopes, and C. Compostella for TOC analyses.

References

Aguado R., O'Dogherty L. & Sandoval J. (2017) - Calcareous nannofossil assemblage turnover in response to the Early Bajocian (Middle Jurassic) palaeoenvironmental changes in the Subbetic Basin. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 472: 128-145.

Aguado R., O'Dogherty L. & Sandoval J. (2008) - Fertility changes in surface waters during the Aalenian (mid Jurassic) of the Western Tethys as re- vealed by calcareous nannofossils and carbon-cycle perturbations. *Mar. Micropaleontol.*, 68: 268-285.

Anderson T.F. & Arthur M.A. (1983) - Stable isotope of oxygen and carbon and their application to sedimentologic and paleo- environmental problems. Society of economic paleontologists and mineralogists, Short Course 10: 1-151.

Bak K., Barski M. & Bak M. (2005) - High resolution microfossil, microfacies and palynofacies studies as the only method in recognition of the Jurassic and Cretaceous "black shales" in a strongly tectonised section of the Czorsztyn Succession, Pieniny Klippen Belt, Poland. *Studia Geol. Polonica*, 124: 171-198.

Barski M., Matyja B.A., Segit T. & Wierzbowski A. (2012) - Early to Late Bajocian age of the "black flysch" (Szlachtowa Fm.) deposits: implications for the history and geological structure of the Pieniny Klippen Belt, Carpathians. *Geol. Quart.*, 56: 391-410.

Bartolini A. & Larson R.L. (2001) - Pacific microplate and the Pangea supercontinent in the Early to Middle Jurassic. *Geology*, 29:735-738.

Bartolini A., Baumgartner P.O. & Hunziker J.C. (1996) - Middle and Late Jurassic carbon stable-isotope stratigraphy and radiolarite sedimentation of the Umbria-Marche Basin (Central Italy). *Eclogae Geol. Helv.*, 89: 811-844.

Bartolini A., Baumgartner P.O. & Guex J. (1999) - Middle and Late Jurassic radiolarian palaeoecology versus carbon-isotope stratigraphy. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 145: 43-60.

Baumgartner P.O. (1987) - Age and genesis of Tethyan Jurassic radiolarites. *Eclog. geol. Helv.*, 80: 831-879.

Baumgartner P.O. (2013) - Mesozoic radiolarites - accumulation as a function of sea surface fertility on Tethyan margins and in ocean basins. *Sedimentology*, 60: 292-318.

Baumgartner P.O., Martire L., Gorican S., O'Dogherty L., Erba E. & Pillevuit A. (1995b) - New Middle and Upper Jurassic radiolarian assemblages co-occurring with ammonites and nannofossils from the Southern Alps (Northern Italy). In: Baumgartner P.O., O'Dogherty L., Gorican S., Urquhart E., Pillevuit A. & De Wever P. (Eds) - Middle Jurassic to Lower Cretaceous Radiolaria of Tethys, 23: 737-749.

Bernoulli D. & Jenkyns H. C. (2009) - Ancient oceans and continental margins of the Alpine-Mediterranean Tethys: deciphering clues from Mesozoic pelagic sediments and ophiolites. *Sedimentology*, 56: 149-160.

Bernoulli D. & Jenkyns H.C. (1974) - Alpine, Mediterranean and Central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In: Dott R.H. Jr & Shaver R.H. (Eds) - Modern and Ancient Geosynclinal Sedimentation. *SEPM Spec. Publ.*, 19: 129-160.

Bertotti G., Picotti V., Bernoulli D. & Castellarin A. (1993) - From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedim. Geol.*, 86: 53-76.

Bjerrum C. J. & Dorsey R. J. (1995) - Tectonic controls on deposition of Middle Jurassic strata in a retroarc foreland basin, Utah-Idaho trough, western interior, United States. *Tectonics*, 14: 962-978.

Blanchet C.L., Kasten S., Vidal L., Poulton S.W., Ganeshram R. & Thouveny N. (2012) - Influence of diagenesis on the stable isotopic composition of biogenic carbonates from the Gulf of Tehuantepec oxygen minimum zone. *Geochem., Geophys., Geosys.*, 13(4): Q04003, doi:10.1029/2011GC003800.

Bodin S., Hönig M.R., Krencker F.-N., Danisch J. & Kabiri, L. (2017) - Neritic carbonate crisis during the Early Bajocian: Divergent responses to a global environmental perturbation. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 468: 184-199.

Bosence D., Procter E., Aurell M., Bel Kahla A., Boudagher-Fadel M., Casaglia F., Cirilli S., Mehdie M., Nieto L., Rey J., Scherreiks R., Soussi M., Waltham D. (2009) - A dominant tectonic signal in high-frequency, peritidal carbonate cycles? A regional analysis of liassic platforms from western Tethys. *J. Sedim. Res.*, 79(6): 389-415.

Bown P.R., Lees J.A. & Young, J.R. (2004) - Calcareous nannoplankton evolution and diversity through time. In: Thierstein, H.R., Young, J.R. (Eds) - Coccolithophores. From Molecular Processes to Global Impact: 481-508. Springer-Verlag, Berlin.

Casellato C.E. (2010) - calcareous nannofossil biostratigraphy of Upper Callovian-Lower Berriasian successions from the Southern Alps, North Italy. *Riv. It. Paleontol. Strat.,* 116: 357-404.

Cobianchi M. (1992) - Sinemurian-Early Bajocian calcareous nannofossil biostratigraphy of the Lombardian Basin (Southern calcareous Alps; Northern Italy). *Att. Tic. Sci. Terra,* 35: 61-106.

Cobianchi M., Erba E. & Pirini Radrizzani C. (1992) - Evolutionary trends of calcareous nannofossil genera Lotharingius and Watznaueria during the Early and Middle Jurassic. *Mem. Sci. Geol.*, 43: 19-25.

Erba E. (2004) - Calcareous nannofossils and Mesozoic oceanic anoxic events. *Mar. Micropaleontol.*, 52: 85-106.

Erba E. (2006) - The first 150 million years history of calcareous nannoplankton: Biosphere - Geosphere interaction. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 232: 237-250.

Fantini Sestini N. (1977) - Hildoceratidae (Ammonoidea) della Zona a Margaritatus (Domeriano). *Riv. It. Paleontol. Strat.*, 83: 697-758.

Gaetani M. (1975) - Jurassic stratigraphy of the Southern Alps: a rewiew. In: C. Squyres (Ed.) - Geology of Italy: 377-402. Earth Sc. Soc. Libyan Arab Rep.

Gaetani M. (2010) - From Permian to Cretaceous: Adria as pivotal between extensions and rotations of Tethys and Atlantic Oceans. In: Beltrando M., Peccerillo A., Mattei M., Conticelli S. & Doglioni C. (Eds) - The Geology of Italy. *J. Virt. Expl.*, 36: paper 5.a.

Gaetani M. & Erba E. (1990) - Il Bacino Lombardo: un sistema paleoalto/fossa in un margine continentale passivo durante il Giurassico. 75° Congresso nazionale S.G.I., Guida alle escursioni pre-Congresso. Escursione A3.

Gaetani M. & Fantini Sestini N. (1978) - La zona a Margaritatus (Domeriano)nella successione dell'Alpe Turati (Como). *Riv. It. Paleontol. Strat.,* 84: 531-560.

Gómez J.J., Canales M.L., Ureta S. & Goy A. (2009) - Palaeoclimatic and biotic changes during the Aalenian (Middle Jurassic) at the southern Laurasian Seaway (Basque-Cantabrian Basin, northern Spain). *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 275:14-27.

Hesselbo S.P., Morgans-Bell H.S., McElwain J.C., Rees P.M., Robinson S.A. & Ross C.E. (2003) - Carbon-cycle perturbation in the middle Jurassic and accompanying changes in the terrestrial paleoenvironment. *J. Geol.*, 111: 259-276.

Jenkyns H.C. (2010) - Geochemistry of oceanic anoxic events. *Geochem., Geophys., Geosys.*, 11, Q03004, https://doi.org/10.1029/2009GC002788, 2010.

Jenkyns H.C., Jones C.E., Gröcke D.R., Hesselbo S.P. & Parkinson D.N. (2002) - Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *J. Geol. Soc., London,* 159: 351-378.

Krobicki M. & Golonka J. (2008) - Geological history of the Pieniny Klippen Belt and Middle Jurassic black shales as one of the oldest deposits of this region - stratigraphical position and palaeoenvironmental significance. *Geoturystyka*, 2: 3-18.

Marshall J.D. (1992) - Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation. *Geol. Mag.*, 129: 143-160.

Mattioli E. & Erba E. (1999) - Synthesis of calcareous nannofossil events in thethyan Lower and Middle Jurassic sucessions. *Riv. It. Paleontol. Strat.*, 105: 349-376.

Molina J.M., Reolid M. & Mattioli E. (2018) - Thin-shelled bivalve buildup of the lower Bajocian, South Iberian paleomargin: development of opportunists after oceanic perturbations. *Facies,* (2018), 64: 19.

Muttoni G., Erba, E., Kent D.V. & Bachdadse V. (2005) - Mesozoic Alpine facies deposition as a result of past latitudinal plate motion. *Nature*, 434: 59-63.

O'Dogherty L., Sandoval J., Bartolini A., Bruchez S., Bill M. & Guex J. (2006) - Carbon-isotope stratigraphy and ammonite faunal turnover for the Middle Jurassic in the Southern Iberian palaeomargin. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 239: 311-333.

Pelosio G. (1968) - Ammoniti del Lias superiore (Toarciano) dell'Alpe Turati (Erba, Como). Parte IV ed ultima: generi *Hildoceras, Phymatoceras, Paroniceras* e *Frechiella* - Conclusioni generali. *Mem. Soc. It. Sc. Nat.*, 27 pp.

Pinna G. (1963) - Ammoniti del Lias superiore (Toarciano) dell'Alpe Turati (Erba, Como). Parte IV ed ultima. Famiglia Dactylioceratidae. *Mem.Soc. It. Sc. Nat.*, 14: 85-136.

Pinna G. (1968) - Ammoniti del Lias superiore (Toarciano) dell'Alpe Turati (Erba, Como). Parte III. Famiglie Lytoceratidae, Nannolytoceratidae, Hammatoceratidae (excl. Phymatoceratidae), Hildoceratidae (excl. Hildoceratinase e Bouleiceratinase). *Mem. Soc. It. Sc. Nat.*, 17 pp.

Santantonio M. & Carminati E. (2011) - Jurassic rifting evolution of the Apennines and Southern Alps (Italy): Parallels and differences. *GSA Bull.*, 123: 468-484.

Suchéras-Marx B., Guihou A., Giraud F., Lécuyer C., Allemand P., Pittet B & Mattioli E. (2012) - Impact of the Middle Jurassic diversification of *Watznaueria* (coccolith-bearing algae) on the carbon cycle and δ13C of bulk marine carbonates. *Glob. Planet. Change*, 86-87: 92-100.

Suchéras-Marx B., Mattioli E., Giraud F. & Escarguel G. (2015) - Paleoenvironmental and paleobiological origins of coccolithophorid genus *Watznaueria* emergence during the late Aalenian-early Bajocian. *Paleobiology*, 41: 415-435.

Venzo S. (1952) - Nuove faune ad Ammoniti del Domeriano-Aaleniano dell'Alpe Turati e dintorni (Alta Brianza). La successione stratigrafica. *Atti Soc. It. Sc. Nat.,* 91: 95-123.

Walkley A. (1947) - A critical examination of a rapid method for determination of organic carbon in soils - effect of variations in digestion conditions and of inorganic soil constituents. *Soil Sci.,* 63: 251-257.

Walkley A. & Black I.A. (1934) - An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.,* 37: 29-37.

Winterer E.L. & Bosellini A. (1981) - Subsidence and sedimentation on Jurassic passive continental margin, Southern Alps, Italy. *Bull. Am. Assoc. Petrol. Geol.*, 65: 394-421.

Zempolich W.G. & Erba E. (1999) - Sedimentologic and chemostratigraphic recognition of third-order se- quences in resedimented carbonate: the Middle Jurassic Vajont Limestone, Venetian Alps, Italy. In: Harris P. M., Saller-Arthur H. & Simo J.A. (Eds) - Advances in carbonate sequence stratigraphy: application to reservoirs, outcrops and models. *SEPM Spec. Publ.,* 63: 335-370.