



**HAL**  
open science

## Stratification and productivity in the Western Tethys (NW Algeria) during early Toarcian.

Hicham Baghli, Emanuela Mattioli, Jorge E. Spangenberg, Wolfgang Ruebsam, Lorenz Schwark, Mustapha Bensalah, Abbès Sebane, Bernard Pittet, Pierre Pellenard, Guillaume Suan

### ► To cite this version:

Hicham Baghli, Emanuela Mattioli, Jorge E. Spangenberg, Wolfgang Ruebsam, Lorenz Schwark, et al.. Stratification and productivity in the Western Tethys (NW Algeria) during early Toarcian.. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2022, 591, pp.110864. 10.1016/j.palaeo.2022.110864 . hal-03613625

**HAL Id: hal-03613625**

**<https://hal.science/hal-03613625v1>**

Submitted on 22 Jul 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Stratification and productivity in the in the Western Tethys (NW Algeria) during**  
2 **early Toarcian**

3

4 Hicham Baghli<sup>1,2</sup>, Emanuela Mattioli<sup>1,3\*</sup>, Jorge E. Spangenberg<sup>4</sup>, Wolfgang Ruebsam<sup>5</sup>,  
5 Lorenz Schwark<sup>5,6</sup>, Mustapha Bensalah<sup>2</sup>, Abbès Sebane<sup>7</sup>, Bernard Pittet<sup>1</sup>, Pierre  
6 Pellenard<sup>8</sup>, Guillaume Suan<sup>1</sup>

7

8 <sup>1</sup>Univ Lyon, UCBL, ENSL, UJM, CNRS, LGL-TPE, F-69622, Villeurbanne, France

9 <sup>2</sup>Laboratoire de Recherche n° 25, Université de Tlemcen, Algérie

10 <sup>3</sup>Institut Universitaire de France (IUF), Paris, France

11 <sup>4</sup>Institute of Earth Surface Dynamics (IDYST), University of Lausanne, Building Géopolis,  
12 CH-1015 Lausanne, Switzerland

13 <sup>5</sup>Institute of Geosciences, Kiel University, Ludewig-Meyn Str. 10, 24118 Kiel, Germany

14 <sup>6</sup>Curtin University, WA-OIGC - Department of Earth and Planetary Sciences, 6845  
15 Bentley Campus, Perth, Australia

16 <sup>7</sup>Laboratoire Géodynamique des Bassins et Bilan sédimentaire (GéoBaBiSé), FSTU,  
17 Département de Géologie, Université Oran2 Mohamed BEN-AHMED, Algérie

18 <sup>8</sup>Biogéosciences, UMR 6282 uB/CNRS, Université Bourgogne Franche-Comté, 6  
19 Boulevard Gabriel, 21000 Dijon

20

21 \* Corresponding author: Emanuela Mattioli, Univ Lyon, UCBL, ENSL, UJM, CNRS,  
22 LGL-TPE, F-69622, Villeurbanne, France and Institut Universitaire de France (IUF),  
23 Paris, France

24

25 E-mail addresses: baghli.hicham@gmail.com (Hicham Baghli), emanuela.mattioli@univ-  
26 lyon1.fr (Emanuela Mattioli), jorge.spangenberg@unil.ch (Jorge E. Spangenberg),  
27 wolfgang.ruebsam@googlemail.com (Wolfgang Ruebsam), lorenz.schwark@ifg.uni-  
28 kiel.de (Lorenz Schwark), mus.bensalah@yahoo.fr (Mustapha Bensalah),  
29 sebane.abbes@yahoo.fr (Abbès Sebane), bernard.pittet@univ-lyon1.fr (Bernard Pittet),  
30 Pierre.Pellenard@u-bourgogne.fr (Pierre Pellenard), guillaume.suan@univ-lyon1.fr  
31 (Guillaume Suan)



32

33 **Abstract**

34

35 Profound environmental changes punctuated the Early Jurassic period, as recorded by  
36 marked carbon and oxygen isotope anomalies and major biotic crises. The response of  
37 low-latitude regions of Northern Gondwana to such intense changes is not documented  
38 as well as that of other Tethys areas. We present new calcareous nannofossil  
39 assemblages from three sections located in NW Algeria, in the Sahara and Tlemcen  
40 Basins, respectively. New stable carbon and nitrogen isotope data are provided from the  
41 Tlemcen Basin to reconstruct local environmental conditions in the wider context of a  
42 Toarcian greenhouse climate. We first established a solid chemo- and biostratigraphic  
43 framework by integrating stable carbon isotope data and calcareous nannofossil events.  
44 Calcareous nannofossil assemblages show common trends in the two basins, such as  
45 the occurrence in high proportions of the deep-dweller species *Mitrolithus jansae*, likely  
46 indicating stratification of the water column with a deep nutricline. This taxon dominated  
47 the assemblage during the negative carbon isotope excursion (CIE) interval, often used  
48 to delineate the base of the Toarcian anoxic event (T-OAE). Such a nannofossil record  
49 is unique in the Western Tethys domain, as *M. jansae* is known to drastically decrease  
50 in abundance during the T-OAE until its disappearance in the aftermath of the event.  
51 The NW Algeria nannofossil record indicates prolonged thermal stratification of water-  
52 masses, finally triggering hyper-oligotrophy and low productivity in shallow waters during  
53 the Toarcian CIE. Such peculiar conditions are likely related to the combined effects of a  
54 warm and arid climate dominating along the northern Gondwana margin and the  
55 presence of a strong clockwise gyre over the epicontinental shelf, which brought warm  
56 equatorial waters from the Tethys Ocean to the NW Algeria shelf.

57

58 *Keywords:* lower Jurassic; Pliensbachian-Toarcian environments; Northern Gondwana;  
59 calcareous nannofossils; C and N stable isotopes.

60

61 **1. Introduction**

62

63           The Early Jurassic was an upheaval period, characterized by considerable climate  
64 and environment changes. These include a drop in seawater temperature in the late  
65 Pliensbachian followed by a warming in the early Toarcian (McArthur et al., 2000; Guex  
66 et al., 2001; Rosales et al., 2004; Gómez et al., 2008; Suan et al., 2008; 2010; Korte and  
67 Hesselbo, 2011; Li et al., 2012; Price et al., 2016; Baghli et al., 2020; Ruebsam et al.,  
68 2020c), the development of widespread anoxia/euxinia in epicontinental basins of the  
69 northern European epicontinental seaway (Jenkyns, 1988; Prauss et al., 1991; Schwark  
70 and Frimmel, 2004; Ruebsam et al., 2018; McArthur, 2019; Remírez and Algeo, 2020a),  
71 as well as biological crises and extinctions (Harries and Little, 1999; Wignall, 2001;  
72 Macchioni and Cecca, 2002; Gómez et al., 2008; Mattioli et al., 2008; Gómez and Goy,  
73 2011). Major environmental changes coincided with a global disturbance of the carbon  
74 cycle as indicated by two negative carbon isotope excursions (CIEs) at the  
75 Pliensbachian/Toarcian boundary and during the so-called Jenkyns Event (Toarcian  
76 Oceanic Anoxic Event, T-OAE; Jenkyns, 1988; Müller et al., 2017). Negative CIEs were  
77 recorded globally in various substrates, including marine carbonates, marine and  
78 terrestrial organic matter, and fossil wood, and in different localities around the world  
79 (e.g., Jenkyns, 1988; Jenkyns and Clayton, 1997; Hesselbo et al., 2000; Schouten et al.,  
80 2000; Kemp et al., 2005; van de Schootbrugge et al., 2005; Suan et al., 2008; Sabatino  
81 et al., 2009; McArthur et al., 2008; Wilmsen and Neuweiler, 2008; Littler et al., 2009;  
82 Baghli et al., 2020; Remírez and Algeo, 2020b). Numerous studies attempted an  
83 improved understanding of the causal links between all the events that occurred during  
84 the late Pliensbachian-early Toarcian interval, and at assessing their impact on marine  
85 and continental biosphere.

86           Significant trends in oxygen isotope values of fossilized marine shells attest to  
87 major warming phases at the Pliensbachian/Toarcian boundary and in the early  
88 Toarcian (Polymorphum-Levisioni zonal transition). As for the CIEs, these temperature  
89 fluctuations are recorded in various regions although with different intensities (see Baghli  
90 et al., 2020 for a review). Conversely, changes in oxygenation (McArthur, 2019) as well  
91 as biotic responses (Mattioli et al., 2008; Rita et al., 2016) seem to have been strongly  
92 modulated by regional processes, with marginal basins of the north-eastern Tethys

93 recording prolonged phases of anoxia, whilst southern and western regions of Tethys  
94 remained relatively well-oxygenated (Baroni et al., 2018; McArthur, 2019).

95 In this paper, we address the palaeoenvironmental changes that took place in NW  
96 Algeria, which was located along the southwestern margin of the Tethys corresponding  
97 to the Northern Gondwana shelf. This region shows peculiar features, since it was  
98 characterized by arid and warm climate conditions during the Jurassic. Temperatures  
99 are assumed to have been 2 to 4°C higher in NW Algeria with respect to other studied  
100 areas (e.g., Portugal, Spain, France, England), attesting for a pronounced latitudinal  
101 temperature gradient in the western Tethys (Baghli et al., 2020). Carbon isotope values  
102 ( $\delta^{13}\text{C}$ ) of biogenic calcite (brachiopod shells) show a systematic positive offset of ~0.5‰  
103 for values in NW Algeria with respect to the regions cited above (Baghli et al., 2020),  
104 suggesting that the C-isotope composition of the Early Jurassic dissolved inorganic  
105 carbon (DIC) was spatially heterogeneous in shallow shelf waters of the SW Tethys,  
106 possibly linked to regional productivity patterns (e.g., oligo- vs. eutrophic regimes,  
107 proximal vs. distal continental sources, upwelling areas, etc.). The response of primary  
108 producers to the environmental perturbations occurring during the late Pliensbachian-  
109 early Toarcian interval in northern Gondwana thus needs to be elucidated, especially for  
110 those periods recording perturbations of the carbon cycle. Calcareous nannoplankton is  
111 an ideal group of microorganisms to address these questions as modern  
112 coccolithophorids coevally perform photosynthesis and biocalcification. Their distribution,  
113 species richness and abundance are largely controlled by temperature, nutrients, and  
114 salinity of surface waters (Winter et al., 1994).

115 Here we present new calcareous nannofossil data, including first (FO) and last  
116 occurrences (LO) of species, and assemblage composition based on absolute and  
117 relative abundances of three NW Algeria sections (Mellala, Raknet El-Kahla, and Djebel  
118 Chemarikh). A biostratigraphic frame based upon calcareous nannofossils is presented  
119 for this region for the first time. We present also new stable carbon isotope  
120 measurements on whole-rock carbonate and bulk organic samples from the Mellala  
121 section. Such analyses on stable carbon isotopes are complemented by measurements  
122 of nitrogen stable isotopes and of weight percent total organic carbon (TOC). These  
123 measurements, along with previously published geochemical data from the Raknet El-

124 Kahla section (Reolid et al., 2012b; Ruebsam et al., 2020a), allow a precise bio- and  
125 chemo-stratigraphic correlation of the two sections. The changes through time of  
126 calcareous nannofossil absolute abundance and assemblage are thus compared with  
127 similar records from other basins in order to evaluate local vs. regional patterns in the  
128 response of marine primary producers to Early Jurassic palaeoenvironmental  
129 perturbations.

130

## 131 **2. Geological setting**

132

133 The studied sections are located in two different settings in NW Algeria, which  
134 during the Jurassic was located in the NW of Gondwana and corresponded to the  
135 southern part of the Western Tethys (Fig. 1). The two regions are nowadays placed on  
136 both sides of the Oran High Plains or “Oran Meseta”, which is located between the  
137 Saharan Atlas to the South and the Tlemcen Domain to the North. From a  
138 palaeogeographic point of view, the Oran Meseta comprised a shallow carbonate  
139 platform during the Pliensbachian, while a partly emerged and restricted sabkha  
140 developed during the Toarcian (Elmi and Alméras, 1984). These areas extended to the  
141 West into the Moroccan High Plateaus.

142 One of the regions studied is located in the Tlemcen Domain, which was a shallow-  
143 sea carbonate platform during the late Sinemurian-early Pliensbachian interval. The  
144 platform was partly flooded during the early Pliensbachian. Eventually, the Tlemcen  
145 Domain differentiated into an intra-cratonic basin divided into wider or narrower sub-  
146 basins separated by persistent shoals, which were alternatively flooded or emerged  
147 according to sea-level changes (Elmi and Alméras, 1984). The selected section in the  
148 Tlemcen domain is Mellala (35°3'54''N, 1°45'39''W; Traras Mountains, Beni Menir  
149 sector). The Traras Mountains are bounded to the North by the Mediterranean Sea, to  
150 the East by the Mio-Plio-Quaternary Tafna Basin, to the West by the Beni Snassen  
151 Mountains (Eastern Middle Atlas in Morocco), and to the South by the Maghnia Trough  
152 (geologic map of Algeria 1/500.000; 2<sup>nd</sup> Edition, 1952). This section was selected  
153 because of the good exposure of a thick and continuous sedimentary succession of the  
154 Pliensbachian/Toarcian transition, with a monotonous succession of alternating marls

155 and marly limestones (Ameur, 1999; Elmi et al. 2006). At Mellala, the exposed  
156 succession includes the Pliensbachian/Toarcian boundary up to the Toarcian Bayada  
157 Formation, which is represented by hemipelagic facies. The common occurrence of  
158 ammonites, brachiopods and foraminifera provides a precise biostratigraphic frame  
159 enabling the recognition of the Emaciatum Ammonite Zone (Elisa Subzone), the  
160 Polymorphum Ammonite Zone (Mirabile and Semicelatum subzones) and the Levisoni  
161 Ammonite Zone (Elmi et al., 2006; Reolid et al., 2014a).

162 The second region of study is located in the Atlas system, which represents the  
163 southern palaeo-margin of the western Tethys and possesses a geometry directly  
164 inherited from the Early Mesozoic rifting of both the Central Atlantic and the Alpine  
165 Tethys domains (Aït Ouali, 1991; Favre, et al., 1991). The successions studied belong to  
166 the Sahara Atlas, which is a slightly deformed Meso-Cenozoic intracontinental mountain  
167 chain (Frizon de Lamotte et al., 2009), extending from the Moroccan Middle and High  
168 Atlas to the West, and passing into the Tunisian Trough to the East. This region was  
169 bounded in Algeria by the Oran Meseta to the North, and by the Sahara platform to the  
170 South. The Sahara Atlas can be subdivided into three sub-domains: the Ksour  
171 Mountains (Western Sahara Atlas), the Djebel Amour (Central Sahara Atlas), and the  
172 Ouled Naïl, Aurès, Hodna and Nememcha-Mzab Mountains (Eastern Sahara Atlas)  
173 (Ritter, 1902; Bracène and Frizon de Lamotte, 2002).

174 Our study is focused on the Pliensbachian-Toarcian sections located in the  
175 Western Sahara Atlas (Ksour Mountain). The core of this inverted-rift structure belt  
176 consists of a Palaeozoic metamorphic basement. The overlying sedimentary cover  
177 comprises marine and continental deposits of Mesozoic and Cenozoic age. The most  
178 prominent feature of the Atlas domain (Ksour Mountains) compared to the Tlemcen  
179 domain is the early development of a carbonate platform, probably as early as the  
180 Rhaetian-Hettangian in the Aïn Ouarka area (Sahara Basin; Elmi et al., 1998), the most  
181 rapidly subsiding sub-basin of the Saharian Atlas.

182 We studied two sections, Djebel Chémarikh (32°41'30"N, 0°10'26"W) and Raknet  
183 El-Kahla (32°44'17"N, 0°7'37"W), which are located in the Aïn Ouarka sector. This area  
184 presents four formations, namely: (i) the Chemarikh dolomite Formation (Hettangian)  
185 corresponding to an inner platform sedimentary environment; (ii) the marl-limestone

186 alternations of Aïn Ouarka Formation (Sinemurian to Pliensbachian in age), showing the  
187 evolution from an external platform, a sedimentary ramp, to a deep basin; (iii) the  
188 rhythmic marl-limestones of the Aïn Rhézala Formation (Toarcian to Aalenian in age),  
189 which are interpreted as having been deposited in the Atlas depocentre; and, finally, (iv)  
190 the Raknet El-Kahla conglomerates (Aalenian to Bajocian in age; Mekahli, 1998;  
191 Mekahli et al., 2004). We focused on the part of the Raknet El-Kahla section covering  
192 the Emaciatum Zone (late Pliensbachian) to the Levisoni Zone (early Toarcian), and on  
193 the Djebel Chemarikh section covering the interval from the middle Toarcian (Bifrons  
194 Zone) to the late Toarcian (Aalensis Zone).

195

### 196 **3. Material and methods**

197

#### 198 *3.1. Carbon isotope composition of carbonates*

199

200 Sixty-one bulk rock samples from the Mellala section (latitude and longitude: 35°3'54"N,  
201 1°45'39"W; along the road RN98 between Tlemcen and Ghazaouet, just at the  
202 intersection with the road RN99A to Nedroma, height comprised between 130 and 150  
203 m), ranging in age from the late Pliensbachian to the middle Toarcian, were analysed for  
204 their carbon isotope composition ( $\delta^{13}\text{C}_{\text{carb}}$ ). The carbon isotope measurements on bulk  
205 rock were performed using a Thermo Fisher Scientific (Bremen, Germany) Gas Bench II  
206 and carbonate preparation device, connected to a Delta Plus XL isotope ratio mass  
207 spectrometer at the Institute of Earth Surface Dynamics of the University of Lausanne.  
208 The  $\text{CO}_2$  extraction was done by reaction of 100–200  $\mu\text{g}$  of powdered carbonate sample  
209 with anhydrous phosphoric acid at 70°C. The carbon isotope ratios ( $R = {}^{13}\text{C}/{}^{12}\text{C}$ ) are  
210 reported in the delta ( $\delta$ ) notation as the per mil (‰) deviation relative to the Vienna Pee  
211 Dee belemnite standard (VPDB):  $\delta_{\text{sample}} (\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}} - 1] \times 1000$ .  
212 The standardization of the  $\delta^{13}\text{C}$  values relative to VPDB was done by replicate analysis  
213 of the in-house working standard Carrara marble (UNIL-CM,  $\delta^{13}\text{C} = 1.95 \text{‰}$ ) within the  
214 analytical sequences. The  $\delta^{13}\text{C}$  values of the reference  $\text{CO}_2$  gas and the UNIL-CM  
215 standard were obtained by normalization with the international reference materials NBS-  
216 19 limestone ( $\delta^{13}\text{C} = +1.95 \text{‰}$ ), NBS-18 carbonatite ( $\delta^{13}\text{C} = -5.01 \pm 0.03 \text{‰}$ ), and  
217 LSVEC lithium carbonate ( $\delta^{13}\text{C} = -46.6 \text{‰}$ ). The used  $\delta^{13}\text{C}$  values were those

218 recommended by Brand et al. (2014). Analytical uncertainty ( $1\sigma$ ), monitored by replicate  
219 analyses of NBS-19 and UNIL-CM was not greater than  $\pm 0.05\text{‰}$  for  $\delta^{13}\text{C}$ .

220

### 221 *3.2. Organic carbon isotopes and TOC*

222

223 The same samples from Mellala analysed for whole-rock carbon stable isotopes  
224 were also analysed for TOC content and for bulk organic carbon isotopes ( $\delta^{13}\text{C}_{\text{org}}$ ) at the  
225 Institute of Geosciences, Kiel University. The TOC content was determined on  
226 decalcified samples. Decalcification was achieved by treating samples with HCl (10%  
227 and 25%) to remove calcium carbonate and dolomite. Subsequently, the samples were  
228 washed and neutralized with deionized water and dried in an oven at  $40^\circ\text{C}$  for 48 hours.  
229 Values determined on decalcified samples were corrected for their carbonate loss to  
230 yield original TOC concentrations. Reproducibility and accuracy were checked by  
231 running replicate analysis of laboratory standards and duplicate analysis of samples and  
232 were better than 0.1 wt.% ( $1\sigma$ ).

233 Stable carbon isotope analysis of the bulk organic carbon ( $\delta^{13}\text{C}_{\text{org}}$  values) were  
234 performed on decalcified samples using a Thermo Scientific Delta V isotope ratio mass  
235 spectrometer coupled to a Flash EA via a Conflow III interface. The measured  $\delta^{13}\text{C}$   
236 values were calibrated to the VPDB scale with the international reference material  
237 caffeine standard (IAEA-600,  $\delta^{13}\text{C} = -27.77\text{‰ VPDB}$ ). Reproducibility and accuracy  
238 were monitored by replicate standard and sample analysis and were better than 0.1‰  
239 ( $1\sigma$ ).

240

### 241 *3.3. Nitrogen isotopes*

242

243 Nitrogen stable isotope analysis of the bulk sediment ( $\delta^{15}\text{N}_{\text{tot}}$ ) was performed on  
244 the original sample material in order to avoid decalcification-induced alteration of the  
245 isotopic signature (Vafeiadou et al., 2013; Schlachter and Connolly, 2014; Ruebsam et  
246 al., 2020a).  $\delta^{15}\text{N}_{\text{tot}}$  measurements were performed using a Thermo Scientific Delta V  
247 isotope ratio mass spectrometer coupled to a Flash EA via a Conflow III interface. The  
248 Flash EA was equipped with a large volume reactor, allowing analysis of samples low in

249 total nitrogen abundances. The nitrogen isotope ratios ( $^{15}\text{N}/^{14}\text{N}$ ) are expressed in the  
250 delta notation, as ‰ deviation relative to the nitrogen in air (Air- $\text{N}_2$ ) standard.  
251 Reproducibility and accuracy were monitored by replicate standard and sample analysis  
252 and were better than 0.1‰ for standard materials and 0.3‰ for samples ( $1\sigma$ ). The  
253 measured  $\delta^{15}\text{N}$  values were calibrated the IAEA-600 caffeine standard ( $\delta^{15}\text{N} = +0.91\text{‰}$ ).

254

### 255 *3.4. Calcareous nannofossils*

256

257 A total of 117 samples were analysed for calcareous nannofossils analysis  
258 including: 34 samples from the Mellala section, spanning from the upper Pliensbachian  
259 to the lower Toarcian (Fig. 2; Table 1), 34 samples from Raknet El-Kahla section,  
260 covering the upper Pliensbachian to the middle Toarcian (Fig. 2; Table 2), and 59  
261 samples from Djebel-Chemarikh section, spanning the middle to upper Toarcian (Fig. 2;  
262 Table 3). Slides for calcareous nannofossil analyses were prepared according to the  
263 settling technique described by Beaufort et al. (2014) slightly modified. A small amount  
264 of sediment powder was mixed in a tube with a known volume of water. After stirring, the  
265 tube was placed in an ultrasonic bath for few seconds to separate sediments and  
266 coccoliths, and the obtained suspension of water and sediment powder was poured onto  
267 a precisely weighted coverslip placed in a Petri dish. After settling for 4 hours, the water  
268 was carefully removed using a water-pump and the slide was dried in an oven to remove  
269 residual water. Once the slide dried, the coverslip was weighted a second time to  
270 calculate the amount of powder homogeneously settled on the slide. Finally, the  
271 coverslip was mounted onto a microscope slide using Rhodopass B resin (polyvinyl  
272 acetate). The obtained slides were observed in a ZEISS Axioscope 40 polarising  
273 microscope, using a 1000X magnification. A minimum of 300 specimens per samples  
274 were counted in a variable area of the slide, and fifty fields of view were further scanned  
275 for each slide in order to identify rare species. The counting of 300 specimens is  
276 statistically significant to record all the species making up more than 1.7% of total  
277 assemblage with 99.5% confidence level (Fatela and Taborda, 2002).

278 An assessment of the degree of preservation was made for each sample, based on  
279 the degree of etching and overgrowth, as reported by Roth (1984). Three classes of



280 preservation were thus used: poor for nannofossil assemblages showing strong etching,  
281 overgrowth or fragmentation, moderate and good when *Schizosphaerella* fragmentation  
282 is limited and delicate coccoliths showing relatively pristine structures were found,  
283 respectively. For the Mellala and Raknet El-Kahla sections, we also calculated the  
284 absolute abundance of calcareous nannofossils per gram of rock using the following  
285 formula:

286

$$287 \quad X = n \times A^t \times m^{-1} \times A^{-1} \quad (1)$$

288

289 where  $X$  is the absolute abundance,  $n$  is the number of counted specimens in a slide,  $A^t$   
290 is the total area of the cover slide,  $m$  is the mass of the weighted rock powder and  $A$  is  
291 the area studied in the slide.

292 In Raknet El-Kahla, the volume of *Mitrolithus jansae* was also estimated on 30  
293 specimens per sample in 14 samples (except in sample RK01, where well preserved  
294 specimens were very rare). For each of the 14 samples, the image from the first 30  
295 specimens randomly recorded was captured with a Leica EC3 digital camera, coupled  
296 with an optical polarized light microscope (X1000 magnification). In the system we used,  
297 1  $\mu\text{m}$  correspond to 17.5 pixels, thus the precision of size measurements is 0.057  $\mu\text{m}$   
298 per pixel. For each coccolith, 4 parameters (H: height of the coccolith with the spine; h:  
299 height of the coccolith; R: diameter at the top of the coccolith; r: diameter at the base of  
300 the coccolith) were measured using the software ImageJ©. The volume of the coccoliths  
301 was thus estimated on the basis of the formula defined by Suan et al. (2008):

302

$$303 \quad V = 1/3 \times \pi \times (H \times h/2) \times (R^2 + R \times r + r^2) \quad (2)$$

304

305 Measurements of the coccolith parameters were used to calculate simple statistical  
306 parameters, such as mean and standard deviation. Statistical analysis was performed  
307 using the PAST 3.01 software package (Hammer et al., 2001).

308

#### 309 **4. Results**

310

#### 311 4.1. Stable isotope data and wt.%TOC

312

313 The new  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$  data obtained for Mellala were compared to the  
314 published data for Raknet El-Kahla (Reolid et al., 2012b; Ruebsam et al., 2020a). The  
315 long-term trends and magnitude of changes in  $\delta^{13}\text{C}_{\text{carb}}$  values are similar in the two  
316 sections (Fig. 2). The  $\delta^{13}\text{C}_{\text{carb}}$  values oscillate around 0‰ in the late Pliensbachian,  
317 decrease at the Pliensbachian/Toarcian boundary (PI/To CIE) and reach minimum  
318 values of about -3.0‰ (-3.1‰ in Raknet El-Kahla, and -2.9‰ in Mellala) at the base of  
319 Polymorphum Zone, then record a positive rebound to approximately +0.8‰ (0.8‰ in  
320 Raknet El-Kahla, and 0.7‰ in Mellala) in the middle-upper part of the Polymorphum  
321 Zone. The  $\delta^{13}\text{C}_{\text{carb}}$  values decrease again in the basal part of the Levisoni Zone in both  
322 sections (down to -1.3‰ in Raknet El-Kahla, and -2.3‰ in Mellala), thus capturing  
323 partially or totally the CIE often associated with the T-OAE.

324 The  $\delta^{13}\text{C}_{\text{org}}$  values measured in Mellala vary from -22.0‰ to -29.4‰. The  $\delta^{13}\text{C}_{\text{org}}$   
325 curve mimics the general trends of the  $\delta^{13}\text{C}_{\text{carb}}$  curve. Two relative minimum  $\delta^{13}\text{C}_{\text{org}}$   
326 values, namely in the lower part of the Toarcian and across the Polymorphum/Levisoni  
327 zones boundary (NJT6a nannofossil zone), interrupt a general increasing trend of  
328  $\delta^{13}\text{C}_{\text{org}}$  values across the lower Toarcian (dark grey shaded areas in Fig. 2).

329 The  $\delta^{15}\text{N}$  values range from 0.3‰ to 3.9‰. The highest values are recorded in the  
330 uppermost Pliensbachian, where the  $\delta^{15}\text{N}$  curve greatly fluctuates from values at around  
331 1‰ to values at around 4‰. In the Mirabile Subzone of earliest Toarcian, values  
332 decrease to 1-2‰ and, in the Semicelatum Subzone,  $\delta^{15}\text{N}$  values attain up to 3‰ in  
333 discrete levels. Some of the lowest values are recorded in the Levisoni Zone, in the  
334 ointerval corresponding to the T-OAE interval (Fig. 2).

335 The TOC contents are overall very low and do not exceed 0.45%, with the lowest  
336 values restricted to intervals corresponding to the two negative CIEs at the base of the  
337 Toarcian, the Mirabile Subzone, and in the Levisoni Zone (Fig. 2).

338

#### 339 4.2. Calcareous nannofossils record

340

##### 341 4.2.1. Calcareous nannofossils bio-events

342

343         Preservation state is poor to moderate in most of the analysed samples of the  
344 three studied sections (Tables 1-3; Plates 1-2). The poor calcareous nannofossil  
345 preservation is coherent with clay mineralogy data, which indicate a strong burial  
346 diagenesis similar to sites in the High-Atlas of Morocco (Supplementary Material).  
347 However, preservation state did not prevent the species identification or the counting of  
348 300 specimens per slide. Thus, it was considered sufficient to evaluate primary changes  
349 in calcareous nannofossil assemblages related to environmental fluctuations.

350         The biostratigraphic scheme used here follows that of Mattioli and Erba (1999),  
351 defining the nannofossil zones and subzones for the Mediterranean Tethys, eventually  
352 implemented by Ferreira et al. (2019). The ammonite zonation of Raknet El-Kahla and  
353 Djebel Chémariikh sections have been previously defined by Mekahli (1998), and that of  
354 Mellala is after Elmi et al. (2006). Several nannofossil bio-events were recorded in the  
355 Raknet El-Kahla section, from the Emaciatum Zone (late Pliensbachian) to the Bifrons  
356 Zone (middle Toarcian) and in the Djebel Chemariikh section, from the middle to the late  
357 Toarcian (Fig. 2). A series of successive events characterizes the  
358 Pliensbachian/Toarcian boundary in Raknet El-Kahla or Mellala, namely the FOs of  
359 *Crepidolithus impontus*, *Diductius constans*, *Biscutum dubium*. Other events are  
360 recorded across the boundary, such as the FO of *Biscutum intermedium*, which is  
361 observed in both sections very close to the Pliensbachian/Toarcian boundary. The FO of  
362 *Discorhabdus ignotus* in the lowermost part of the Polymorphum Zone coincides in both  
363 sections with the PI/To CIE (Fig. 2; Tables 1 and 2). This species is temporarily absent  
364 in the samples coinciding with the CIE of the early Toarcian (T-OAE equivalent interval)  
365 in Raknet-El-Khala section (Fig. 2; Table 2).

366         The FO of *Carinolithus superbus* (*C. superbus crassus* of Visentin et al., 2020),  
367 which is the marker of the NJT6 nannofossil zone, was identified in the Raknet El-Kahla  
368 and Mellala sections in the Polymorphum ammonite Zone, concomitant with the positive  
369 rebound of the carbon isotope curve. The NJT6 zone includes the CIE often used to  
370 define the base of the T-OAE (Fig. 2). In several sections of the Tethys domain, this  
371 zone is subdivided into a and b according to the LO of *Mitrolithus jansae* (Ferreira et al.,

372 2019). This is not possible in the Raknet El-Khala section because the LO of *M. jansae*  
373 is recorded after the FO of *D. striatus*.

374 The FO of *Discorhabdus striatus* is recorded in the interval just above the T-OAE  
375 negative CIE in Raknet El-Kahla (Fig. 2). This event marks the base of the NJT7 zone.  
376 This event is closely followed by the FO of *Watznaueria colacicchii* in the Levisoni Zone  
377 and by the LO of *Mitrolithus jansae* in the upper part of Levisoni Zone. In the Bifrons  
378 Zone of Raknet El-Kahla, thin and elongated specimens of *Carinolithus superbus* first  
379 occur (*C. superbus superbus* of Visentin et al., 2020).

380 In Djebel Chemarikh section, the presence of *Watznaueria fossacincta* was  
381 identified in sample at the base of the Bifrons Zone (Sublevisoni Subzone). The FOs of  
382 *Triscutum sullivanii* and of *Biscutum depravatum* followed by the FO of *Discorhabdus*  
383 *criotus* in the also occur in the Bifrons Zone (Fig. 2; Table 3). Finally, the FO of  
384 *Watznaueria contracta* characterizes the top of the late Toarcian Meneghinii Zone, and  
385 the FO of *Hexalithus magharensis* the base of the Aalenian (Fig. 2; Table 3).

386

#### 387 4.2.2. Nannofossils absolute abundances

388

389 Absolute and relative abundances were calculated for samples ranging from the  
390 upper Pliensbachian to the middle Toarcian, of the Raknet El-Kahla and Mellala sections.  
391 Nannofossils were deemed too scarce in the Djebel Chémariikh section (middle to upper  
392 Toarcian) to estimate their absolute abundance per gram of rock. This scarcity is partly  
393 attributable to a poor preservation but possibly also to an originally very low calcareous  
394 phytoplankton primary productivity.

395 The highest nannofossil absolute abundance values in the Raknet El-Kahla section  
396 are recorded in the Emaciatum Zone, with values up to  $120 \times 10^6$  nannofossils per gram  
397 of rock. Then values show a decreasing trend across the Pliensbachian/Toarcian  
398 boundary, except for ~~unless~~ a positive peak of  $100 \times 10^6$  at the boundary. The absolute  
399 abundance values show an average of  $40 \times 10^6$  during the Polymorphum Zone, with  
400 minimum values being attained in Levisoni Zone, corresponding to the T-OAE interval  
401 (Fig. 3).

402 In the Mellala section, absolute abundance shows values higher than at Raknet El-  
403 Khala. Average values are around  $350 \times 10^6$  in the Polymorphum Zone, although  
404 regularly fluctuating between  $\sim 150$  and  $600 \times 10^6$ . Such fluctuations are related to the  
405 lithology. In fact, values are lower in limestone beds and more important in marls. before  
406 Absolute abundance values show a drastic drop down to around  $80 \times 10^6$  between the top  
407 of the Polymorphum Zone and the base of the Levisoni Zone (Fig. 4).

408

#### 409 4.2.3. Trends in calcareous nannofossils assemblages

410

411 In both sections (Raknet El-Kahla and Mellala), the relative abundance of *M.*  
412 *jansae* (which is a murolith-coccolith; Bown, 1987) is quite high compared to other  
413 species (Figs. 4 and 5). In the Raknet El-Kahla section the relative abundance of *M.*  
414 *jansae* in the late Pliensbachian up to the Levisoni Zone fluctuate between 30% and 70%  
415 of total coccoliths (Fig. 3). Despite low total nannofossil absolute abundances, the  
416 relative abundance of *M. jansae* stays high during the T-OAE interval. A drastic  
417 decrease to values lower than 10% is observed in the upper part of the Levisoni Zone,  
418 forewarning the disappearance of this taxon at the base of the Bifrons Zone.

419 In the Mellala section, the dominance of *M. jansae* over coccoliths is not as  
420 important as in Raknet El-Kahla section, high relative abundances are recorded across  
421 the Emaciatum and Polymorphum Zones ( $\sim 40\%$ ), then they fall down to  $\sim 5\%$  in the  
422 upper part of the Mirabile Subzone. *Mitrolithus jansae* relative abundances increased  
423 again to about 20% in the Semicelatum Subzone, and remained high ( $>20\%$ ) in the  
424 basal Levisoni Zone, in which nannofossils absolute abundances decreased markedly  
425 (Fig. 4).

426 In the two sections studied, *C. crassus* dominated within the *Crepidolithus* pool. It  
427 is more abundant in Raknet El-Kahla (average 12%) than in Mellala (average 6%). The  
428 relative abundances of *Crepidolithus* spp. increased only in the Levisoni Zone, above  
429 the CIE interval, when the *M. jansae* relative abundances decreased.

430 Within the placolith-coccolith group (definition in Bown, 1987), the relative  
431 abundances of *Lotharingius* spp. display in both sections an increase after the  
432 Pliensbachian/Toarcian boundary and stay high in the Polymorphum and Levisoni Zones.

433 The Biscutaceae show high percentages in both sections, especially in the  
434 Polymorphum Zone of the Mellala section, where their relative abundances exceed  
435 those of *M. jansae*. However, an opposite trend in relative abundances of these two taxa  
436 is observed (Fig. 4).

437 Absolute and relative abundances of the *incertae sedis* *Schizosphaerella* spp.  
438 display a peculiar pattern (Figs. 4 and 5), with relatively high abundances although  
439 fluctuating in the late Pliensbachian and early Toarcian. A clear decrease is observed  
440 across the Pliensbachian/Toarcian boundary in the Mellala section, passing from  
441 abundances >25% below the boundary to ~10% above the boundary. A similar trend is  
442 observed in Raknet El-Kahla section, with abundances >20% below, and <10% above  
443 the Pliensbachian/Toarcian boundary. However, the most relevant decrease in the taxon  
444 abundance is observed at the base of the T-OAE CIE, with values <5% of the total  
445 nannofossil assemblage in both sections.

446 The measurements of *M. jansae* in the Raknet El-Kahla section (Fig. 3) show an  
447 average volume of 85.67  $\mu\text{m}^3$  and no significant stratigraphic changes. In particular, *M.*  
448 *jansae* volumes remained relatively constant across the two CIEs at the  
449 Pliensbachian/Toarcian boundary and the T-OAE (Fig. 3).

450

## 451 **5. Discussion**

452

### 453 *5.1. Ecology of nannofossil taxa*

454

455 Before discussing the nannofossil trends in the studied sections, a brief review on  
456 the ecological preference of main taxa is presented here. Lower Jurassic nannofossils  
457 are composed of coccoliths and *Schizosphaerella* (*incertae sedis*). This latter taxon has  
458 been long considered as affiliated to dinoflagellate cysts (Bown, 1987). Recently,  
459 unicellular planktonic algae of the genus *Phacotus* (Chlorophyta) were reported from  
460 lakes of the temperate zone (Szelag-Wasielewska et al., 2018), which are composed of  
461 two calcite valves very much resembling the shape of Jurassic *Schizosphaerella* (Menini  
462 et al., 2021). Claps et al. (1995) and Tremolada et al. (2005) interpreted  
463 *Schizosphaerella* as a deep-dweller taxon, in a way similar to the modern

464 coccolithophorid *Florisphaera profunda* (Molfino and McIntyre, 1990). A deep-dweller  
465 habitat for *Schizosphaerella* was, however, challenged because this taxon was  
466 dominating in both proximal, shallow areas and in deeper, and distal settings (Mattioli  
467 and Pittet, 2004; Reggiani et al., 2010). *Schizosphaerella* is dominant over coccoliths  
468 along the southern Tethyan margin (Bown, 1987; Mattioli et al., 2008), conversely it was  
469 recorded as rare in the NW European shelf (Bucefalo Palliani et al., 2002; Mattioli et al.,  
470 2008). *Schizosphaerella* might have proliferated in overall oligotrophic waters in times of  
471 nutriment recycling in surface waters because of intensified storms (Mattioli, 1997;  
472 Mattioli and Pittet, 2004).

473 *Mitrolithus jansae*, which is conspicuously recorded in NW Algeria, likely had a  
474 deep (or intermediate) dweller ecology (Bucefalo Palliani and Mattioli, 1998; Erba, 2004;  
475 Mattioli and Pittet, 2004), and dominated over other coccoliths in times of stratification of  
476 the water column when the nutricline settled deep in the photic zone. A possible modern  
477 analogous is the deep-dweller species *Florisphaera profunda*, which is dominating the  
478 assemblages when surface waters are oligotrophic and the nutricline settles deep  
479 (Molfino and McIntyre, 1990). *Mitrolithus jansae* is a typical component of southern  
480 Tethyan settings and is rare in the sections located along the northern margin of Tethys  
481 (Bown, 1987; Mattioli et al., 2008). A similar deep-dweller habitat has been proposed for  
482 the species *Crepidolithus crassus* (Bour et al., 2007; Mattioli et al., 2008; Reggiani et al.,  
483 2010; Fraguas, 2014), but this taxon was more widespread along the N-Tethyan margin  
484 (Mattioli et al., 2008).

485 The small placolith-coccoliths belonging to *Lotharingius* and to Biscutaceae may  
486 indicate moderate-to-high nutrient concentrations in the shallow photic-zone waters  
487 (Pittet and Mattioli, 2002; Mattioli and Pittet, 2004; Olivier et al., 2004; Tremolada et al.,  
488 2005). *Lotharingius* and Biscutaceae are very tiny, small coccoliths. In modern oceans,  
489 similar coccolith morphology is typical of meso-eutrophic species, which are common in  
490 the surface oceanic waters or proximal settings (Young, 1994).

491

## 492 5.2. Biostratigraphy and chemostratigraphy

493

### 494 5.2.1. Nannofossil biozonation and correlation of the studied sections

495

496 The recent work of Ferreira et al. (2019), who updated the calcareous nannofossil  
497 biostratigraphy of the Lower and Middle Jurassic strata exposed in Portugal, was applied  
498 in this study because the locations were situated in a similar paleogeographic and  
499 paleoclimatic realm. The nannofossils zones and subzones that have been recognized  
500 in Mellala section range from NJT5b to NJT6a, in Raknet El-Kahla range from NJT5b to  
501 NJT7b, whereas in Djebel Chemarikh from NJT7a to NJT8f (Fig. 2). The base of the  
502 Mellala and Raknet El-Kahla sections is attributed to the nannofossil subzones NJT5b  
503 and c, spanning the latest Pliensbachian to earliest Toarcian, because of the consistent  
504 presence of *Lotharingius crucicentralis* in the stratigraphically lowermost samples. The  
505 species *Zeugrhabdothus erectus*, which defines the boundary between the two  
506 subzones NJT5b and c, roughly corresponding to the Pliensbachian/Toarcian boundary,  
507 was not recorded in NW Algeria. However, the studied sites record other auxiliary events  
508 characterizing the Pliensbachian/Toarcian boundary in several Tethys regions (Fig. 2;  
509 Menini et al., 2019).

510 The base of the NJT6 zone is defined by the FO of *Carinolithus superbus*, and its  
511 top is defined by the FO of *Discorhabdus striatus*. According to Ferreira et al. (2019), the  
512 NJT6 is subdivided into two subzones, NJT6a and b, on the basis of the LO of *M. jansae*.  
513 However, in NW Algeria *M. jansae* last occurs above the FO of *D. striatus*, i.e. in a  
514 reverse order compared to most Tethys records, likely because this species survived  
515 longer in South Tethys refuge areas. The lower boundary of the nannofossils zone NJT7  
516 is characterized by the FO of *Discorhabdus striatus* in Raknet El-Khala, but the upper  
517 boundary is not defined since we did not record the FO of *Retecapsa incompta* in Djebel  
518 Chemarikh. In both Raknet El-Kahla and Djebel Chemarikh sections, two subzones can  
519 be identified, namely the NJT7a ranging between the FO of *D. striatus* and the FO  
520 *Watznaueria colacicchii*, and the NJT7b whose top is defined by the FO of *Discorhabdus*  
521 *criotus* (Fig. 2). These two subzones are not clearly differentiated because the NJT7a  
522 corresponds to a very reduced thickness in both sections (Fig. 2a). In Djebel Chemarikh  
523 section, two other nannofossil subzones are recognized, namely the NJT7c which  
524 ranges between the FO of *D. criotus* and the *Lotharingius* size shift; then after an  
525 interval ~20m thick which is not dated by nannofossils, the FO of *Watznaueria contracta*



526 allowed us to define the base of the NJT8d subzone. Finally, the base of the NJT8f is  
527 characterized by the FO of *Carinolithus magharensis* at the top of Djebel Chemarikh  
528 section, also marking the base of the Aalenian.

529 When comparing the nannofossil record and the  $\delta^{13}\text{C}$  negative excursion of both  
530 whole rock carbonate and TOC at the PI/To boundary in Mellala, it appears that some  
531 events (mainly FOs) are stratigraphically separated, whilst in many other Tethys  
532 sections including the GSSP in Peniche they occurred very close to each other (Menini  
533 et al., 2019). This pattern can be explained by the exceptional continuity of the  
534 sedimentary record and higher accumulation rates across the PI/To boundary in the  
535 Mellala section. In fact, this section was originally considered as a potential GSSP  
536 candidate for the Pliensbachian/Toarcian, due the remarkable continuity of the  
537 sedimentary record and the well-established ammonite biozonation (Elmi et al., 2006).  
538 This continuity is relevant because, in many other Tethys settings, sedimentary  
539 condensation and hiatuses occur in the same interval (Pittet et al., 2014; Bougeault et al.,  
540 2017; Menini et al., 2019; Ruebsam and Al-Husseini, 2020). This sedimentary continuity  
541 likely resulted from the tectonic context of the Mellala area, which was defined as a  
542 subsiding "umbilicus" (Elmi et al., 2006).

543

#### 544 *5.2.2. The record in NW Algeria of carbon cycle perturbations based on trends in* 545 *$\delta^{13}\text{C}_{\text{carb}}$ , $\delta^{13}\text{C}_{\text{org}}$ and TOC values*

546

547 The  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$  profiles in the Mellala section record two CIEs, which  
548 occurred at the Pliensbachian/Toarcian boundary (PI/To CIE) and in the early Toarcian  
549 (T-OAE CIE). Trends in inorganic and organic carbon isotopes can be correlated with  
550 coeval sites and reflect times of profound carbon cycle perturbations. Both negative  
551 CIEs, recognized in various oceanic and continental settings, likely resulted from  
552 massive injections of  $^{13}\text{C}$ -depleted carbon into the ocean and atmosphere reservoirs  
553 (e.g., Hesselbo et al., 2000; 2007; Ruebsam et al., 2020b). Our new data from the  
554 Mellala site record the onset of the prominent T-OAE CIE, thus showing many  
555 similarities with the  $\delta^{13}\text{C}_{\text{carb}}$  and the  $\delta^{13}\text{C}_{\text{org}}$  data previously obtained for the Raknet El-  
556 Kahla section (Reolid et al. 2012b; Ruebsam et al. 2020a) (Fig. 2). This was expected,

557 given the geographical proximity between the two sites. Recently, the PI/To CIE has also  
558 been recorded in brachiopod calcite from NW Algeria (Baghli et al., 2020).

559 Following this marked carbon isotope event, a prominent positive  $\delta^{13}\text{C}_{\text{carb}}$  and  
560  $\delta^{13}\text{C}_{\text{org}}$  rebound is recorded in the Polymorphum Zone (early Toarcian) of both Mellala  
561 and Raknet El-Khala. This event, also recorded in several Tethys sites, has been  
562 attributed to increased sequestration of atmospheric carbon, possibly through reduced  
563 carbon emission rates or higher primary production in shallow marine waters (Hesselbo  
564 et al., 2007). The bio- and chemostratigraphic data allowed a correlation of the proximal  
565 Mellala and the Raknet El-Kahla sections.

566 The organic carbon content at Mellala (less than 0.5 wt.% TOC) is overall very low,  
567 especially if compared to NW Europe sites, where values can attain up to 16 wt.% TOC  
568 (e.g., Hesselbo, 2000; Röhl et al., 2001; Hermoso et al., 2013; Suan et al., 2015;  
569 Ruebsam et al., 2018). The lowest TOC values are bound to the two negative CIEs at  
570 the PI/To and T-OAE equivalent intervals. Although TOC contents are overall very low  
571 (in the range of 0.2 to 0.3 wt.%) also in Raknet El-Kahla, a moderate increase in TOC up  
572 to ~0.6% occurs in the T-OAE CIE interval of this latter section and has been attributed  
573 to the development of oxygen-deficient bottom and pore waters (Ruebsam et al., 2020a).  
574 In this view, although TOC values are very low in both sections, the record of Mellala  
575 differs from the one reported from Raknet El-Khala. One explanation might be that  
576 oxygen-deficient conditions did not develop at Mellala in the interval of the T-OAE CIE,  
577 potentially due to the proximity to the open-shelf sea and less hydrological restriction  
578 (Fig. 1). Alternatively, low TOC values during the T-OAE CIE at Mellala may be related  
579 to a decreased primary productivity in surface waters. In fact, nannofossil absolute  
580 abundances are the lowest in this interval, the meso-eutrophic forms (such as  
581 Biscutaceae) are rare, while the deep-dwellers (such as *M. jansae*) indicating marine-  
582 water stratification and oligotrophy in the upper photic-zone layer (Bucefalo Palliani and  
583 Mattioli, 1998; Mattioli and Pittet, 2004; Erba, 2004; Mattioli et al., 2008) dominate (Fig.  
584 2).

585

586 *5.2.3. Nutricline fluctuations based on trends of  $\delta^{15}\text{N}$*

587

588 The  $\delta^{15}\text{N}$  values measured at Mellala were compared to data acquired in Raknet  
589 El-Khala (Ruebsam et al., 2020a). Overall, values are comprised between 0 and 4 ‰ in  
590 Mellala, and between 2 and 4 ‰ at Raknet El-Khala. Some of the lowest and steadiest  
591 values were recorded in both sections in the intervals corresponding to the two negative  
592 CIEs in the PI/To and T-OAE intervals. More fluctuating values are observed in the  
593 Pliensbachian of Mellala and in the upper part of Polymorphum of both sections.

594 Nitrogen fixing diazotroph cyanobacteria add nitrogen to the surface ocean with a  
595 fractionation of  $-3\text{‰}$  to  $-1$  relative to the atmospheric  $\text{N}_2$  source ( $\delta^{15}\text{N}_{\text{air}} \sim 0\text{‰}$ ) (Brandes  
596 and Devol, 2002; Gruber, 2008). The present-day oceanic value of organic matter  $\delta^{15}\text{N}$   
597 formed from nitrate assimilation is mostly determined by the  $\delta^{15}\text{N}$  of nitrate delivered to  
598 the euphotic zone (the subsurface source), which in turn is dependent on the degree of  
599 water column denitrification, and on the degree of nitrate consumption at the ocean  
600 surface. Accordingly, changes in organic matter  $\delta^{15}\text{N}$  can reflect the variability of the  
601 source nitrate  $\delta^{15}\text{N}$  and of the degree of nitrate consumption, but will also vary as  
602 function of redox-controlled denitrification rates (e.g., Gruber, 2008; Casciotti, 2016).  
603 Throughout the Mellala section, significant changes in the redox conditions are not  
604 apparent from sedimentological observations. Thus, the  $\delta^{15}\text{N}$  values most likely vary in  
605 response to changes in N-uptake (related to primary productivity changes) and in  
606 vertical shifts of the nutricline. A reduced N-uptake because of reduced primary  
607 productivity drives a decline in  $\delta^{15}\text{N}$  (Casciotti, 2016; Schoepfer et al., 2016). A shallow  
608 nutricline (mesotrophic surface waters) can be linked to nitrate introduced into the water  
609 column. This process results in lower  $\delta^{15}\text{N}$  values. A deep nutricline (oligotrophic surface  
610 waters) can be linked to organic matter formed from nitrate assimilation in regions where  
611 plankton uses most of the available nitrate. Its remineralization will increase the  $\delta^{15}\text{N}$  of  
612 ambient nitrate (Casciotti, 2016). However, distinguishing the impact of both processes  
613 on sedimentary  $\delta^{15}\text{N}$  signature might be difficult.

614 Shifts in the position of nutricline depth or in nanoplankton production are  
615 indicated by calcareous nannofossil assemblages at Mellala, namely the successive  
616 dominance of shallow- and deep-dwellers and the absolute abundance of nannofossils  
617 per gram of rock (Fig. 4). Accordingly, the most prominent feature in the  $\delta^{15}\text{N}$  trend is  
618 the decrease occurring at the transition between the Elisa and Mirabile Subzones, at the

619 inception of the negative PI/To CIE (Fig. 2), simultaneously marking the transition to a  
620 shallower nutricline. In the Semicelatum Subzone,  $\delta^{15}\text{N}$  steadily fluctuates between 1‰  
621 and 3‰ (Fig. 2). In the same interval, trophic levels and the nutricline fluctuated, as  
622 indicated by nannofossil assemblages (Fig. 4). In contrast, the initial T-OAE CIE interval  
623 records very steady  $\delta^{15}\text{N}$  values of about 2‰, along with very low absolute nannofossil  
624 abundances and high proportions of *M. jansae* commonly interpreted as a deep-dweller  
625 (for the ecological affinity of taxa, see section 5.1). The very steady  $\delta^{15}\text{N}$  values may  
626 point to a prolonged sourcing of recycled nitrate under stratified water-column conditions.  
627 Furthermore, a decline in the marine primary productivity during hyperthermals  
628 associated with the PI/To CIE and the T-OAE CIE may have additionally contributed to  
629 preferentially light  $\delta^{15}\text{N}$  values. The scenario discussed above for the Toarcian events  
630 would be most valid for a high-nitrate low-chlorophyll setting, where nitrate utilization is  
631 incomplete. Accordingly, primary productivity must have been limited by micronutrients  
632 or other environmental parameters. A similar scenario has been drafted for the dramatic  
633 latest-Rhaetian crisis, where major negative excursions in  $\delta^{15}\text{N}$  correspond to periods of  
634 depressed marine productivity, linked to the development of a stable pycnocline, limited  
635 vertical mixing and, finally, limited N availability in surface waters (Schoepfer et al.,  
636 2016).

637 Alternatively, in the Algeria basins primary productivity was limited by nitrate  
638 availability, and nitrate utilization was essentially complete, leading to no net  
639 fractionation. In this scenario, fluctuations in  $\delta^{15}\text{N}$  reflect the balance of nitrogen fixation  
640 and water-column denitrification. This is compatible with the scenario described above  
641 on the basis of nannofossil assemblages, of intense stratification and low productivity. In  
642 a stratified ocean (especially during the T-OAE CIE interval; Fig. 6A), little nitrate is  
643 mixed upward from deep water. Nannofossil abundances likely declined due to a lack of  
644 macronutrients in surficial waters, and deep dwellers thrived when nutricline settled deep.  
645 Thus, low  $\delta^{15}\text{N}$  values in sedimentary organic matter was likely due to nitrogen-fixing  
646 diazotrophs adding nitrogen to the surface ocean with a low  $\delta^{15}\text{N}$  value. Conversely, in  
647 times of increased vertical mixing of remineralized nitrate, a likely temporarily increased  
648 productivity occurred (like in the upper part of the Polymorphum Zone; Fig. 6B). The  
649 overall values measured in this study ( $\sim 2\text{‰}$ ) are typical of greenhouse intervals of Earth

650 history, where sedimentary denitrification leads to decreased N recycling and enhanced  
651 nitrogen fixation (Algeo et al., 2014).

652

### 653 *5.3. Palaeoenvironmental conditions in NW Algeria*

654

655 A palaeoenvironmental reconstruction is attempted for the late Pliensbachian-early  
656 Toarcian interval, which was studied in the Mellala (Tlemcen Basin) and Raknet El-  
657 Kahla (Sahara Basin) sections. Although nannofossil absolute abundance is much  
658 higher in Mellala than in Raknet El-Kahla, the trends are similar in both sections, with  
659 absolute abundances reaching maxima during the Polymorphum Zone before falling at  
660 the beginning of the T-OAE. Another noticeable feature of both sections is represented  
661 by the overall high proportions of the species *Mitrolithus jansae*, which is acknowledged  
662 to be a taxon with south-Tethys affinities (Bown, 1987; Mattioli et al., 2008) thus  
663 proliferating in N-Gondwana basins.

664 Nannofossil absolute abundances as well as the relative abundance of small  
665 placolith-coccoliths (i.e., species of the *Lotharingius* genus and Biscutaceae) are much  
666 higher in Mellala than in Raknet El-Khala in the early Toarcian Polymorphum Zone (Figs.  
667 4 and 5). The nannofossil record from NW Algeria can be thus interpreted in terms of  
668 availability of nutrient resources. Higher absolute abundances of all nannofossils and  
669 higher proportions of meso-to-eutrophic taxa may likely indicate a higher productivity in  
670 Mellala than in Raknet El-Kahla. Interestingly, Raknet El-Khala was located in a small  
671 basin bounded by the Sahara Craton to the South and by the Oran Massif to the North.  
672 This basin was likely characterized by a restricted water circulation, while the Tlemcen  
673 Basin was connected to the open-ocean Tethys to the North. Given the arid regime  
674 dominating along the N-Gondwana margin in the Early Jurassic (van de Schootbrugge  
675 et al. 2005; Baghli et al., 2020), the Raknet El-Khala section likely lacked significant  
676 riverine discharges. Such arid conditions, along with a probable thermal stratification of  
677 basin waters, as discussed in Baghli et al. (2020), prevented nutrient replenishment of  
678 surface waters where coccolithophore were thriving. The persistent water stratification is  
679 further supported by the dominance in nannofossil assemblage of *M. jansae* (proportions  
680 usually higher than 50%), which is commonly interpreted as being a deep-dweller,

681 proliferating in times of stratification and oligotrophy of the upper part of the water  
682 column (see section 5.1). The Tlemcen Basin, conversely, was connected by a narrow  
683 passage to the North with the Tethys Ocean. The connexion with open-ocean waters  
684 might have produced water mixing and, finally, phases of temporary nutrient  
685 replenishment in surface waters, favouring proliferation of shallow-dweller species. Such  
686 phases alternated with surface water stratification, as indicated by the high proportions  
687 of the deep-dweller *M. jansae*, although this latter species is less abundant (in general,  
688 proportions lower than 50%) than in Raknet El-Khala. Such fluctuating conditions  
689 between stratified and mixed waters, and the subsequent vertical migration of the  
690 nutricline, are further supported by the  $\delta^{15}\text{N}$  record from Mellala and Raknet El-Khala.  
691 Thereby, high and although fluctuating  $\delta^{15}\text{N}$  values in the upper Emaciatum to the lower  
692 Polymorphum ammonite Zones may reflect a fluctuating nutricline and re-occurring  
693 mixing events, promoting mesotrophic surface waters (Fig. 5B). On the contrary, low and  
694 stable  $\delta^{15}\text{N}$  values during the T-OAE are explained by a deep nutricline, oligotrophic  
695 surface waters and low primary productivity (at least for nanoplankton) (Fig. 5A).

696 Common trends between the two sections are recorded in the two CIE intervals.  
697 Within the P-T boundary CIE interval, the absolute abundance of nannofossils is quite  
698 high although fluctuating (especially in Mellala). The relative abundances of the meso-  
699 eutrophic taxa, such as Biscutaceae, are the highest while the relative abundances of  
700 the deep-dweller *M. jansae* and of the incertae sedis *Schizosphaerella* spp. are low in  
701 this interval. Such observations suggest relatively high trophic conditions in surface  
702 waters during the earliest Toarcian, which are also coherent with low proportions of the  
703 deep-dweller *M. jansae*.

704 Concomitant with the T-OAE negative CIE, also coinciding with anoxia  
705 development in several epicontinental basins (McArthur, 2019), extremely low absolute  
706 nannofossil abundances are recorded, especially in the Mellala section. In this interval,  
707 high proportions of the deep-dweller *M. jansae* occur, while the taxa commonly  
708 interpreted as shallow-dwellers (*Schizosphaerella* spp., *Lotharingius* spp. and  
709 Biscutaceae) display very low relative abundances. Nannofossil abundance and  
710 assemblages are consistent with very low nannofossil production. In a context of the  
711 early Toarcian global warming, the negative offset of  $\sim 1.5\%$  for  $\delta^{18}\text{O}$  values (vs. V-

712 SMOW) observed in NW Algeria compared to European sections has been interpreted  
713 as an evidence for higher seawater temperatures along the southern margin of Tethys  
714 (Baghli et al., 2020). Accordingly, we attribute this very low nannofossil production to the  
715 development of hyper-oligotrophic conditions within the photic zone in NW Algeria  
716 basins due to extreme and persistent thermal stratification of the water column.

717  
718 *5.4. Comparison between the NW Algeria calcareous nannofossil assemblage and other*  
719 *Tethys basins*

720  
721 The nannofossil absolute abundances of the Raknet El-Khala section from the  
722 Polymorphum Zone are overall lower than those measured in other sections in the  
723 western Tethys in the time-equivalent interval. Conversely, Mellala shows nannofossil  
724 amounts which are in the same order of magnitude than those recorded in Peniche  
725 (Mattioli et al., 2008) or in La Cerradura (Reolid et al., 2014b). In the interval comprised  
726 between the upper part of the Polymorphum and the lower half of the Levisoni Zone,  
727 time-equivalent to the T-OAE, nannofossil absolute abundances are sensibly low  
728 ( $\leq 50 \times 10^6$  specimens per gram of rock) in NW Algeria as well as in all the areas around  
729 the western Tethys (Mattioli et al., 2008; 2009; Reolid et al., 2014b). It is thus likely that  
730 extremely low nannofossil palaeo-production occurred in various Tethys areas  
731 concomitant with global warming during the T-OAE interval. Calcareous nannofossil  
732 abundances and fluxes are the highest in the aftermath of the T-OAE interval in most of  
733 the Tethys sections (Mattioli et al., 2009), but in Raknet El-Khala values increased very  
734 little in the upper part of the Levisoni Zone.

735 The most relevant difference between calcareous nannofossil assemblages within  
736 the Tethys settings is represented by the high abundances of *M. jansae* in NW Algeria.  
737 In fact, this taxon occurs very rarely or temporarily disappears in sediments deposited  
738 concomitant with the T-OAE in the majority of Tethysn sites (Tremolada et al., 2005;  
739 Mattioli et al., 2008), until its LO is recorded in the aftermath of the T-OAE interval  
740 (Ferreira et al., 2019). Conversely, in NW Algeria this taxon is dominant (up to 50% of  
741 coccoliths) in the T-OAE time-equivalent interval and is still commonly recorded in the  
742 upper part of the Levisoni/Serpentinus Zone, before it last occurred at the very base of

743 the Bifrons Zone (Figs. 2 and 4). This peculiar pattern may be interpreted as an  
744 evidence of prolonged thermal stratification of marine waters in NW Algeria basins  
745 (Baghli et al., 2020). The nutricline likely settled deep in the photic zone under such  
746 conditions, producing a palaeo-production decrease of shallow-dweller species and,  
747 conversely, promoting proliferation of deep-dwellers. In this view, the NW Algeria basins  
748 acted as refugia during the T-OAE, a sort of oases for deep-dwellers that escaped the  
749 worst effects of the Toarcian event. Similar narrowly habitable zones, or refuges, within  
750 the otherwise lethal Early Triassic world have permitted marine life initially recovered  
751 from end-Permian extinction (Godbold et al., 2017).

752         Stratification alone cannot account for the peculiar pattern in NW Algeria records.  
753 Stratification has been indeed invoked as the main mechanism favouring anoxia  
754 development in many epi-continental basins, especially in the northern margin of NW  
755 Europe (Farrimond et al., 1989; Prauss et al., 1991; Bucefalo Palliani et al., 2002;  
756 McArthur, 2019). These areas were under the influence of a wet climate, with riverine  
757 discharges of fresh waters (van de Schootbrugge et al., 2005; Mattioli et al., 2008;  
758 Hermoso and Pellenard, 2014; Philippe et al., 2017) (Fig. 1). Stratification of the water  
759 column was thus likely more effective in the northern Tethys margin because it was  
760 driven by both thermal and haline gradients. Anoxia reached at times the photic zone, as  
761 some Tethys black shales contain organic compounds derived from photosynthesizing  
762 bacteria that use hydrogen sulphide (Schouten et al., 2000; Pancost et al., 2004;  
763 Schwark and Frimmel, 2004; van Breugel et al., 2006). Intermittent anoxia attaining the  
764 deep photic zone is possibly another factor inhibiting the deep-dweller *M. jansae* to  
765 develop in epicontinental North Tethys basins (Mattioli et al., 2008).

766         By contrast, previous studies on NW Algeria settings have shown that benthic  
767 organisms such as ostracods or foraminifers only temporarily disappeared, likely related  
768 to (probable) brief episodes of oxygen depletion of bottom waters of the Sahara Basin  
769 (Sebane et al., 2007; Reolid et al., 2012a; Soulimane et al., 2017; Ruebsam et al.,  
770 2020a) (Fig. 5B). Benthic foraminifer assemblages are indicative of suboxic conditions in  
771 the Tlemcen Basin, where shallow and deep infauna survived the T-OAE conditions,  
772 although locally they are present in very low amounts, and only epifauna disappeared



773 (Reolid et al., 2014) (Fig. 5A). Because of the relevant development of the deep-dweller  
774 *M. jansae*, it seems likely that anoxia did not expand upwards in the water column.

775 Such characteristics are not unique to the Tlemcen Basin. In the Betic Cordillera  
776 (Spain) the ichnofacies of the Fuente de la Vidriera section, which was located at the  
777 same palaeolatitude as Mellala, revealed oxic or slightly dysoxic bottom waters  
778 (Rodríguez-Tovar and Uchman, 2010). The absence of anoxia was further confirmed by  
779 the analysis of benthic foraminifers, and by the size of pyrite framboids on the same  
780 section (Reolid, 2014a). The Fonte Coberta section in the Lusitanian Basin (Portugal)  
781 similarly showed abundant trace fossils in the T-OAE time-equivalent interval. The  
782 absence of brachiopods typically reflecting low oxygenation conditions at the sea-bottom  
783 allowed Miguez-Salas et al. (2017) to discard the hypothesis of sea floor dysoxia.

784 The TOC in sediments of most of the sections located along the southern margin of  
785 Tethys is commonly as low as 0.5% (or lesser), such as in the Traras section (Algeria;  
786 Reolid et al., 2012 a and b; Ruebsam et al., 2020a), Amellago (Morocco, Bodin et al.,  
787 2010), La Cerradura (South Spain, Reolid et al., 2014b) and others, which is consistent  
788 with the absence of black-shales in this sector of the Tethys. It seems like black-shale  
789 development was limited to the NW European regions, mainly due to hydrographic  
790 restriction rather than to the consequences of a whole-ocean anoxia (McArthur, 2019).

791 A recent ocean circulation model developed by Baroni et al. (2018) reconstructed  
792 the Toarcian marine current pathway in the western Tethys. In line with the new data  
793 from NW Algeria, this model suggests that bottom waters on the southwestern part of  
794 the Tethys shelf were mainly oxic during the T-OAE time-equivalent, while those in the  
795 north-western basins were mostly anoxic. Modelling shows the presence of a strong  
796 clockwise gyre over the European Epicontinental Shelf, which brought oxygenated  
797 equatorial waters from the Tethys Ocean to the southern shelf. The northwest branch of  
798 the gyre was progressively weakened due to the irregular palaeogeography of the  
799 northern shelf, rendering this region prone to ocean stratification and anoxia  
800 development. This model also suggests that the Sahara Basin was more affected by  
801 restriction of water masses and more prone to bottom water anoxia than the Tlemcen  
802 Basin, in which mixing with oxygenated equatorial waters from the Tethys Ocean  
803 occurred.

804

## 805 **6. Conclusions**

806

807 A comprehensive study of calcareous nannofossils was conducted in three  
808 sections from NW Algeria, namely Djebel Chemarikh and Raknet El-Khala, located in  
809 the Sahara Basin, and Mellala, in the Tlemcen Basin. Comparisons with carbon and  
810 nitrogen stable isotope data allowed a comprehensive reconstruction of  
811 palaeoenvironmental conditions occurring along the N-Gondwana margin concomitant  
812 with the Pliensbachian and Toarcian climate perturbations. The main findings of this  
813 study are:

814 • An integrated chrono- and bio-stratigraphic scheme has been established for the  
815 first time for NW Algeria. Two negative CIEs are well expressed in the  $\delta^{13}\text{C}_{\text{carb}}$  and  
816  $\delta^{13}\text{C}_{\text{org}}$  records of NW Algeria, namely at the Pliensbachian/Toarcian boundary and  
817 concomitant with the T-OAE interval. These new stratigraphic data allow a precise  
818 correlation of the two CIEs to isotope records from western Tethys settings.

819 • The Raknet El-Khala and Mellala sections contain high proportions of the Tethyan  
820 coccolith *M. jansae* that was dominant even during the T-OAE CIE. This record is unique  
821 in the western Tethys because *M. jansae* is commonly reported to drastically decrease  
822 in abundance then to disappear in the aftermath of the T-OAE. It seems that *M. jansae*  
823 survived longer in NW Algeria basins, which probably acted as refuge areas.

824 • Concomitant with the Pliensbachian/Toarcian CIE, nannofossil abundance are  
825 quite high in the Mellala section and the assemblage is dominated by coccoliths  
826 interpreted as shallow-dwellers, indicative of meso-eutrophic conditions in surface  
827 waters, which is corroborated by positive carbon and nitrogen isotope composition.  
828 Conversely, during the Toarcian CIE, absolute abundance of all nannofossils but *M.*  
829 *jansae* are extremely low both in Raknet El-Khala and Mellala. We interpret these data  
830 as reflecting prolonged stratification and hyper-oligotrophy during the T-OAE in NW  
831 Algeria due to thermal stratification. Such an interpretation is compatible with the low  
832  $\delta^{15}\text{N}$  values and low organic carbon accumulation measured in Mellala.

833 • Because of the consistent occurrence of *M. jansae* and low TOC values in Mellala,  
834 and due to the presence of benthic fauna in the T-OAE interval, it seems that anoxia did

835 not develop in the Tlemcen Basin. The Sahara Basin was likely more restricted than the  
836 Tlemcen Basin and more prone to bottom water anoxia than the Tlemcen Basin, in  
837 which mixing with oxygenated equatorial waters from the Tethys Ocean occurred.

838

### 839 **Acknowledgements**

840

841 This paper is a contribution to the IGCP-655 UNESCO project. Funding was provided by  
842 IUF to EM. HB benefitted of an Eiffel excellence grant (Campus France). Nannofossil  
843 slides are curated at the Collections de Géologie de Lyon (FSL N°: from 768823 to  
844 768856 for Mellala; from 768795 to 768822 for Raknet El-Khala; from 768661 to 768794  
845 for Djebel Chemarikh). WR and LS acknowledge funding by DFG grant Schw554/25 and  
846 Schw554/29. This MS benefitted of valuable comments by Shane Schoepfer and an  
847 anonymous reviewer. Thomas Algeo is acknowledged for his careful editorial work.

848

### 849 **Legend of the figures**

850

851 Figure 1. (a) Palaeogeographic map of the Western Tethys during the Early Jurassic  
852 (modified after Thierry et al., 2000). The main current circulation pattern is shown, as  
853 well as the main climatic modes (i.e., arid vs. wet) for northern and southern Tethys  
854 margins, respectively (modified after Dera and Donnadieu, 2012). (b) map insert  
855 showing north-western Algeria during the Toarcian (modified after Elmi and Benshilil,  
856 1987) with the position of the two studied sites.

857

858 Figure 2. Litho-, bio-stratigraphic and geochemical data of the studied sections in the Aïn  
859 Ouarka sector, Sahara Basin (Djebel Chemarikh and Raknet El-Khala), and in the  
860 Tlemcen sector (Mellala). Ammonite biostratigraphy for Djebel Chemarikh and Raknet  
861 El-Khala sections is after Mekahli (1998), for the Mellala section it is after Elmi et al.  
862 (2006). In Elmi et al. (2006), the base of the Toarcian in Mellala section was initially  
863 placed in the bed 38, bearing the earliest *Paltarpites paltus* (Buckman) but without  
864 *Eodactylites*. Bed 40 has yielded several *Dactylioceras (Eodactylites) polymorphum*  
865 (Fucini), *D. (E.) mirabile* (Fucini) and *D. (E.) pseudocommune* (Fucini) (corresponding to

866 “1. first *Eodactylites*” in the figure). *Eodactylites* becomes abundant, especially in bed 44  
867 (our “2. principal bed with *Eodactylites*”). According to the ratified GSSP at Peniche,  
868 Portugal, the base of the Toarcian Stage is marked by the concomitant first occurrence  
869 of several *Eodactylites*, such as *D. (E.) simplex*, *D. (E.) pseudocommune* and *D. (E.)*  
870 *polymorphum*. Accordingly, in this paper we have placed the base of the Toarcian stage  
871 at Mellala to the bed 40 of Elmi et al. (2006). Stable carbon and nitrogen isotope values,  
872 and wt.%TOC for the Raknet El-Khala section are after Reolid et al. (2012b) and  
873 Ruebsam et al. (2020a). For the Mellala section, we present new stable isotope (bulk  
874 carbonate carbon, bulk organic carbon, nitrogen) and organic carbon content (wt.%TOC).  
875 Nannofossil biostratigraphy allowed the establishment of nannofossil zones for the NW  
876 Algeria sector, according to the bio-chronology of Mattioli and Erba (1999) and Ferreira  
877 et al. (2019). Note the different vertical scale: 1 scale bar = 10 meters at Djebel  
878 Chemarikh; 1 bar = 1 meter at Raknet El-Khala and Mellala.

879  
880 Figure 3. Calcareous nannofossil absolute (specimens per gram of rock) and relative  
881 (percentage) abundance in the Ratnek El-Kahla section. The percentages of the main  
882 coccolith taxa (normalized to total coccolith content) and of the *incertae sedis*  
883 *Schizosphaerella* (normalized to nannofossil content) are shown. The volume of 30  
884 specimens of *M. jansae* per sample (except for the lowermost sample) has been  
885 calculated on the basis of images captured with the software ImageJ©. The black line  
886 represents average values, grey lines shows the standard deviation as calculated with  
887 PAST.

888  
889 Figure 4. Calcareous nannofossil absolute (specimens per gram of rock) and relative  
890 (percentage) abundance in the Mellala section. The percentages of the main coccolith  
891 taxa (normalized to over total coccolith content) and of the *incertae sedis*  
892 *Schizosphaerella* (normalized to over total nannofossil content) are shown.

893  
894 Figure 5. Schematic representation of palaeoenvironmental conditions prevailing within  
895 the two NW Algeria basins during the Toarcian CIE corresponding to the T-OAE interval  
896 (A) and to the Polymorphum Zone, prior to the T-OAE interval (B). Upward and

897 downward arrows indicate increase or decrease in organism abundances. N<sub>2</sub> fixation by  
898 diazotroph cyanobacteria is shown. In particular, (A) Calcareous nannofossiles  
899 interpreted as being shallow-dwellers are rare during the T-OAE interval especially at  
900 Raknet El-Khala, while deep-dwellers were relatively more abundant. Anoxia at Raknet  
901 El-Khala developed both in bottom and pore-waters. At Mellala, infauna foraminifera  
902 were present throughout the T-OAE, although in low proportions, and only epifauna  
903 disappeared (after Reolid et al., 2014). (B) Some of the highest abundance of both  
904 shallow- and deep-dweller nannofossil taxa are recorded in the upper part of the  
905 Polymorphum Zone, corresponding to periods of vertical mixing and remineralization of  
906 nitrates. See the text for more explanations.

907  
908 Tables 1 to 3. Distribution chart of calcareous nannofossils in the three studied sections.

909  
910 Plates 1 and 2. Selected nannofossil taxa from the studied sections. The scale bar is 2  
911 µm.

912

## 913 **References**

914

915 Aït Ouali, R., 1991. Le rifting des Monts des Ksour au Lias. Organisation du bassin,  
916 diagenèse des assises carbonatées, place dans les ouvertures mésozoïques au  
917 Maghreb. Unpublished PhD Thesis Univ. STHB Alger, 298 pp..

918 Algeo, T.J., Meyers, P.A., Robinson, R.S., Rowe, H. and Jiang, G.Q., 2014. Icehouse-  
919 greenhouse variations in marine denitrification. *Biogeosciences*, 11(4), 1273–1295.

920 Ameur, M., 1999. Histoire d'une plate-forme carbonatée de la marge Sud-Téthysienne:  
921 L'autochtone des Traras (Algérie occidentale) du Trias Supérieur jusqu'au  
922 Bathonien Moyen. *Docum. Lab. Géol. Lyon*, n°150,1999. 1–399.

923 Baghli, H., Mattioli, E., Spangenberg, J.E., Bensalah, M., Arnaud-Godet, F., Pittet, B.,  
924 Suan, G., 2020. Early Jurassic climatic trends in the south-Tethyan margin.  
925 *Gondwana Research*. <https://doi.org/10.1016/j.gr.2019.06.016>

926 Baroni, I.R., Pohl, A., van Helmond, N.A.G.M., Papadomanolaki, N.M., Coe, A.L., Cohen,  
927 A.S., van de Schootbrugge, B., Donnadieu, Y., Slomp, C.P., 2018. Ocean

928           Circulation in the Toarcian (Early Jurassic): A Key Control on Deoxygenation and  
929           Carbon Burial on the European Shelf. *Paleoceanography and Paleoclimatology*, 33,  
930           994–1012. <https://doi.org/10.1029/2018PA003394>

931   Beaufort, L., Barbarin, N., Gally, Y., 2014. Optical measure-  
932           ments to determine the thickness of calcite crystals and the mass of thin carbonate particles such as  
933           coccoliths. *Nature Protocols* 9, 633–642.

934   Bodin, S., Mattioli, E., Fröhlich, S., Marshall, J.D., Boutib, L., Lahsini, S., Redfern, J.,  
935           2010. Toarcian carbon isotope shifts and nutrient changes from the Northern  
936           margin of Gondwana (High Atlas, Morocco, Jurassic): palaeoenvironmental  
937           implications. *Palaeogeography Palaeoclimatology Palaeoecology* 297, 377–390.  
938           <https://doi.org/10.1016/j.palaeo.2010.08.018>.

939   Bougeault, C., Pellenard, P., Deconinck, J.F., Hesselbo, S.P., Dommergues, J.L.,  
940           Bruneau, L., Cocquerez, T., Laffont, R., Huret, E., Thibault, N.R., 2017. Climatic  
941           and palaeoceanographic changes during the Pliensbachian (Early Jurassic)  
942           inferred from clay mineralogy and stable isotope (CO) geochemistry (NW Europe).  
943           *Global and Planetary Change* 149, 139–152.

944   Bour, I., Mattioli, E., Pittet, B., 2007. Nannofacies analysis as a tool to reconstruct  
945           palaeoenvironmental changes during the Early Toarcian anoxic event.  
946           *Palaeogeography, Palaeoclimatology, Palaeoecology* 249, 58–79.

947   Bown, P.R., 1987. Taxonomy, evolution and biostratigraphy of Late Triassic-early  
948           Jurassic calcareous nannofossils. *Special Papers in Paleontology* 38, 1–118.

949   Bown, P.R., Cooper, M.K.E., 1998. Jurassic. In: Bown, P. R. (Ed.), *Calcareous*  
950           *Nannofossil Biostratigraphy*, British Micropalaeontological Society Series.  
951           Chapman and Hall/Kluwer Academic Publishers, London, 86–131.

952   Bracène, R., Frizon de Lamotte, D., 2002. The origin of intraplate deformation in the  
953           Atlas system of western and central Algeria: from Jurassic rifting to Cenozoic–  
954           Quaternary inversion. *Tectonophysics* 357, 207–226.  
955           [https://doi.org/10.1016/S0040-1951\(02\)00369-4](https://doi.org/10.1016/S0040-1951(02)00369-4)

956   Brand, W.A., Coplen, T.B., Vogl, J., Rosner, M., Prohaska, T., 2014. Assessment of  
957           international reference materials for isotope-ratio analysis. *Pure and Applied*  
958           *Chemistry* 8866, 425–467.

- 959 Brandes, J.A., Devol, A.H., 2002. A global marine-fixed nitrogen iso-  
960 topic budget: implications for Holocene nitrogen cycling, *Glob. Biogeochem. Cy.*, 16, 1120,  
961 doi:10.1029/2001GB001856, 1–14, 2002.
- 962 Breugel, van, Y., Baas, M., Schouten, S., Mattioli, E., Sinninghe-Damste, J.S., 2006.  
963 Isorenieratane record in black shales from the Paris Basin, France: Constraints on  
964 recycling of respired CO<sub>2</sub> as a mechanism for negative carbon isotope shifts  
965 during the Toarcian oceanic anoxic event. *Paleoceanography* 21, PA4220,  
966 doi:10.1029/2006PA001305, 2006.
- 967 Bucefalo-Palliani, R., Mattioli, E., 1998. High resolution potential of the calcareous  
968 nannofossil and dinoflagellate cyst integrated biostratigraphy in the Lower Jurassic  
969 (Late Pliensbachian-Lower Toarcian) of Central Italy. *Journal of Micropaleontology*  
970 17, 153-172.
- 971 Bucefalo-Palliani, R., Mattioli, E., Riding, J., 2002. The response of marine  
972 phytoplankton and sedimentary organic matter to the early Toarcian (Lower  
973 Jurassic) oceanic anoxic event in northern England. *Marine Micropaleontology* 46,  
974 223-245.
- 975 Casciotti, K.L., 2016. Nitrogen and Oxygen Isotopic Studies of the Marine Nitrogen  
976 Cycle. *Annu. Rev. Mar. Sci.* 8, 379-407.
- 977 Claps, M., Erba, E., Masetti, D., Melchiorri, F., 1995. Milankovitch-type cycles recorded  
978 in Toarcian black shales from the Belluno Trough (Southern Alps Italy). *Memorie di*  
979 *Scienze Geologiche de Padova* 47, 179–188.
- 980 Deconinck, J.F., Hesselbo, S.P., Pellenard, P., 2019. Climatic and sea-level control of  
981 Jurassic (Pliensbachian) clay mineral sedimentation in the Cardigan Bay Basin,  
982 Llanbedr (Mochras Farm) borehole Wales. *Sedimentology* 66, 2769–2783.
- 983 Dera, G., Donnadieu, Y., 2012. Modeling evidences for global warming, Arctic seawater  
984 freshening, and sluggish oceanic circulation during the Early Toarcian anoxic event.  
985 *Paleoceanography*, 27, 1–15.
- 986 Elmi, S., Alm eras, Y., 1984. Physiography, palaeotectonics and palaeoenvironments as  
987 controls of changes in ammonite and brachiopod communities (an example from  
988 the Early and Middle Jurassic of Western Algeria). *Palaeogeography*  
989 *Palaeoclimatology Palaeoecology* 47, 347–360.

- 990 Elmi, S., Benshilil, K., 1987. Relations entre la structuration tectonique, la composition  
991 des peuplements et l'Évolution : exemple du Toarcien du Moyen Atlas méridional  
992 (Maroc). Bull. Soc. Paleontol. Ital 26, 47–62.
- 993 Elmi, S., Alméras, Y., Bassoullet, J.P., Boutakiout, M., Benhamou, M., Marok, A.,  
994 Mekahli, L., Mekkaoui, A., Mouterde, R., 1998. Stratigraphic and palaeogeographic  
995 survey of the Lower and Middle Jurassic along a north–south transect in western  
996 Algeria. Mémoires Mus. Natl. d'Hist. Nat. 179, 145–211.
- 997 Elmi, S., Marok, A., Sebane, A., Alméras, Y., 2006. Importance of the Mellala section  
998 (Traras Mountains, northwestern Algeria) for the correlation of the Pliensbachian-  
999 Toarcian boundary. Volumina Jurassica VII, 37–45.
- 1000 Erba, E., 2004. Calcareous nannofossils and Mesozoic oceanic anoxic events. Marine  
1001 Micropaleontology 52, 85–106.
- 1002 Farrimond, P., Eglinton, G., Brassell, S.C., Jenkyns, H.C., 1989. Toarcian anoxic event  
1003 in Europe: an organic geochemical study. Mar. Petrol. Geol., 6, 136–147.
- 1004 Fatela, F., Taborda, R., 2002. Confidence limits of species proportions in microfossil  
1005 assemblages. Marine Micropaleontology 45, 169-174.
- 1006 Favre, P., Stampfli, G., Wildi, W., 1991. Jurassic sedimentary record and tectonic  
1007 evolution of the northwestern corner of Africa. Palaeogeography Palaeoclimatology  
1008 Palaeoecology 87, 53-73.
- 1009 Ferreira, J., Mattioli, E., Sucherás-Marx, B., Giraud, F., Duarte, L.V., Pittet, B., Suan, G.,  
1010 Hassler, A., Spangenberg, J.E., 2019. Western Tethys Early and Middle Jurassic  
1011 calcareous nannofossil biostratigraphy. Earth Science Review.  
1012 <https://doi.org/10.1016/j.earscirev.2019.102908>
- 1013 Fraguas, A., 2014. *Crepidolithus cantabriensis* nov. sp., a new calcareous nannofossil  
1014 (Prymnesiophyceae) from the Lower Jurassic of northern Spain. Geobios 47, 31–  
1015 38. <http://dx.doi.org/10.1016/j.geobios.2013.10.004>
- 1016 Frizon de Lamotte, D., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O.,  
1017 Guillocheau, F., Michard, A., 2009. Mesozoic and Cenozoic vertical movements in  
1018 the Atlas system (Algeria, Morocco, Tunisia): an overview. Tectonophysics 475, 9–  
1019 28.



- 1020 Godbold, A., Schoepfer, S., Shen, S., Henderson, C.M., 2017. Precarious ephemeral  
1021 refugia during the earliest Triassic. *Geology* 45(7), 607–610. doi:10.1130/G38793.1
- 1022 Gómez, J.J., Goy, A., 2011. Warming-driven mass extinction in the Early Toarcian (Early  
1023 Jurassic) of northern and central Spain. Correlation with other time-equivalent  
1024 European sections. *Palaeogeography Palaeoclimatology Palaeoecology* 306, 176–  
1025 195.
- 1026 Gómez, J.J., Goy, A., Canales, M.L., 2008. Seawater temperature and carbon isotope  
1027 variations in belemnites linked to mass extinction during the Toarcian (Early  
1028 Jurassic) in Central and Northern Spain. Comparison with other European sections.  
1029 *Palaeogeography Palaeoclimatology Palaeoecology* 258, 28–58. [https://doi.org/10.](https://doi.org/10.1016/j.palaeo.2007.11.005)  
1030 [1016/j.palaeo.2007.11.005](https://doi.org/10.1016/j.palaeo.2007.11.005).
- 1031 Guex, J., Morard, A., Bartolini, A., Morettini, E., 2001. Découverte d'une importante  
1032 lacune stratigraphique à la limite Domérien-Toarcien: implications paléo-  
1033 océanographiques. *Bull. Soc. Vaud. Sci. Nat.*, 345, 277–284.
- 1034 Gruber, N., 2008. Chapter 1 - The marine nitrogen cycle: Overview and challenges. In:  
1035 Capone, D.G., Bronk, D.A., Mulholland, M.R., Carpenter, E.J., (Eds.). *Nitrogen in*  
1036 *the marine environment*. Elsevier, p. 1-50.
- 1037 Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software  
1038 package for education and data analysis. *Palaeontol. Electron.* 4, 1–9.
- 1039 Harries, P.J., Little, C.T.S., 1999. The early Toarcian (Early Jurassic) and the  
1040 Cenomanian–Turonian (Late Cretaceous) mass extinctions: similarities and  
1041 contrasts. *Palaeogeography Palaeoclimatology Palaeoecology* 154, 39–66.
- 1042 Hermoso, M., Pellenard, P., 2014. Continental weathering and climatic changes inferred  
1043 from clay mineralogy and paired carbon isotopes across the early to middle  
1044 Toarcian in the Paris Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*  
1045 399, 385-393.
- 1046 Hermoso, M., Minoletti, F., Pellenard, P., 2013. Black shale deposition during Toarcian  
1047 super-greenhouse driven by sea level. *Clim. Past* 9, 2703–2712.
- 1048 Hesselbo, S.P., Gröcke, D.R., Jenkyns, H.C., Bjerrum, C.J., Farrimond, P., Morgans Bell,  
1049 H.S., Green, O.R., 2000. Massive dissociation of gas hydrate during a Jurassic  
1050 oceanic anoxic event. *Nature* 406, 392–395. <https://doi.org/10.1038/35019044>.

- 1051 Hesselbo, S.P., Jenkyns, H.C., Duarte, L.V., Oliveira, L.C.V., 2007. Carbon-isotope  
1052 record of the Early Jurassic (Toarcian) oceanic anoxic event from fossil wood and  
1053 marine carbonate (Lusitanian Basin, Portugal). *Earth and Planetary Science  
1054 Letters* 253, 455–470. <https://doi.org/10.1016/J.EPSL.2006.11.009>.
- 1055 Jenkyns, H.C., 1988. The early Toarcian (Jurassic) event: stratigraphy, sedimentary,  
1056 and geochemical evidence. *American Journal of Science* 288, 101–151. [https://doi.  
1057 org/10.2475/ajs.288.2.101](https://doi.org/10.2475/ajs.288.2.101).
- 1058 Jenkyns, H.C., Clayton, C.J., 1997. Lower Jurassic epicontinental carbonates and  
1059 mudstones from England and Wales: chemostratigraphic signals and the early  
1060 Toarcian anoxic event. *Sedimentology* 44, 687–706. [https://doi.org/10.1046/j.1365-  
1061 3091.1997.d01-43.x](https://doi.org/10.1046/j.1365-3091.1997.d01-43.x).
- 1062 Kemp, D.B., Coe, A.L., Cohen, A.S., Schwark, L., 2005. Astronomical pacing of methane  
1063 release in the Early Jurassic period. *Nature* 437, 396–399.
- 1064 Korte, C., Hesselbo, S.P., 2011. Shallow marine carbon and oxygen isotope and  
1065 elemental records indicate icehouse-greenhouse cycles during the Early Jurassic.  
1066 26, 1–18. <https://doi.org/10.1029/2011PA002160>.
- 1067 Li, Q., McArthur, J.M., Atkinson, T.C., 2012. Lower Jurassic belemnites as indicators of  
1068 palaeo-temperature. *Palaeogeography Palaeoclimatology Palaeoecology* 315–316,  
1069 38–45. <https://doi.org/10.1016/j.palaeo.2011.11.006>.
- 1070 Littler, K., Hesselbo, S.P., Jenkyns, H.C., 2009. A carbon-isotope perturbation at the  
1071 Pliensbachian-Toarcian boundary: evidence from the Lias Group, NE England.  
1072 *Geological Magazine* 147, 181–192. <https://doi.org/10.1017/S0016756809990458>
- 1073 Macchioni, F., Cecca, F., 2002. Biodiversity and biogeography of middle–late liassic  
1074 ammonoids: implications for the early Toarcian mass extinction. *Geobios* 35, 165–  
1075 175. [https://doi.org/10.1016/S0016-6995\(02\)00057-8](https://doi.org/10.1016/S0016-6995(02)00057-8).
- 1076 Mattioli, E., Erba, E., 1999. Biostratigraphic synthesis of calcareous nannofossil events in  
1077 the Tethyan Jurassic. *Rivista Italiana di Paleontologia e Stratigrafia* 105(3), 343-  
1078 376.
- 1079 Mattioli, E., Pittet, B., 2004. Spatial and temporal distribution of calcareous nannofossils  
1080 along a proximal-distal transect in the Umbria-Marche basin (Lower Jurassic; Italy).  
1081 *Palaeogeography, Palaeoclimatology, Palaeoecology* 205, 295-316.

- 1082 Mattioli, E., Pittet, B., Suan, G., Mailliot, S., 2008. Calcareous nannoplankton changes  
1083 across the early Toarcian oceanic anoxic event in the western Tethys.  
1084 *Paleoceanography* 23, 1–17. <https://doi.org/10.1029/2007PA001435>.
- 1085 Mattioli, E., Pittet, B., Petitpierre, L., Mailliot, S., 2009. Dramatic decrease of the pelagic  
1086 carbonate production by nannoplankton across the Early Toarcian Anoxic Event  
1087 (T-OAE). *Global and Planetary Changes* 65, 134-145.  
1088 doi:10.1016/j.gloplacha.2008.10.018
- 1089 Mattioli, E., Planq, J., Boussaha, M., Duarte, L.V., Pittet, B., 2013. Calcareous  
1090 nanofossil biostratigraphy: new data from the Lower Jurassic of the Lusitanian  
1091 Basin. *Comunicações Geológicas* (2013) 100, Especial I, 69-76 ISSN: 0873-948X;  
1092 e-ISSN: 1647-581X
- 1093 McArthur, J.M.Y., Donovan, D.T., Thirlwall, M.F., Fouke, B.W., 2000. Strontium isotope  
1094 profile of the early Toarcian (Jurassic) oceanic anoxic event, the duration of  
1095 ammonite biozones, and belemnite palaeotemperatures. *Earth and Planetary  
1096 Science Letters* 179, 269–285. [https://doi.org/10.1016/S0012-821X\(00\)00111-4](https://doi.org/10.1016/S0012-821X(00)00111-4).
- 1097 McArthur, J. M., Algeo, T. J., van de Schootbrugge, B., Li, Q., Howarth, R. J., 2008.  
1098 Basinal restriction, black shales, Re-Os dating, and the Early Toarcian (Jurassic)  
1099 oceanic anoxic event. *Paleoceanography* 23 (4).
- 1100 McArthur, J.M., 2019. Early Toarcian black shales: A response to an oceanic anoxic  
1101 event or anoxia in marginal basins. *Chemical Geology* 522, 71-83,  
1102 <https://doi.org/10.1016/j.chemgeo.2019.05.028>
- 1103 Mekahli, L., 1988. Le jurassique inferieur et moyen de la partie occidentale du horst de  
1104 Rhar-Roubane (Tlemcen, Algerie Occidentale) : stratigraphie, sedimentologie et  
1105 cadre dynamique. Thèse de Magistère. Université d'Oran, pp. 1–245 Unpublished.
- 1106 Mekahli, L., Elmi, S., Benhamou, M., 2004. Biostratigraphy, sedimentology and tectono-  
1107 eustatic events of the Lower and Middle Jurassic of the Ksour Mountains (Western  
1108 Saharian Atlas, Southern Algeria). 32nd International Geological Congress 5, Field  
1109 Trip Guide Book-P 52, Florence, p. 28.
- 1110 Menini, A., Mattioli, E., Spangenberg, J. E., Pittet, B., Suan, G., 2019. New calcareous  
1111 nanofossil and carbon isotope data for the Pliensbachian/Toarcian boundary

1112 (Early Jurassic) in the western Tethys and their paleoenvironmental implications.  
1113 Newsletters on Stratigraphy 52, 173-196, doi:10.1127/nos/2018/0476 (2019).

1114 Menini, A., Mattioli, E., Hesselbo, S.P., Ruhl, M. Suan, G., 2021. Primary v. carbonate  
1115 production in the Toarcian, a case study from the Llanbedr (Mochras Farm)  
1116 borehole, Wales). From: Reolid, M., Duarte, L. V., Mattioli, E. and Ruebsam, W.  
1117 (Eds) Carbon Cycle and Ecosystem Response to the Jenkyns Event in the Early  
1118 Toarcian (Jurassic). Geological Society, London, Special Publications, 514,  
1119 <https://doi.org/10.1144/SP514-2021-74>.

1120 Miguez-Salas, O., Rodríguez-Tovar, F.J., Duarte, L.V., 2017. Selective incidence of the  
1121 Toarcian oceanic anoxic event on macroinvertebrate marine communities: a case  
1122 from the Lusitanian basin, Portugal. *Lethaia* 50, 548–560.

1123 Molfino, B., McIntyre, A., 1990. Precessional forcing of nutricline dynamics in the  
1124 equatorial Atlantic. *Science* 249, 766–769.

1125 Moore, D.M., Reynolds, R.C., 1997. X-ray Diffraction and the Identification and Analysis  
1126 of 679 Clay Minerals. Oxford University Press, New York, 400 pp..

1127 Müller, T., Price, G.D., Bajnai, D., Nyerges, A., Kesjár, D., Raucsik, B., Varga, A., Judik,  
1128 K., Fekete, J., May, Z., Pálffy, J., 2017. New multiproxy record of the Jenkyns Event  
1129 (also known as the Toarcian Oceanic Anoxic Event) from the Mecsek Mountains  
1130 (Hungary): Differences, duration and drivers *Sedimentology* 64, 66–86.  
1131 <https://doi.org/10.1111/sed.12332>.

1132 Olivier, N., Pittet, B., Mattioli, E., 2004. Palaeoenvironmental control on sponge-reefs  
1133 and contemporaneous deep-shelf marl-limestone deposition (Late Oxfordian,  
1134 southern Germany). *Palaeogeography, Palaeoclimatology, Palaeoecology* 212,  
1135 233-263.

1136 Pancost, R. D., Crawford, N., Magness, S., Turner, A., Jenkyns, H. C., & Maxwell, J. R.  
1137 (2004). Further evidence for the development of photic-zone euxinic conditions  
1138 during Mesozoic Oceanic Anoxic Events. *Journal of the Geological Society of*  
1139 *London*, 161(3), 353–364.

1140 Philippe, M., Puijalon, S., Suan, G., Mousset, S., Thévenard, F., Mattioli, E., 2017. The  
1141 palaeolatitudinal distribution of fossil wood genera as a proxy for European

- 1142 Jurassic terrestrial climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*  
1143 466, 373–381.
- 1144 Pittet, B., Mattioli, E., 2002. The carbonate signal and calcareous nannofossil distribution  
1145 in an Upper Jurassic section (Balingen-Tieringen, Late Oxfordian, southern  
1146 Germany). *Palaeogeography, Palaeoclimatology, Palaeoecology* 179, 71-96.
- 1147 Pittet, B., Suan, G., Lenoir, F., Duarte, L.V., Mattioli, E., 2014. Carbon isotope evidence  
1148 for sedimentary discontinuities in the lower Toarcian of the Lusitanian Basin  
1149 (Portugal): sea level changes at the onset of the Oceanic Anoxic Event.  
1150 *Sedimentary Geology* 303, 1-14.
- 1151 Prauss, M., Ligouis, B., Luterbacher, H., 1991. Organic matter and palynomorphs in the  
1152 'Posidonienschiefer' (Toarcian, Lower Jurassic) of southern Germany, in *Modern  
1153 and Ancient Continental Shelf Anoxia*. In: R.V. Tyson and T.H. Pearson (Eds.),  
1154 *Geological Society Special Publication London*, 58, 335–352.
- 1155 Price, G.D., Baker, S.J., VanDeVelde, J., Clémence, M.-E., 2016. High-resolution  
1156 carbon cycle and seawater temperature evolution during the Early Jurassic  
1157 (Sinemurian- Early Pliensbachian). *Geochemistry, Geophysics, Geosystems* 17,  
1158 3917–3928. <https://doi.org/10.1002/2016GC006541>.
- 1159 Reggiani, L., Mattioli, E., Pittet, B., Duarte, L.V., Veiga de Oliveira, L.C., Comas-Rengifo,  
1160 M.J., 2010. Pliensbachian (Early Jurassic) calcareous nannofossils from the  
1161 Peniche section (Lusitanian Basin, Portugal): A clue for palaeoenvironmental  
1162 reconstructions *Marine Micropaleontology* doi:10.1016/j.marmicro.2010.02.002
- 1163 Remírez, M.N., Algeo, T.J., 2020a. Paleosalinity determination in ancient epicontinental  
1164 seas: A case study of the T-OAE in the Cleveland Basin (UK). *Earth-Science  
1165 Reviews*, 201, p.103072. doi.org/10.1016/j.earscirev.2020.103283
- 1166 Remírez, M.N., Algeo, T.J., 2020b. Carbon-cycle changes during the Toarcian (Early  
1167 Jurassic) and implications for regional *versus* global drivers of the Toarcian  
1168 oceanic anoxic event. *Earth-Science Reviews*, p. 103283.  
1169 doi.org/10.1016/j.earscirev.2019.103072
- 1170 Reolid, M., Rodríguez-Tovar, F.J., Marok, A., Sebane, A., 2012a. The Toarcian Oceanic  
1171 Anoxic Event in the Western Saharan Atlas, Algeria (North African Paleomargin):

- 1172 Role of Anoxia and Productivity. *Geological Society of America Bulletin* 124, 1646–  
1173 1664. <https://doi.org/10.1130/B30585.1>
- 1174 Reolid, M., Sebane, A., Rodríguez-Tovar, F.J., Marok, A., 2012b. Foraminiferal  
1175 morphogroups as a tool to approach the Toarcian Anoxic Event in the Western  
1176 Saharan Atlas (Algeria). *Palaeogeography Palaeoclimatology Palaeoecology* 323–  
1177 325, 87–99.
- 1178 Reolid M., Marok A., Sebane A., 2014a. Foraminiferal assemblages and geochemistry  
1179 for interpreting the incidence of Early Toarcian environmental changes in North  
1180 Gondwana palaeomargin (Traras Mountains, Algeria). *Journal of African Earth  
1181 Sciences* 95,105–122.
- 1182 Reolid, M., Mattioli, E., Nieto, L.M., Rodríguez-Tovar, F.J., 2014b. The Early Toarcian  
1183 Oceanic Anoxic Event in the External Subbetic (Southiberian Palaeomargin,  
1184 Westernmost Tethys): Geochemistry, nannofossils and ichnology.  
1185 *Palaeogeography, Palaeoclimatology, Palaeoecology* 411, 79-94.
- 1186 Rita, P., Reolid, M., Duarte, L.V., 2016. Benthic foraminiferal assemblages record major  
1187 environmental perturbations during the Late Pliensbachian–Early Toarcian interval  
1188 in the Peniche GSSP, Portugal. *Palaeogeography Palaeoclimatology  
1189 Palaeoecology* 454, 267–281.
- 1190 Ritter E., 1902. Le Djebel Amour et les Monts des Oulad Naïl. *Bull. Serv. Carte Géol.  
1191 Algérie*, 2° série, n°3, 100 p., 4 pl. h.t.
- 1192 Rocha, da, R., Mattioli, E., Duarte, L.V., Pittet, B., Elmi, S., Mouterde, R., Cabral, M.C.,  
1193 Comas-Rengifo, M.J., Gómez, J.J., Goy, A., Hesselbo, S.P., Jenkyns, H.C., Littler,  
1194 K., Mailliot, S., Veiga de Oliveira, L.C., Osete, M.L., Perilli, N., Pinto, S., Ruget, C.  
1195 Suan, G., 2016. Base of the Toarcian Stage of the Lower Jurassic defined by the  
1196 Global Boundary Stratotype Section and Point (GSSP) at the Peniche section  
1197 (Portugal). *Episodes* 39, 460-481.
- 1198 Rodríguez-Tovar, F.J., Uchman, A., 2010. Ichnofabric evidence for the lack of bottom  
1199 anoxia during the Lower Toarcian oceanic anoxic event (T-OAE) in the Fuente de  
1200 la Vidriera section, Betic Cordillera, Spain. *Palaios* 25, 576–587,  
1201 [doi:10.2110/palo.2009.p09-153r](https://doi.org/10.2110/palo.2009.p09-153r).

- 1202 Röhl, H.J., Schmidt-Röhl, A., Oschmann, W., Frimmel, A., Schwark, L., 2001. The  
1203 Posidonia Shale (Lower Toarcian) of SW-Germany: an oxygen-depleted  
1204 ecosystem controlled by sea level and palaeoclimate. *Palaeogeogr. Palaeoclimatol.*  
1205 *Palaeoecol.* 165, 27–52.
- 1206 Rosales, I., Quesada, S., Robles, S., 2004, Paleotemperature variations of Early  
1207 Jurassic seawater recorded in geochemical trends of belemnites from the Basque-  
1208 Cantabrian Basin, northern Spain. *Palaeogeography, Palaeoclimatology,*  
1209 *Palaeoecology* 203, 253–275.
- 1210 Roth, P.H., 1984. Preservation of calcareous nanofossils and fine-grained carbonate  
1211 particles in mid-Cretaceous sediments from the southern Angola Basin. In: Hay, W.  
1212 W. (Ed.), *Initial Reports of Deep Sea Drilling Project 75*. U. S. Government Printing  
1213 Office, Washington, pp. 651–655.
- 1214 Ruebsam, W., Al-Husseini, M., 2020. Calibrating the Early Toarcian (Early Jurassic) with  
1215 stratigraphic black holes (SBH). *Gondwana Research* 82, 317–336.
- 1216 Ruebsam, W., Müller, T., Kovács, J., Pálffy, J., Schwark, L., 2018. Environmental  
1217 response to the early Toarcian carbon cycle and climate perturbations in the  
1218 northeastern part of the West-Tethys shelf. *Gondwana Res.* 59, 144–158.
- 1219 Ruebsam, W., Reolid, M., Marok, A., Schwark, L., 2020a. Drivers of benthic extinction  
1220 during the early Toarcian (Early Jurassic) at the northern Gondwana paleomargin:  
1221 Implications for paleoceanographic conditions. *Earth-Science Reviews* 203,  
1222 103177.
- 1223 Ruebsam, W., Reolid, M., Schwark, L., 2000b.  $\delta^{13}\text{C}$  of terrestrial vegetation records  
1224 Toarcian  $\text{CO}_2$  and climate gradients. *Nature Scientific Reports* 10, 117.
- 1225 Ruebsam, W., Reolid, M., Sabatino, N., Masetti, D., Schwark, L., 2020c. Molecular  
1226 paleothermometry of the early Toarcian climate perturbation. *Global and Planetary*  
1227 *Change*. doi.org/10.1016/j.gloplacha.2020.103351
- 1228 Sabatino, N., Neri, R., Bellanca, A., Jenkyns, H., Baudin, F., Parisi, G., Masetti, D., 2009.  
1229 Carbon-isotope records of the Early Jurassic (Toarcian) oceanic anoxic event from  
1230 the Valdorbia (Umbria–Marche Apennines) and Monte Mangart (Julian Alps)  
1231 sections: palaeoceanographic and stratigraphic implications. *Sedimentology* 56,  
1232 1307–1328.

- 1233 Schlachter, T.A., Connolly, R.M., 2014. Effects of acid treatment on carbon and nitrogen  
1234 stable isotope ratios in ecological samples: a review and synthesis. *Methods Ecol.*  
1235 *Evol.* 5, 541–550.
- 1236 Schootbrugge, van de, B., Bailey, T.R., Rosenthal, Y., Katz, M.E., Wright, J.D., Miller,  
1237 K.G., Feist-Burkhardt, S., Falkowski, P. G., 2005. Early Jurassic climate change  
1238 and the radiation of organic-walled phytoplankton in the Tethys Ocean.  
1239 *Paleobiology* 31, 73–97.
- 1240 Schouten, S., Van Kaam-Peters, H.M.E., Rijpstra, W.I.C., Schoell, M., Sinninghe  
1241 Damsté, J.S., 2000. Effects of an oceanic anoxic event on the stable carbon  
1242 isotopic composition of Early Toarcian carbon. *American Journal of Sciences* 300,  
1243 1–22.
- 1244 Schwark, L., Frimmel, A., 2004. Chemostratigraphy of the Posidonia black shale, SW-  
1245 Germany II. Assessment of extent and persistence of photic-zone anoxia using aryl  
1246 isoprenoid distributions. *Chemical Geology* 206, 231–248. [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.chemgeo.2003.12.008)  
1247 [chemgeo.2003.12.008](https://doi.org/10.1016/j.chemgeo.2003.12.008).
- 1248 Schoepfer, S.D., Algeo, T.J., Ward, P.D., Williford, K.H., Haggart, J.W., 2016. Testing  
1249 the limits in a greenhouse ocean: Did low nitrogen availability limit marine  
1250 productivity during the end-Triassic mass extinction?. *Earth and Planetary Science*  
1251 *Letters* 451, 138-148. [doi.org/10.1016/j.epsl.2016.06.050](https://doi.org/10.1016/j.epsl.2016.06.050)
- 1252 Sebane, A., Marok, A., Elmi, S., 2007. Évolution des peuplements de foraminifères  
1253 pensant la crise toarcienne à l'exemple des données des Monts des Ksour (Atlas  
1254 Saharien Occidental, Algérie). *Comptes Rendus Palévol.* 6, 189–196,  
1255 [doi:10.1016/j.crpv.2006.10.002](https://doi.org/10.1016/j.crpv.2006.10.002).
- 1256 Soulidane, C., Reolid, M., Marok, A., 2017. Ostracod assemblages from the uppermost  
1257 Pliensbachian and Lower Toarcian of the Traras Mountains (Tlemcen Domain,  
1258 north Algeria). *Arabian Journal of Geosciences* 10, 393.  
1259 <https://doi.org/10.1007/s12517-017-3180-0>
- 1260 Suan, G., Mattioli, E., Pittet, B., Mailliot, S., Lécuyer, C., 2008. Evidence for major  
1261 environmental perturbation prior to and during the Toarcian (Early Jurassic)  
1262 oceanic anoxic event from the Lusitanian Basin, Portugal. *Paleoceanography* 23,  
1263 1–14. <https://doi.org/10.1029/2007PA001459>.



- 1264 Suan, G., Mattioli, E., Pittet, B., Lécuyer, C., Suchéras-Marx, B., Duarte, L.V., Philippe,  
1265 M., Reggiani, L., Martineau, F., 2010. Secular environmental precursors to Early  
1266 Toarcian (Jurassic) extreme climate changes. *Earth and Planetary Science Letters*  
1267 290, 448–458. <https://doi.org/10.1016/J.EPSL.2009.12.047>.
- 1268 Suan, G., van de Schootbrugge, B., Adatte, T., Fiebig, J., Oschmann, W., 2015.  
1269 Calibrating and magnitude of the Toarcian carbon cycle perturbation.  
1270 *Paleoceanography* 30, PA2758.
- 1271 Tremolada, F., Van de Schootbrugge, B. Erba, E., 2005. Early Jurassic  
1272 schizosphaerellid crisis in Cantabria, Spain: Implications for calcification rates and  
1273 phytoplankton evolution across the Toarcian oceanic anoxic event.  
1274 *Paleoceanography* 20, PA2011, doi:10.1029/2004PA001120.
- 1275 Vafeiadou, A.M., Helena, A., De Troch, M., Moens, T., 2013. Sample acidification effects  
1276 on carbon and nitrogen stable isotope ratios of macrofauna from a *Zostera noltii*  
1277 bed. *Mar. Freshw. Res.* 64, 741–745.
- 1278 Visentin, S., Faucher, G., Mattioli, E. Erba, E., 2020. Taxonomic revision of genus  
1279 *Carinolithus* (Early - Middle Jurassic) based on morphometric analyses and  
1280 diagenesis observations: Implications for biostratigraphy and evolutionary trends.  
1281 *Marine Micropaleontology*. <https://doi.org/10.1016/j.marmicro.2020.101950>
- 1282 Wignall, P.B., 2001. Large igneous provinces and mass extinctions. *Earth Science*  
1283 *Reviews* 53, 1–33. [https://doi.org/10.1016/S0012-8252\(00\)00037-4](https://doi.org/10.1016/S0012-8252(00)00037-4).
- 1284 Wilmsen, M., Neuweiler, F., 2008. Biosedimentology of the Early Jurassic post-extinction  
1285 carbonate depositional system, central High Atlas rift basin, Morocco.  
1286 *Sedimentology* 55, 773–807. <https://doi.org/10.1111/j.1365-3091.2007.00921.x>
- 1287 Winter, A., Jordan, R.W., Roth, P.H., 1994. Biogeography of living coccolithophores in  
1288 ocean waters. In: Winter, A., Siesser, W. (Eds.), *Coccolithophores*. Cambridge  
1289 University Press, Cambridge, pp. 161–177.
- 1290 Young, J.R., 1994. Functions of coccoliths. In: Winter, A., Siesser, W. (Eds.),  
1291 *Coccolithophores*. Cambridge University Press, pp. 63–82.
- 1292
- 1293 Supplementary Material.

1294 Figure A. X-ray diagrams of the clay fraction of samples from the Mellala section (MLL)  
1295 and from Raknet El-Khala (RK). All values are expressed as d-spacings. I=illite;  
1296 C+CV=mixture of chlorite and chlorite-vermiculite mixed-layer; IS=illite-smectite R1-R3  
1297 type mixed-layer; Q=quartz.

1298 The clay mineral assemblages in the two sections, Mellala and Raknet El-Kahla,  
1299 consist mainly of a mixture of relatively well-crystallized illite (main  $d_{(001)}$  peaks at 10, 5  
1300 and 3.33 Å) and chlorite (main  $d_{(001)}$  peaks at 14.2, 7.1, 4.72, 3.53 Å; Fig. A). Small  
1301 proportions of undistinguishable R1 and R3 type illite-smectite mixed-layers (R1-R3 IS)  
1302 indicated by peaks close to those of illite are also recognized and are responsible for the  
1303 asymmetry of the 10 Å peak (Fig. A). The enlargement and the displacement to lower  
1304 values of the 14.1 and 3.53 Å peaks within the heating treatment likely indicate that  
1305 chlorite is mixed with vermiculite, so that true chlorite and chlorite-vermiculite may  
1306 coexist in the assemblage. No trace of smectite, R0 type IS mixed-layer or kaolinite was  
1307 evidenced by XRD analyses.

1308 The most prominent feature of the clay assemblage of the Mellala and Raknet El-  
1309 Kahla sections is the absence of kaolinite, although this mineral is common in the  
1310 uppermost Pliensbachian and Toarcian sediments from the Tethys domain (Dera et al.,  
1311 2009; Hermoso and Pellenard 2014; Bougeault et al., 2017; Deconinck et al., 2019).  
1312 This absence can either be attributed to arid or semi-arid climate conditions, preventing  
1313 the formation of kaolinite during pedogenesis, or can be related to the disappearance of  
1314 kaolinite by illitization processes during burial diagenesis, as generally observed for  
1315 burial temperatures higher than 120°C (Chamley et al., 1989; Lanson et al., 2002). The  
1316 absence of smectite and R0 type IS mixed-layer clay minerals is expected, as these  
1317 latter are more sensitive to burial diagenesis and illitization processes. However, under  
1318 arid climates they should have been formed abundantly in soils introduced from adjacent  
1319 areas. Here, it is not possible to definitively discriminate between diagenetic and climatic  
1320 processes, as significant burial diagenesis occurred thus preventing the use of clay  
1321 mineral assemblages for climate and palaeoenvironment interpretations. However, clay  
1322 mineralogy data are coherent with the poor preservation of calcareous nannofossils that  
1323 can be explained by a strong burial diagenesis, as also reported for the High-Atlas of  
1324 Morocco (Dera et al., 2009; Mercuzot et al., 2019). The overall conditions at Mellala and

1325 Raknet El-Kahla, which were located at low latitudes and characterized by an arid  
1326 climate during the end Pliensbachian and Toarcian, however, were unfavourable for  
1327 kaolinite formation, as it was also suggested for the Asturian Basin (North Spain;  
1328 Deconinck et al., 2020).

1329

1330 Supplementary references

1331

1332 Bougeault, C., Pellenard, P., Deconinck, J.F., Hesselbo, S.P., Dommergues, J.L.,  
1333 Bruneau, L., Cocquerez, T., Laffont, R., Huret, E., Thibault, N.R., 2017. Climatic  
1334 and palaeoceanographic changes during the Pliensbachian (Early Jurassic)  
1335 inferred from clay mineralogy and stable isotope (CO) geochemistry (NW Europe).  
1336 *Global and Planetary Change* 149, 139–152.

1337 Chamley, H., 1989. *Clay Sedimentology*. Springer Verlag, 623 pp.

1338 Deconinck, J.F., Hesselbo, S.P., Pellenard, P., 2019. Climatic and sea-level control of  
1339 Jurassic (Pliensbachian) clay mineral sedimentation in the Cardigan Bay Basin,  
1340 Llanbedr (Mochras Farm) borehole Wales. *Sedimentology* 66, 2769–2783.

1341 Deconinck, J.F., Gómez, J.J., Baudin, F., Biscay, H., Bruneau, L., Cocquerez, T.,  
1342 Mathieu, O., Pellenard, P., Santoni, A.L., 2020. Diagenetic and environmental  
1343 control of the clay mineralogy, organic matter and stable isotopes (C, O) of  
1344 Jurassic (Pliensbachian-Lowermost Toarcian) sediments of the Rodiles section  
1345 (Asturian Basin, Northern Spain). *Marine and Petroleum Geology*, 115, 104286,  
1346 <https://doi.org/10.1016/j.marpetgeo.2020.104286>

1347 Dera, G., Pellenard, P., Neige, P., Deconinck, J.-F., Pucéat, E., Dommergues, J.-L.,  
1348 2009b. Distribution of clay minerals in Early Jurassic Peritethyan seas:  
1349 Palaeoclimatic significance inferred from multiproxy comparisons.  
1350 *Palaeogeography, Palaeoclimatology, Palaeoecology* 271, 39–51.

1351 Hermoso, M., Pellenard, P., 2014. Continental weathering and climatic changes inferred  
1352 from clay mineralogy and paired carbon isotopes across the early to middle  
1353 Toarcian in the Paris Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*  
1354 399, 385-393.

- 1355 Lanson, B., Beaufort, D., Berger, G., Bauer, A., Cassagnabere, A., Meunier, A., 2002.  
1356 Authigenic kaolin and illitic minerals during burial diagenesis of sandstones: a  
1357 review. *Clay minerals* 37, 1-22.
- 1358 Mercuzot, M., Pellenard, P., Durllet, C., Bougeault, C., Meister, C., Dommergues, J.L.,  
1359 Thibault, N., Baudin, F., Mathieu, O., Bruneau, L., Huret, E., El Mhidi, K., 2019.  
1360 Carbon-isotope events during the Pliensbachian (Lower Jurassic) on the African  
1361 and European margins of the NW Tethyan Realm. *Newsletters on Stratigraphy*.  
1362 Published online 10.1127/nos/2019/0502  
1363

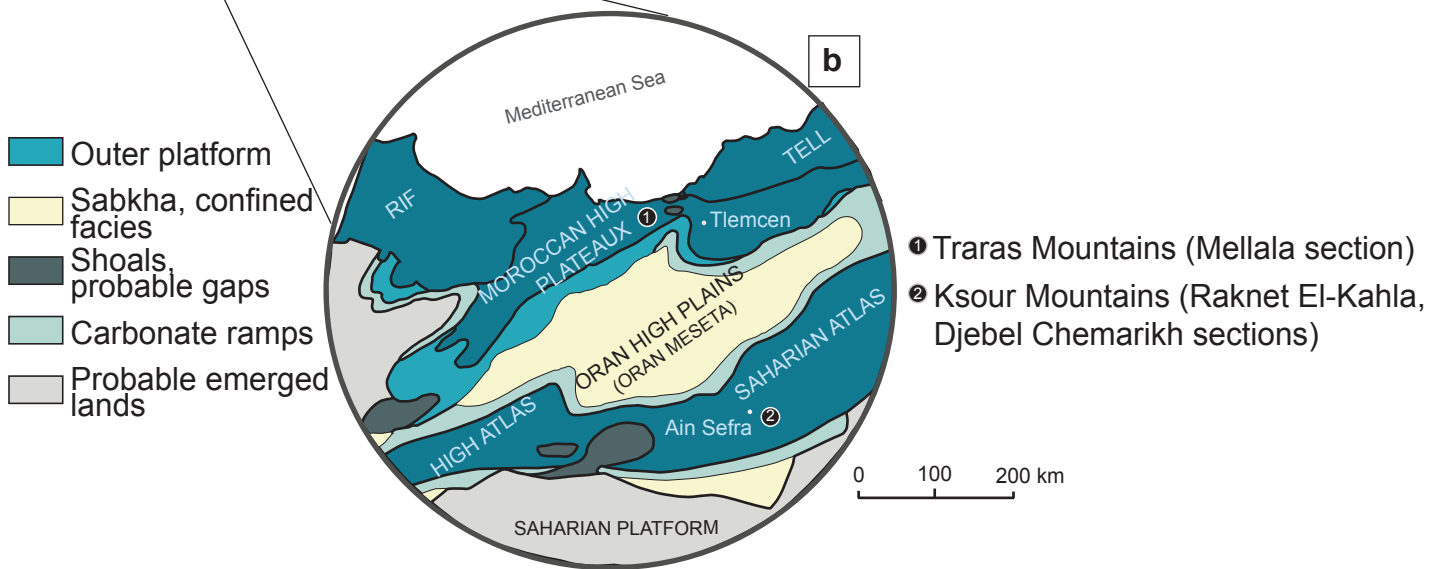
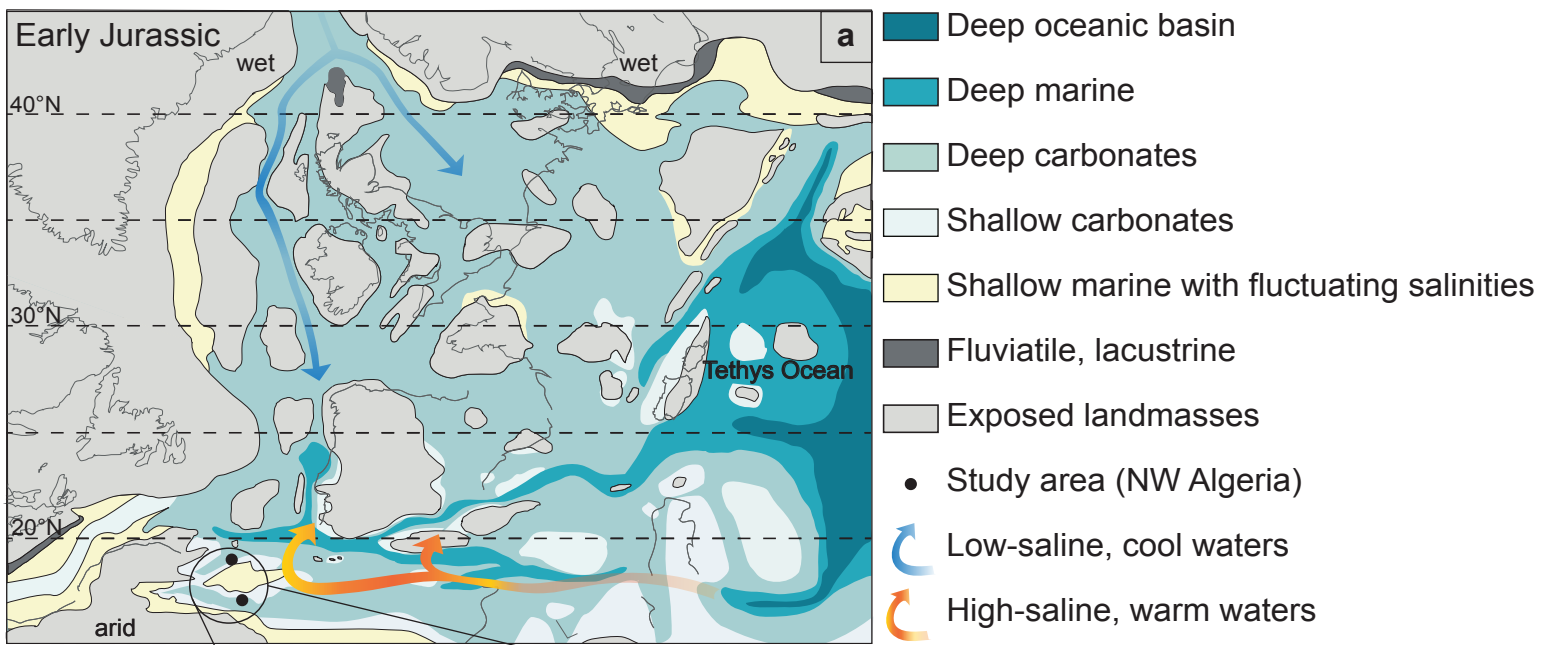


Figure 1 (Baghli et al.)

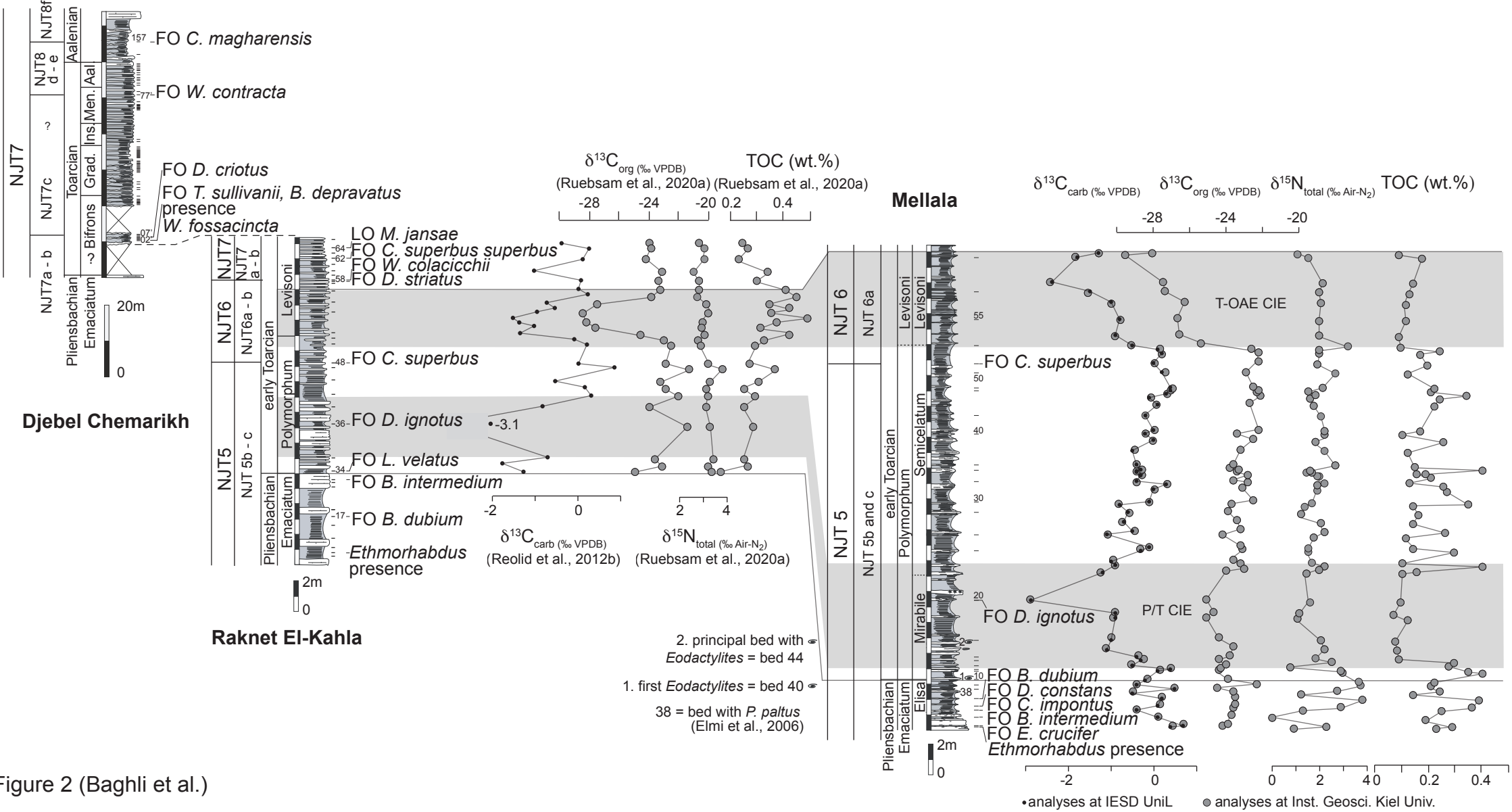


Figure 2 (Baghli et al.)

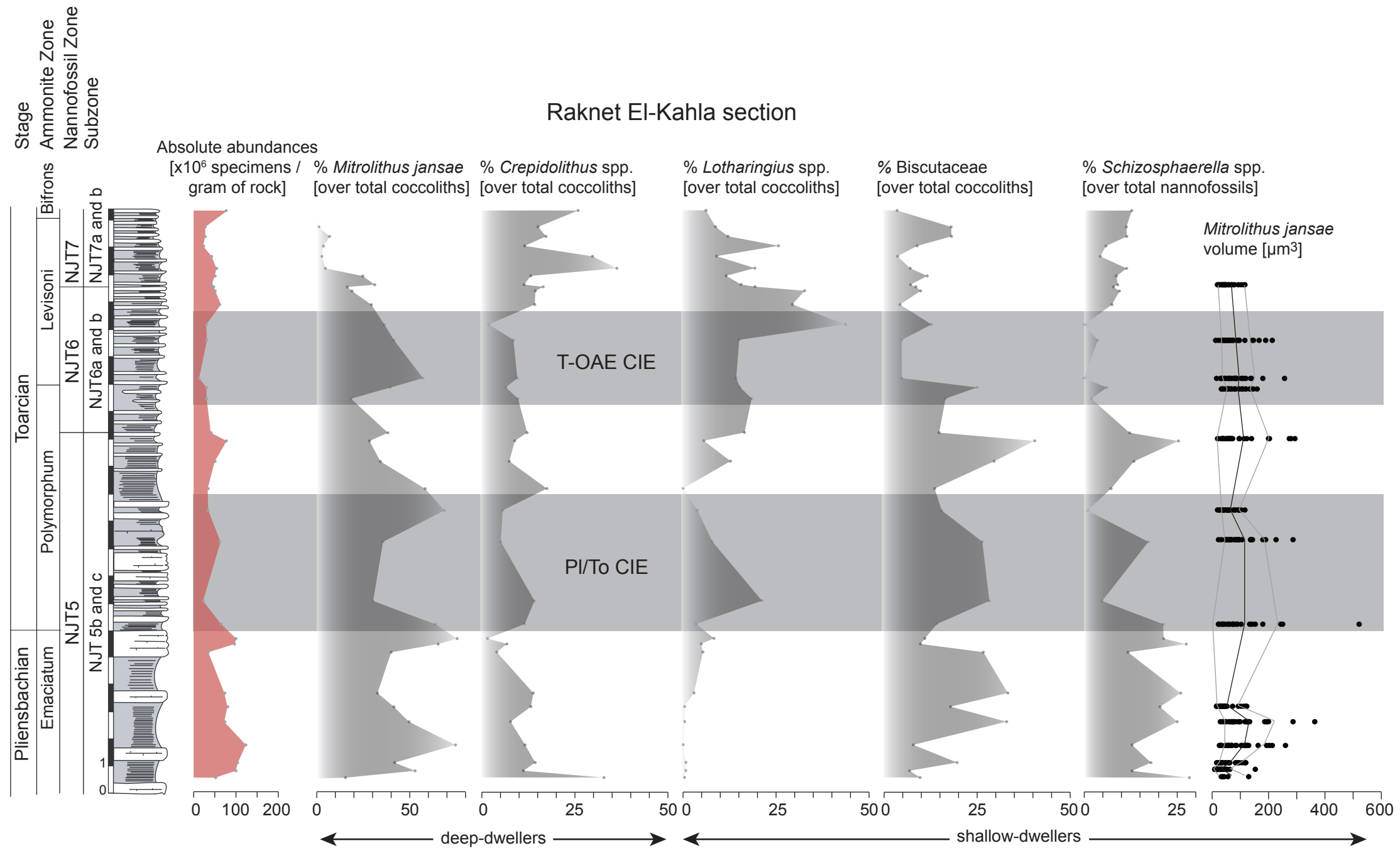


Figure 3 (Baghli et al.)

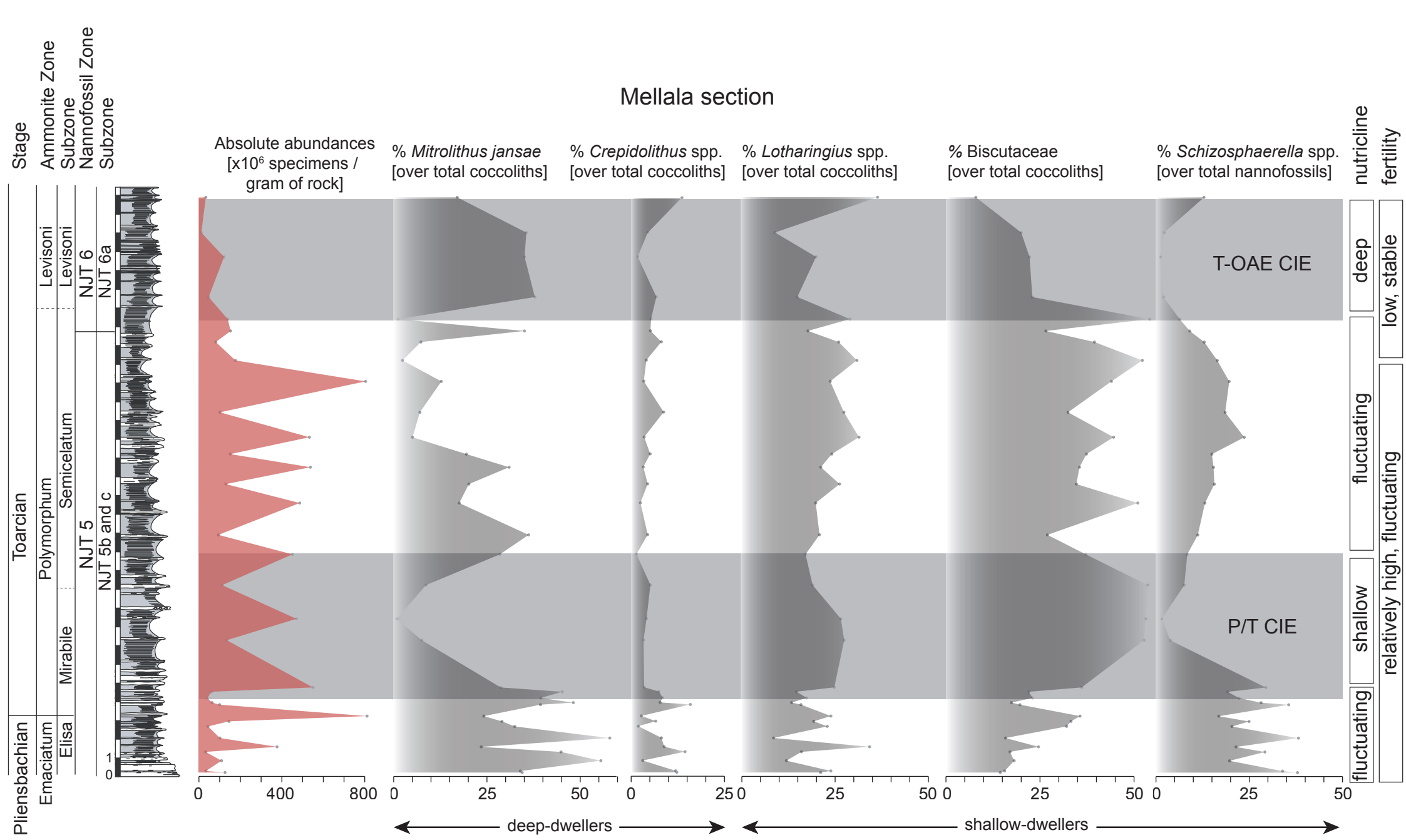


Figure 4 (Baghli et al.)



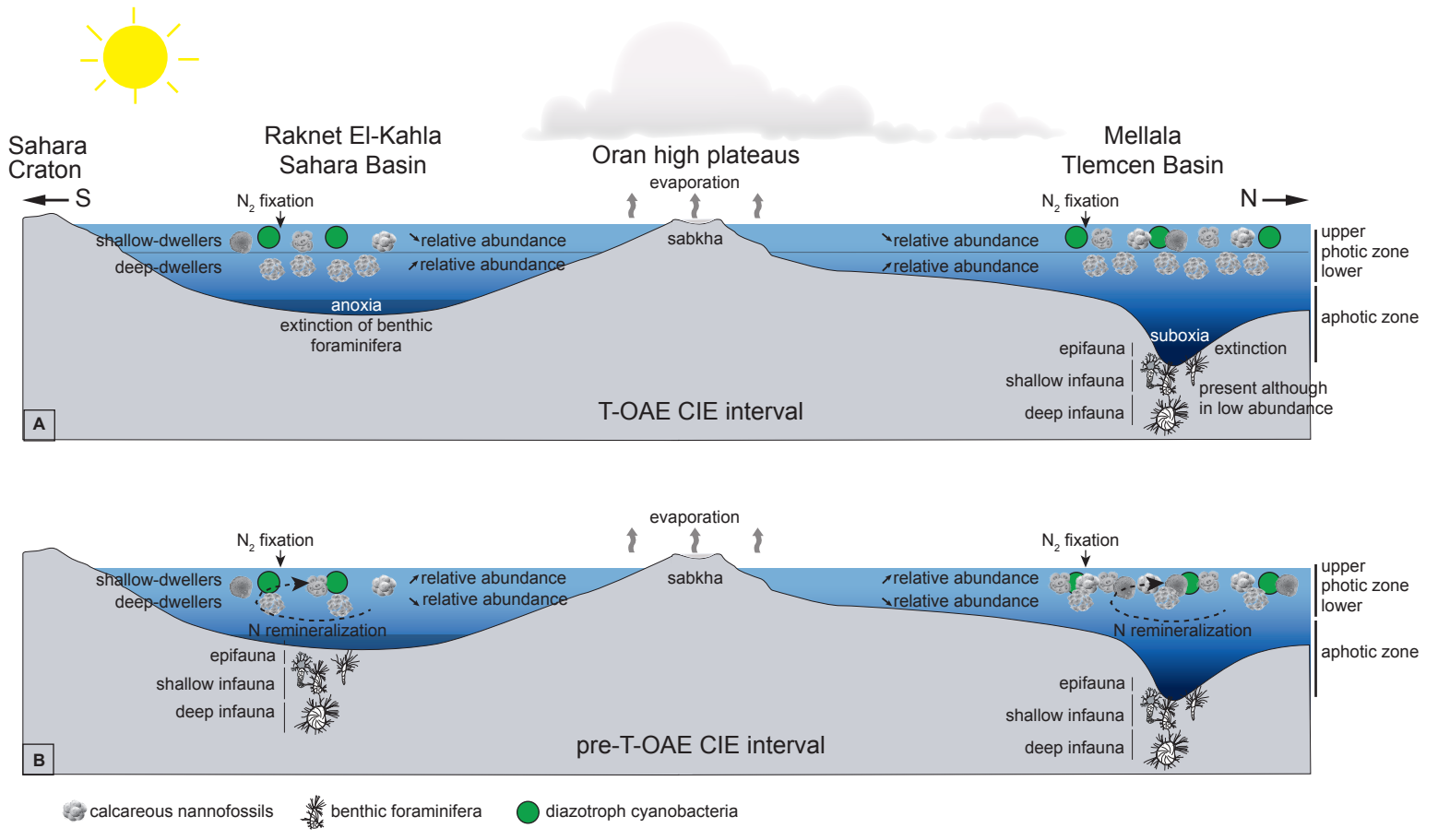


Figure 5 (Baghli et al.)

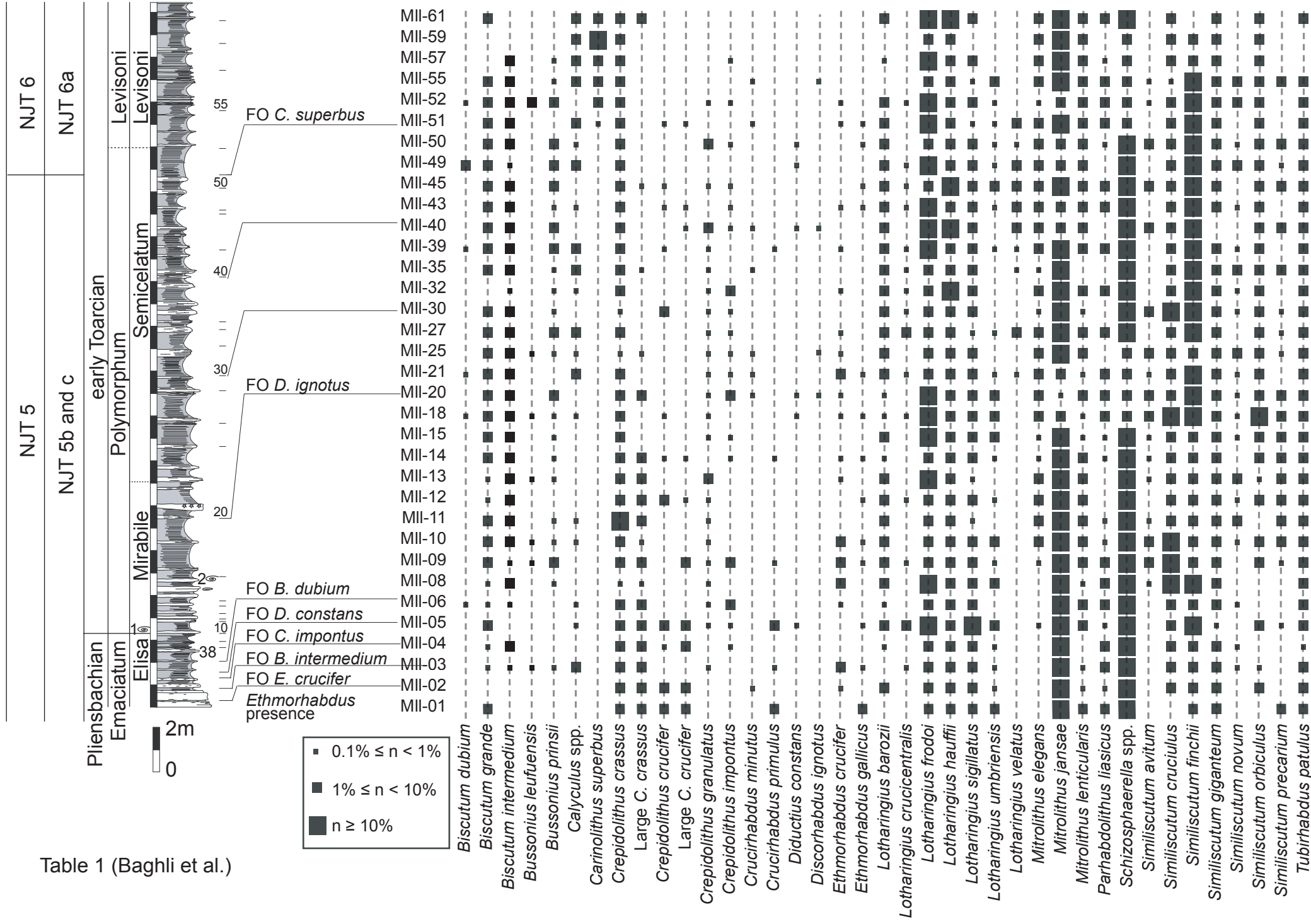
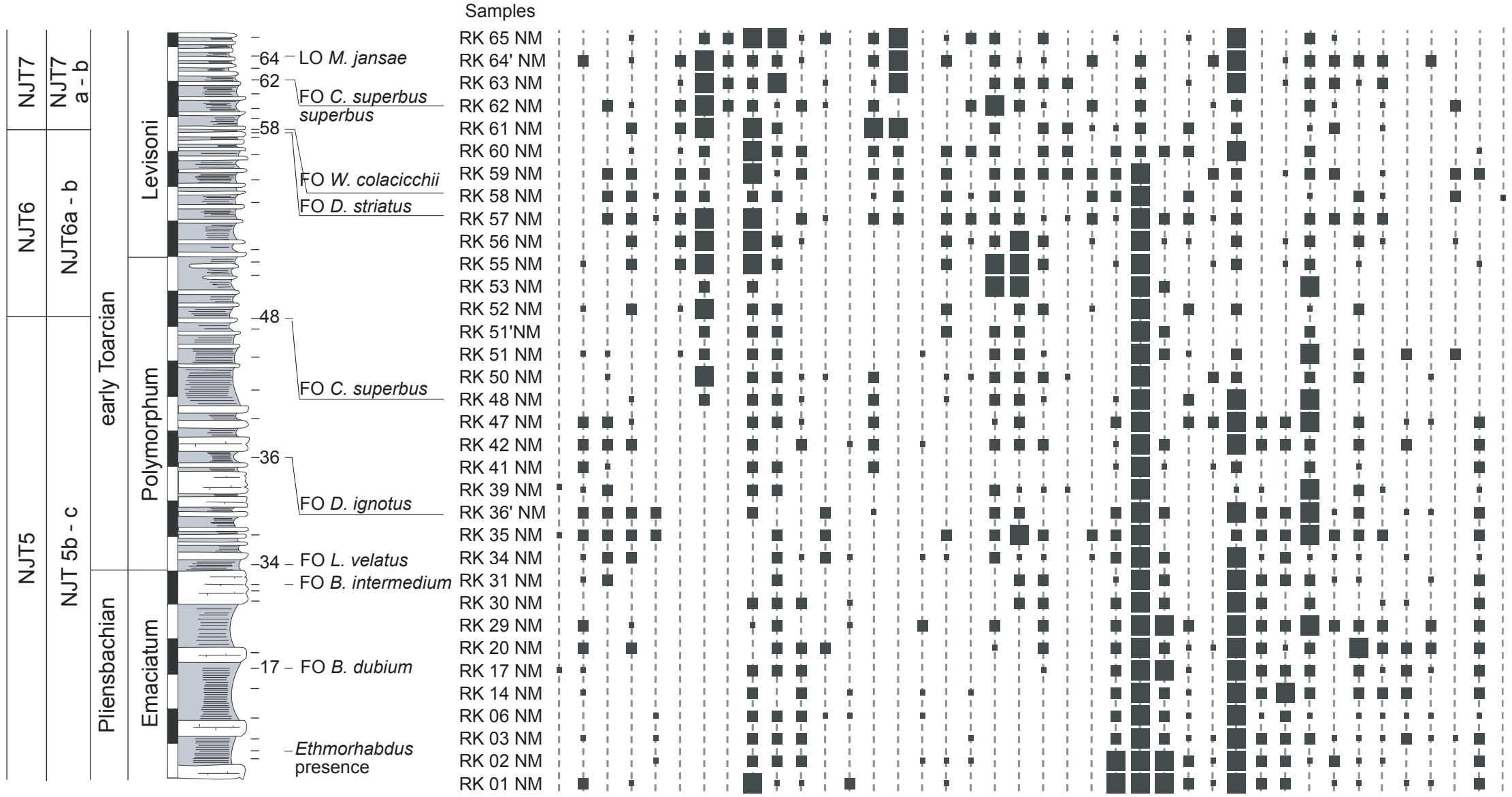
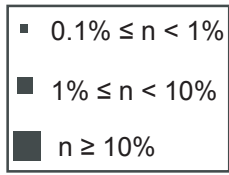


Table 1 (Baghli et al.)



Raknet El-Kahla section



- Biscutum dubium*
- Biscutum grande*
- Biscutum intermedium*
- Calyculus* spp.
- Large *Calyculus* spp.
- Carinolithus poulnabronei*
- Carinolithus superbus*
- C. superbus superbus*
- Crepidolithus crassus*
- Large *C. crassus*
- Crepidolithus crucifer*
- Large *C. crucifer*
- Crepidolithus granulatus*
- Discohabdus ignotus*
- Discohabdus striatus*
- Ethmorhabdus crucifer*
- Lotharingus barozii*
- Lotharingus crucecentralis*
- Lotharingus frodoi*
- Lotharingus hauffii*
- Lotharingus sigillatus*
- Lotharingus umbrensis*
- Lotharingus velatus*
- Mitrolithus elegans*
- Mitrolithus jansae*
- Mitrolithus lenticularis*
- Parhabdolithus liasicus*
- P. liasicus distinctus*
- Schizosphaerella* spp.
- Similiscutum avitum*
- Similiscutum cruciulus*
- Similiscutum finchii*
- Large *S. finchii*
- Similiscutum giganteum*
- Similiscutum novum*
- Similiscutum orbiculus*
- Similiscutum precarium*
- Tubirhabdus patulus*
- Tubirhabdus* sp.
- W. fossacincta*

Djebel Chemarikh section

