



## The middle-late Aalenian event: A precursor of the Mesozoic Marine Revolution

Alicia Fantasia, Emanuela Mattioli, Jorge E. Spangenberg, Thierry Adatte, Enrique Bernárdez, Jorge Ferreira, Nicolas Thibault, François-Nicolas Krencker, Stéphane Bodin

### ► To cite this version:

Alicia Fantasia, Emanuela Mattioli, Jorge E. Spangenberg, Thierry Adatte, Enrique Bernárdez, et al.. The middle-late Aalenian event: A precursor of the Mesozoic Marine Revolution. *Global and Planetary Change*, 2022, 208, 10.1016/j.gloplacha.2021.103705 . insu-03710175

**HAL Id: insu-03710175**

**<https://insu.hal.science/insu-03710175>**

Submitted on 5 Jan 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

# The middle-late Aalenian event: a precursor of the Mesozoic Marine Revolution

Alicia Fantasia<sup>1,2\*</sup>, Emanuela Mattioli<sup>2,3</sup>, Jorge E. Spangenberg<sup>4</sup>, Thierry Adatte<sup>5</sup>, Enrique Bernárdez<sup>6</sup>, Jorge Ferreira<sup>2</sup>, Nicolas Thibault<sup>7</sup>, François-Nicolas Krencker<sup>1</sup>, Stéphane Bodin<sup>1</sup>

<sup>1</sup>*Department of Geoscience, Aarhus University, 8000 Aarhus C, Denmark*

<sup>2</sup>*Univ Lyon, UCBL, ENSL, UJM, CNRS, LGL-TPE, F-69622, Villeurbanne, France*

<sup>3</sup>*Institut Universitaire de France (IUF), Paris Cedex 05, France*

<sup>4</sup>*Institute of Earth Surface Dynamics, University of Lausanne, 1015 Lausanne, Switzerland*

<sup>5</sup>*Institute of Earth Sciences, University of Lausanne, 1015 Lausanne, Switzerland*

<sup>6</sup>*Instituto Superior de Correlación Geológica, Miguel Lillo 205 (CP 4000), San Miguel de Tucumán, Argentina*

<sup>7</sup>*Department of Geosciences and Natural Resource Management, University of Copenhagen, 1350 Copenhagen K, Denmark*

\*corresponding author: [alicia.fantasia@univ-lyon1.fr](mailto:alicia.fantasia@univ-lyon1.fr)

## Abstract

The Aalenian was a time marked by profound environmental and carbon cycle changes. Still, the scarcity of detailed studies hinders a better understanding of the triggering mechanisms and the larger-scale context of Lower to Middle Jurassic environmental perturbations. This study provides an unprecedented high-resolution biostratigraphically well-constrained carbon isotope record ( $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{13}\text{C}_{\text{carb}}$ ) for the upper Toarcian–lower Bajocian interval of two expanded limestone-marl alternation successions in France (French Subalpine Basin) and Chile (Andean Basin). The comparison with available records from the Tethyan and Boreal domains highlights that medium-term carbon isotope fluctuations are reproducible across different palaeoceanographic settings from both hemispheres, providing for the first time compelling evidence for recurrent perturbations of the global carbon cycle during the Aalenian. Combined with a review of geological events, climate modes, abundance

and diversity of major fossil groups, and trophic conditions inferred from the calcareous nannofossil record, our study fills the gap in our understanding of global environmental changes in a so-far poorly documented Middle Jurassic stage, intercalated between the early Toarcian Oceanic Anoxic Event and the early Bajocian carbonate crisis. Importantly, this compilation indicates that the Aalenian was a pivotal time interval of environmental perturbations, likely triggering the Mesozoic Marine Revolution.

**Keywords:** Carbon isotope stratigraphy; Recurrent carbon cycle perturbations; Biotic events; Jurassic

## 1. Introduction

The Mesozoic was punctuated by several episodes of environmental changes associated with climatic instabilities, severe biotic crises, and perturbations of the global carbon cycle expressed as prominent carbon isotope excursions (CIEs) in marine and terrestrial inorganic and organic materials (e.g., [Jenkyns et al., 2002](#); [Dera et al., 2011](#); [Bodin et al., 2015](#); [Korte et al., 2015](#); [Storm et al., 2020](#)). These perturbations were often associated with the development of marine anoxia and the deposition of organic-matter rich strata and are commonly reported as Oceanic Anoxic Events (OAEs, see [Jenkyns, 2010](#) for a review). Over the last decades, the Toarcian-OAE (or T-OAE; e.g., [Hesselbo et al., 2000](#); [van Breugel et al., 2006](#); [Suan et al., 2011](#); [Bodin et al., 2016](#); [Xu et al., 2017](#); [Fantasia et al., 2018](#); [Krencker et al., 2020](#)) and the early Bajocian Event (e.g., [Suchéras-Marx et al., 2013](#); [Bodin et al., 2017, 2020](#)) have attracted much attention because they represent such episodes of global environmental change associated with large-amplitude CIEs.

The T-OAE was one of the most extreme hyperthermal events of the Mesozoic, likely triggered by intense volcanic activity in the Karoo-Ferrar Province and associated massive release of greenhouse gases into the atmosphere-ocean system (e.g., [Courtillot, 1994](#); [Duncan et al., 1997](#); [Pálffy and Smith, 2000](#); [Svensen et al., 2007](#); [Suan et al., 2008](#)). The defining benchmark for the T-OAE is a negative CIE thought to result from the injection of isotopically light volcanogenic, thermogenic, and/or biogenic carbon into the exogenic reservoirs (e.g., [Hesselbo et al., 2000](#); [Kemp et al., 2005](#); [McElwain et al., 2005](#); [Cohen et al., 2007](#); [Svensen et al., 2007](#); [Suan et al., 2008](#); [Them et al., 2017](#); [Krencker et al., 2019](#)). The early Bajocian Event is characterized by faunal and floral turnovers in pelagic ecosystems, which may represent part of the Mesozoic Marine Revolution ([Vermeij, 1977](#); [Wiggan et al., 2017](#); [Suchéras-Marx et al., 2019](#); [Rojas et al., 2021](#)). These changes are associated with a global carbon cycle perturbation expressed as a positive CIE, thought to reflect elevated rates of organic carbon burial linked to enhanced primary productivity ([Bartolini et al., 1999](#); [Jenkyns et al., 2002](#); [Hesselbo et al., 2003](#); [O'Dogherty et al., 2006](#); [Suchéras-Marx et al., 2013](#); [Giraud et al., 2016](#); [Erba et al., 2019](#); [Bodin et al., 2020](#)). Magmatic pulses related to major tectonic rearrangement during the early Middle Jurassic ([Bartolini and Larson, 2001](#); [Bill et al., 2001](#); [Labails et al., 2010](#)) have been proposed as a potential trigger of the early Bajocian Event. The injection of CO<sub>2</sub> and/or methane clathrates into the atmosphere may have induced a cascade of environmental feedbacks, including greenhouse conditions, enhanced hydrological cycle and weathering, marine eutrophication, and shallow water carbonate production crisis (e.g., [Suchéras-Marx et al., 2015](#); [Bodin et al., 2017](#)).

Bracketed in between the Toarcian and the Bajocian, the Aalenian has received much less attention, although it was likely a time of environmental instabilities marked by carbon cycle perturbations and marine biotic turnovers (e.g., [O'Dogherty et al., 2006](#); [Sandoval et al., 2008](#); [Gómez et al., 2009](#)). Hence, some important information can be gained from this

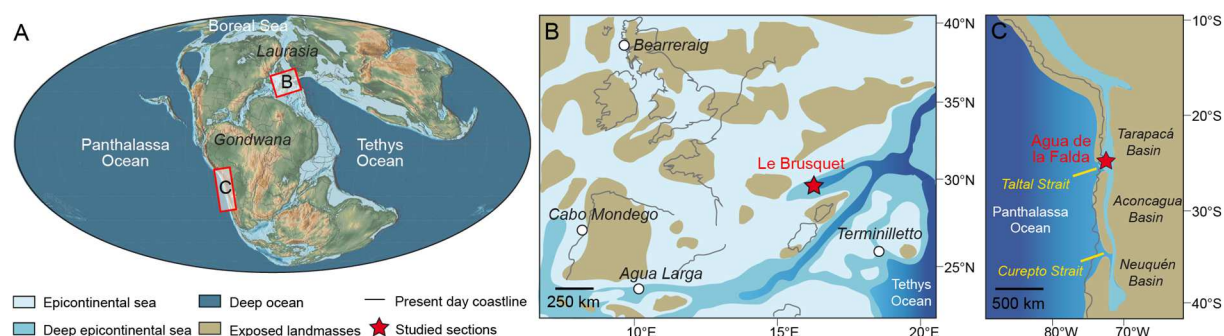
bridging time interval to put the T-OAE and early Bajocian Event into a broader context and better understand global carbon cycle dynamics during the Mesozoic.

Here, we present a high-resolution biostratigraphic (calcareous nannofossils), sedimentological and geochemical (stable carbon isotopes, Rock-Eval pyrolysis) study of two expanded successions, namely Le Brusquet (French Subalpine Basin, SE France) and Agua de la Falda (Andean Basin, N Chile). These successions were previously dated by ammonite faunas and spanned the upper Toarcian–lower Bajocian interval. The main objective of this paper is to assess the potential causal links between the carbon isotope perturbations and palaeoenvironmental changes significantly affecting the carbonate factory, as depicted from various inorganic, organic, and biotic proxies. Specifically, this study provides (i) detailed carbon isotope records of bulk organic matter and carbonates, (ii) a correlation of the studied sections with coeval sites using nannofossil biostratigraphy and carbon isotope stratigraphy, and (iii) an evaluation of the stratigraphic reproducibility of the carbon isotope variations and an appraisal of the influence of local processes on the global signal.

## **2. Geological setting**

Le Brusquet and Agua de la Falda localities offer extended and continuously exposed strata of upper Toarcian–lower Bajocian age and include both the Toarcian/Aalenian and the Aalenian/Bajocian boundaries, according to previously established ammonite biozones (Le Brusquet: [Mouterde et al., 1966](#); [Caloo, 1970](#); [de Graciansky et al., 1993](#); Agua de la Falda: [von Hillebrandt and Schmidt-Effing, 1981](#); [Marticorena and Tapia, 1982](#)). The successions are composed of marly limestone-marl alternations, deposited in the French Subalpine Basin and the Andean Basin, respectively ([Fig. 1](#)).

The development of the French Subalpine Basin began during the Middle to Late Triassic (e.g., [de Granciansky et al., 1993](#); [Razin et al., 1996](#); [Mariotti et al., 2012](#)). During the Middle Jurassic, the basin was a transitional zone between the epicontinental sea of the Paris Basin and the deeper Ligurian Tethys, along the NW margin of the Tethys ([Fig. 1](#); [Ferry and Rubino, 1989](#); [Thierry, 2000](#)). The Le Brusquet succession is now exposed in SE France ([Fig. 1](#)), ~10 km NE of the town of Digne-les-Bains along the Bouinenc stream and the D22 road linking the villages of Marcoux and Draix (GPS coordinates, base of the section: 44°08'10.07''N; 06°18'14.19''E). In the studied area, Middle Jurassic sedimentary successions were covered by at least 3 km of Upper Jurassic to Eocene sedimentary deposits and are part of the Digne thrust sheets, which overthrust autochthon strata towards the SW ([Gidon and Pairis, 1992](#); [Lickorish and Ford, 1998](#)). The Le Brusquet succession was buried under ca. 3 km overburden ([Haccard et al., 1989](#)) and was likely impacted by burial diagenesis and complex tectonic history. These transformations are also suggested by the degree of organic matter maturation (oil window-beginning of gas window stage; [Levert, 1989](#)) of Middle Jurassic deposits in the Digne area.



**Fig. 1 :** (A) Global Middle Jurassic palaeogeographic reconstruction (after [Scotese, 2014](#)), with the location of the French Subalpine (B) and Andean (C) basins. (B) Palaeogeographic map of the western Tethys (after [Thierry, 2000](#)) with the location of Le Brusquet section (French Subalpine Basin, France) and other comparative key sites discussed in the text: Cabo Mondego (Lusitanian Basin, Portugal), Agua Larga (Subbetic Basin, Spain), Bearerraig (Hebrides Basin, the United Kingdom), and Terminillette (Umbria-Marche Basin, Italy). Note that the central Tethys was not yet open during the Aalenian. (C) Palaeogeographic map of the Andean Basin, which was divided into the Tarapacá, Aconcagua and Neuquén subbasins. The location of the Agua de la Falda section and the position of the communicating straits with the Panthalassa Ocean are shown.

The Andean Basin was an elongated back-arc basin along the SW Gondwana margin, which developed in response to extensional and/or transtensional tectonics related to the subduction of the proto-Pacific plate and the formation of the Andean magmatic arc during the Jurassic and Early Cretaceous (Uliana et al., 1989; Vicente, 2005; Charrier et al., 2007). Despite the development of the volcanic arc to the west, a connection with Panthalassa Ocean was likely possible through marine connecting straits during the Middle Jurassic (Gröschke et al., 1988; Prinz et al., 1994). The Agua de la Falda succession is exposed in N Chile (Fig. 1), near the Potrerillos locality in the Atacama Region (GPS coordinates: 26°30'34.03''S; 69°20'34.5''W). The succession was likely not too strongly affected by burial diagenesis and eventually by the tectonic history related to the formation of the Andean Cordillera since this was not the case for older deposits of Toarcian age in the same area (Fantasia et al., 2018).

### 3. Material and methods

#### 3.1. Sampling

Le Brusquet and Agua de la Falda sections were measured and sampled for geochemical analyses with a vertical resolution of 45–90 cm and 5–20 cm, respectively. In parallel, the lithology, sedimentary features, fossil content, and ichnofossil associations were described for each level sampled. The samples showing clear evidence of diagenetic neoformed, recrystallized calcite, or containing macroscopic allochems were avoided. About 10–20 g of macroscopically homogeneous sample were selected, dried at 45°C, crushed, and powdered using an agate mortar at the Department of Geoscience, Aarhus University prior to analysis.

### 3.2. Calcareous nannofossil biostratigraphy

Smear slides for calcareous nannofossil identification were prepared at the LGL-TPE, Université Claude Bernard Lyon 1. A total of 76 samples from Le Brusquet and 20 from the Agua de la Falda were selected at regular space intervals in the marl-limestone alternations. A small amount of crushed rock was mixed with water before spreading onto a cover slide (Bown and Young, 1998). Cover slides were then mounted onto the microscope slide using Rhodopass B resin (polyvinyl acetate). Sample slides were then studied using a Leica DM750P optical microscope at 1000x magnification. Two transverses of the slide (12.8 mm<sup>2</sup>) were scanned and the encountered nannofossils were counted. The slides were further analysed to recover rare species. The preservation state of the nannofossils was evaluated based on etching and overgrowth of the specimens, using the preservation index and criteria proposed by Roth (1994).

### 3.3. Carbon and oxygen isotopes

Carbon and oxygen isotope compositions ( $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$ , ‰ VPDB) of aliquots of powdered whole-rock samples (Le Brusquet:  $n=395$ , Agua de la Falda:  $n=41$ ) were determined using a Thermo Fisher Scientific (Bremen Germany) Gas Bench II connected to a Delta Plus XL isotope mass spectrometer at the Institute of Earth Surface Dynamics of the University of Lausanne (IDYST–UNIL). The measured  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  values were normalized to VPDB scale using reference laboratory standard (Carrara Marble,  $\delta^{13}\text{C} = +2.05\text{‰}$ ,  $\delta^{18}\text{O} = -1.7\text{‰}$ ) and international reference materials NBS18 carbonatite ( $\delta^{13}\text{C} = -5.01\text{‰}$ ,  $\delta^{18}\text{O} = -23.01\text{‰}$ ) and NBS19 limestone ( $\delta^{13}\text{C} = +1.95\text{‰}$ ,  $\delta^{18}\text{O} = -2.2\text{‰}$ ). Analytical uncertainty ( $1\sigma$ ) monitored by replicate analyses of the laboratory standard Carrara Marble was not greater than  $\pm 0.05\text{‰}$  for  $\delta^{13}\text{C}$  and  $\pm 0.1\text{‰}$  for  $\delta^{18}\text{O}$ .



Carbon isotope compositions of bulk organic matter ( $\delta^{13}\text{C}_{\text{org}}$ , ‰ VPDB) were determined on decarbonated (treatment with 10% HCl) powdered whole-rock samples (Le Brusquet:  $n=689$ , Agua de la Falda:  $n=303$ ) by using an elemental analyser Carlo Erba 1108 connected to a Thermo Fisher Scientific Delta V Plus isotope ratio mass spectrometer at IDYST–UNIL. The repeatability and intermediate precision of the  $\delta^{13}\text{C}_{\text{org}}$  values were better than 0.05‰.

### 3.4. Rock-Eval pyrolysis

Total organic carbon (TOC, wt.%) content, mineral carbon (MinC, wt.%) content, hydrogen index (HI, mg HC/g TOC, HC=hydrocarbons), oxygen index (OI, mg  $\text{CO}_2$ /g TOC), and  $T_{\text{max}}$  (°C) were measured on powdered whole-rock samples (Le Brusquet:  $n=639$ , Agua de la Falda:  $n=298$ ) using a Rock-Eval 6 (Espitalié, 1985; Behar et al., 2001) at the Institute of Earth Sciences of the University of Lausanne (ISTE–UNIL). Measurements were calibrated using the IFP160000 standard.  $T_{\text{max}}$  estimates of the thermal maturation level of the organic matter (Espitalié et al., 1977; Peters, 1986). HI values were not interpreted for TOC  $\leq 0.2$  wt.%, and  $T_{\text{max}}$  values were rejected when  $\text{S}_2 \leq 0.3$  mg HC/g avoiding misinterpretation of flat thermograms (Peters, 1986). The parameter  $Q_{\text{carb}} = 7.976 \cdot \text{MinC}$  (Jiang et al., 2017) was used to estimate the proportion of carbonate with MinC values as the sum of mineral carbon obtained during pyrolysis and oxidation phases (Lafargue et al., 1998).

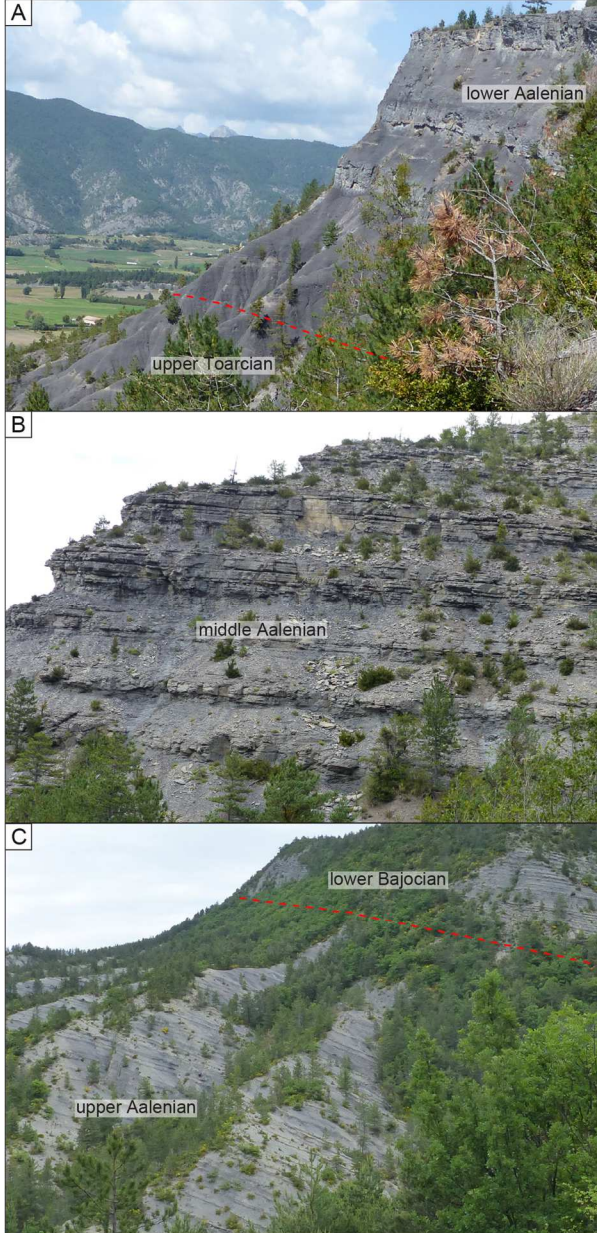
## 4. Results

### 4.1. Lithological description and biostratigraphy

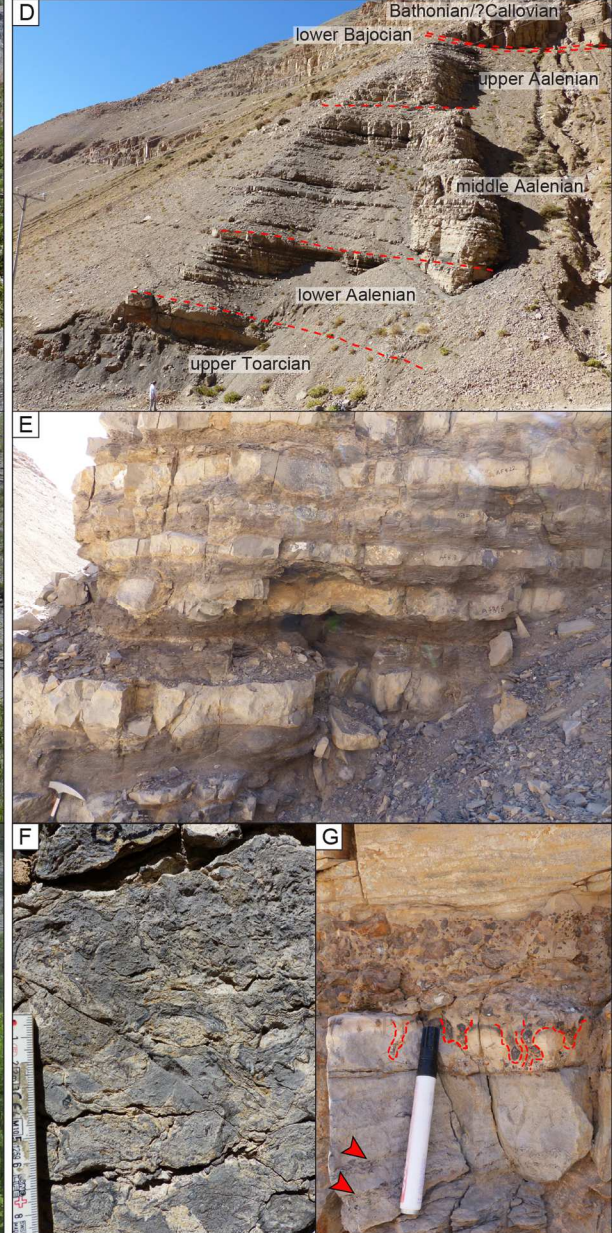
#### 4.1.1. Le Brusquet

The upper Toarcian–lower Bajocian at Le Brusquet is about 400 m-thick and dominated by dm- to m-thick alternations of offshore marl and marly limestone (Fig. 2). The succession shows relatively monotonous lithology and is expanded compared to previously documented contemporaneous European sections (Fig. 3; e.g., Sandoval et al., 2008; Gomez et al., 2009; Price, 2010; Korte et al. 2015). The lithostratigraphy and ammonite biostratigraphy of equivalent successions in Le Brusquet area have been previously described by Mousterde et al. (1966), Caloo (1970) and de Graciansky et al. (1993), and the following ammonite zones have been recognised: Aalensis (late Toarcian), Opalinum (early Aalenian), Murchisonae (middle Aalenian), Concavum (late Aalenian), and Discites (early Bajocian). The ammonite biostratigraphy is complemented here by nannofossil data (Fig. 3). The base of the succession is dominated by dark grey marl, intercalated with few yellowish lenticular, nodular, dm-thick limestone beds (Fig. 2A), assigned to the uppermost Toarcian (Aalensis zone). The transition towards the Aalenian is marked by a progressive evolution to rhythmic marly limestone-marl alternations (Fig. 2A). The lower Aalenian (Opalinum zone) is composed of marly limestone-dominated rhythmic alternations, with few dm-thick lenticular limestone beds at the base. A 5 cm-thick brown clayey layer is intercalated at 80 m. The middle Aalenian (Murchisonae zone) is composed of massive marly limestone-marl rhythmic alternations (Fig. 2B), with the limestone becoming progressively thinner and more marly towards the top of the interval. The upper Aalenian (Concavum zone) shows marl with rhythmic intercalations of thin marly limestone beds (Fig. 2C). The lower Bajocian (Discites zone) is composed of marl, which grades into regular limestone-marl alternations (Fig. 2C).

# Le Brusquet, France



# Agua de la Falda, Chile



**Fig. 2 :** (A) Representative field photographs of Le Brusquet (A–C) and Agua de la Falda (D–G) sections. (A) The Upper Toarcian–lower Aalenian transition is marked by an evolution from marl-dominated to limestone-dominated deposits. (B) The middle Aalenian is composed of limestone–marl rhythmic alternations. (C) The upper Aalenian shows marl with rhythmic intercalations of thin marly limestone beds, which grades into regular marl and limestone alternations in the lower Bajocian. (D) The upper Toarcian–lower Bajocian–Bathonian–(?) Callovian shows an alternation of marl and limestone. (E) Close-up view of the lower Aalenian marl (sometimes finely laminated)–limestone alternations. (F) Close-up view of the limestone marker bed at 26 m, which is almost entirely composed of oysters. (G) The upper Aalenian–Bajocian transition is marked by a limestone bed with bivalve concentrations (red arrows). The top of the bed, representing the unconformity between the lowermost Bajocian and the Bathonian–(?) Callovian, is a hard ground with borings (dashed lines) infilled with phosphatic clasts from the phosphorite conglomerate bed. This bed is the basis of a Bathonian–(?) Callovian succession composed of silicified limestone.



#### 4.1.2. Agua de la Falda

The Agua de la Falda locality in the Potrerillos area was selected because it presents one of the most expanded and well-exposed upper Toarcian–lower Bajocian succession in Chile, offering a globally-distributed insight of the environmental conditions. It is composed of a 52 m-thick alternation of marl and marly limestone (Fig. 2). The Agua de la Falda outcrop belt can be followed laterally to the Quebrada El Asiento section (~2.5 km away from Agua de la Falda), which was previously described for its lithostratigraphy and ammonite biostratigraphy (von Hillebrandt and Schmidt-Effing 1981; Marticorena and Tapia 1982; Perez 1982). In addition, the T-OAE interval has been identified further down in the succession (Fantasia et al., 2018), bracketing the stratigraphic framework of the studied succession. The ammonite biostratigraphy is based on the scheme developed for the Andean regions and correlated with the European Standard Ammonite zones (von Hillebrandt and Schmidt-Effing, 1981; von Hillebrandt and Westermann, 1985; Riccardi, 2008). Specifically, the following ammonite assemblage zones were distinguished in the Potrerillos area: (i) *Pleydellia* cf. *fluitans* (~Aalensis), (ii) *Bredya* *manflasensis* (~Opalinum), (iii) *Zurcheria* *groeberi* (~Murchisonae), (iv) *Puchenquia* *malarguensis* (~Concavum), (v) horizon of *Podagrosiceras* *maubeugei* (~Aalenian/Bajocian boundary). *Pseudotoites* cf. *sphaeroceroides* indicates the lowermost Bajocian, (vi) (?) *Xenoccephalites* sp. and (?) *Epistrenoceras* sp. of late Bathonian to Callovian age (von Hillebrandt and Westermann, 1985).

The base of the section (Aalensis zone, upper Toarcian) is composed of wavy to nodular marly limestone beds, rarely bioclastic, alternating with thin marl interbeds. Those alternations grade up-section into a dark brown marl-dominated interval, which contains limestone nodules and large ammonites (unidentifiable, ~30 cm diameter) and alternates with nodular marly limestone beds. The marl-dominated interval is overlain by massive dm-thick bioclastic limestone beds, equivalent to the beds 8 described by von Hillebrandt and Schmidt-

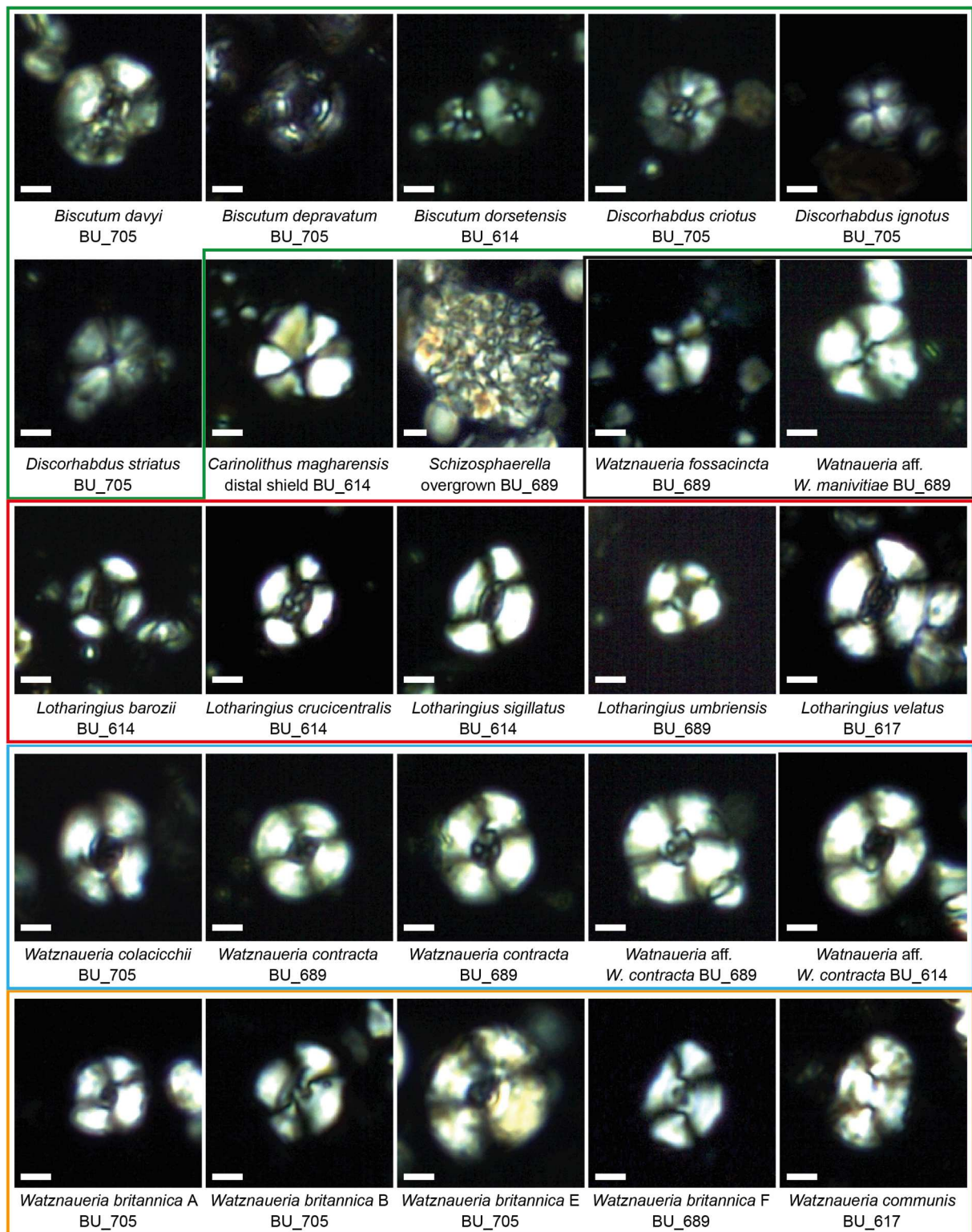
Effing (1981) at the Toarcian–Aalenian transition. The rest of the succession is dominated by wavy to nodular, bioclastic (wackestone to packstone), bioturbated, marly limestone beds, which alternate with dark brown, organic-matter rich, thin-bedded to laminated, marls (Fig. 2E). The marls contain limestone nodules and mm-scale phosphatic peloids. Several firm grounds are present. The macrofossil content in the bioclastic limestones consists of bivalves (mostly oysters), brachiopods (mostly terebratulids), crinoids, ammonites, and scarce belemnites and gastropods. The shells are poorly sorted, wholly or almost entirely fragmented, and are oriented along cross bedding, or are normally graded. At 26 m, a 60 cm-thick normally-graded limestone bed with an erosive base and almost composed by articulated oysters (*Lopha* sp.), is a marker bed in the studied succession (Fig. 2F). This coquina bed is equivalent to bed 12 described by von Hillebrandt and Schmidt-Effing (1981), which is assigned to a middle–late Aalenian age (Murchisonae–Concavum zones). The limestone and marl become silty to sandy from 40 m upwards, and the proportion of marl relative to limestone increases. The silty marl-dominated interval is capped by a 20 cm-thick erosive-based limestone bed including thin-shelled bivalves accumulated in distinct layers (Fig. 2G). The upper part of the limestone bed presents borings filled with phosphatic clasts. This is overlain by a cm-thick phosphorite conglomerate bed (Fig. 2G), laterally discontinuous with an erosive base containing heterometric, sub-angular to rounded, poorly sorted phosphate clasts (Fig. 2G). The limestone bed below the conglomerate corresponds to bed 16 described by von Hillebrandt and Schmidt-Effing (1981), which was assigned to an early Bajocian age. The conglomerate of early Bajocian age is disconformably overlain by silicified limestone (Fig. 2G), with ripple laminations, of late Bathonian–(?) Callovian age described as bed 17 by von Hillebrandt and Schmidt-Effing, 1981. Most of the Bajocian interval is hence largely condensed and/or missing, and marked by reworked deposits.

#### 4.2. Calcareous nannofossils

At Le Brusquet, calcareous nannofossils were identified in 76 samples throughout the upper Toarcian–lower Bajocian interval providing a suite of biostratigraphic events (see Supplementary Information and Fig. S1), whereas the analysed samples at Agua de la Falda were all barren. At Le Brusquet, the dominant calcareous nannofossil taxa are represented by *Schizosphaerella*, Biscutaceae (including various species of *Similiscutum*, *Biscutum* and *Discorhabdus*), several species of *Lotharingius*, *Watznaueria* with a cross structure in the central area (namely: *W. colacicchii*, *W. contracta*, and *Watznaueria* aff. *W. contracta*), *Watznaueria* with a bridge in the central area (*W. communis* and several morphotypes of *W. britannica* defined in Giraud et al., 2006), and *Watznaueria* without structures in the central area (*W. fossacincta* and *Watznaueria* aff. *W. manivitiae*; Fig. 3). The assemblage composition shows important variations across the Aalenian (Fig. 4). The base and intermediate, carbonate-rich part of the succession (Aalensis to middle Murchisonae zones; upper Toarcian to middle Aalenian) are characterized by the lowest nannofossil content and by the dominance in nannofossil assemblage of *Schizosphaerella* spp. (an *incertae sedis*, commonly considered to be a dinoflagellate cyst; Bown, 1987). The coccolith fraction, although very rare, is dominated by Biscutaceae, with a peak at around 140–160 m (Murchisonae zone; middle Aalenian), while *Lotharingius* coccoliths show an inverse trend. However, being the dominant coccolith forms, such inverse trend in Biscutaceae and *Lotharingius* can be due to the closed-sum effect. The carbonate-rich interval also bears micrometre-sized plant debris commonly observed in the smear slides. A sudden change in the assemblage composition is observed from ~220 m up to the top of the section (middle Murchisonae to Discites zones; middle Aalenian to lower Bajocian), where nannofossil amounts progressively increased and *Watznaueria* spp. became dominant. In particular, this

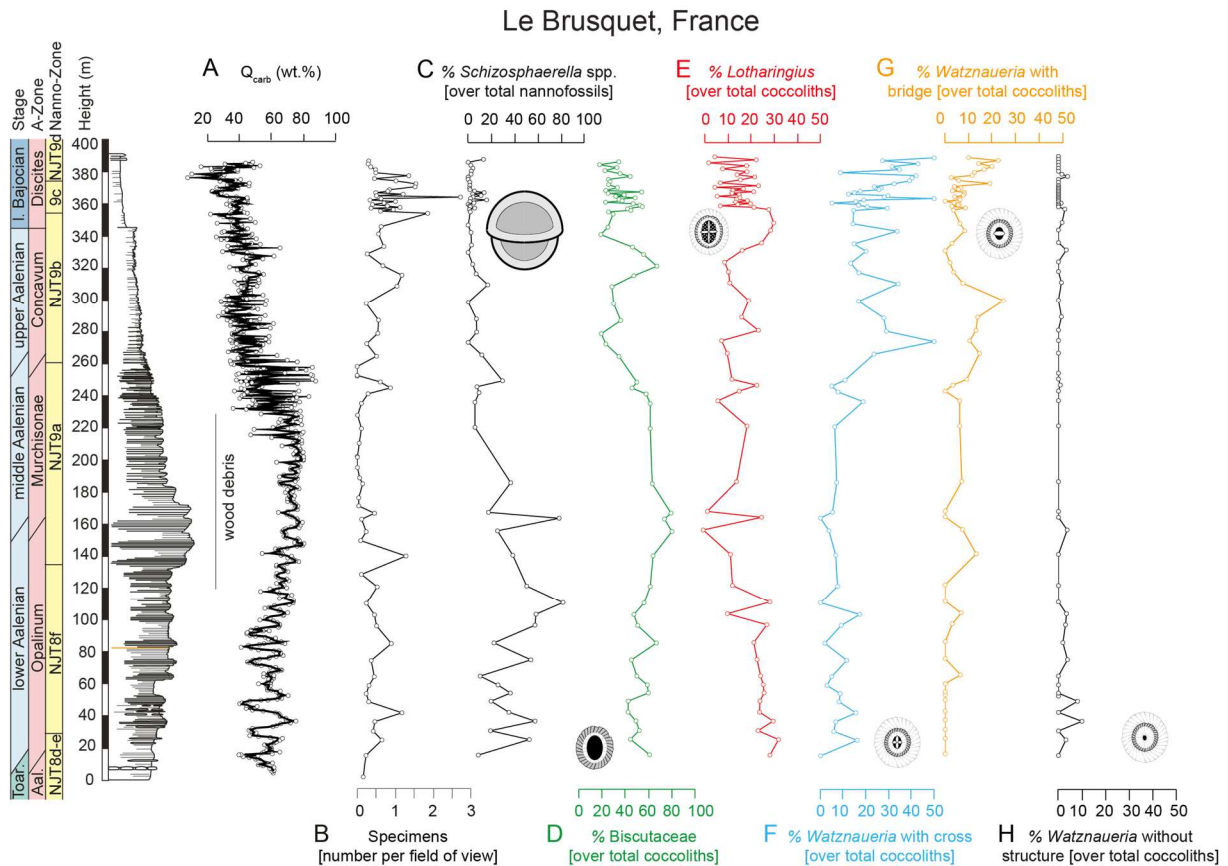
306 shift to *Watznaueria* spp. dominance is driven by elevated proportions (20 to 50%) of those  
307 forms bearing a cross structure in the central area.

308



**Fig. 3 :** Micrographs of representative calcareous nannofossils from Le Brusquet section, under cross-polarized light. The colour code refers to the dominant taxa shown in Figure 5: Biscutaceae (green), *Lotharingius* (red), *Watznaueria* with a cross structure in the central area, (blue), *Watznaueria* with a bridge in the central area (orange), and *Watznaueria* without structures (black).





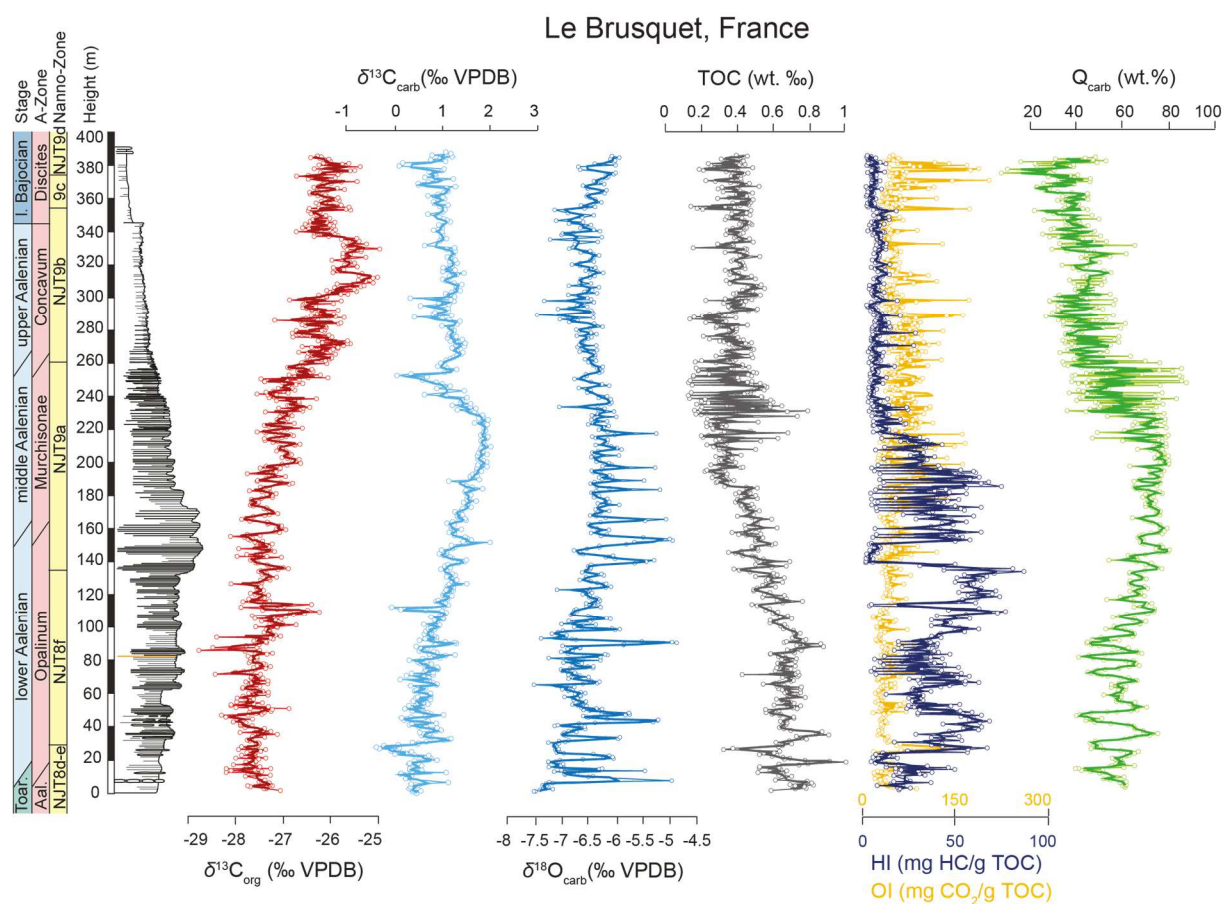
**Fig. 4:** (A) Carbonate content ( $Q_{carb}$ ) for Le Brusquet section is shown next to (B) the calcareous nannofossil abundances, and the percentages of the dominant taxa, i.e., (C) *Schizosphaerella*, (D) Biscutaceae, (E) *Lotharingius*, (F) *Watznaueria* with a cross structure in the central area, (G) *Watznaueria* with a bridge in the central area, and (H) *Watznaueria* without structures. Note the significant increase in *Watznaueria* across the middle–late Aalenian. Wood debris are particularly present in the middle Aalenian.

### 4.3. Organic matter and carbonate contents

#### 4.3.1. Le Brusquet

At Le Brusquet, TOC contents are comprised between 0.1 and 1.0 wt.%, with maximum values in the Aalensis and Opalinum zones (Fig. 5). The TOC values are high (average 0.7 wt.%) up to the Opalinum–Murchisonae zonal transition before gradually decreasing up to the lower Murchisonae zone. This is followed by a scattered increase of the TOC in the upper Murchisonae zone, with values up to 0.8 wt.% in the marl and minimum values of 0.1 wt.% in the limestone. This is followed by steady TOC contents up to the top of

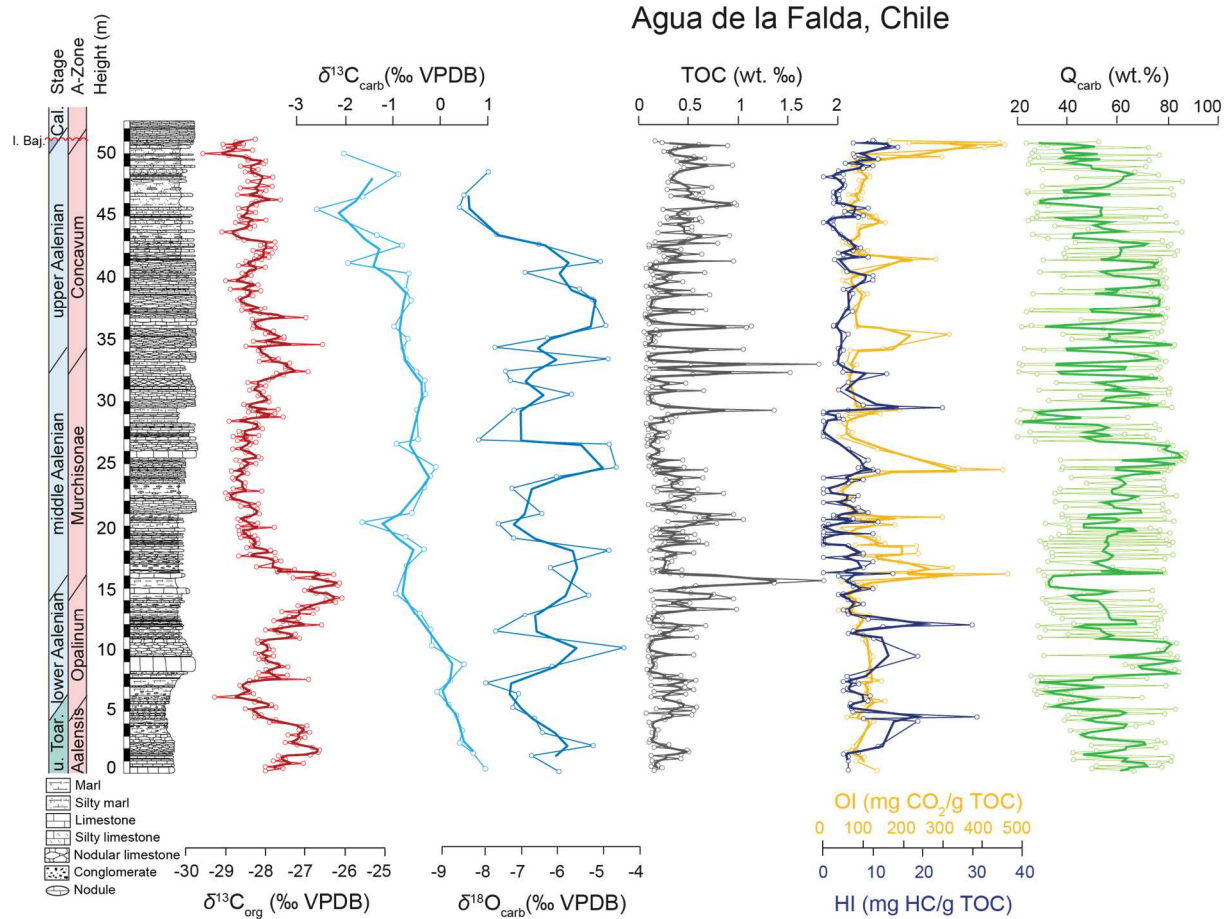
the section, with values fluctuating around 0.5 wt.%. HI (2–87 mg HC g<sup>-1</sup> TOC; average 21 mg HC g<sup>-1</sup> TOC) and OI (18–284 mg CO<sub>2</sub> g<sup>-1</sup> TOC; average 61 mg CO<sub>2</sub> g<sup>-1</sup> TOC) values are relatively low throughout the section (Fig. 5), with the highest HI and lowest OI recorded from the Aalensis zone up to the lower Murchisonae zone. This is followed by a decrease of the HI and generally higher OI (≤ 284 mg CO<sub>2</sub> g<sup>-1</sup> TOC) up to the top of the section. The *T*<sub>max</sub> values are uniform within 494–498 °C. *Q*<sub>carb</sub> values fluctuate between 7.8 and 87.3 wt.% and broadly mirror TOC values, with a long-term increasing trend from the base of the section up to the Murchisonae–Concavum zonal transition. This gradual increase in *Q*<sub>carb</sub> values is expressed as a change to more massive marly limestone-marl rhythmic alternations. This is followed by a decrease in the Concavum zone and relatively steady values up to the top of the section (Fig. 5).



**Fig. 5:** Isotopic composition ( $\delta^{13}\text{C}_{\text{org}}$ ,  $\delta^{13}\text{C}_{\text{carb}}$ ,  $\delta^{18}\text{O}_{\text{carb}}$ ), total organic carbon (TOC) content, hydrogen index (HI), oxygen index (OI), and carbonate content (*Q*<sub>carb</sub>) at Le Brusquet. The trend lines correspond to a 4-points moving average.

### 4.3.2. Agua de la Falda

At Agua de la Falda, TOC content is generally higher than at Le Brusquet, with values up to 1.9 wt.% (Fig. 6).



**Fig. 6:** Isotopic composition ( $\delta^{13}\text{C}_{\text{org}}$ ,  $\delta^{13}\text{C}_{\text{carb}}$ ,  $\delta^{18}\text{O}_{\text{carb}}$ ), total organic carbon (TOC) content, hydrogen index (HI), oxygen index (OI), and carbonate content ( $Q_{\text{carb}}$ ) at Agua de la Falda. The trend lines correspond to a 4-points moving average.

A gradual increase is recorded up to the Opalinum–Murchisonae zonal transition, with a maximum of 1.9 wt.% in the laminated marl. This is followed by a decrease at the base of the Murchisonae zone and a slight increase up to the middle Murchisonae zone. This trend is followed by a gradual decrease of the TOC values up to the upper Murchisonae zone, and

then a scattered increase across the Murchisonae–Concavum zonal transition. TOC values show a general increase in the Concavum zone, followed by a decreasing trend near the Bajocian–Bathonian–(?) Callovian disconformity surface. HI values are generally low ( $\leq 31$  mg HC g<sup>-1</sup> TOC; average 6 mg HC g<sup>-1</sup> TOC), whereas OI values are moderately high ( $\leq 449$  mg CO<sub>2</sub> g<sup>-1</sup> TOC; average 116 mg CO<sub>2</sub> g<sup>-1</sup> TOC), and both index fluctuate throughout the section (Fig. 6). Q<sub>carb</sub> values vary between 0.2 and 83.8 wt.%, and show a high scatter which reflects the alternation between marl and limestone. Three intervals of decreasing Q<sub>carb</sub> values are recorded at the Toarcian/Aalenian boundary, in the Opalinum zone, in the upper Murchisonae zone, and in the Concavum zone, respectively (Fig. 6).

#### 4.4. Carbon and oxygen isotopes

##### 4.4.1. Le Brusquet

At Le Brusquet, the  $\delta^{13}\text{C}_{\text{org}}$  values range between  $-29.9$  and  $-24.9\text{‰}$  (Figs. 5 and 7) and show a long-term gradual increase of about  $3.0\text{‰}$  from the upper Toarcian to the uppermost Aalenian, which culminates with maximum values in the Concavum zone. Distinct  $\delta^{13}\text{C}_{\text{org}}$  medium-term fluctuations are superimposed on this long-term positive trend. The  $\delta^{13}\text{C}_{\text{org}}$  profile shows a  $\sim 1\text{‰}$  negative excursion near the Toarcian/Aalenian boundary, followed by a  $\sim 1\text{‰}$  increase in the Opalinum zone, reaching values up to  $-26\text{‰}$  with a first maximum in the upper Opalinum zone. Two distinct  $\sim 1.5\text{‰}$  negative shifts are recorded at the Opalinum–Murchisonae zonal transition and in the Murchisonae zone, followed by an increase in  $\delta^{13}\text{C}_{\text{org}}$  values reaching  $-25.5\text{‰}$  at the Murchisonae–Concavum zonal transition. The  $\delta^{13}\text{C}_{\text{org}}$  shows two  $\sim 1.0$ – $1.5\text{‰}$  negative shifts in the Concavum zone that interrupt a progressive increase to a maximum value of  $-24.9\text{‰}$ . The Aalenian/Bajocian boundary is marked by a decrease in  $\delta^{13}\text{C}_{\text{org}}$  (Fig. 5).

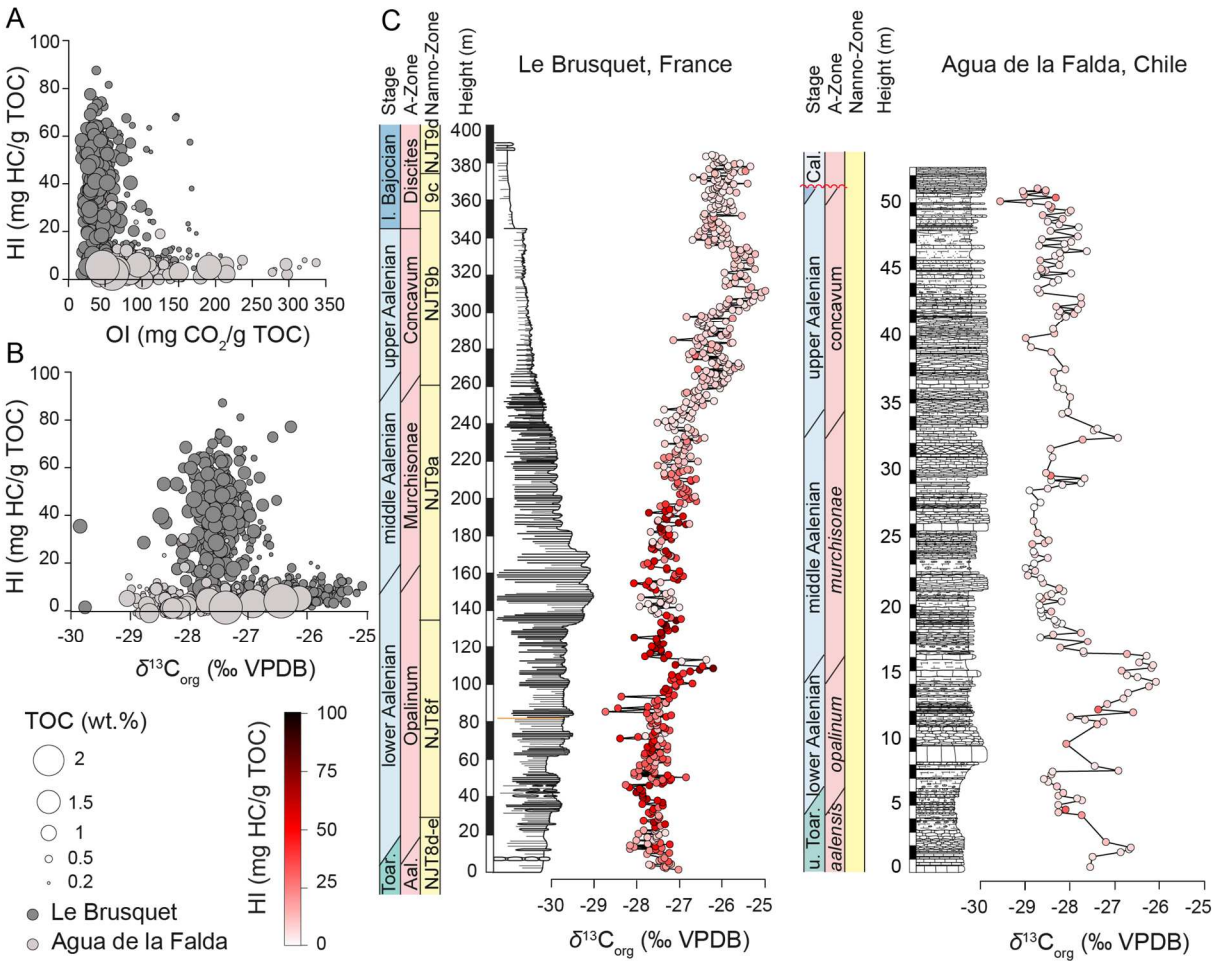
The  $\delta^{13}\text{C}_{\text{carb}}$  values vary between  $-0.5$  and  $2.0\text{‰}$  (Fig. 5) and show a general increasing trend from the Aalensis zone up to the middle Murchisonae zone, which mimics the increase of carbonate content in the section. The increasing trend is followed by a shift to more negative  $\delta^{13}\text{C}_{\text{carb}}$  in the upper part of the section, where the lithology changes toward marl-dominated deposits. The  $\delta^{18}\text{O}_{\text{carb}}$  values fluctuate between  $-7.5$  and  $-1.7\text{‰}$  (Fig. 5), displaying broadly a similar trend as the  $\delta^{13}\text{C}_{\text{carb}}$  values.

#### 4.4.2. Agua de la Falda

At Agua de la Falda,  $\delta^{13}\text{C}_{\text{org}}$  values range between  $-29.6$  and  $-25.1\text{‰}$ , with consecutive medium-term shifts of  $\sim 1.0$ – $2.5\text{‰}$  magnitude (Figs. 6 and 7). The  $\delta^{13}\text{C}_{\text{org}}$  profile shows a  $\sim 2\text{‰}$  negative shift at the Toarcian/Aalenian boundary, followed by an increase of up to  $-26\text{‰}$  at the Opalinum–Murchisonae zonal transition, associated with high TOC. The Murchisonae zone shows a broad stepped  $\sim 2.5\text{‰}$  negative  $\delta^{13}\text{C}_{\text{org}}$  shift, followed by an increase to a maximum value of  $-27\text{‰}$  near the Murchisonae–Concavum zonal transition, coupled with an increase in TOC. The  $\delta^{13}\text{C}_{\text{org}}$  values show two  $\sim 1.5\text{‰}$  negative shifts in the lower Concavum zone and a decrease near the Aalenian/Bajocian boundary. These negative shifts are followed by a marked increase to the maximum value of  $-25.1\text{‰}$  below the lower Bajocian–Bathonian–(?) Callovian disconformity surface (Fig. 6).

The  $\delta^{13}\text{C}_{\text{carb}}$  values fluctuate between  $-3.3$  and  $1.0\text{‰}$  (Fig. 6) and show a long-term decreasing trend throughout the section, interrupted by more positive values across the Murchisonae–Concavum zonal transition. The  $\delta^{18}\text{O}_{\text{carb}}$  values fluctuate between  $-8.6$  and  $-4.3\text{‰}$  (Fig. 6).





**Fig. 7:** (A) Scatterplot of the hydrogen index (HI) versus the oxygen index (OI) in relation with the total organic carbon (TOC) content for Le Brusquet and Agua de la Falda sections. (B) Relationship between  $\delta^{13}C_{org}$  and hydrogen index for Le Brusquet and Agua de la Falda sections. (C) Bulk organic matter isotopic composition ( $\delta^{13}C_{org}$ ) for Le Brusquet and Agua de la Falda sections, compared to the stratigraphic evolution of the hydrogen index (HI) values. Note the absence of clear relationship between the type/preservation of the organic matter and the  $\delta^{13}C_{org}$  trend.

## 5. Discussion

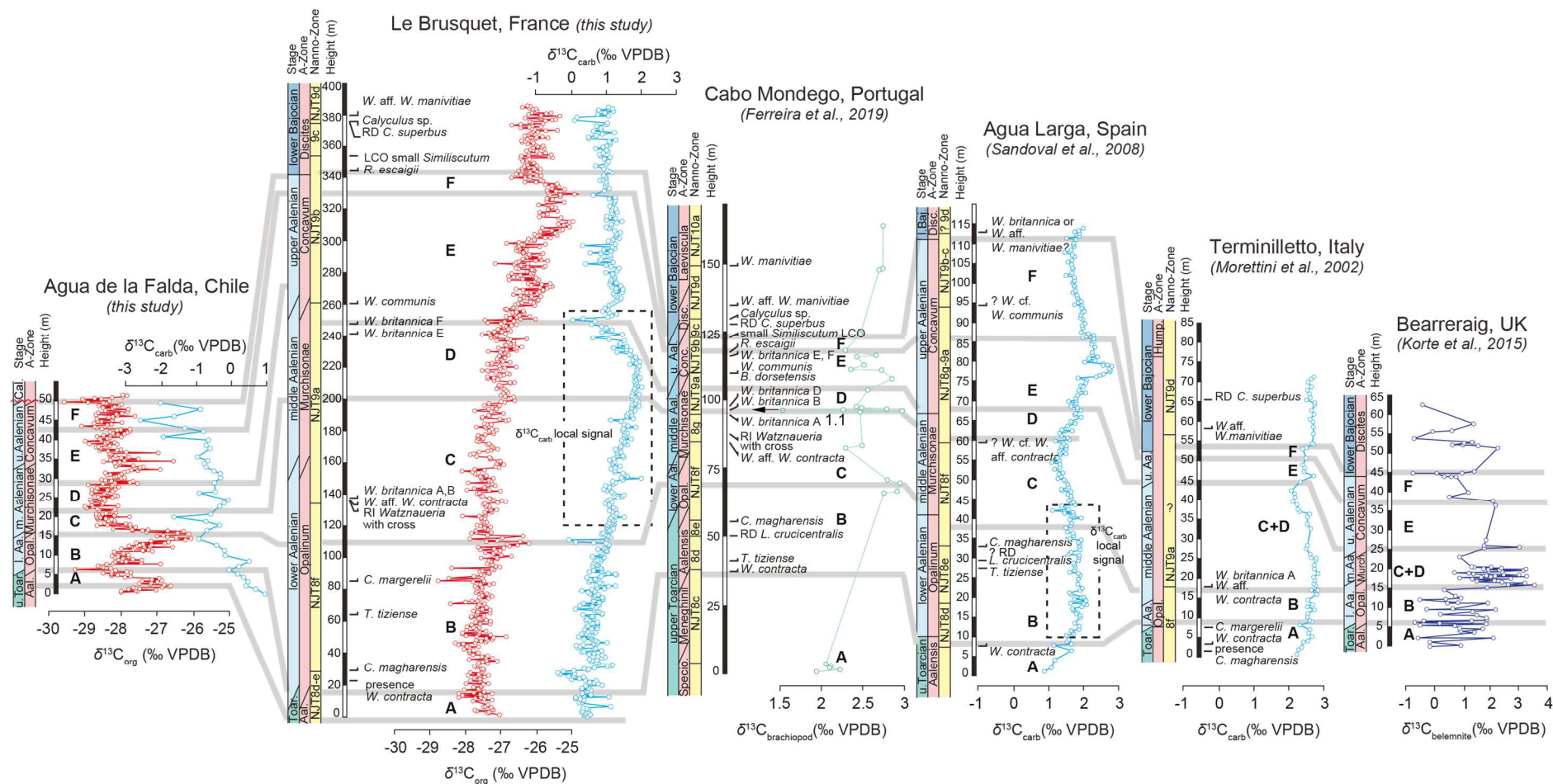
### 5.1. Calcareous nannofossils

#### 5.1.1. Biostratigraphic constraints

The chronostratigraphic frame and age assignment provided by ammonites for Le Brusquet section (Caloo, 1970; de Graciansky et al. 1993) is confirmed by our new calcareous nannofossil biostratigraphy (Fig. S1). In particular, the occurrence of *W. contracta* and *C.*

*magharensis* approximate the Toarcian/Aalenian boundary, which correlates to the base of the NJT8 zone of the [Ferreira et al. \(2019\)](#) biochronological scheme (also used in the GTS 2020). The middle Aalenian was identified by the consecutive FOs of *W. britannica* morphotype A and *W. communis* (NJT9a zone). The Aalenian/Bajocian boundary and basal Bajocian were recognised by the FO of *R. escaigii* and the LCO of small *Similiscutum* (NJT9c zone).

Calcareous nannofossil data are also available for the Agua Larga (Spain, [Sandoval et al., 2008](#)) and Terminilletto (Italy, [Baumgartner et al., 1995](#)) sections, where whole-rock  $\delta^{13}\text{C}_{\text{carb}}$  have been measured ([Aguado et al., 2008](#); [Sandoval et al., 2008](#); [Morettini et al., 2002](#)). The nannofossil and carbon isotope data of these sections were compared with the new dataset from Le Brusquet and Agua de la Falda ([Fig. 8](#)). To ensure accurate comparisons with the studied sections, nannofossil data from Terminilletto (studied by one of us, EM) and from Agua Larga ([Aguado et al., 2008](#)) were reconsidered in the light of recently published taxonomic revision (see the synthesis in [Ferreira et al., 2019](#)). In particular, the specimen of *W. contracta* shown by [Aguado et al. \(2008; figure 5-39\)](#) is larger than 7  $\mu\text{m}$ ; thus it should be considered as a *W. aff. W. contracta* according to [Tiraboschi and Erba \(2010\)](#). [Aguado et al. \(2008\)](#) reported a sharp increase in proportions of *W. contracta* in the Agua Larga section from 59.40 m. After reconsideration, this increase may instead correspond to the inception of *W. aff. W. contracta*. If so, the record of the Agua Larga section is consistent with that of Le Brusquet ([Fig. 8](#)). Likewise, the specimens of *W. britannica* shown by [Aguado et al. \(2008; figure 5-44\)](#) might correspond to a transitional form close to *W. manivitiae*. We hence added the FO of *W. aff. W. manivitiae* as an alternative to the FO of *W. britannica* reported by [Aguado et al., 2008 \(Fig. 8\)](#).



**Fig. 8:** High-resolution carbon isotope records ( $\delta^{13}\text{C}_{\text{org}}$ ,  $\delta^{13}\text{C}_{\text{carb}}$ ) of the upper Toarcian–lower Bajocian interval of Le Brusquet and Agua de la Falda sections, and comparison with available key records from the European area: Cabo Mondego, Lusitanian Basin, Portugal (Ferreira et al., 2019); Agua Larga, Subbetic Basin, Spain (Sandoval et al., 2008); Terminillette, Umbria-Marche Basin, Italy (Morettini et al., 2002); Bearreraig, Hebrides Basin, the United Kingdom (Korte et al., 2015). Note that the grey lines correspond to correlations proposed in this study, based on biostratigraphy and chemostratigraphy and highlights carbon isotope shifts (intervals A–F) that can be correlated between the different sites from the Panthalassa, and Tethyan and Boreal realms. At Le Brusquet and Agua Larga, the box with dashed line indicates the interval where the  $\delta^{13}\text{C}_{\text{carb}}$  signal is likely influenced by the carbonate ooze exported from adjacent platforms.



The comparison between nannofossil events at Le Brusquet, Agua Larga, and Terminilletto shows that some events can be traced across the three sections (Fig. 8). The nannofossil record of Agua Larga and Terminilletto allows a tentative application of the nannofossil zones of Ferreira et al. (2019) that provides correlation with Le Brusquet record (Fig. 8). In particular, the occurrence of *W. contracta* is relatively consistent between the three sections, and similarly to Le Brusquet, *W. aff. W. contracta* and *W. britannica* A occur close to each other at Terminilletto. According to our stable isotope and biostratigraphic data, the FO of *W. aff. W. manivitiae* is consistent between the three sections and further allow potential recognition of subzone NJT9d despite the lack of observation of the LO of *Calyculus* spp. at Agua Larga and Terminilletto (Fig. 8).

#### 5.1.2. Palaeoenvironmental implications

Although calcareous nannofossils are very rare at Le Brusquet (Fig. 5), the percentage of the dominant taxa can be interpreted in terms of palaeoenvironmental changes, especially in the carbonate-rich part of the section between 130 and 220 m. Calcareous nannofossil abundances (Fig. 4B) provide raw information on the general trends. The Aalensis to Opalinum zones (upper Toarcian to lower Aalenian, 0–130 m) display moderate values of nannofossil abundances along with relatively high percentages of shallow-dweller taxa, proliferating either in times of relative oligotrophy (such as *Schizosphaerella* spp.; Fig. 4C) or meso-eutrophic conditions of surface waters (such as Biscutaceae and *Lotharingius* spp.; Fig. 4D–E). *Schizosphaerella* was likely better adapted to overall oligotrophic conditions in shallow-waters, where nutrients were probably recycled in times of intensified storms (Mattioli and Pittet, 2004; Aguado et al., 2008; Reggiani et al., 2010). However, some authors (Claps et al., 1995; Erba, 2004; Tremolada et al., 2005) interpreted *Schizosphaerella* as a

deep-dweller taxon, proliferating in time of surface-water oligotrophy. Biscutaceae are commonly associated with eutrophic environments both in the Jurassic and in the Cretaceous, thriving in high-fertility surface-waters (Roth and Bowdler, 1981; Premoli Silva et al., 1989; Watkins, 1989; Erba, 1992; Mattioli and Pittet, 2004; Tremolada et al., 2006; Mattioli et al., 2008). *Lotharingius* probably dwelled in shallow-waters and was adapted to moderately high nutrient concentrations (Pittet and Mattioli, 2002; Mattioli and Pittet, 2004; Olivier et al., 2004; Tremolada et al., 2005; Mattioli et al., 2008). Overall, calcareous nannofossil assemblage at the base of the Le Brusquet section can be considered as indicative of alternating high- and low-fertility conditions in surface waters.

The Opalinum to middle Murchisonae zones (lower to middle Aalenian, ~130–220 m) is marked by the lowest relative abundances in nannofossils, decreasing proportions of *Schizosphaerella* spp. and low percentages of *Lotharingius* spp., whereas Biscutaceae show the highest values (Fig. 4C–E). Moreover, this interval also corresponds to the most carbonate-rich part of the succession and with the highest concentration in micrometer-sized wood debris observed in smear slides (Fig. 4). Such observations may suggest either increased continental runoff and bio-limiting elements input to epicontinental basins or relative proximity from source areas at times of platform progradation. Whatever the cause, the observed dominance of Biscutaceae may have been triggered by enhanced continent-derived nutrient input.

The dominant features observed in the middle Murchisonae to Discites zones (middle Aalenian to lower Bajocian, ~220–400 m) comprise the overall decreasing trend in Biscutaceae proportions and the progressive and prominent increase in *Watznaueria* bearing a cross in its central area (Fig. 4D and F). This trend encompasses an increase in *Watznaueria* bearing a bridge in the central area (Fig. 4G), which were likely opportunistic forms, proliferating in times of global eutrophication related to major oceanic reorganisation (Giraud

et al., 2016). Alternatively, they may have developed the ability to bloom in nutrient-rich environments previously unexploited by other species (Suchéras-Marx et al., 2015). Likewise, major changes have been documented in the siliceous microplankton, with a major radiolarian turnover across the middle–late Aalenian (Yao, 1997; Bartolini et al., 1999; Aguado et al., 2009). This faunal change has been interpreted as the biological response to palaeotectonic rearrangements in the Western Tethys linked to the central Atlantic spreading, which likely induced palaeoceanographic modifications, with global ocean chemistry changes and eutrophication (e.g., Aguado et al., 2008; Sandoval et al., 2008).

## 5.2. Effects of diagenesis and different carbonate phases on the isotope records

The potential diagenetic overprint on the marly limestone-marl alternations was evaluated at Le Brusquet and Agua de la Falda to assess if the  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  data could be used as primary environmental indicators. Diagenetic processes on pelagic carbonates generally have less influence on the carbon isotopes than oxygen isotopes (e.g., Schrag et al., 1995). The organic matter mineralization releases  $^{13}\text{C}$ -depleted dissolved inorganic carbon (DIC). Therefore, recrystallization-neomorphism of carbonate phases during burial diagenesis will lower the  $\delta^{13}\text{C}_{\text{carb}}$  values (e.g., Weissert et al., 1979; Marshall, 1992; Schrag et al., 1995). Actually, Le Brusquet section is composed of micrite-rich deposits, which are less prone to diagenetic fluid migration and carbon buffered. At Le Brusquet, the moderate correlation between  $\delta^{13}\text{C}_{\text{carb}}$  and  $Q_{\text{carb}}$  values ( $r=0.45$ ,  $p<0.001$ ) suggests a relationship between the whole-rock carbonate content and the carbon isotope composition. The long-term marine carbon isotope record is mainly governed by changes in the organic carbon fluxes relative to the total carbon in the different carbon pools (e.g., Berner, 1987). Long-term  $\delta^{13}\text{C}_{\text{carb}}$  records can however potentially be influenced by regional carbon cycling processes. These include

the incorporation of carbonate particles with varying carbon isotope compositions exported from platforms and pelagic mud (e.g., [Swart and Eberli, 2005](#); [Godet et al., 2006](#); [Bodin et al., 2016](#)). It has however been demonstrated that the contribution of nannofossil carbonate to the global oceanic carbon cycle is negligible during the Middle Jurassic ([Suchéraz-Marx et al., 2012](#)) and hence did likely not significantly contribute to the  $\delta^{13}\text{C}_{\text{carb}}$  record of Le Brusquet. Long-term fluctuations in the contribution of riverine DIC fluxes to the ocean can also induce shifts in the  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  profiles (e.g., [Kump and Arthur, 1999](#); [Kemp et al., 2020](#)), which are decoupled from global changes in the carbon cycle. Given the difference between the carbon isotope record from Le Brusquet and other European sites, it is hence not excluded that the  $\delta^{13}\text{C}_{\text{carb}}$  profile from Le Brusquet likely do not solely reflect changes in the global carbon cycle but also the superimposed influence of local carbon cycling processes. Furthermore, in the studied area, Middle Jurassic sedimentary successions were covered by at least 3 km of Jurassic to Eocene sediments and underwent a complex regional alpine tectonic history (Digne Nappe; [Levert, 1989](#); [Lickorish and Ford, 1998](#)), pointing to the influence of burial diagenesis on the deposits. At Le Brusquet, the relationship between  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  values ( $r=0.57$ ,  $p<0.001$ ) together with generally low  $\delta^{18}\text{O}_{\text{carb}}$  values suggest a significant overprint of burial diagenesis, precluding the use of the  $\delta^{18}\text{O}_{\text{carb}}$  as a reliable environmental proxy. The influence of burial diagenesis is further supported by high  $T_{\text{max}}$  values (494–498°C), which indicate mature organic matter (gas window; [Espitalié et al., 1985](#)).

At Agua de la Falda, the correlation between  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  values is very weak ( $r=0.19$ ,  $p=0.12$ ), suggesting that burial diagenesis had no significant influence on the carbon isotope values. This low diagenetic overprint is also supported by the lack of correlation between  $\delta^{13}\text{C}_{\text{carb}}$  and  $Q_{\text{carb}}$  values ( $r=0.18$ ,  $p=0.11$ ). Nonetheless, the long-term negative  $\delta^{13}\text{C}_{\text{carb}}$  trend is paralleled by a lithological transition towards the shallowest facies observed

throughout the succession and the increasing proportion of detrital material. This suggests that diagenetic processes, including organic matter oxidation and incorporation of  $^{13}\text{C}$ -depleted carbon and/or changes in the relative content of carbonate ooze, may have driven the negative  $\delta^{13}\text{C}_{\text{carb}}$  trend without any link with the global signal. Interpretation of  $\delta^{18}\text{O}_{\text{carb}}$  values is excluded from the discussion since they are particularly low, suggesting diagenetic overprint related to dissolution and recrystallization-neomorphism (Schrage et al., 1995). The absence of  $\text{S}_2$  peak hampers any reliable interpretation of  $T_{\text{max}}$  values and the influence of thermal diagenesis.

### 5.3. Evaluation of the degree of preservation of the organic matter

At Le Brusquet, burial diagenesis impacted the type of preserved organic matter. The more refractory terrestrial organic matter was likely preferentially preserved during burial diagenesis than the labile marine organic matter (e.g., de Lange et al., 1994; Arndt et al., 2013). Low HI and OI values (averages 21 mg HC g<sup>-1</sup> TOC and 61 mg CO<sub>2</sub> g<sup>-1</sup> TOC, respectively; Fig. 5) and high  $T_{\text{max}}$  values (494–498°C) well within the gas window point to overmature organic matter in these rocks. This high thermal maturity prevented the assessment of the organic matter type in the HI vs. OI plot (Fig. 7A). Although a minor contribution of overmature phytoplankton-derived marine organic matter can not be excluded, the occurrence of microscopic and macroscopic fossil wood particles (e.g., between 130–220 m) suggests a predominance of terrestrial organic matter, likely conveyed to the French Subalpine Basin from the surrounding emerged landmasses such as the Massif Central. At Agua de la Falda, the source of the preserved organic matter is difficult to assess because it has been overprinted by diagenetic processes ( $\text{S}_2 < 0.3$  mg HC/g and therefore not reliable  $T_{\text{max}}$  values). The absence of smectite in the Pliensbachian–Toarcian interval from the same area

(Fantasia et al., 2018) confirms that burial diagenesis affected the deposits. However, this overprint was likely not too strong in the studied area as indicated by the presence of kaolinite (Fantasia et al., 2018), which supports higher thermal burial than smectite before transformation into illite or chlorite (e.g., Burtner and Warner, 1986; Chamley, 1989).

Nonetheless, although the studied successions underwent diagenetic overprint related to the complex diagenetic and tectonic history of the studied areas, similar medium-term shifts and range of  $\delta^{13}\text{C}_{\text{org}}$  values were recorded at both sites, suggesting that the carbon isotope composition of the preserved organic matter may not have been strongly modified. Furthermore, the isotope composition of the kerogen is generally preserved from low thermal maturation degrees until relatively high degree of metamorphism (e.g., McKirdy and Powell, 1974; Schoell, 1984; Spangenberg and Macko, 1998). No high thermal gradients were reached at Le Brusquet and Agua de la Falda, supporting the use of the  $\delta^{13}\text{C}_{\text{org}}$  as an environmental signal. Additionally, the absence of a relationship between the preservation of the organic matter type (HI values) and the  $\delta^{13}\text{C}_{\text{org}}$  values at both localities (Fig. 7) sustained the organic carbon isotope records as an environmental proxy.

#### 5.4. Recurrent global carbon cycle disturbances across the Aalenian

The Aalenian carbon isotope stratigraphy was hitherto derived from  $\delta^{13}\text{C}$  records of whole-rock carbonates and biogenic calcite from Tethyan and Boreal sites (Spain: Sandoval et al., 2008; Gómez et al., 2009, Italy: Morettini et al., 2002, United Kingdom: Jenkyns, 2002; Price et al., 2010; Korte et al., 2015, Portugal: Ferreira et al., 2015, 2019, Morocco: Krencker et al., 2014). Besides the Agua Larga succession in Spain, which is presently the most expanded high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  record for the upper Toarcian–lower Bajocian interval, the other records generally present low resolution data, restricted to short stratigraphic intervals,

and/or poor biostratigraphic constraints. Based on the correspondence between the different Tethyan and Boreal records, it has been suggested that some of the  $\delta^{13}\text{C}_{\text{carb}}$  shifts may relate to supraregional controls (e.g., [Price, 2010](#); [Sandoval et al., 2008](#)). Nonetheless, records from outside the Tethyan and Boreal domains and derived from organic matter were inexistent before our study leaving large uncertainties about the global extent of the carbon cycle perturbations and about triggering mechanisms.

Comparing our  $\delta^{13}\text{C}$  records and published datasets highlights that similar medium-term  $\delta^{13}\text{C}$  patterns are shared between sites from both hemispheres. However, the interplay between global and local processes on the long-term carbon isotope signal varies between palaeoceanographic settings. Consecutive medium-term shifts can indeed be compared across Tethyan, Boreal, and Panthalassic sites ([Fig. 8](#)), providing compelling evidence that recurrent global carbon cycle perturbations occurred during the Aalenian. The Le Brusquet carbon isotope record not only depicts several medium-term shifts that were previously identified in Tethyan and Boreal sites (e.g., [Price, 2010](#); [Sandoval et al., 2008](#)) but also other undescribed fluctuations. Hence, the Aalenian  $\delta^{13}\text{C}$  record appears much more complex than previously thought as our results allow identifying seven intervals (A to F; [Fig. 8](#)) of global carbon cycle perturbations.

At Le Brusquet, the uppermost Toarcian is marked by a negative shift (interval A) in the  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{13}\text{C}_{\text{carb}}$  values, reaching the lowest values at the Toarcian/Aalenian boundary. This trend is also observed in Chile at Agua de la Falda. This negative carbon isotope shift was previously identified in the  $\delta^{13}\text{C}_{\text{carb}}$  records of hemipelagic carbonates and marine biogenic carbonates at different sites from the Tethyan and Boreal realms (Spain: [Sandoval et al., 2008](#); Portugal: [Ferreira et al., 2019](#); Italy: [Morettini et al., 2002](#); United Kingdom: [Price, 2010](#); [Korte et al., 2015](#); France: [Harazim et al., 2013](#); Morocco: [Krencker et al., 2014](#)). The

615 lower Aalenian (Opalinum zone) is marked by positive shifts in  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{13}\text{C}_{\text{carb}}$  (interval  
 616 B) at Le Brusquet and at Agua de la Falda and were previously identified in carbonates from  
 617 Tethyan and Boreal sites (Price et al., 2010; Sandoval et al., 2008). The lower–middle  
 618 Aalenian transition (Opalinum–Murchisonae zonal transition) from Le Brusquet is marked by  
 619 a negative  $\delta^{13}\text{C}_{\text{org}}$  excursion (interval C) which was not observed in the  $\delta^{13}\text{C}_{\text{carb}}$  record.  
 620 Nonetheless, a negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion marked the Opalinum–Murchisonae transition at  
 621 Agua Larga in Spain (Sandoval et al., 2008), suggesting that local conditions may have  
 622 modulated the  $\delta^{13}\text{C}_{\text{carb}}$  record at Le Brusquet. Indeed, interval C at Le Brusquet shows the  
 623 highest carbonate content associated with more massive marly limestone-marl rhythmic  
 624 alternations (Fig. 5), suggesting that material exported from neritic environments may have  
 625 shifted the  $\delta^{13}\text{C}_{\text{carb}}$  record towards more positive values. Hence, the influence of local  
 626 conditions related to different amounts of carbonate ooze exported from adjacent platforms  
 627 may explain differences between the  $\delta^{13}\text{C}_{\text{carb}}$  profiles from Le Brusquet and Agua Larga (e.g.,  
 628 Swart and Eberli, 2005; Godet et al., 2006; Bodin et al., 2016) (Fig. 8). Alternatively, a  
 629 change in the organic matter type and/or preservation may explain differences between the  
 630 organic and inorganic records. However, the absence of a relationship between HI and  $\delta^{13}\text{C}_{\text{org}}$   
 631 values suggests that the  $\delta^{13}\text{C}_{\text{org}}$  trend reflects a genuine supraregional/global signal. This  
 632 interpretation is likely supported by a similar decrease in  $\delta^{13}\text{C}$  values in the bulk carbonate  
 633 from Spain, belemnites from the United Kingdom and brachiopod shells from Portugal (Fig.  
 634 8, interval C). At Le Brusquet, the Murchisonae zone (interval D) is marked by a distinct  
 635 negative shift in the  $\delta^{13}\text{C}_{\text{org}}$ . A similar trend can be identified in Chile at Agua de la Falda, but  
 636 it is more difficult to trace in the less expanded successions (Fig. 8).

637 Notably, at Le Brusquet the Murchisonae–Concavum zonal transition (middle–late  
 638 Aalenian) is associated with a marked positive  $\delta^{13}\text{C}$  trend (interval E) which can be identified



in both carbonates and organic matter. This is followed by a negative carbon isotope excursion across the Aalenian/Bajocian boundary (interval F) and then a return to less negative  $\delta^{13}\text{C}$  values in the early Bajocian. These negative and positive excursions are traceable in both organic matter and carbonates across the different sites from the Tethys, Boreal domain, and Panthalassa (Fig. 9) and were previously identified as reflecting global events (e.g., Spain: O'Dogherty et al., 2006; Sandoval et al., 2008; Gomez et al., 2009, France: Corbin, 1994; Suchéras-Marx et al., 2013, Italy: Morettini et al., 2002; United Kingdom: Jenkyns et al., 2002; Hesselbo et al., 2003; Price, 2010, Morocco: Bodin et al., 2020).

The dataset from Le Brusquet and Agua de la Falda highlights for the first time the occurrence of recurrent perturbations of the global carbon cycle during the Aalenian. Although the long-term  $\delta^{13}\text{C}$  trend seems to be influenced by local processes across the Aalenian, medium-term shifts (intervals A–F) are reproducible between different palaeogeographic settings in both hemispheres. Therefore, these shifts reflect synchronous changes in the organic and carbonates carbon and calls for the implication of global driving mechanisms.

### *5.5. Aalenian environmental perturbations*

The evolution of environmental conditions across the Aalenian has been so far undervaluated compared to early Toarcian and early Bajocian events. However, evidences of climatic and environmental changes during the Aalenian (Fig. 9) indicate that it might represent a key time interval to better understand the wider context and environmental feedback mechanisms surrounding such major events.

Our results suggest that environmental changes occurred across the middle–late Aalenian. At Le Brusquet, a general increase in carbonate content associated with a decrease in calcareous nannofossil abundances is recorded across the middle Aalenian (Murchisonae zone; [Fig. 7](#)). A similar pattern was recorded in contemporaneous hemipelagic settings from Portugal ([Ferreira et al., 2019](#)) and Spain ([Sandoval et al., 2008](#)). Hence, the evolution of carbonate content at Le Brusquet likely represents a supraregional trend and reflects the intensity of carbonate production and export from surroundings platforms. The middle Aalenian was likely a time of high carbonate export into basinal settings from the Tethyan realm during a relative sea level fall ([Hardenbol et al., 1998](#); [Jacquin et al., 1998](#)). A relative sea-level fall during the middle Aalenian has been inferred from the presence of unconformities and development of prograding shallow platform sediments in most Western Tethyan sites during this time interval and has been related to the Mid-Cimmerian tectonic uplift ([de Graciansky et al., 1993](#); [Durlet and Thierry, 2000](#); [Léonide et al., 2007](#)). Middle Aalenian platform environments surrounding the French Subalpin Basin (e.g., Beaujolais, Provence and Grands Causses subbasins) and other Tethyan sites (e.g., Bulgaria, Saudi Arabia, France, Germany) were marked by abrupt lithological changes such as the deposition of bioclastic (crinoids, brachiopods, sponges) calcarenitic limestone ([Elmi and Rulleau, 1993](#); [Ciszak et al., 1996](#); [Rousselle, 2001](#); [Floquet 2000](#)), iron-rich oolitic limestones (e.g., [Ohmert et al., 1996](#); [Rulleau et al., 2001](#)), or hiatuses ([Metodieff, 1997](#); [Le Nindre et al., 1990](#); [Delfaud et al., 2000](#)). Such changes in the sedimentation style during the middle Aalenian in platform settings point out to the initiation of a deterioration in environmental conditions. Importantly, these changes in the platform carbonate factory and pelagic carbonate producers correspond to the onset of a positive carbon isotope trend in bulk organic matter and bulk and brachiopod carbonate in contemporaneous Tethyan sites ([Fig.9](#); Portugal, Spain, France).

Severe palaeoenvironmental changes are recorded during the middle–late Aalenian (Murchisonae–Concavum zonal transition) as attested by the sharp decrease in carbonate content at Le Brusquet and in other contemporaneous successions from France, Portugal, and Spain, where the highest calcareous nannofossil abundances are observed. In contemporaneous platform settings from the Tethyan area, peculiar sedimentation unknown in earlier sequences have been reported as thin-shelled bivalve buildups (Spain: [Molina et al., 2018](#)), siliceous sponge mud-mounds (Portugal: [Duarte et al., 2001](#); France: [Floquet et al., 2000; 2012](#)), iron-rich oolitic limestones (Switzerland: [Lauper et al., 2021](#)), and hiatuses and/or condensed/reduced deposits (Arabia Saoudia: [Le Nindre et al., 1990](#); Bulgaria: [Metodiev, 1997](#); France: [Delfaud et al., 2000](#); [Rousselle, 2001](#); Germany: [Ohmert et al., 1996](#)). Such lithological changes in different palaeogeographic settings indicate a supraregional event of carbonate factory demise. The relative sea-level rise recorded during the late Aalenian in almost all series of Western Europe ([de Granciansky et al., 1998](#); [Durlet and Thierry, 2000](#)) likely participated in the deterioration of neritic carbonate factory (e.g., [Gabilly et al., 1985](#); [Léonide et al., 2007](#)). Nonetheless, biotic changes ([Fig. 9](#)) indicate that besides local factors, global changes in water mass circulation and chemistry across the middle–late Aalenian may have played a key role in driving the environmental changes. Specifically, this time interval saw the emergence of *Watznaueria*, in particular the forms with a cross spanning the central area, which will dominate up to the early Bajocian ([Fig. 9](#); [this study](#); [Suchéras-Marx et al., 2015](#); [Giraud et al., 2016](#)). These forms have been interpreted as opportunistic, proliferating in times of environmental instability related to enhanced nutrient concentrations or temperature changes ([Giraud et al., 2016](#)). The genus *Watznaueria* as a whole was in fact very sensitive to paleoceanographic and paleoclimatic changes across the Aalenian/Bajocian boundary and the rise of these forms is likely related to the increase in carrying capacity in the photic zone ([Suchéras-Marx et al., 2015](#)). The

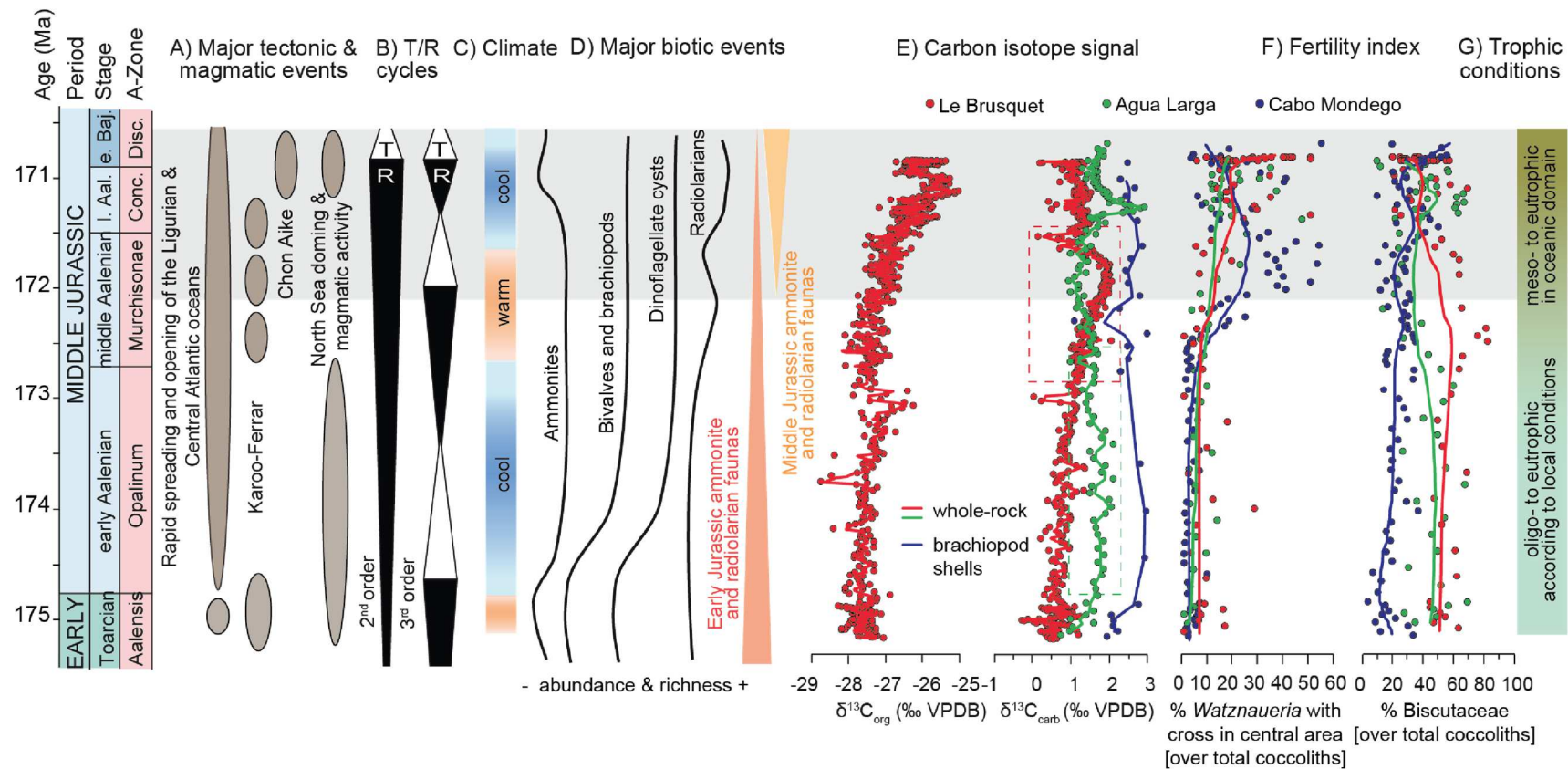
supraregional increase in *Watznaueria* also coincides locally with the dominance of Biscutaceae (Sandoval et al., 2008; Aguado et al., 2009), generally also interpreted as eutrophic forms developing in nutrient-rich surface waters (e.g., Roth and Bowdler, 1981; Mattioli and Pittet, 2004; Tremolada et al., 2006). The concomitant emergence of *Watznaueria* in different Tethyan sites (Fig. 9; Portugal, Spain, France) testifies to a global change towards eutrophic conditions in the oceanic domain, whereas the presence of Biscutaceae most likely relates to local conditions specific to each basin (Fig. 9). There is compelling evidence that the Aalenian was a time of palaeoenvironmental changes, biotic reorganisation and carbon cycle perturbation. The development of eutrophic conditions during the middle Aalenian combined to relative sea-level variations likely triggered the initiation of environmental changes while the most severe changes occurred across the late Aalenian. Indeed, our results suggest that this time interval was marked by the demise of platform carbonate factories associated to an increase in eutrophic calcareous nannofossils (genus *Watznaueria*) which are concomitant with the most positive carbon isotope values. The middle–upper Aalenian positive  $\delta^{13}\text{C}$  excursion may hence reflect increasing productivity in sea-surface waters as previously suggested (Sandoval et al., 2008) and a carbonate productivity crisis. This middle–late Aalenian event certainly represents a precursor episode of environmental changes prior to the early Bajocian event. The increase in TOC coupled to the positive  $\delta^{13}\text{C}_{\text{org}}$  values recorded at Le Brusquet and Agua de la Falda across the middle–upper Aalenian can hence be interpreted as the record of increased marine primary productivity and/or enhanced organic matter burial.

The early Middle Jurassic was a critical time interval of evolutionary and ecological changes (Fig. 9; Table 1), major tectonic rearrangement, and major changes in Mesozoic oceanic current patterns. A shift from a Toarcian warm mode to an Aalenian cold mode has been suggested based on a compilation of oxygen isotope data (Korte et al., 2015). Though

the climatic evolution is still poorly documented across the Aalenian, rising seawater temperatures have been deduced from oxygen isotopes of belemnites from Spain (Gomez et al., 2009). However, the lack of supporting data hampers to evaluate the global or local extent of this middle Aalenian warming event and to assess its causal mechanisms. The coccolithophorid event presented in this study coincides with other important biotic changes in other planktonic groups in worldwide distributed sites (e.g., Wiggan et al., 2017). Indeed, a dinoflagellate turnover has been reported across the Aalenian, and radiolarians have a quasi-completely replaced the Early Jurassic fauna (Yao, 1997; Sandoval et al., 2008).

Interestingly, the revolution in planktonic biota coincides with the diversification of planktivorous fish (Friedman et al., 2010; Guinot and Cavin, 2016) and cephalopods, together with the extinction of Early Jurassic ammonite taxa and their replacement by families that dominated throughout the Middle Jurassic (Fig. 9; Sandoval et al., 2001; O'Dogherty et al., 2006; Wiggan et al., 2018). Conversely, within other nekton, a crisis has been documented in belemnites (Dera et al., 2016). Moreover, bivalves, brachiopods, bryozoans, and benthic foraminifera also underwent evolutionary changes across the Aalenian (Hallam, 1976; Alméras and Fauré, 2000; Taylor and Ernst, 2008; Canales and Henriques, 2008; Gómez et al., 2009). Hence, the change observed in planktonic groups across the middle–late Aalenian likely triggered a reorganisation of the entire food chain. Our study provides compelling evidence for biotic and environmental changes in both pelagic and neritic environments at a supraregional scale, pointing out to a middle–late Aalenian event. So far, the lower Bajocian event has been seen as the most extreme episode of environmental changes in the Middle Jurassic, with a major carbonate crisis and a shift to biogenic silica production and sedimentation (Bartolini et al., 1996; 1999; Cobianchi et al., 2002; Gorican et al., 2012; Giraud et al., 2016). However, our study indicates that palaeoceanographic, palaeoenvironmental, and palaeoecological changes occurred already earlier, and that the

761 middle–late Aalenian event may hence represent a precursor to the early Bajocian event,  
762 initiating the Mesozoic Marine Revolution. Although establishing a precise correspondence  
763 between the onset of volcanic activity and environmental changes remains to date elusive, one  
764 cannot exclude that magmatic pulses may have started earlier than previously thought, i.e.,  
765 before the early Bajocian. Indeed, evidence of global warming, major biotic and carbon cycle  
766 changes during the middle–late Aalenian suggests a similar cascade of environmental  
767 feedbacks driven by volcanism known from other Mesozoic events (e.g., [Caruthers et al.,](#)  
768 [2013](#); [Bond](#) [and](#) [Wignall,](#) [2014](#)).



769

770 **Fig. 9:** Summary of key features recorded during the Aalenian time interval. (A) Timing of the main tectonic and magmatic events (after Dera et al., 2011 and reference therein). (B) 2<sup>nd</sup> and 3<sup>rd</sup>  
 771 order transgressive (T) and regressive (R) sequences (Hardenbol et al., 1998). (C) Climate modes are inferred from the oxygen-isotope data from belemnites, brachiopods and bivalves (Jenkyns  
 772 et al., 2002; Gomez et al., 2009; Price, 2009; Dera et al., 2011; Korte et al., 2015; Ferreira et al., 2019). (D) Major biotic events observed in different taxa, refer to the text for more details  
 773 (Hallam, 1976; Yao, 1997; Alméras and Fauré, 2000; O'Dogherty et al., 2006; Sandoval et al., 2008; Taylor and Ernst, 2008; Wiggan, 2017). (E) Compilation of carbon isotopic records from Le  
 774 Brusquet in France (this study), Cabo Mondego in Portugal (Ferreira et al., 2019), and Agua Larga in Spain (Sandoval et al., 2008). At Le Brusquet and Agua Larga, the box with dashed line  
 775 indicates the interval where the  $\delta^{13}\text{C}_{\text{carb}}$  signal is likely influenced by the carbonate ooze exported from adjacent platforms. The trend lines correspond to a 4-points moving average. (F) Fertility  
 776 index refers to the percentage of *Watznaueria* and Biscutaceae from Le Brusquet (this study), Cabo Mondego (Ferreira et al., 2019) and Agua Larga (Sandoval et al., 2008). The trend lines are  
 777 calculated using a LOWESS smoothing ( $\alpha = 0.2$ ) with the PAST software package (Hammer et al., 2001). (G) Trophic conditions are based on the proportions of *Watznaueria* and Biscutaceae.  
 778 Note that the grey interval highlights the major increase in calcareous nannofossils species indicative of fertility of oceanic water across the middle-late Aalenian.

## 6. Conclusions

This study provides high-resolution carbon isotope records for the Aalenian time interval and shows for the first time a record from the southern hemisphere. Consecutive medium-term  $\delta^{13}\text{C}$  fluctuations expressed in different carbon sources and identified in Tethyan, Boreal, and Panthalassic sites, suggest that the Aalenian was marked by recurrent changes in the global carbon cycle. An increase in calcareous nannofossils species related to seawater fertility coincides with an episode of platform carbonate factory demise across the middle–late Aalenian, indicating that supraregional biotic and environmental changes in both pelagic and neritic environments occurred earlier than the well-known Bajocian event. The middle–late Aalenian coincided with evolutionary and ecological changes in different taxa in worldwide-distributed sites, indicating that the middle–late Aalenian was a time of palaeoceanographic and palaeoenvironmental changes. To date, there is no consensus about the triggering mechanisms leading to these palaeoenvironmental changes. Still, tectonic rearrangement and volcanic activity during the early Middle Jurassic might have potentially played an important role. There is now compelling evidence that the Aalenian was marked by recurrent global carbon cycle perturbations associated with palaeoenvironmental and palaeoceanographic changes, which likely acted as precursors of the early Bajocian event, initiating the Mesozoic Marine Revolution.

## Acknowledgements

This research was funded by the Swiss National Science Foundation (project P2LAP2\_181440). We express our deepest gratitude to Myette Guiomar and Didier Bert from the Reserve Géologique de Haute-Provence for providing fieldwork and sampling permits. We would like to thank Tiffany Monnier, Brahimsamba Bomou (University of Lausanne),



and Mickaël Charpentier for their assistance in the laboratory, Ghislaine Broillet (Université Claude Bernard Lyon 1) for smear slide preparation, Paula Engell and Lasse Christiansen for their help during fieldwork. We acknowledge the constructive review by James Riding and Helmut Weissert. Calcareous nannofossil slides are cured at the Collections de Géologie de Lyon with a FSL number.

## References

- Aguado, R., O'Dogherty, L., Sandoval, J., 2008. Fertility changes of surface waters during the Aalenian of the Western Tethys as revealed by calcareous nannofossils and carbon cycle perturbations. *Marine Micropaleontology*, 68, 268–285
- Alméras, Y., Fauré, P., 2000. Les Brachiopodes liasiques des Pyrénées. *Paléontologie, Biostratigraphie, Paléobiogéographie et Paléoenvironnements. Strata, série 2*, 10, 36–39
- Arndt, S., Jørgensen, B.B., LaRowe, D.E., Middelburg, J.J., Pancost, R.D., Regnier, P., 2013. Quantifying the degradation of organic matter in marine sediments: a review and synthesis. *Earth Sci. Rev.*, 123, 53–86
- Bartolini, A., Baumgartner, P.O., Hunziker, J.C., 1996. Middle and late Jurassic carbon stable-isotope stratigraphy and radiolarite sedimentation of the Umbria-Marche Basin (Central Italy). *Eclogae Geol. Helv.* 89, 811–844
- Bartolini, A., Baumgartner, P.O., Guex, J., 1999. Middle and Late Jurassic radiolarian palaeoecology versus carbon-isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 145, 43–60
- Bartolini, A., Larson, R. L., 2001. Pacific microplate and the Pangea supercontinent in the Early to Middle Jurassic. *Geology*, 29 (8), 735–738
- Behar, F., Beaumont, V., Penteadó, H.L.D., 2001. Rock-Eval 6 technology: performances and developments. *Oil Gas Sci. Technol.* 56 (2), 111–134

829 Bill, M., O'Dogherty, L., Guex, J., Baumgartner, P.O., 844 Masson, H., 2001. Radiolarite  
830 ages in Alpine-Mediterranean ophiolites: Constraints on the oceanic spreading and the  
831 Tethys-Atlantic connection. *Geological Society of America Bulletin* 113, 129-143

832 Bodin, S., Meissner, P., Janssen, N.M.M., Steuber, T., Mutterlose, J., 2015. Large igneous  
833 provinces and organic carbon burial: Controls on global temperature and continental  
834 weathering during the Early Cretaceous. *Global and Planetary Change*, 133, 238-253

835 Bodin, S., Krencker, F.N., Kothe, T., Hoffmann, R., Mattioli, E., Heimhofer, U., Kabiri, 2016.  
836 Perturbation of the carbon cycle during the late Pliensbachian-early Toarcian: New  
837 insight from high-resolution carbon isotope records in Morocco. *J. Afr. Earth Sci.*,  
838 116, 89-104

839 Bodin, S., Hönig, M.R., Krencker, F.-N., Danish, J., Kabiri, L., 2017. Neritic carbonate crisis  
840 during the Early bajocian: Divergent responses to a global environmental perturbation.  
841 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 468, 184-199

842 Bodin, S., Mau M., Sadki, D., Danisch, J., Nutz, A., Krencker, F.-N., Kabiri, L., 2020.  
843 Transient and secular changes in global carbon cycling during the Bajocian event:  
844 Evidence for Jurassic cool climate episodes. *Global and Planetary Change*, 194,  
845 103287

846 Bown, P.R., 1987. Taxonomy, evolution, and biostratigraphy of Late Triassic – Early Jurassic  
847 calcareous nannofossils. *Palaeontol. Assoc., Spec. Pap. Palaeontol.* 38. 118 pp Bown,  
848 P.R., Cooper, M.K.E. 1998. Jurassic. In: Bown, P.R. (ed.) *Calcareous Nannofossil*  
849 *Biostratigraphy*. British Micropalaeontological Society Publication Series. Chapman  
850 & Hall, London, 34–85

851 Bown, P.R., Young, J.R. 1998. Techniques. In: Bown, 866 P.R. (ed.) *Calcareous*  
852 *Nannoplankton Biostratigraphy*. British Micropalaeontological Society Publication  
853 Series. Chapman & Hall, London, 16–28

854 Burtner, R.L., Warner, M.A., 1986. Relationship between illite/smectite diagenesis and  
855 hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek Shales of the  
856 northern Rocky Mountain area. *Clay Miner.* 34, 390–402

- 857 Caloo, B., 1970. Biostratigraphie de l'Aalénien et de la base du Bajocien dans la région de  
858 Digne (Basses-Alpes, France). Comptes rendus des séances de l'Académie des  
859 Sciences (D) 271, 1938–1940
- 860 Canales, M.L., Henriques, M.H., 2008. Foraminifera from the Aalenian and the Bajocian  
861 GSSP (Middle Jurassic) of Murtinheira section (Cabo Mondego, West Portugal):  
862 Biostratigraphy and paleoenvironmental implications. *Marine Micropaleontology*, 67,  
863 155-179
- 864 Caruthers, A.H., Smith, P.L., Gröcke, D.R., 2013. The Pliensbachian-Toarcian (Early  
865 Jurassic) extinction, a global multi-phased event. *Palaeogeogr. Palaeoclimatol.*  
866 *Palaeoecol.* 386, 104–118
- 867 Chamley, H., 1989. *Clay Sedimentology*. Springer Verlag, Berlin Ciszak, R., Magné, J.,  
868 Peybernès, B., 1986. Interprétation du complexe chaotique “triasique” d’Oranie  
869 (Algérie occidentale) comme un olistostrome sénonien localement réinjecté dans les  
870 accidents alpins. *C. R. Acad. Sc. Paris*, 302, 6, 357-362
- 871 Cobianchi, M., Erba, E., Pirini-Radrizzani, C., 1992. Evolutionary trends of calcareous  
872 nannofossil genera *Lotharingius* and *Watznaueria* during the Early and Middle  
873 Jurassic. *Memorie di Scienze Geologiche*, Padova 43, 19-25
- 874 Cohen, A.S., Coe, A.L., Harding, S.M., Schwark, L., 2004. Osmium isotope evidence for  
875 the regulation of atmospheric CO<sub>2</sub> by continental weathering. *Geology*, 32, 157–160
- 876 Corbin, J.C., 1994. Evolution géochimique du Jurassique du Sud-Est de la France: influence  
877 du niveau marin et de la tectonique. *Paris VI*, pp. 198
- 878 Courtillot, V., 1994. Mass extinctions in the last 300 million years: one impact and seven  
879 flood basalts? *Isr. J. Earth Sci.* 43, 255–266
- 880 Curry, G.B., Brunton, C.H.C., 2007. Stratigraphic distribution of brachiopods. In Selden, P.A.  
881 (Ed), *Treatise on Invertebrate Paleontology. Part H. Brachiopoda. Revised. Vol. 6.*  
882 *Geological Society of America, University of Kansas, Boulder and Lawrence*, 2901-  
883 3081
- 884 de Graciansky, P.C., Dardeau, G., Dumont, T., Jacquin, T., Marchand, D., Mousterde, R., Vail,  
885 P.R., 1993. Depositional sequence cycles, transgressive-regressive facies cycles, and

886 extensional tectonics: example from the southern Subalpine Jurassic basin, France.  
887 Bull. Soc. Géol., France, 5, 709-718

888 De Kaenel, E., Bergen, J.A., 1993. New Early and Middle Jurassic coccolith taxa and  
889 biostratigraphy from the eastern proto-Atlantic (Morocco, Portugal and DSDP Site  
890 547B). *Eclogae Geologicae Helvetiae* 86: 861-907

891 de Lange, G.J., van Os, B., Pruysers, P.A., Middelburg, J.J., Castradori, D., Van Santvoort, P.,  
892 Müller, P.J., Eggenkamp, H., Prahl, F.G., 1994. Possible early diagenetic alteration of  
893 paleoproxies. In: Zahn, R. (ed.) *Carbon Cycling in the Glacial Ocean: Constraints on*  
894 *Ocean's Role in Global Climate Change*. NATO ASI Series, 17, 225–258

895 Delfaud, J., Revert, J., Sabrier, R., 2000. La limite Lias–Dogger et la naissance de la  
896 plateforme occitane. *Strata*, série 1, 10, 67-69

897 Dera, G., Brigaud, B., Monna, F., Laffont, R., Pucéat, E., Deconinck, J.-F., Pellenard, P.,  
898 Joachimski, M.M., Durlet, C., 2011. Climatic ups and downs in a disturbed Jurassic  
899 world. *Geology*, 39, 3, 215-218

900 Dera, G., Toumoulin, A., De Baets, K., 2016. Diversity and morphological evolution of  
901 Jurassic belemnites from South Germany. *Palaeogeography, Palaeoclimatology,*  
902 *Palaeoecology*, 457, 80–97

903 Duarte, L.V., Krautter, M., Ferreira Soares, A., 2001. Bioconstructions a spongiaires siliceux  
904 dans le Lias terminal du Bassin lusitanien (Portugal); stratigraphie, sedimentologie et  
905 signification paleogeographique. *Bull. Soc. Géol. France*, 172 (5), 637-646

906 Duncan, R.A., Hooper, P.R., Rahacek, J., Marsh, J.S., Duncan, A.R., 1997. The timing and  
907 duration of the Karoo igneous event, southern Gondwana. *J. Geophys. Res.* 102,  
908 18127–18138

909 Durlet, C., Thierry, J., 2000. Modalites sequentielles de la transgression aaleno-bajocienne sur  
910 le sud-est du Bassin parisien. *Bull. Soc. Géol. France*, 171 (3), 327-339

911 Elmi, S., Rulleau, L., 1993. Le Jurassique du Beaujolais méridional, bordure orientale du  
912 Massif Central, France. *GEOBIOS*, 15, 139-155

913 Erba E., 2004. Calcareous nannofossils and Mesozoic oceanic anoxic events. *Mar.*  
914 *Micropaleontol.*, 52: 85-106. Erba, E., Gambacorta, G., Tiepolo, M., 2019. The lower

915 Bajocian Gaetani level: Lithostratigraphic marker of a potential Oceanic Anoxic  
916 Event. *Riv. Ital. Paleontol. Stratigr.* 125, 219–230

917 Erba, E., Gambacorta, G., Tiepolo, M., 2019. The Lower Bajocian Gaetani Level:  
918 Lithostratigraphic marker of a potential oceanic anoxic event. *Rivista Italiana di*  
919 *Paleontologia e Stratigrafia*, 125 (1), 219-230

920 Espitalié, J., Deroo, G., Marquis, F., 1985. La pyrolyse Rock-935 Eval et ses applications;  
921 première partie. *Rev. Inst. Fr. Pétrol.* 40, 563–579

922 Fantasia, A., Föllmi, K.B., Adatte, T., Bernárdez, E., Spangenberg, J.E., Mattioli, E., 2018.  
923 The Toarcian Oceanic Anoxic Event in southwestern Gondwana: an example from the  
924 Andean Basin, northern Chile. *J. Geol. Soc.* 175, 883–902

925 Ferreira, J., Mattioli, E., Pittet, B., Cachão, M., Spangenberg, J.E., 2015. Palaeoecological  
926 insights on Toarcian and lower Aalenian calcareous nannofossils from the Lusitanian  
927 Basin (Portugal). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 436, 245–262

928 Ferreira, J., Mattioli, E., van de Schootbrugge, B., 2017. Palaeoenvironmental vs.  
929 Evolutionary control on size variation of coccoliths across the Lower-Middle Jurassic.  
930 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 465, 177–192

931 Ferreira, J., Mattioli, E., Sucherás-Marx, B., Giraud, F., Duarte, L.D., Pittet, B., Suan, G.,  
932 Hassler, A., Spangenberg, J.E., 2019. Western Tethys Early and Middle Jurassic  
933 calcareous nannofossil biostratigraphy. *Earth-Science Reviews*, 197, 1002908

934 Ferry, S., Rubino, J.-L., 1989. Mesozoic eustacy record on western Tethyan margins. *hal-*  
935 *02013144*

936 Floquet, M., Marchand, D., Sida, B. & Contini, D., 2000. Monticules micritiques à  
937 spongiaires et discontinuités sédimentaires marqueurs de l'enneigement de la  
938 plateforme carbonatée de Basse Provence à l'Aalénien supérieur Bajocien inférieur.  
939 In: *Les événements du passage Lias-Dogger* (Ed. by J. Rey & F. Ronchini). *Strata*, 10,  
940 83-85

941 Floquet, M., Neuweiler, F., Léonide, P., 2012. The impact of depositional events and burial  
942 rate on carbonate-silica diagenesis in a Middle Jurassic stromatolite carbonate mud  
943 moundm Sainte-Baume Massif, SE France. *Journal of Sedimentary Research*, 82,

- 944 958 521–539
- 945 Friedman, M., Shimada, K., Martin, L.D., Everhart, M.J., Liston, J., Maltese, A., Triebold,  
946 M., 2010. 100-million-year dynasty of Giant Planktivorous bony fishes in the  
947 Mesozoic seas. *Science* 327, 990–993
- 948 Gabilly, J., Cariou, E., Hantzpergue, P. 1985. Les grandes discontinuités stratigraphiques au  
949 Jurassique ; témoins d'événements eustatiques, biologiques et sédimentaires. *Bulletin*  
950 *de la Société Géologique de France*, 3, 391-401.
- 951 Gidon, M., Pairis, J.L., 1992. Relations entre le charriage de la Nappe de Digne et la structure  
952 de son autochtone dans la vallée du Be s. *Eclogae geol. Helv.*, 85/2, 327-359
- 953 Giraud, F., Mattioli, E., López-Otálvaro, G.E., Lécuyer, C., Suchéras-Marx, B., Alméras, Y.,  
954 Martineau, F., Arnaud-Godet, F., de Kænel, E., 2016. Deciphering processes  
955 controlling mid-Jurassic coccolith turnover. *Mar. Micropaleontol.* 125, 36–50
- 956 Godet, A., Bodin, S., Föllmi, K.B., Vermeulen, J., Gardin, S., Fiet, N., Adatte, T., Berner, Z.,  
957 Stüben, D., Van de Schootbrugge, B., 2006. Evolution of the marine stable carbon  
958 isotope record during the early cretaceous: a focus on the late Hauterivian and  
959 Barremian in the Tethyan realm. *Earth Planet. Sci. Lett.* 242, 254–271
- 960 Gómez, J.J., Canales, M.L., Ureta, S., Goy, A., 2009. Palaeoclimatic and biotic changes  
961 during the Aalenian (Middle Jurassic) at the southern Lurasian Seaway (Basque–  
962 Cantabrian Basin, northern Spain). *Palaeogeography, Palaeoclimatology,*  
963 *Palaeoecology*, 275, 14–27
- 964 Gorican, S., Pavsic, J., Rozic, B., 2012. Bajocian to Tithonian age of radiolarian cherts in  
965 Tolmin Basin (NW Slovenia). *Bull. Soc. Géol. France*, 183 (4), 369-382
- 966 Gröschke, M., von Hillebrandt, A., Prinz, P., Quinzio, L.A. & Wilke, H.-G. 1988. Marine  
967 Mesozoic paleogeography in northern Chile between 21°–26°S. In: Bahlburg, H.,  
968 Breitkreuz, C. & Giese, P. (eds) *The Southern Central 979 Andes. Lecture Notes in*  
969 *Earth Sciences*, 17. Springer, Berlin
- 970 Guinot, G., Cavin, L., 2016. ‘Fish’ (Actinopterygii and Elasmobranchii) diversification  
971 patterns through deep time. *Biol. Rev.* (2016), 91, 950–981



- 972 Haccard, D., Beaudoin, B., Gigot, P., Jorda M., 1989. Notice explicative de la carte  
973 géologique de la France (1/50 000), feuille La Javie (918). – BRGM, Orléans, 152p
- 974 Hallam, A. 1976. Stratigraphic distribution and ecology of European Jurassic bivalves.  
975 *Lethaia*, 9, 245-249
- 976 Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software  
977 package for education and data analysis. *Palaeontologia Electronica* 4, 1-9
- 978 Harazim, D., van de Schootbrugge, B., Sorichter, K., Fiebig, J., Weug, A., Suan, G.,  
979 Oschmann, W., 2013. Spatial variability of watermass conditions within three  
980 European epicontinental seaways during the Early Jurassic (Pliensbachian–Toarcian).  
981 *Sedimentology* 60, 359–390.
- 982 Hardenbol, J., Thierry, J., Farley, M.B., de Graciansky, P.-C., Vail, P.R., 1998. Mesozoic and  
983 Cenozoic sequence chronostratigraphic framework of European basins. In: de  
984 Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), *Mesozoic and*  
985 *Cenozoic Sequence Stratigraphy of European Basins*. SEPM Spec. Publ., 60, 3–13
- 986 Hesselbo, S.P., Gröcke, D.R., Jenkyns, H.C., Bjerrum, C.J., Farrimond, P., Morgans Bell,  
987 H.S., Green, O.R., 2000. Massive dissociation of gas hydrate during a Jurassic oceanic  
988 anoxic event. *Nature*, 406, 392–395
- 989 Hesselbo, S.P., Morgans-Bell, H.S., McElwain, J.C., Rees, 1000 P.M., Robinson, S.A., Ross,  
990 C.E., 2003. Carbon-Cycle perturbation in the Middle Jurassic and accompanying  
991 changes in the terrestrial paleoenvironment. *Journal of Geology*, 111, 259–276
- 992 Jacquin, T., Dardeau, G., Durllet, C., de Graciansky, P.-C., Hantzpergue, P., 1998. The North  
993 Sea cycle: an overview of 2nd-order transgressive/regressive facies cycles in western  
994 Europe. In: de Graciansky, P.C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.),  
995 *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Spec.  
996 Publ. 60, pp. 445–466
- 997 Jenkyns, H.C., Jones, C.E., Gröcke, D.R., Hesselbo, S.P., Parkinson, D.N., 2002.  
998 Chemostratigraphy of the Jurassic System: applications, limitations and implications  
999 for palaeoceanography. *Journal of the Geological Society of London* 159, 351–378

1000 Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events. *Geochem. Geophys. Geosyst.*  
1001 11

1002 Jiang C., Chen, Z., Lavoie, D., Percival, J.B., Kabanov, P., 2017. Mineral carbon MinC(%)  
1003 from Rock-Eval analysis as a reliable and cost-effective measurement of carbonate  
1004 contents in shale source and reservoir rocks. *Marine and Petroleum Geology*, 83, 184-  
1005 194

1006 Kemp, D.B., Coe, A.L., Cohen, A.S., Schwark, L., 2005. Astronomical pacing of methane  
1007 release in the Early Jurassic period. *Nature*, 437, 396–399

1008 Kemp, D. B., Selby, D., Izumi, K., 2020. Direct coupling between carbon release and  
1009 weathering during the Toarcian oceanic anoxic event. *Geology*, 48 (10), 976-980

1010 Korte, C., Hesselbo, S.P., Ullmann, C.V., Dietl, G., Ruhl, 1021 M., Schweigert, G., Thibault,  
1011 N., 2015. Jurassic climate mode governed by ocean gateway. *Nature Communications*,  
1012 6:10015

1013 Krencker, F.N., Bodin, S., Hofmann, R., Suan, G., Mattioli, E., Kabiri, L., Föllmi, K.B.,  
1014 Immenhauser, A., 2014. The middle Toarcian cold snap: Trigger of mass extinction  
1015 and carbonate factory demise. *Global and Planetary Change*, 117, 64-78

1016 Krencker, F.N., Lindstrom, S., Bodin, S., 2019. A major sea-level drop briefly precedes the  
1017 Toarcian oceanic anoxic event: implication for Early Jurassic climate and carbon cycle.  
1018 *Sci. Rep.* 9

1019 Krencker, F.-N., Fantasia, A., Danisch, J., Martindale, R., Kabiric, L., El Ouali, M., Bodin, S.,  
1020 2020. Two-phased collapse of the shallow-water carbonate factory during the  
1021 latePliensbachian–Toarcian driven by changing climate and enhanced continental  
1022 weathering in the Northwestern Gondwana Margin. *Earth-Science Reviews*, 208,  
1023 103254

1024 Kump, L.R., Arthur, M.A., 1999. Interpreting carbon-isotope excursions: carbonates and  
1025 organic matter. *Chem. Geol.* 161, 181–198

1026 Labails, C., Olivet, J.-L., Aslanian, D., Roest, W.R., 2010. An alternative early opening  
1027 scenario for the Central Atlantic Ocean. *Earth and Planetary Science Letters* 297, 355-  
1028 368

- 1029 Lafargue, E., Marquis, F., Pillot, D., 1997. Rock-Eval 6 Applications in Hydrocarbon  
1030 Exploration, Production, And Soil Contamination Studies. *Revue de l'Institut Français*  
1031 *du Pétrole*, 53, 4
- 1032 Lauper, B., Zimmerli, G. N., Jaeggi, D., Deplazes, G., Wohlwend, S., Rempfer, J., Foubert,  
1033 A. 2021. Quantification of lithological heterogeneity within Opalinus Clay: Toward a  
1034 uniform subfacies classification scheme using a novel automated core image  
1035 recognition tool. *Front. Earth. Sci.*, 9:645596. doi: 10.3389/feart.2021.645596
- 1036 Léonide, P., Floquet, M., Villier, L., 2007. Interaction of tectonics, eustasy, climate and  
1037 carbonate production on the sedimentary evolution of an early/middle Jurassic  
1038 extensional basin (Southern Provence Sub-basin, SE France). *Basin Res.*, 19, 125–152
- 1039 Le Nindre, Y.M., Manivit, J., Manivit, H., Vaslet, D., 1990. Stratigraphie séquentielle du  
1040 Jurassique et du Crétacé en Arabie Saoudite. *Bull. Soc. Géol. France*, VI (6), 1025-  
1041 1034
- 1042 Levert, J., 1989. Origine diagénétique complexe des minéraux argileux dans le Mésozoïque  
1043 Subalpin. *Geobios, mémoire special*, 11, 239-251
- 1044 Lickorish, W.H., Ford, M., 1998. Evolution of the Digne thrust system, southern Subalpine  
1045 chains: kinematics and timing of deformation. In: Mascle, A., Puigdefabregas, C.,  
1046 Luterbacher, H.P., Fernandez, M. (eds) *Cenozoic foreland basins of Western Europe*.  
1047 Geological Society, London, Special Publication, 134, 189-211
- 1048 López-Otálvaro, G.-E., Suchéras-Marx, B., Giraud, F., Mattioli, E., Lécuyer, C., 2012. Marine  
1049 Micropaleontology, 94-95, 45-57
- 1050 Mattioli, E., 1996. New calcareous nannofossil species from the Early Jurassic of Tethys.  
1051 *Rivista Italiana di Paleontologia e Stratigrafia*, 102, 397-412
- 1052 Mattioli, E., 1997. Nannoplankton productivity and diagenesis in the rhythmically bedded  
1053 Toarcian– Aalenian Fiuminata section (Umbria– Marche Apennine, central Italy).  
1054 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 130, 113– 133
- 1055 Mattioli, E., Erba, E., 1999. Biostratigraphic synthesis of calcareous nannofossil events in the  
1056 Tethyan Jurassic. *Rivista Italiana di Paleontologia e Stratigrafia*, 105 (3), 343-376

1057 Mattioli, E., Pittet, B., Young, J.R., Bown, P.R., 2004. Biometric 1064 analysis of  
1058 Pliensbachian-Toarcian (Lower Jurassic) coccoliths of the family Biscutaceae: intra-  
1059 and interspecific variability versus palaeoenvironmental influence. *Mar.*  
1060 *Micropaleontol.* 52, 5–27

1061 Mattioli, E., Pittet, B., 2004. Spatial and temporal distribution of calcareous nannofossils  
1062 along a proximal–distal transect in the Lower Jurassic of the Umbria–Marche Basin  
1063 (central Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 205, 295– 316.

1064 Mattioli, E., Pittet, B., Suan, G., Mailliot, S., 2008. Calcareous nannoplankton changes across  
1065 the early Toarcian oceanic anoxic event in the western Tethys. *Paleoceanography*, 23

1066 Mariotti, N., Weis, R., Di Cencio, A., Clément, A., De Baets, K., 2012. New records of early  
1067 Middle Jurassic belemnites in the French Subalpine Basin and their  
1068 paleobiogeographic significance. *Geobios*, 45, 99-108

1069 Marticorena, L., and Tapia, I., 1982. Situacion estratigrafica del Jurasico del area de  
1070 Pedernales-Quebrada Asientos. *Congreso Geologico Chileno*

1071 Marshall, J.D. 1992. Climatic and oceanographic isotopic signals from the carbonate rock  
1072 record and their preservation. *Geological Magazine*, 129, 143–160

1073 McElwain, J.C., Wade-Murphy, J. & Hesselbo, S.P. 2005. Changes in carbon dioxide during  
1074 an oceanic anoxic event linked to intrusion into Gondwana coals. *Nature*, 435, 479–  
1075 482

1076 McKirdy, D. M., Powell, T. G., 1974. Metamorphic alteration of carbon isotopic composition  
1077 in ancient sedimentary organic matter. New evidence from Australia and South Africa  
1078 *Geology*, 2, 591-595

1079 Metodiev, L., 2000. Etude de la limite Toarcien–Aalénien 1086 et stratigraphie de l’Aalénien  
1080 dans quelques coupes du Mont Balkan occidental et central en Bulgarie. *Strata*, série  
1081 1, 10, 117-121

1082 Molina, J.M., Reolid, M., Mattioli, E., 2018. Thin-shelled bivalve buildup of the lower  
1083 Bajocian, South Iberian paleomargin: development of opportunists after oceanic  
1084 perturbations. *Facies*, 64, 19

- 1085 Morettini, E., Santantonio, M., Bartolini, A., Cecca, F., Baumgartner, P.O., Hunziker, J.C.,  
1086 2002. Carbon-isotope stratigraphy and carbonate production during the Early–Middle  
1087 Jurassic: examples from the Umbria–Marche–Sabina Apennines (central Italy).  
1088 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 184, 251–273
- 1089 Mouterde, R., Kerrien, Y., Labourguigne, J., Manivit, J., 1966. Le Lias et le Bajocien de la  
1090 Javie (Basses-Alpes). *Bull. Soc. Géol. De France*, 7, 347-352
- 1091 O'Dogherty, L., Sandoval, J., Bartolini, A., Bruchez, S., Bill, M., Guex, J., 2006. Carbon  
1092 isotope stratigraphy and ammonite faunal turnover for the Middle Jurassic in the  
1093 Southern Iberian palaeomargin. *Palaeogeography, Palaeoclimatology, Palaeoecology*,  
1094 239, 311–333
- 1095 Ohmert, W., Allia, V., C. Arias, C., Baldanza, A., Bergen, J. A., Bucefalo Palliani, R.,  
1096 Canales, M. L., deKaenel, E., Garcia Joral, F., Goy, A., Herrero, C., Höhndorf, A.,  
1097 Martinez, G., Mattioli, E., Perilli, N., Riegraf, W., Rolf, C., Ureta, S., Wetzel, A. &  
1098 Wonik, T. 1996. Die Grenzziehung Unter-/Mitteljura (Toarcium/Aalenium) bei  
1099 Wittnau und Fuentelsaz. *Informationen Geologisches Landesamt Baden-*  
1100 *Württemberg* 8:1-52Pálffy, J. & Smith, P.L. 2000. Synchrony between Early Jurassic  
1101 extinction, oceanic anoxic event, and the Karoo–Ferrar flood basalt volcanism.  
1102 *Geology*, 28, 747–750
- 1103 Peters, K. E., 1986. Guidelines for evaluating petroleum source rock using programmed  
1104 pyrolysis. *Am. Assoc. Pet. Geol. Bull.*, 70, 318-329
- 1105 Pérez, E. 1982. Bioestratigrafía del Jurásico de Quebrada Asientos, norte de Potrerillos,  
1106 Región de Atacama. *Boletín* 37. Servicio Nacional de Geología y Minería, Santiago
- 1107 Pittet, B., Mattioli, E., 2002. The carbonate signal and 1108 calcareous nannofossil  
1108 distribution in an Upper Jurassic section (Balingen– Tieringen, Late Oxfordian,  
1109 southern Germany). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 179, 71– 96
- 1110 Premoli Silva, I., Erba, E., Tornaghi, M.E., 1989. Paleoenvironmental signals and changes in  
1111 surface fertility in Mid Cretaceous Corg-rich pelagic facies of the Fucoïd Marls  
1112 (central Italy). *Géobios, Mém. Spec.*, 11, 225–236

- 1113 Price, G.D., 2010. Carbon-isotope stratigraphy and temperature change during the Early-  
1114 Middle Jurassic (Toarcian-Aalenian), Raasay, Scotland, UK. *Palaeogeography,*  
1115 *Palaeoclimatology, Palaeoecology*, 285, 255-263
- 1116 Rojas, A., Calatayud, J., Kowalewski, M., Neuman, M., Rosvall, M., 2021. A multiscale view  
1117 of the Phanerozoic fossil record reveals the three major biotic transitions.  
1118 *Communications Biology*, 4, 309
- 1119 Roth, P.H. 1984. Preservation of calcareous nannofossils and fine-grained carbonate particles  
1120 in mid-Cretaceous sediments from the southern Angola Basin, site 530. Initial Reports  
1121 of the Deep Sea Drilling Project, 75. US Government Printing Office, Washington,  
1122 DC, 651–655
- 1123 Roth, P.H., Bowdler, J.L., 1981. Middle Cretaceous calcareous nannoplankton biogeography  
1124 and oceanography of the Atlantic Ocean. *Soc. Econ. Paleontol. Mineral., Spec. Publ.*  
1125 32, 517– 546
- 1126 Rousselle, B., 2001. Géologie de la «Pierre Dorée » des Monts d'Or et du Beaujolais (Rhône,  
1127 France). *Bulletin mensuel de la Société linnéenne de Lyon*, 3, 45-60
- 1128 Rulleau, L., and Elmi, S. 2001. Géologie et paléontologie des dépôts ferrugineux du Toarcien  
1129 et de l'Aalénien aux environs de Lyon. *Travaux et Documents des Laboratoires de*  
1130 *Géologie de Lyon*, 154
- 1131 Sandoval, J., O'Dogherty, L., Aguado, R., Bartolini, A., Bruchez, S., Bill, M., 2008. Aalenian  
1132 carbon-isotope stratigraphy: Calibration with ammonite, radiolarian and nannofossil  
1133 events in the Western Tethys. *Palaeogeography, Palaeoclimatology,* 1131  
1134 *Palaeoecology*, 267, 115-137.
- 1135 Schoell, M., 1984. Recent advances in petroleum isotope geochemistry *Org. Geochem.*, 6,  
1136 645-663
- 1137 Schrag, D.P., DePaolo, D.J. & Richter, F.M. 1995. Reconstructing past sea surface  
1138 temperatures from oxygen isotope measurements of bulk carbonate. *Geochimica et*  
1139 *Cosmochimica Acta*, 59, 2265–2278
- 1140 Spangenberg, J. E., Macko, S. A., 1998. Organic geochemistry of the San Vicente zinc-lead  
1141 district, eastern Pucará Basin, Peru. *Chemical Geology*, 146, 1-23



1142 Storm, M. S., Hesselbo, S. P., Jenkyns, H. C., Ruhl, M., Ullmann, C. V., Xu, W., Leng, M. J.,  
1143 Riding, J. B., Gorbanenko, O., 2020- Orbital pacing and secular evolution of the Early  
1144 Jurassic carbon cycle. *Earth, Atmospheric, and Planetary Sciences*, 1-9, 1912094117

1145 Suan, G., Mattioli, E., Pittet, B., Mailliot, S., Lécuyer, C., 2008a. Evidence for major  
1146 environmental perturbation prior to and during the Toarcian (Early Jurassic) oceanic  
1147 anoxic event from the Lusitanian Basin, Portugal. *Paleoceanography* 23 PA1202

1148 Suan, G., Nikitenko, B.L., Rogov, M.A., Baudin, F., Spangenberg, J.E., Knyazev, V.G.,  
1149 Glinskikh, L.A., Goryacheva, A.A., Adatte, T., Riding, J.B., Föllmi, K.B., Pittet, B.,  
1150 Mattioli, E., Lécuyer, C., 2011. Polar record of Early Jurassic massive carbon  
1151 injection. *Earth Planet. Sci. Lett.*, 312, 102–113

1152 Suchéras-Marx, B., Mattioli, E., Pittet, B., Escarguel, G., Suan, G., 2010. Astronomically  
1153 paced coccolith size variations during the early Pliensbachian (Early Jurassic).  
1154 *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 295, 281–292

1155 Suchéras-Marx, B., Guihou, A., Giraud, F., Lécuyer, C., Allemand, P., Pittet, B.,  
1156 Mattioli, E., 2012. Impact of the Middle Jurassic diversification of *Watznaueria*  
1157 (coccolith bearing algae) on the carbon cycle and  $\delta^{13}\text{C}$  of bulk marine carbonates.  
1158 *Glob. Planet. Chang.*, 86-87, 92–100

1159 Suchéras-Marx, B., Giraud, F., Fernandez, V., Pittet, B., Lécuyer, C., Olivero, D., Mattioli,  
1160 E., 2013. Duration of the early Bajocian and the associated  $\delta^{13}\text{C}$  positive excursion  
1161 based on cyclostratigraphy. *J. Geol. Soc.*, 170, 107–118

1162 Suchéras-Marx, B., Mattioli, E., Giraud, F., Escarguel, G., 2015. Paleoenvironmental and  
1163 paleobiological origins of coccolithophorid genus *Watznaueria* emergence during the  
1164 late Aalenian–early Bajocian. *Paleobiology*, 41, 415–435

1165 Suchéras-Marx, B., Mattioli, E., Allemand, P., Giraud, F., Pittet, B., Plancq, J., Escarguel, G.,  
1166 2019. The colonization of the oceans by calcifying pelagic algae. *Biogeosciences*, 16,  
1167 2501-2510

1168 Svensen, H., Planke, S., Chevallier, L., Mørbye, A., Corfu, F., Jamveit, B., 2007.  
1169 Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming.  
1170 *Earth Planet. Sci. Lett.*, 256, 554–566

1171 Swart, P.K., Eberli, G.P., 2005. The nature of the  $\delta^{13}\text{C}$  of periplatform sediments:  
 1172 Implications for stratigraphy and the global carbon cycle. *Sediment. Geol.*, 175, 115–  
 1173 129

1174 Taylor, P.D., Ernst, A., 2008. Bryozoans in transition: the depauperate and patchy Jurassic  
 1175 biota. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 263, 9–23

1176 Them II, T.R., Gill, B.C., Caruthers, A.H., Gröcke, D.R., Tulskey, E.T., Martindale, R.C.,  
 1177 Poulton, T.P., Smith, P.L., 2017b. High-resolution carbon isotope records of the  
 1178 Toarcian Oceanic Anoxic Event (Early Jurassic) from 1176 North America and  
 1179 implications for the global drivers of the Toarcian carbon cycle. *Earth Planet. Sci.*  
 1180 *Lett.*, 459, 118–126

1181 Thierry, J., 2000. Late Toarcian. In: Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju-  
 1182 Duval, B., Brunet, M.F., Cadet, J.P., Crasquin, S., Sandulescu, M. (Eds.), *Atlas Peri-*  
 1183 *Tethys. Palaeogeographical Maps*

1184 Tiraboschi, D., Erba, E., 2010. Calcareous nannofossil biostratigraphy (Upper Bajocian–  
 1185 Lower Bathonian) of the Ravin du Bès section (Bas Auran, Subalpine Basin, SE  
 1186 France): Evolutionary trends of *Watznaueria barnesiae* and new findings of  
 1187 “*Rucinolithus*” morphotypes. *Geobios*, 43, 59–76

1188 Tremolada, F., van de Schootbrugge, B., Erba, E., 2005. Early Jurassic schizosphaerellid  
 1189 crisis in Cantabria, Spain: implications for calcification rates and phytoplankton  
 1190 evolution across the Toarcian oceanic anoxic event. *Paleoceanography*, 20,  
 1191 doi:10.1029/2004PA001120

1192 Uliana, M.A., Bibble, K.T. & Cerdan, J. 1989. Mesozoic extension and the formation of  
 1193 Argentine sedimentary basins. In: Tankard, R.J. & Balkwill, H.R. (eds) *Extensional*  
 1194 *Tectonics and Stratigraphy of the North Atlantic Margin*. AAPG Memoirs, 46, 599–  
 1195 614

1196 van Breugel, Y., Baas, M., Schouten, S., Mattioli, E., Sinninghe-Damsté, J.S., 2006.  
 1197 Isorenieratane record in black shales from the Paris Basin, France: constraints on  
 1198 recycling of respired  $\text{CO}_2$  as a mechanism for negative carbon isotope shifts during  
 1199 the Toarcian oceanic anoxic event. *Paleoceanography*, 21, 1–8

- 1200 Vermeij, G.J., 1977. The Mesozoic marine revolution: evidence 1198 from snails, predators  
1201 and grazers. *Paleobiology* 3, 245–258. Vicente, J.C. 2005. Dynamic paleogeography of  
1202 the Jurassic Andean Basin: pattern of transgression and localisation of main straits  
1203 through the magmatic arc. *Revista de la Asociacion Geologica Argentina*, 60, 221–250
- 1204 Visentin, S., Faucher, G., Mattioli, E., Erba, E., 2020. Taxonomic revision of the genus  
1205 *Carinolithus* (Early - Middle Jurassic) based on morphometric analyses and diagenesis  
1206 observations: Implications for biostratigraphy and evolutionary trends. *Marine*  
1207 *Micropaleontology*, 162, 101950
- 1208 von Hillebrandt, A., and Schmidt-Effing, R. 1981. Ammoniten aus dem Toarcium (Jura) von  
1209 Chile (Südamerika). *Zitteliana*, 6, 3–74
- 1210 von Hillebrandt, A., and Westermann, G.E.G., 1985. Aalenian (Jurassic) Ammonite Faunas  
1211 and Zones of the Southern Andes. *Zitteliana*, 12, 3-55
- 1212 Watkins, D., 1986. Calcareous nannofossil paleoceanography of the Cretaceous Greenhorn  
1213 Sea. *Geol. Soc. Am. Bull.*, 97, 1239– 1249
- 1214 Weissert, H., McKenzie, J., Hochuli, P. 1979. Cyclic anoxic events in the Early Cretaceous.  
1215 *Geology*, 7 (3): 147-151
- 1216 Wiggan, N.J., Riding, J.B., Franz, M., 2017. Resolving the Middle Jurassic dinoflagellate  
1217 radiation: the palynology of the Bajocian of Swabia, Southwest Germany. *Rev.*  
1218 *Palaeobot. Palynol.* 238, 55–87. Xu, W., Ruhl, M. et al. 2017. Carbon sequestration in  
1219 an expanded lake system during the Toarcian oceanic anoxic event. *Nature*  
1220 *Geoscience*, 10, 129–135
- 1221 Yao, A., 1997. Faunal change of Early–Middle Jurassic radiolarians. In: Yao, A. (Ed.),  
1222 *Proceedings of the Fifth Radiolarian Symposium. News of Osaka*  
1223 *Micropaleontologists*, special Volume, 10. 155–182
- 1224