



The Lower Jurassic at Peniche (Lusitanian Basin): recent advances in Stratigraphy and Sedimentary Geology

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Abstract

In the Lusitanian Basin (west-central Portugal), the Lower Jurassic deposits are well exposed and are dominated by carbonates. Framed by a beautiful and unique Atlantic coastal landscape, the Peniche Peninsula shows the most important and continuous section of the Lower Jurassic in Portugal, providing a record of around 20 Myr of Portuguese geological history (Sinemurian to Toarcian). The importance of this site is testified by the large number of recent research studies in different domains of sedimentary geology and stratigraphy. This field-trip focuses on three main topics of international scientific interest: a) the Sinemurian and Pliensbachian organic-rich deposits, one of the chief intervals of hydrocarbon source potential in the western Iberian margin; b) the Pliensbachian–Toarcian boundary at Ponta do Trovão, which has been ratified as the Toarcian Global Boundary Stratotype Section and Point (GSSP)^a; and c) the early Toarcian oceanic anoxic event recorded at Abalo beach.

Keywords: Lower Jurassic, Stratigraphy, Palaeoenvironment, Peniche, Portugal.

Resumo

Na Bacia Lusitânica (centro-oeste de Portugal) o Jurássico Inferior está muito bem representado e exposto, através de um claro domínio de sedimentos carbonatados. Enquadrada por uma paisagem costeira de elevada beleza cénica, a península de Peniche mostra a secção mais contínua e completa do Jurássico Inferior de Portugal, representando um registo de cerca de 20 milhões de anos da sua história geológica (Sinemuriano a Toarciano). A importância deste local é testemunhada pelo vasto número de atividades de investigação científica recentemente realizadas, relacionadas com diferentes domínios da geologia sedimentar e estratigrafia. Sendo assim, esta saída de campo é focalizada em três principais temas de interesse científico internacional: a) a sedimentação rica em matéria orgânica do Sinemuriano e Pliensbaquiano, um dos principais intervalos potencialmente geradores de hidrocarbonetos da margem ocidental da Península Ibérica; b) o limite Pliensbaquiano-Toarciano em Ponta do Trovão, ratificado como estratótipo (Global Boundary Stratotype Section and Point, GSSP) do limite Pliensbaquiano-Toarciano; c) o evento oceânico anóxico do Toarciano Inferior registado na praia do Abalo.

Palavras-chave: Jurássico Inferior, Estratigrafia, Paleoambiente, Peniche, Portugal.

^aThis proposition was unanimously ratified by the IUGS Executive Committee in December 2014. Consequently, the GSSP for the base of the Toarcian is accepted as the base of bed 15e (base of the *Polymorphum* Zone) at the Ponta do Trovão (Peniche) section.

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1. Introduction

One of the best expressed records of Early Jurassic is observed in the Lusitanian Basin (LB), located in the western sector of the Iberian Peninsula, corresponding in the main to a thick marine carbonate

series (Fig.1; e.g., Soares *et al.*, 1993; Azerêdo *et al.*, 2003; Duarte *et al.*, 2004). Part of this succession, namely the interval between the Sinemurian and the Toarcian stages, is dominated by marl–limestone alternations.

Several outcrops of the LB provide crucial information about the Lower Jurassic. The reference section of Peniche (Fig. 2), located about 80 km north of Lisbon, presents the most complete succession of Lower Jurassic sediments in Portugal, framed by an important geological heritage character and a spectacular scenic environment (Duarte, 2004). In recent years, this section has been the focus of intense scientific activity, related mainly to stratigraphy and sedimentary geochemistry (e.g., Rocha, 2007; Hesselbo *et al.*, 2007; Suan *et al.*, 2008a, 2008b, 2010; Mattioli *et al.*, 2008, 2009; Duarte *et al.*, 2010, 2011; Reggiani *et al.*, 2010a, 2010b; Silva *et al.*, 2011b, 2012). In addition to introducing the sedimentary context, describing the stratigraphy, and characterizing the whole succession (Stop 1), on this field-trip we also discuss: a) the Pliensbachian organic-rich marl–limestone deposits, one of the main intervals of hydrocarbon source potential in the West Iberian Margin (Stop 2); b) the Pliensbachian–Toarcian boundary at Ponta do Trovão, which has been ratified as the Toarcian Global Boundary Stratotype Section and Point (GSSP) (Stop 3); and c) the early Toarcian oceanic anoxic event (T-OAE) and its record at Abalo beach (Stop 4). All of these themes are presented and supported by an integrated stratigraphic analysis involving a range of sedimentological, geochemical, and palaeontological methodologies.

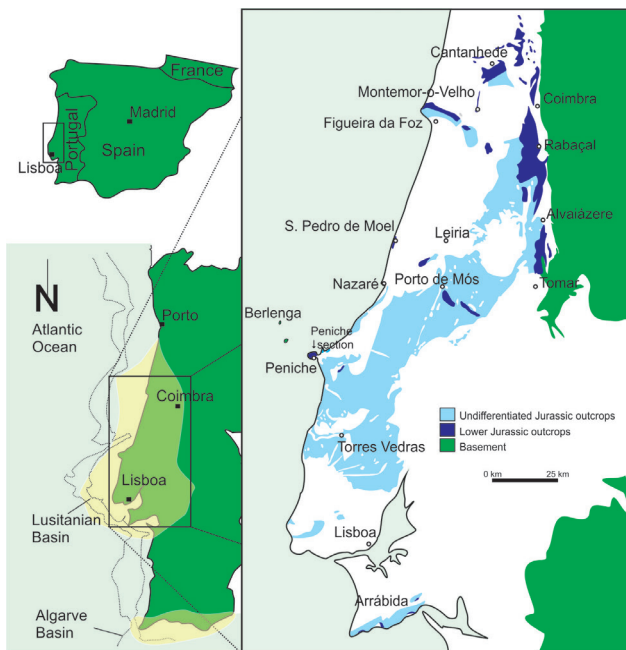


Fig. 1 - Simplified geological map of the central-northern part of the Lusitanian Basin (Portugal) showing the distribution of Lower Jurassic carbonate units of (based on Duarte *et al.*, 2010) and the location of the Peniche section.

2. The Lower Jurassic in the Lusitanian Basin

The LB is a narrow, small north–south-trending elongated basin limited to the west by the Variscan (granitic and metamorphic) Berlenga Horst (e.g., Wilson *et al.*, 1989; Kullberg *et al.*, 2013) and to the east by the Porto–Tomar shear zone (Fig. 1). This basin had its origin in the Triassic and was the result of the extensional phase that preceded the genesis of the North and Central Atlantic Ocean (e.g., Wilson *et al.*, 1989). In the western portion of the Hesperian Massif, this extensional phase was represented by the formation of half-grabens, originally filled by a thick siliciclastic series of continental deposits (Silves Group; e.g., Kullberg *et al.*, 2013).

In the LB, the Lower Jurassic generically corresponds to shallow- to deeper-marine carbonate deposits (Soares *et al.*, 1993; Azerêdo *et al.*, 2003). The base of the Jurassic is marked by a fine-grained, mainly siliciclastic, sedimentation with some dolomitic and evaporitic intercalations (the Pereiros and Dagorda formations). These units are of Hettangian age and show a typical set of lagoonal environments controlled by arid climate conditions. These Hettangian facies are capped by the Coimbra Formation (Fm) (Sinemurian), which is the first true carbonate unit represented at a basinal scale.

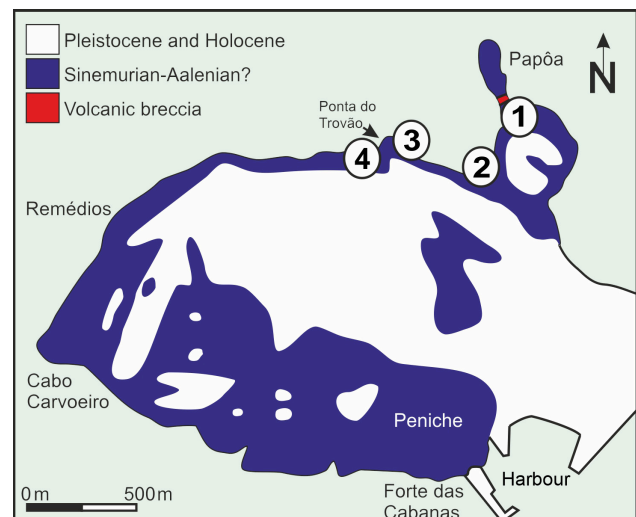


Fig. 2 - Simplified geological map of the Peniche Peninsula (modified from Camarate França *et al.*, 1960) showing the locations of the main stops of this field-trip.

The Coimbra Fm is composed of a succession of dolostones and limestones, with the latter lithotype being more extensively expressed at the top of the unit and in its westernmost sectors, corresponding to a marginal-marine palaeoenvironmental setting. In the upper Sinemurian, located in the western part of the basin, the deposits are characterized by an organic-matter-rich marl–limestone series with ammonites

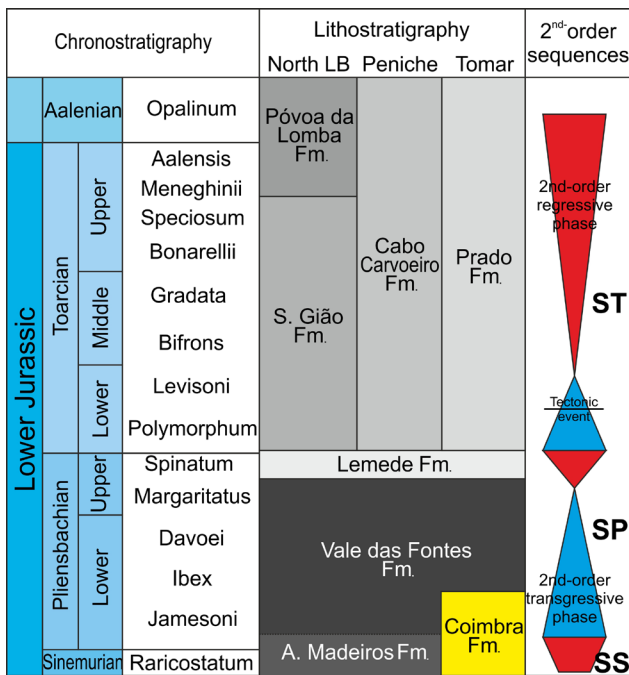


Fig. 3 - Stratigraphic chart for the upper Sinemurian–lower Aalenian succession in great part of the LB (modified from Duarte, 2007) and incorporating new biostratigraphic data from Comas-Rengifo *et al.*, 2013).

(Água de Madeiros Fm) that mark the onset of the development of open-marine conditions in the basin. This fine-grained sedimentation extends throughout the basin in the lower Pliensbachian–upper Toarcian interval, corresponding to the Vale das Fontes, Lemedé, S. Gião, and Póvoa da Lomba formations (Fig. 3; Duarte & Soares, 2002). The ammonites and calcareous nannofossils recorded in these units allow a closely constrained biostratigraphic control of the series to be achieved (e.g., Phelps, 1985; Elmi, 2006; Perilli & Duarte, 2006; Mouterde *et al.*, 2007; Rocha, 2007; Oliveira *et al.*, 2007; Silva *et al.*, 2011b; Silva, 2013; Comas-Rengifo *et al.*, 2013; Mattioli *et al.*, 2013; Paredes *et al.*, 2013). The weak lateral facies variation observed across the basin suggests that these sediments were deposited in a marine carbonate ramp system dipping towards the west to northwest and controlled by N–S- and NE–SW-oriented tectonic trends (Duarte, 2007). Despite the general hemipelagic sedimentation, some particular sedimentary aspects can be recognized at several locations in the southern half of the LB, such as Tomar (Prado Fm) and Peniche (Cabo Carvoeiro Fm) (Duarte & Soares, 2002) (Figs 1 and 3). In this latter locality, the deposition of siliciclastic and redeposited oolitic sediments during the Toarcian confirm a palaeogeography controlled by the uplift of the western igneous Berlenga block (e.g., Wright & Wilson, 1984; Duarte, 1997; Duarte *et al.*, 2004).

3. Stop 1. The Lower Jurassic succession at Peniche (L. V. Duarte, R. L. Silva, M. J. Comas-Rengifo² & R. B. Rocha)

The perimeter of the Peniche peninsula exhibits a succession of sedimentary carbonate rocks, consisting of marls, locally organic-rich, and marly, micritic, dolomitic, bioclastic, oolitic, oncolitic, and sandy limestones. These deposits belong to the Coimbra, Água de Madeiros, Vale das Fontes, Lemedé, and Cabo Carvoeiro formations (Figs 3 and 4). The latter three units have their type-sections in this location (Duarte & Soares, 2002). In addition, given the very specific geological features, coupled with an inferred turbiditic sedimentation that evolves into peri-marginal environments (see Wright & Wilson, 1984; Duarte, 1997), the Cabo Carvoeiro Fm is exclusive to the Peniche area. The whole succession presents a thickness of more than 450 m.

The entire series is paleontologically very rich in nektonic (ammonites and belemnites) and benthonic (including brachiopods, bivalves, gastropods, crinoids, echinoderms, and corals) macrofauna and various types of trace fossils. The ammonites, present throughout the upper Sinemurian (Raricostatum Zone) to middle Toarcian (Gradata Zone) (e.g., Mouterde, 1955; Phelps, 1985; Dommergues, 1987; Mouterde *et al.*, 2007), allow a detailed biostratigraphic zonation to be made, in some cases at the subzone scale. Recent biostratigraphic data have allowed aspects of the Sinemurian and Pliensbachian succession to be revealed in detail (see Silva *et al.*, 2011b; Paredes *et al.*, 2013; Silva, 2013). Intra- and extra-basinal correlations are also established on the basis of calcareous nannofossil biostratigraphy for the Pliensbachian–Toarcian interval at Peniche (Mattioli *et al.*, 2013).

Five lithostratigraphic units are recognized in the Peniche peninsula area (based on Duarte & Soares, 2002; Duarte, 2007), as follows (Fig. 4).

The **Coimbra Fm** is the oldest unit observed in Peniche, being Sinemurian in age, and displays a succession of micritic, bioclastic, oncolitic, and oolitic limestones with very rare intercalations of marly levels (Fig. 5A). Several facies are bioturbated (*Thalassinoides*) and rich in bivalves and gastropods. The formation is around 50 m thick.

The **Água de Madeiros Fm** consists of a sequence of calcareous and/or laminated marls, with

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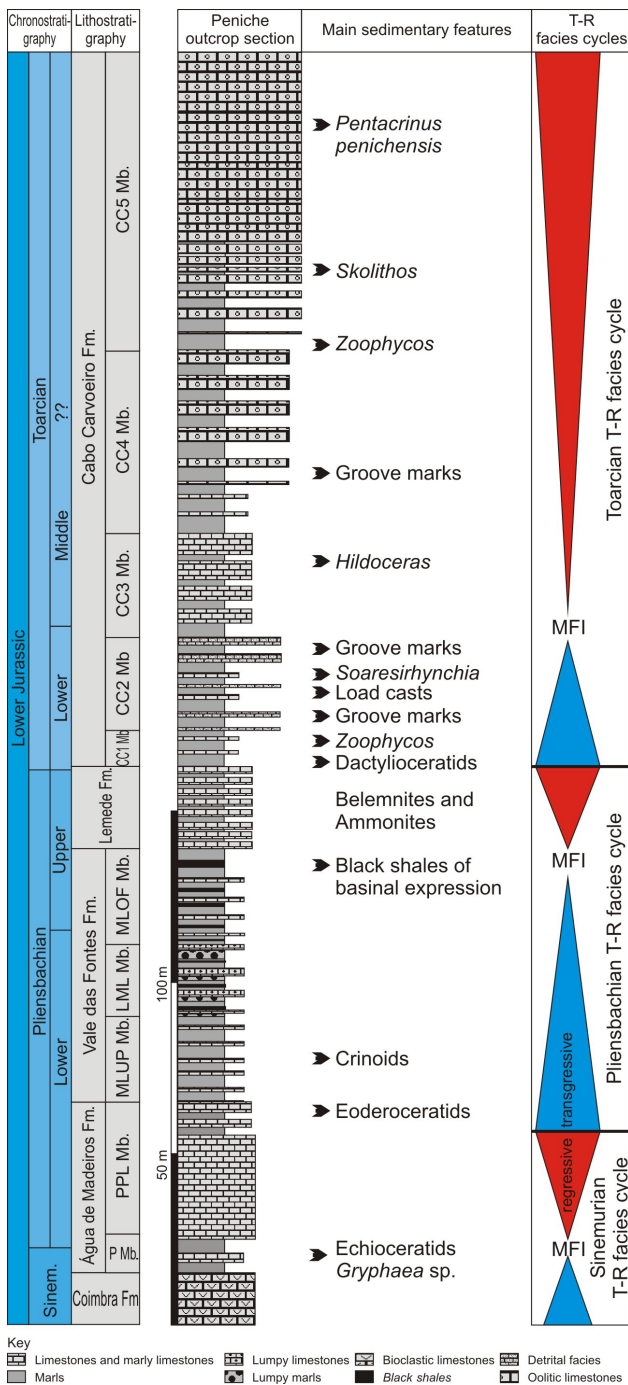


Fig. 4 - Stratigraphic chart of the Sinemurian–Aalenian (?) succession of Peniche (modified from Duarte *et al.*, 2004; Duarte, 2007; includes the new biostratigraphic data from Paredes *et al.*, 2013).

some horizons rich in organic matter, and marly, micritic, and bioclastic limestones. The formation is divided into the Polvoeira and Praia da Pedra Lisa members, which have thicknesses at Peniche of 10 and ~40-50 m, respectively. The former member corresponds to a sequence of alternating marl and marly limestones, slightly bioclastic and very rich in nektonic (ammonites and belemnites) and benthonic macrofauna (mainly brachiopods and bivalves) (Fig.

5A). The Polvoeira member also includes the ichnogenes *Diplocraterion*, *Thalassinoides*, and *Rhizocorallium*. The Praia da Pedra Lisa member (Mb) is dominantly calcareous and comprises mainly bioclastic facies. The intense fracturing hinders a more detailed analysis to be made. Ammonite data constrain the base of the Água de Madeiros Fm to the top of the *Raricostatum* Zone–base of the *Jamesoni* Zone (Paredes *et al.*, 2013).

The **Vale das Fontes Fm** is dated as ranging from the base of the *Jamesoni* Zone to the upper *Margaritatus* Zone and marks the return to marly–limestone sedimentation, with some horizons being enriched in organic matter (Fig. 5B). At Peniche, this unit has a thickness of around 76 m and is subdivided into three informal members: The marls and limestones with *Uptonia* and *Pentacrinus* (MLUP) mb, the lumpy marls and limestones (LML) mb, and the marly limestones with organic-rich facies (MLOF) mb.

MLUP mb (25 m; *Jamesoni* Zone): alternations of bioturbated decimeter-scale marl and centimetre-thick marly limestone with nektonic and benthonic macrofauna (crinoids, brachiopods, and bivalves).

LML mb (21 m; *Jamesoni* Zone to *Ibex* Zone): defined by the occurrence of lumpy facies interbedded with a marl–limestone succession with rare organic-rich facies (Fig. 5C). Benthic macrofauna are scarce, but ammonites and belemnites are present throughout. The lumps consist of micritic lumpy concretions, generally subspherical shaped and reaching several centimeters in size (Fig. 5D) and which are apparently related to microbial activity (e.g., Dromart & Elmi, 1986; Elmi *et al.* 1988; Fernández-López *et al.*, 2000).

MLOF mb (30 m; uppermost *Ibex* Zone–upper *Margaritatus* Zone; Silva *et al.*, 2011b; Silva, 2013): this member is differentiated from the framing units by an increase in the marly and organic matter character of the series, locally with diverse and abundant small benthonic macrofauna (crinoids, brachiopods, bivalves, and gastropods), ammonites, and belemnites.

The **Lemede Fm** has a thickness of around 23 m and displays a predominantly limestone character with an abundance of belemnites and ammonites (Fig. 5E). The base of this unit is assigned to the uppermost *Margaritatus* Zone (Silva *et al.*, 2011; Silva, 2013). The top of the unit corresponds to the extreme base of the Toarcian (*Polymorphum* Zone, *Mirabile* Subzone).

The **Cabo Carvoeiro Fm** is exclusive to Peniche and has its own special features marked by the occur-



Fig. 5 - Some sedimentological and stratigraphic features of the Lower Jurassic deposits at Peniche. A - Intra-Sinemurian discontinuity (dotted line) between Coimbra and Água de Madeiros formations at Peniche. B - General view over part of the Vale das Fontes Fm in Portinho da Areia do Norte. C - General view of LML mb at Portinho da Areia do Norte beach. D - Detail of lumps in the LML mb of Vale das Fontes Fm. E - General view of the Lemede Fm showing the cyclicity of the limestone-marl alternations. F - Subarkosic facies of the CC2 mb in the Abalo beach. G - General view of the calciclastic limestone-marl alternations of the CC4 mb at Baixa do Outeiro. H - Calciclastic and siliciclastic facies and stratonomy of the CC5 mb at Carvoeiro Cap.

rence of a set of detrital (Fig. 5F), oolitic, and bioclastic facies (see Wright & Wilson, 1984; Duarte, 1997). According to Duarte & Soares (2002), this formation is subdivided into the following five members:

The CC1 mb (11 m; Polymorphum Zone, Semicelatum Subzone): corresponds to a predominantly grey marly unit with some intercalations of marly limestones (biomicrites/wackestones). This unit is very fossiliferous, including ammonites, belemnites, tiny brachiopods, bivalves and *Zoophycos*.

The CC2 mb (25 m; Levisoni Zone): corresponds to a marly dominated succession, poor in macrofauna (only ammonites and some brachiopods), and presents several lenticular siliciclastic facies and wood fragments. The lithofacies are very diversified, from greyish marls and limestones to subarkosic microconglomerates (Fig. 5F). The siliciclastic facies, with variable thickness (≤ 75 cm) and erosional structures like groove marks and load casts show typical turbidite features (e.g., Wright & Wilson, 1984).

The CCC3 mb (30 m thick; Levisoni–Bifrons zones): marks the disappearance of the siliciclastic facies. This unit corresponds to a monotonous marl/limestone alternation with an increase of the calcareous components towards the top. These beds show strong bioturbation (sometimes, *Chondrites*), abundant ammonites but the macrobenthonic record is scarce.

The CC4 mb (54 m; Bifrons Zone–Bonarellii? Zone): despite the marly nature of the base, this member is characterized by the occurrence of centimetric to decimetric grainstones (oosparites and oopel-sparites) levels with some grey-greenish marly facies (Fig. 5G). The base of grainstone facies is generally sharp and frequently shows groove and tool marks. The top surfaces are very irregular and, sometimes, bioturbated (including *Skolithos*).

The CC5 mb (>90 m; Speciosum? Zone–Aalenian): tends to be similar to the CC4 mb, although without the marly levels and with an observable increase in bed thickness and siliciclastic character (quartz particles) (Fig. 5H). In some levels, the paleontological associations, rich in bivalves, gastropods, crinoids (*Pentacrinus penichensis*) and ahermatipic corals, indicate that deposition took place in a shallow-water palaeoenvironment.

The vertical analysis of the different units cropping out in the Peniche Peninsula allows three third-order transgressive–regressive facies cycles to be recognized (see Duarte *et al.*, 2004, 2010; Duarte, 2007) (Fig. 4).

4. Stop 2. Sedimentary and palaeoenvironmental constrains on the Pliensbachian organic-rich deposition in the Lusitanian Basin (Ricardo L. Silva & L. V. Duarte)

4.1. Introduction

One of the main characteristics of the Pliensbachian series of the LB is the occurrence of several organic-rich intervals (e.g., Duarte *et al.*, 2010; Silva *et al.*, 2011b, 2012; Silva, 2013). The first main step in the characterization of the organic-rich facies of this unit was achieved by the work of Oliveira *et al.* (2006), where the authors present the geochemical characterization of this time interval in the reference section of Peniche, based on total organic carbon (TOC), Rock-Eval pyrolysis and biomarkers. Afterwards, Duarte *et al.* (2010), based in a detailed biostratigraphic framework (especially complete in the Peniche section), sedimentological data and TOC variation, present a consolidated 2nd-order transgressive–regressive facies cycles scheme for the Lower Jurassic carbonate series of the LB and compared them with those observed in the Basque-Cantabrian neighbouring basin. Nowadays, these organic-rich levels are intensively studied throughout the basin, using several innovative techniques, including conventional isotope geochemistry in kerogen (Silva *et al.*, 2011b), biogeochemistry (Silva *et al.*, 2012), outcrop gamma-ray spectrometry (Correia *et al.*, 2012), biomarkers and palynofacies (e.g., Ferreira *et al.*, 2010; Silva *et al.*, 2010, 2011a).

4.2. The MLOF MB: characterization and regional framing

At Peniche, the MLOF mb crops out in the Portinho da Areia do Norte beach (UTM coordinates 29 S, 467389m; 4357730m) (Fig. 2). In this sector this unit is characterized by the pervasive occurrence of organic-rich facies, including several black shales (e.g., Oliveira *et al.*, 2006; Duarte *et al.*, 2010; Silva *et al.*, 2011b, 2012; Silva, 2013).

The first metres of the series, corresponding to the Ibex Zone, are composed of regular marl-limestone alternations, grading to a more irregular marl-dominated interval dated from the Davoei Zone (Fig. 6). The limit with the LML mb is sharp and marked by the disappearance of the lumpy facies. At the beginning of the late Pliensbachian, the more regular marl-limestone alternations resume, persisting until the limit with the Lemedé Fm.

A very precise biostratigraphic control of the MLOF

mb at a basin wide scale is attained in this section. The ammonites allow a detailed biostratigraphic zonation (Mouterde, 1955; Phelps, 1985; Mouterde *et al.*, 2007; Rocha *et al.*, 2013) reinforced by additional new data from recent ammonite collection campaigns (see, for example, Silva *et al.*, 2011b; Silva, 2013) (Figs 6 and 7A). The newly collected bed-by-bed ammonite data are, at a broader scale, in good agreement with the biozonation charts established for the Pliensbachian of the LB.

Nevertheless, these data allowed improving of some biostratigraphic boundaries. The main one is related with the age of the Lemedé Fm, which was pre-

viously assigned to the Emaciatum (Spinatum) Zone (e.g., Mouterde, 1955; Duarte & Soares, 2002) (Fig. 6). The new high-resolution biostratigraphic data reveal that the base of this formation corresponds to the Margaritatus Zone, uppermost Gibbosus Subzone, with a distinct level of *Arietoceras* gr. *algovianum* occurrence found approximately 4 m above the base of this unit (Silva *et al.*, 2011b; Silva, 2013).

Based on sedimentological criteria, it is possible to distinguish three main sedimentation domains in MLOF mb (Silva *et al.*, 2012; Silva, 2013), relating to different environmental subdivisions as predicted

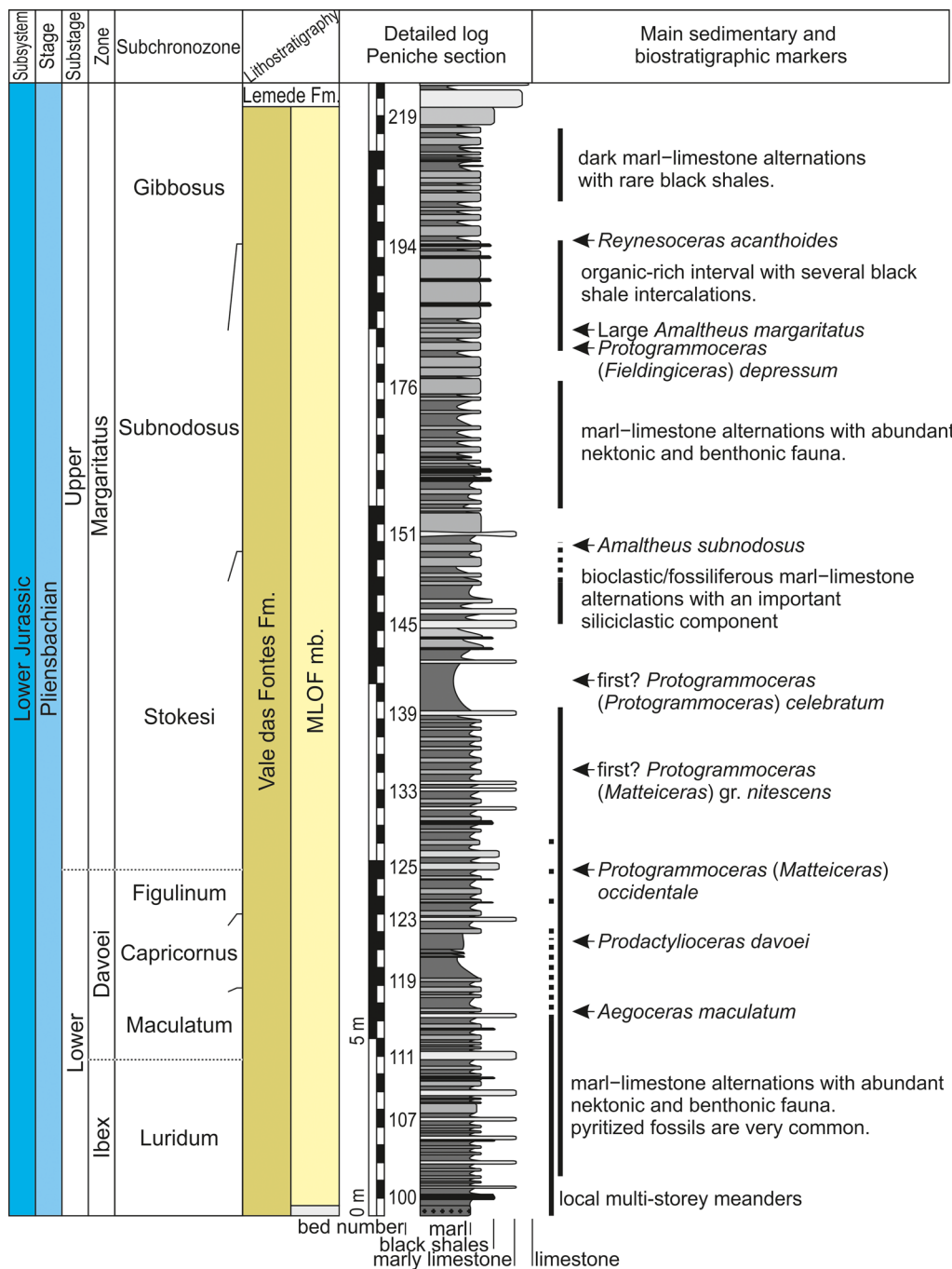


Fig. 6 - Detailed log of the MLOF mb and base of Lemedé Fm in the Peniche reference section of the LB (modified from Silva *et al.*, 2011b; Silva, 2013).

for carbonate ramp systems (see Burchette & Wright, 1992 and references therein). Westwards, corresponding to Peniche and S. Pedro de Moel sections and Figueira da Foz sector, the main feature of the MLOF mb is its richness in organic-matter (Silva *et al.*, 2011a, 2011b, 2012; Silva, 2013). Palaeobathymetric estimates based in microfossil data suggest that water column thickness averaged around 100-200 metres (e.g., N'zaba-Makaya *et al.*, 2003). The central-eastern domain, namely at Rabaçal, is distinguished by the significant occurrence of nautiloids and the widespread presence of usually small mud-wacke-packstone carbonate build-ups. Locally, organic-rich facies are observed, although these are not that relevant when compared with the Western domain. The Tomar facies, in the Southeastern domain (Fig. 1), represents the shallowest of the studied environments.

4.3. Organic-rich facies: origin, preservation and palaeoenvironmental constrains

The organic-rich facies of the MLOF mb vary between massive dark marls to true black shales (see Duarte *et al.*, 2010; Silva *et al.*, 2011b, 2012; Silva, 2013). The former are often bioturbated and macrofauna is rarely present. The black shales usually have a net laminated base, sometimes non-bioturbated over a few centimetres. Generally, they grade upwards to a more bioturbated (mainly *Phymatoderma* and *Chondrites*) calcareous facies where benthonic and nektonic macrofauna is abundant (Silva, 2013). From the analysis of the TOC vertical variation, Duarte *et al.* (2010 and references therein) defined three main organic-rich intervals, dated from the Davoei and Margaritatus zones, which present, at Peniche, maximum TOC values of 12, 15 and 15%, respectively.

The palynofacies analysis and the study of the origin-related biomarkers show that the organic matter of this interval consists in a variable mixture of marine and continental components, preserved in a marine environment and under variable redox conditions (e.g., Ferreira *et al.*, 2010; Silva *et al.*, 2012) (Fig. 7B and C).

Carbonate and kerogen carbon isotopic data obtained in the Peniche section (Silva *et al.*, 2011b) allow demonstrating a relationship between an episode of accumulation and preservation of organic matter in the LB and a global perturbation of the carbon cycle (e.g., Jenkyns & Clayton, 1986). Comparing the geological record of the LB with several others worldwide, Silva *et al.* (2011b) suggested that the

Pliensbachian interval was characterized by several well constrained episodes (at least of regional extension) of deposition and preservation of organic matter (the late Pliensbachian Organic Matter Preservation Interval), which, interestingly, preceded the T-OAE (e.g., Hesselbo *et al.*, 2007).

Biogeochemical studies performed across the basin show that carbohydrates and proteins are present in low concentrations, reaching up to 385.13 and 451.13 µg/g rock, respectively (Fig. 7D). The main variations are observed in the lipid contents, ranging from 197.67 to 8446.36 µg/g rock, reached at Peniche. The samples with the highest amounts of lipids seem to correlate with low [O₂] time intervals, suggesting selective lipid preservation under oxygen depleted and hydrogen sulfide-rich environments (Silva *et al.*, 2012).

5. Stop 3. The Pliensbachian-Toarcian boundary at Ponta do Trovão (R. B. Rocha)

The Global Stratotype Section and Point (GSSP) for the lower boundary of Toarcian Stage was recently proposed at the base of micritic limestone bed 15e at Ponta do Trovão (39°22'15"N, 9°23'07"W), in the topmost part of the Lemedo Fm and marked by the first appearance of several species of *Dactyloceras* (*Eodactylites*) sp. (see Elmi, 2006; Rocha, 2007; Rocha *et al.*, 2013). The uppermost part (around 1m thick) of this unit, as well as the stratigraphic distribution of ammonite taxa, were described by Choffat (1880) and Mouterde (1955) as a particular unit named *Couches de passage* (Transition beds). These have yielded a continuous and diversified fossil record and have been intensively sampled. Shells are commonly concentrated, forming irregular heaps. *Plicatula* and serpulids are fixed on ammonite shells or casts. Because of these features, the *Couches de passage* are interpreted as being deposited under a low sedimentation rate regime although hiatuses did not occur. The highest bed (15e) has yielded a characteristic association of dactyloceratids that is classically interpreted as marking the beginning of the Toarcian. The detailed description of the *Couches de passage* succession is presented here, from the bottom to the top (Elmi *et al.*, in Rocha, 2007) (Figs 8 and 9):

Emaciatum/Spinatum Zone, Elisa/Hawskerense Subzone

Bed 15a (0.15 m) – It corresponds to the *Canavaria* bed. Bioturbated, micritic limestone with some irregular nodular lumps. *Canavaria zancleana* (Fucini) is associated with *Emaciatoceras emaciatum* (Catullo), *E.*

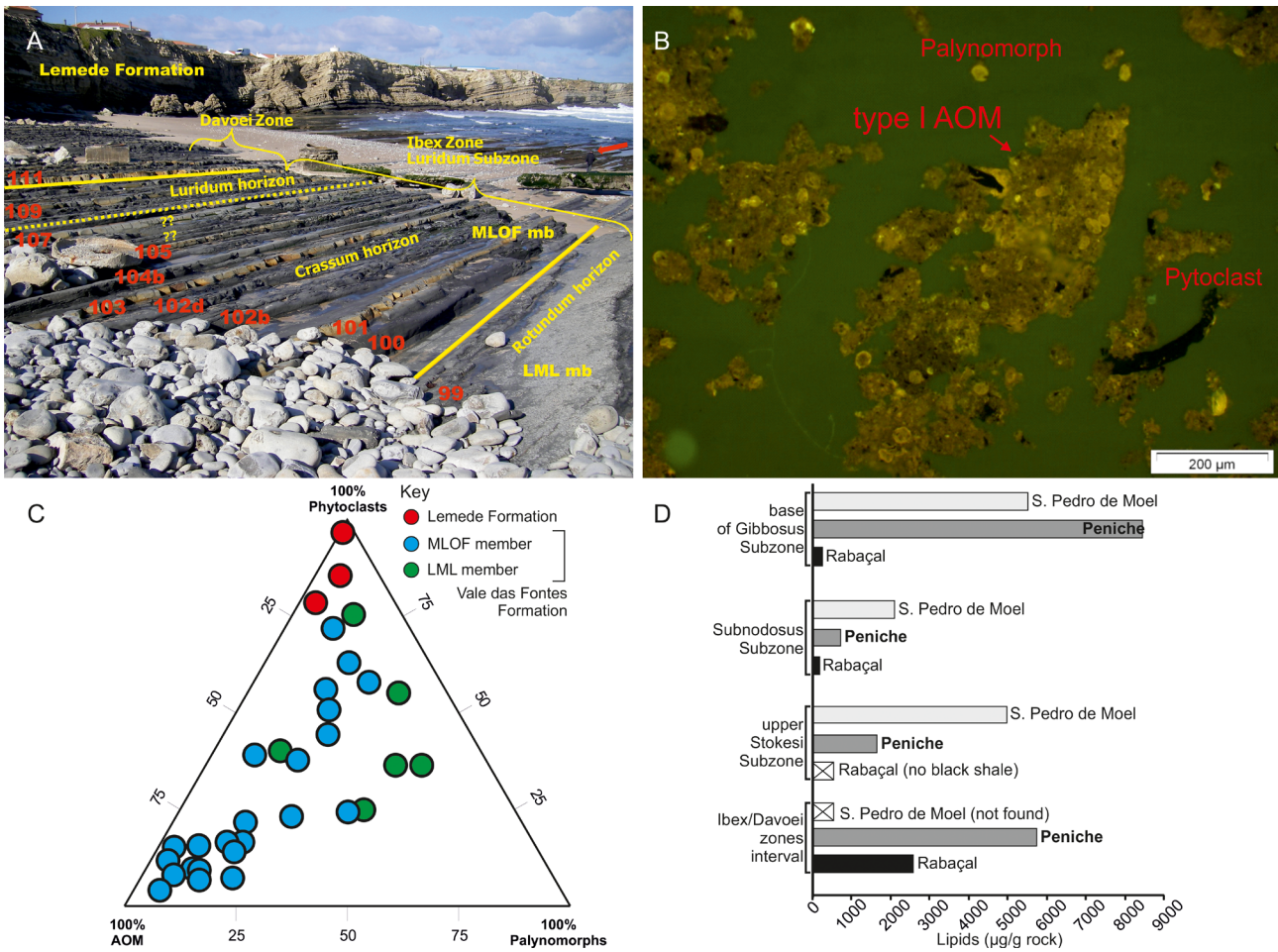


Fig. 7 – A - Base of the MLOF mb and biostratigraphy (in Silva, 2013). B - Palynofacies sample evidencing the dominance of marine Amorphous Organic Matter (AOM) (modified from Silva *et al.*, 2012). C - Amorphous Organic Matter-Phytoclasts-Palynomorphs ternary plot for part of the Pliensbachian series at Peniche (modified from Ferreira *et al.*, 2010). D - Lateral and temporal variation of the lipids content in the Rabaçal, Peniche and S. Pedro de Moel outcrop sections (modified from Silva *et al.*, 2012).

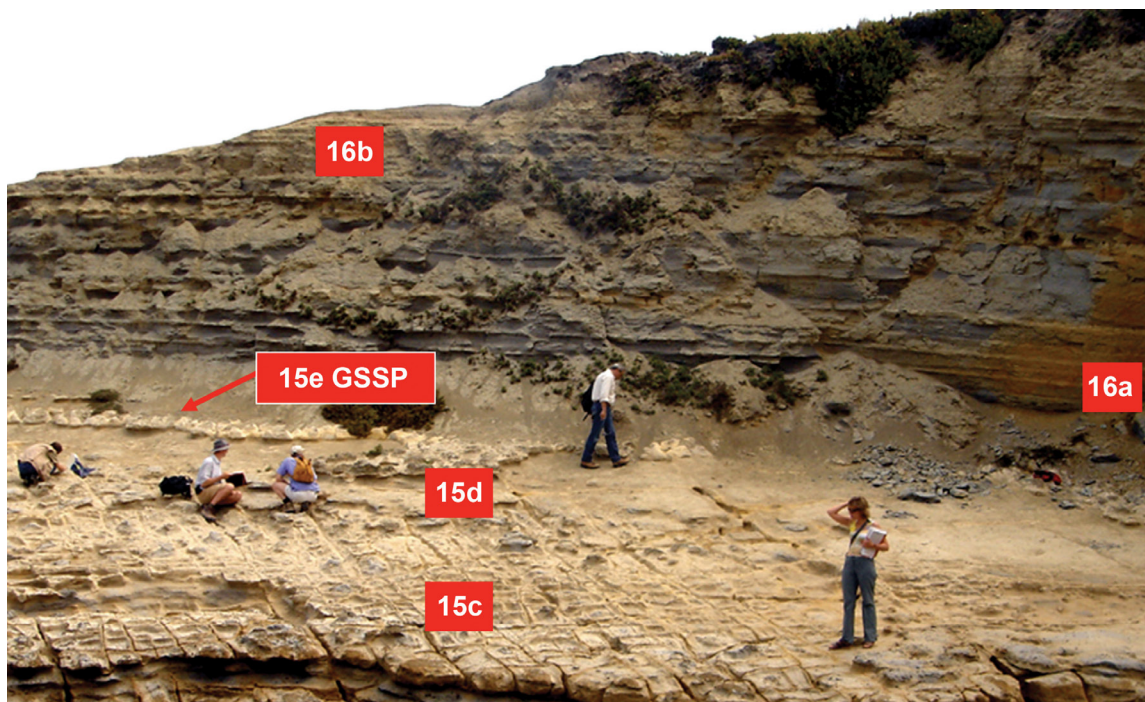


Fig. 8 - Detail of the Couches de passage (levels 15a-15e) at the top of the Lemedo Fm (level 15e). The boundary between 15d and 15e marks the Pliensbachian-Toarcian boundary at Ponta do Trovão (Peniche).

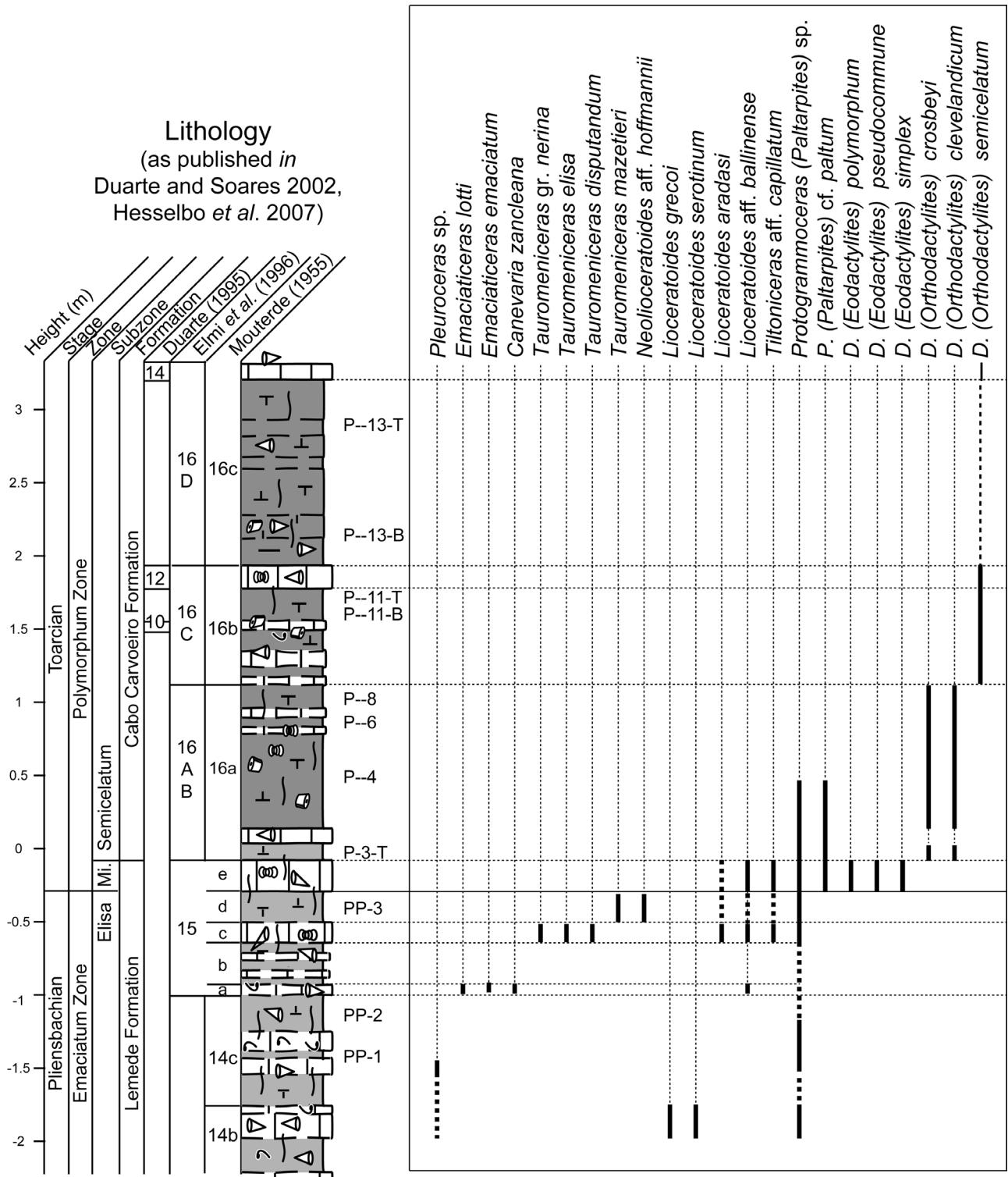


Fig. 9 - Detailed ammonite record across the Pliensbachian-Toarcian boundary at Ponta do Trovão (Peniche) (after Elmi *et al.* 1996; Elmi *et al.*, in Rocha, 2007; Rocha *et al.*, 2013; modified).

lotti (Fucini) and *Lioceratoides* aff. *ballinense* (Haas).

Bed 15b (0.25/0.30 m) - Calcareous laminated marls with brachiopods (*Zeilleria* sp.), belemnites, gastropods and bivalves [*Plicatula* (*P.*) *spinosa* (Sowrby) var. *pectinoides* (Lamarck)].

Bed 15c (0.25/0.30 m) – It is also known as the *Taoumeniceras* bed. It is formed of bioturbated mic-

ritic limestones, with *Taoumeniceras elisa* (Fucini), *T. disputandum* Dubar, *T. gr. nerina* (Fucini), *Lioceratoides aradasi* (Fucini), *L. aff. ballinense* (Haas), *Tiltoniceras* aff. *capillatum* (Denckmann), *Protogrammoceras* (*Paltarpites*) sp., *Spiriferina* gr. *rosstrata* Schlotheim and *P. (P.) spinosa* var. *pectinoides* (Lamarck).

Bed 15d (0.20/0.30 m) - It corresponds to a marly limestone enriched in belemnites and spiriferinids. *Tauromeniceras mazetieri* (Dubar), *Neolioceratoides* aff. *hoffmanni* (Gemmellaro), *Spiriferina* gr. *rostrata* Schlot., *Zeilleria* sp. and *P. (P.) spinosa* var. *pectinoides* (Lam.) are commonly recorded taxa.

Polymorphum/Tenuicostatum Zone, Mirabile/Paltum Subzone

Bed 15e (0.20 m) – This corresponds to the *Eodactylites* bed, composed of micritic limestone bearing numerous ammonites, many of those occurring at the top of the bed. Ammonites generally correspond to oxidized-pyrite internal moulds. *Eodactylites* are abundant and diversified: *Dactylioceras (Eodactylites) simplex* (Fucini), *D. (E.) pseudocommune* Fuc., *D. (E.) polymorphum* Fuc. The association of *D. (O.)*

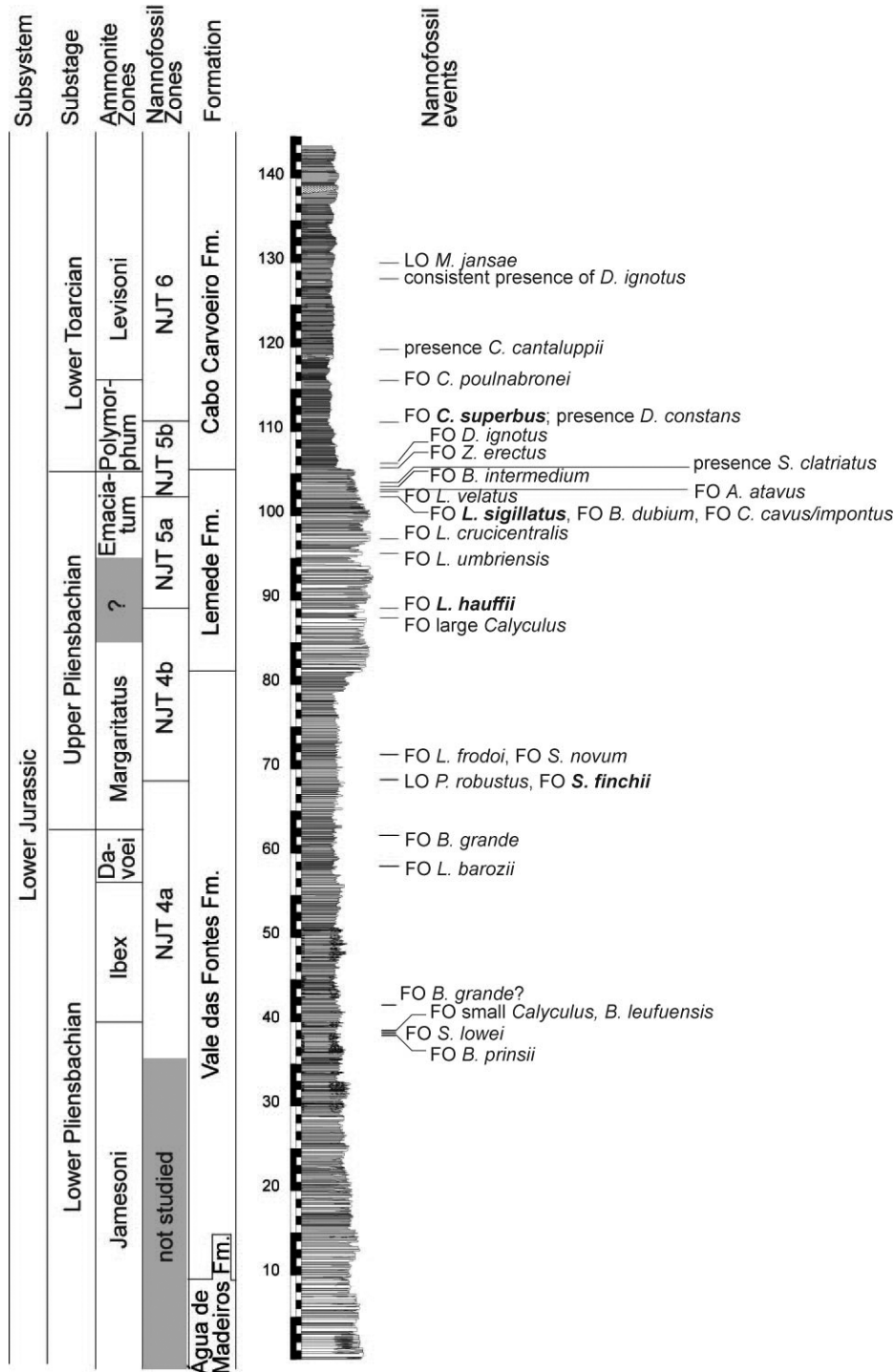


Fig. 10 - Stratigraphic positions of calcareous nannofossil events, both first occurrence (FO) and last occurrence (LO) in the Pliensbachian to lower Toarcian interval of the Peniche section.

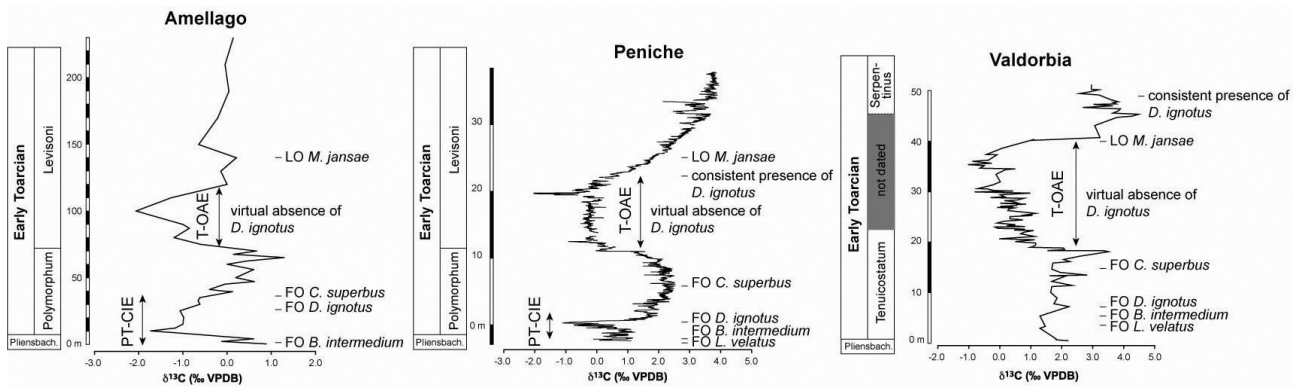


Fig. 11 - Comparison of carbon isotope record and the succession of calcareous nannofossil events of the Peniche section with Amellago (Morocco; Bodin *et al.*, 2011) and Valdorbia [central Italy; isotope data from Sabatino *et al.* (2009); nannofossil biostratigraphy was previously established by Reale *et al.* (1992); the same samples as Sabatino *et al.* (2009) were re-studied by E.M., unpublished data].

simplex with *D. (O.) pseudocommune* may indicate a slight condensation, compared to data from the Iberian Ranges. This interpretation, however, requires further confirmation from data collected in other areas. Other ammonites recorded in the *Eodactylites* bed testify the survival of late Pliensbachian specimens, such as *Tiloniceras aff. capillatum* (Denck.) and *Lioeratooides aff. ballinense* (Haas). The presence of *Protogrammoceras (Paltarpites) cf. paltum* (Buck.) in this bed is especially important for correlations with NW Europe. Brachiopods (*Spiriferina* sp., *Zeileria* sp. and *Rhynchonella* sp.), belemnites and bivalves [*P. (P.) spinosa* var. *pectinoides* (Lam.)] are also common. This bed marks the beginning of the Toarcian (Mirabile/Paltum Subzone of the Polymorphum/Tenuicostatum Zone).

Polymorphum/Tenuicostatum Zone, Semicelatum Subzone

Bed 16a (1.70 m) – Bed 16 marks the lower part of the Cabo Carvoeiro Fm. The lowest two metres of this marl-dominated unit contain small pyritized internal moulds of specimens attributed to NW European species of *Orthodactylites* namely, *D. (O.) crosbeyi* (Simpson), *D. (O.) clevelandicum* Howarth, associated with *Protogrammoceras (Paltarpites)* sp. The record of these specimens allows a tentative correlation with the Crosbeyi/Clevelandicum Subzone of Britain, and supports the hypothesis that the absence of *Eodactylites* in many classic NW European sections is due to a sedimentary gap, rather than to a palaeogeographical controlled distribution of this genus. This bed also yields an abundant assemblage of belemnites, gastropods and brachiopods. Bioturbation is widespread (*Zoophycos* and pyritised tubular burrows). The upper part of Bed 16 contains several fossiliferous layers yielding mainly *D. (O.) semice-*

latum (Simpson). These ammonites are commonly found in random orientation, probably as a result of bioturbation.

6. Stop 4. The early Toarcian anoxic event (E. Mattioli, B. Pittet¹ & G. Suan¹)

6.1. Calcareous nannofossil stratigraphy

Several nannofossil events, both first (FO) and last occurrences (LO), characterize the Pliensbachian and the lower Toarcian interval and allow the recognition of three nannofossil zones (NJT 4 to NJT 6) and four subzones (Fig. 10). Concerning the uppermost Pliensbachian–lower Toarcian interval, the FOs of *L. crucicentralis* and of *L. velatus* in the upper part of the Emaciatum Zone are of particular interest as these two species were previously reported from the lower Toarcian (Bown & Cooper, 1998; Mattioli & Erba, 1999; Mattioli *et al.*, 2008). It is worth to notice that the oldest recorded *L. velatus* have all the diagnostic characters described by Bown & Cooper (1989), but are slightly smaller in size and the rim is thinner.

Another intriguing biostratigraphic pattern of the Peniche section is the FO of *D. ignotus* at the base of the Polymorphum Zone, basal Toarcian, whilst in previous works this event was noticed in the upper part of the lower Toarcian (Bown, 1987; Mattioli & Erba, 1999; Mattioli *et al.*, 2004, 2008). In the Amellago section, Morocco (Bodin *et al.*, 2010) and in Valdorbia section, Central Italy (personal observation), *D. ignotus* is similarly first recorded in the basal Toarcian (Fig. 11). A possible explanation of this discrepancy is due to the fact that the basal Toarcian sediments are often very condensed or lacking due to hiatuses occurring in many Western Tethyan areas,

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(Wignall, 1991; Morard *et al.*, 2003; Röhl & Schmid-Röhl, 2005; Léonide *et al.*, 2012), but not in Peniche and Amellago. Furthermore, *D. ignotus* behave as a Lazarus species being absent from the sediments corresponding to the T-OAE in Peniche and Amellago. The consistent occurrence of *D. ignotus* is then recorded by the end of the T-OAE (Fig. 11).

Useful nannofossil events are: the FO of *D. ignotus* that occurs at the end of the Pliensbachian/Toarcian Carbon Isotope Event (PT-CIE), the FO of *C. superbis* that characterizes the positive carbon isotope rebound between the two main negative CIEs during the Pliensbachian/Toarcian and during the early Toarcian, and the LO of *M. jansae* that marks the end of the early Toarcian CIE.

6.2. Duration of the early Toarcian CIE

Spectral analysis of a dataset generated from the sedimentary record (wt.% CaCO₃) of the hemipelagic section of Peniche allowed Suan *et al.* (2008b) to establish a cyclostratigraphic calibration of the early Toarcian interval. A duration of ≥1.9 Myr for the early Toarcian was estimated and of ~900 kyr for the entire carbon isotope excursion (Fig. 12). The shift to-

wards lower carbon isotope values occurred in ~150 kyr, and carbon isotope values remained low for ~450 kyr; the subsequent increase of carbon isotope values lasted ~300 kyr. These results, although challenged by Kemp *et al.* (2011), were used in the recent Geological Timescale of Gradstein *et al.* (2012). Suan *et al.* (2008b) show that the OAE records a transition from eccentricity/precession dominated sedimentary cycles to eccentricity/obliquity cycles, suggesting that the Toarcian event was accompanied by a fundamental change in heat redistribution on the Earth's surface that made the obliquity signal, normally better recorded at high latitudes, giving the pace for the formation of short-term sedimentary cycles at low latitudes. This cyclostratigraphic calibration of the CIE implies a long-lasting carbon release and supports the hypothesis of a long-lasting CO₂ degassing, most likely related to the emplacement of the large igneous province of Karoo–Ferrar as the main cause of the Toarcian CIE. Suan *et al.* (2008b) results also indicate that abrupt and cyclical negative shifts in δ¹³C took place in less than 20 kyr at the onset of the CIE, suggesting that orbitally-paced pulses of carbon release may have occurred at the base of the CIE. A combination of two processes may then explain the

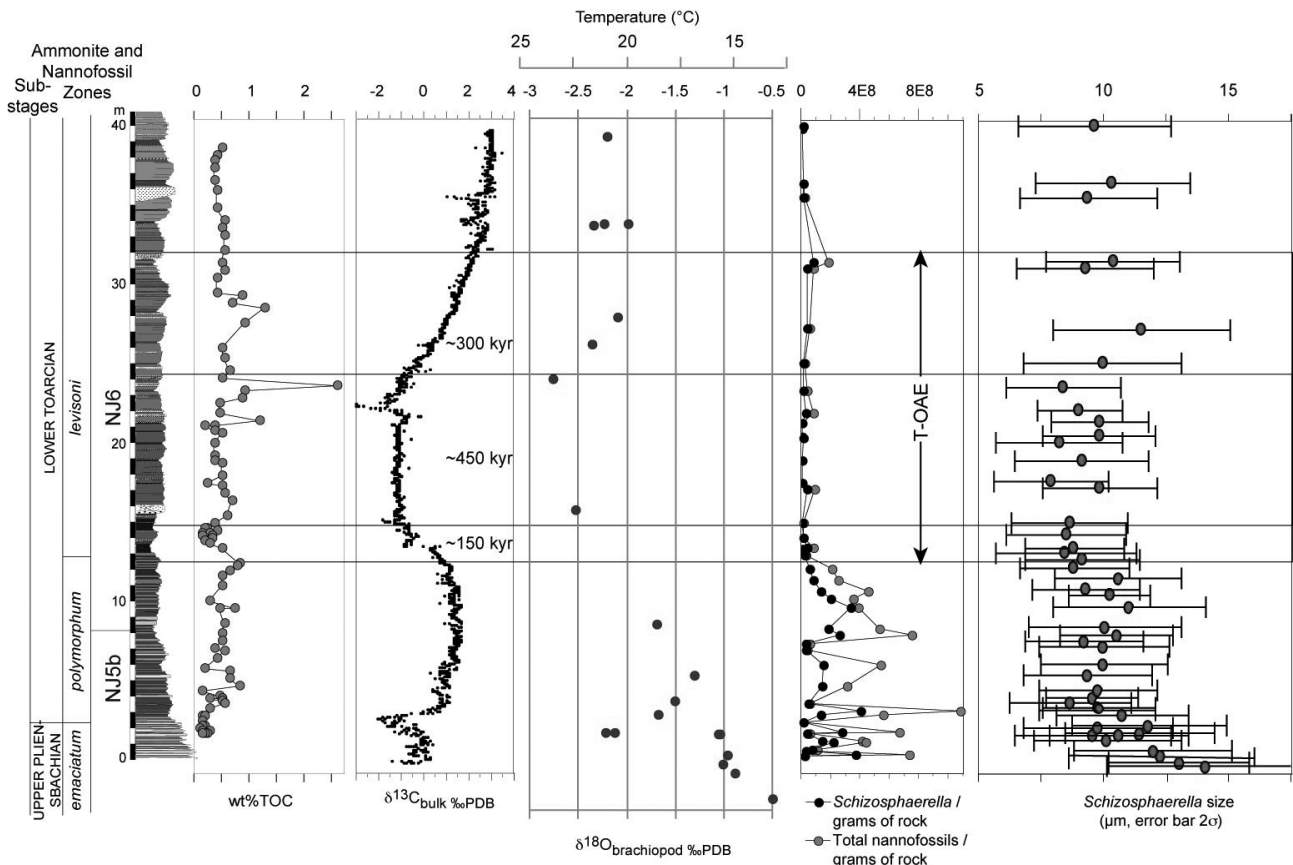


Fig. 12 - Comparison between the high-resolution TOC and carbon isotope curve (Hesselbo *et al.*, 2007), oxygen isotopes measured on brachiopod calcite, nannofossil absolute abundance and *Schizosphaerella* size (Suan *et al.*, 2008a).

development and duration of the CIE, involving brief pulses of gas hydrate destabilisation in the early phases of Karoo–Ferrar eruption followed by long-lasting release of isotopically light carbon via volcanism.

6.3. Palaeoenvironmental changes during the early Toarcian CIE: evidence from calcareous nannofossils

A quantification of nannofossil size and absolute abundance performed on the upper Pliensbachian–lower Toarcian marl–limestone alternations of the Peniche section (Fig. 12) reveals that calcareous nannofossil abundance per gram of rock is very high in the uppermost Pliensbachian and lowermost Toarcian but values are drastically lower in the interval of rock corresponding to the T-OAE (Mattioli *et al.*, 2008, 2009; Suan *et al.*, 2008a, 2010). The size of *Schizosphaerella (incertae sedis)*, a major carbonate producer during the Jurassic, shows the highest values in the uppermost Pliensbachian, with lower values in the interval corresponding to the CIE of the Pliensbachian–Toarcian boundary. A size recovery occurs in the basal Toarcian, with a second, more drastic decrease in the negative carbon isotope excursion recorded in the lower Toarcian (Fig. 12). Coeval shifts to lower values of brachiopod oxygen isotope compositions and closely correlated northward migrations of Mediterranean ammonite fauna suggest that both C isotope negative excursions and *Schizosphaerella* size decreases coincided with major rises in seawater temperatures (Suan *et al.*, 2008a). The results of Suan *et al.* (2008a, 2010) and Mattioli *et al.* (2008, 2009) indicate that these two excursions occurred synchronously with significant carbonate production crises in both neritic and pelagic domains, as suggested by concomitant decreases in platform-derived carbonate mud and dramatic reductions in the size of the main pelagic carbonate-producer *Schizosphaerella*. These data are best explained by two distinct phases of massive release of isotopically light CO₂ and enhanced greenhouse conditions, which in turn affected the calcification potential and trophic levels of both pelagic and neritic systems.

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