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FIELD TRIP GUIDE BOOK

The Lower Jurassic organic-rich facies in the Lusitanian Basin (Portugal)

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Field Trip Guide Book

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Preface

On behalf of the Organizing Committee, we are pleased to welcome you to the field trip of the **77th Annual Meeting of the International Committee for Coal and Organic Petrology (ICCP)**, entitled "The Lower Jurassic Organic-Rich Facies in the Lusitanian Basin, Portugal".

This field trip is an integral part of the scientific programme of the 77th ICCP Annual Meeting and has been organised by the University of Coimbra, the University of Minho, and the Federal University of Rio de Janeiro. It provides an opportunity to explore some of the most representative Lower Jurassic successions of the Lusitanian Basin and to discuss their sedimentological, stratigraphic, palaeoenvironmental and organic geochemical significance directly in the field.

Over the course of the field trip, we will travel along the central western coast of Portugal, from São Pedro de Moel to Peniche, visiting exceptional coastal exposures that document the Early Jurassic evolution of the Lusitanian Basin. These successions provide an outstanding record of the interplay between sedimentation, environmental change, organic matter accumulation and preservation, and major perturbations of the global carbon cycle.

Particular attention will be given to the Lower Jurassic organic-rich intervals and to the geological record associated with the Toarcian Oceanic Anoxic Event (T-OAE). The field observations will provide the basis for discussing changes in depositional environments and organic matter characteristics within the broader context of the Early Jurassic palaeoenvironmental evolution of the Lusitanian Basin.

The itinerary will culminate at Ponta do Trovão, Peniche, an internationally recognised reference section for the Lower Jurassic and the location of the Global Stratotype Section and Point (GSSP) for the base of the Toarcian Stage. Here, participants will have the opportunity to examine this remarkable stratigraphic succession and, of course, take a memorable photograph with the iconic "golden spike".

This Field Guide was prepared to provide participants with the geological and stratigraphic framework necessary to accompany the observations and discussions throughout the excursion. We hope that it will serve not only as a practical guide during the field trip, but also as a useful reference for understanding the Lower Jurassic record of the Lusitanian Basin and its significance for the study of organic-rich sedimentary systems and major palaeoenvironmental changes.

We would like to thank all those who contributed to the preparation and organisation of this field trip and Field Guide. Most importantly, we thank all participants for joining us and hope that these two days will provide an enjoyable opportunity for scientific discussion, exchange of ideas, and the development of new collaborations and friendships.

We wish you an excellent field trip and hope you enjoy discovering the geology and landscapes of the Portuguese Atlantic coast.

The Field Trip Organizers

The Lower Jurassic organic-rich facies in the Lusitanian Basin (Portugal)

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I. General Introduction

One of the most complete and well-exposed Lower Jurassic successions is preserved in the Lusitanian Basin (hereinafter referred to as the LB), located in the western sector of the Iberian Peninsula. This succession is largely composed of thick marine carbonate deposits (e.g., Soares et al., 1993; Azerêdo et al., 2003; Duarte, 2004, 2007; Duarte et al., 2010, 2018; Silva et al., 2015). Part of this succession, corresponding to the interval between the Sinemurian and Toarcian stages, is characterized by marl–limestone alternations. According to the lithostratigraphic framework proposed by Duarte and Soares (2002) for the central–northern sector of the basin, this interval comprises the Coimbra, Água de Madeiros, Vale das Fontes, Lemede and S. Gião formations, together with their lateral equivalents, the Cabo Carvoeiro and Prado formations. Over the last two decades, these units have been the focus of extensive research in sedimentology, stratigraphy and geochemistry, including elemental geochemistry, stable carbon and oxygen isotope geochemistry, and organic geochemistry. The distinctive Sinemurian and Pliensbachian sedimentary record, including organic matter (OM)-rich intervals, together with the major sedimentological changes observed between the Pliensbachian and Middle Toarcian (see Duarte, 1997, 2007), has provided the basis for numerous studies addressing chemostratigraphic, palaeoceanographic and palaeoenvironmental evolution (e.g., Duarte, 1997, 1998; Duarte et al., 2004, 2007, 2010, 2012, 2014, 2022; Oliveira et al., 2006; Hesselbo et al., 2007; Suan et al., 2008a, 2008b, 2010; Mattioli et al., 2009; Azerêdo et al., 2010; Poças Ribeiro et al., 2011; Silva et al., 2011, 2012, 2015, 2021, 2025; Rocha et al., 2016; Fantasia et al., 2019; Ferreira et al., 2019; Muller et al., 2020; Rodrigues et al., 2020; Ullmann et al., 2020). Several of these studies have had a significant international impact, particularly those addressing the Toarcian Oceanic Anoxic Event (T-OAE). This scientific importance is further enhanced by the exceptional quality and continuity of the outcrops and by the palaeogeographic position of the LB, located at the interface between the Atlantic and Tethyan realms (Figure I.1).

Several outcrops of the LB are of major importance for the scientific knowledge and study of the Lower Jurassic (Duarte and Soares, 2002; Duarte, 2007). In this context, and considering the importance and role of the OM in the sedimentation dynamics during this time interval, for this field trip is proposed the examination of the S. Pedro de Moel and Peniche areas (Figure I.2). These two locations constitute worldwide references for the study of Lower Jurassic, from the palaeoenvironmental to oil generation perspective, complemented by an important geological heritage and spectacular scenic environment (Duarte, 2004; Duarte et al., 2017). In addition to the observation of the different sedimentary characteristics, several aspects of organic (Total Organic Carbon, Rock-Eval pyrolysis, Palynofacies and Biomarkers) and isotopic (carbon and oxygen stable isotopes) geochemistry will be presented and discussed. Based on an extensive knowledge of the stratigraphy of the S. Pedro de Moel and Peniche areas/sections, these data will be integrated in terms of depositional environments, global context and the potential for hydrocarbon generation.

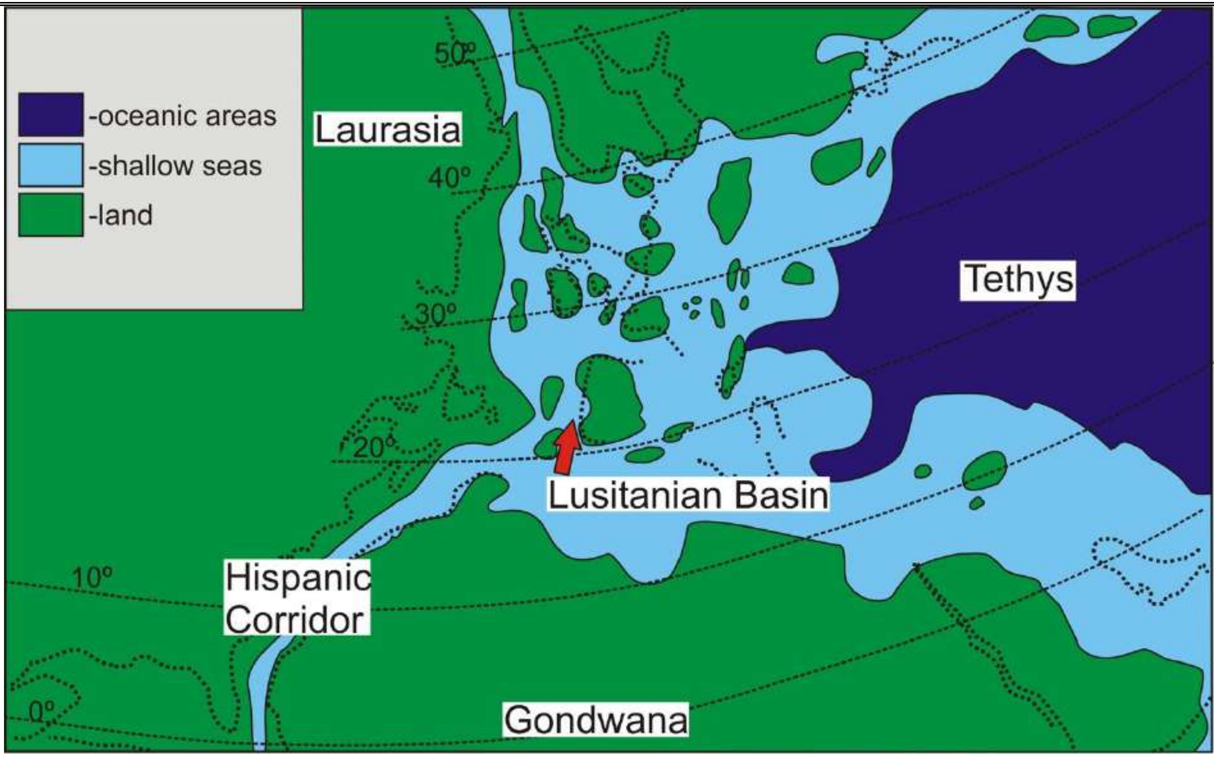

Figure I.1. Western Tethys palaeogeography and location of the Lusitanian Basin during the late Early Jurassic (modified and simplified from Bassoulet et al., 1993).

1. Outline of the Mesozoic evolution of the Lusitanian Basin

1.1. The Lusitanian Basin

In Portugal, the main Mesozoic onshore records are positioned in two very distinct geostructural contexts located to the west (LB) and south (Algarve Basin) of the Hesperian Massif (Figure I.2). The LB is a narrow and small North–South elongated basin limited to the west by the Variscan (granitic and metamorphic) Berlenga Horst (e.g., Wilson et al., 1989; Pinheiro et al. 1996; Kullberg et al., 2013). To the east, it is bounded by the Porto–Tomar shear zone. The LB had its origin in the Triassic, as the result of the extensive phase that preceded the genesis of the North and Central Atlantic Ocean (Kullberg et al., 2013; among others). In the western portion of the Hesperian Massif, this phase is materialized by the formation of half-grabens (conditioned by the basement preexistent structures), originally filled by a thick siliciclastic series of continental nature that corresponds to the Silves Group (red beds; Palain, 1976; Soares et al., 2012; Vilas-Boas et al., 2021). From the Jurassic to the Late Cretaceous, the sedimentary infill includes a great variety of sediments, facies and palaeoenvironmental changes. In terms of the LB sedimentary evolution, several phases have been identified, bounded by regional unconformities (e.g., Wilson et al., 1989; Pinheiro et al., 1996; Kullberg et al., 2013). The first cycle, ranging from the Triassic–Callovian, includes the stratigraphic interval here presented and discussed (Figure I.3).

1.2. The Lower Jurassic in the Lusitanian Basin

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 (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 (Sinemurian), which is the first truly carbonated unit represented at a basinal scale (Figure I.3). It is composed by a succession of dolostones and limestones, with the later lithotype being more expressive at the top of the unit and in its most western sectors, corresponding to a marginal-marine palaeoenvironmental setting (Azerêdo et al., 2010; Dimuccio et al., 2016; Duarte et al., 2022). During the late Sinemurian, namely in the west of the basin (Peniche, S. Pedro de Moel and Figueira da Foz), the sedimentation is characterized by a marl–limestone series with ammonites and rich in OM (Água de Madeiros Formation). This unit (subdivided into the Polvoeira and Praia da Pedra Lisa members according to Duarte and Soares, 2002; Duarte et al., 2010) marks the onset of the development of open marine conditions in the basin. This fine grained sedimentation extends throughout the basin during the Lower Pliensbachian–Upper Toarcian interval, corresponding to the Vale das Fontes (subdivided into the Marls and limestones with *Uptonia* and *Pentracinus*, Lumpy marlstones and limestones and Marly limestones with organic facies members), Lemede, S. Gião (subdivided into the Marly limestones with *Leptaena* facies, Thin Nodular Limestones, Marls and marly limestones with *Hildaites* and *Hildoceras*, Marls and marly limestones with sponge bioconstructions and Marls and marly limestones with brachiopods) and Póvoa da Lomba formations (e.g., Duarte, 1997; Duarte et al., 2001, 2004, 2010; Silva et al., 2015).

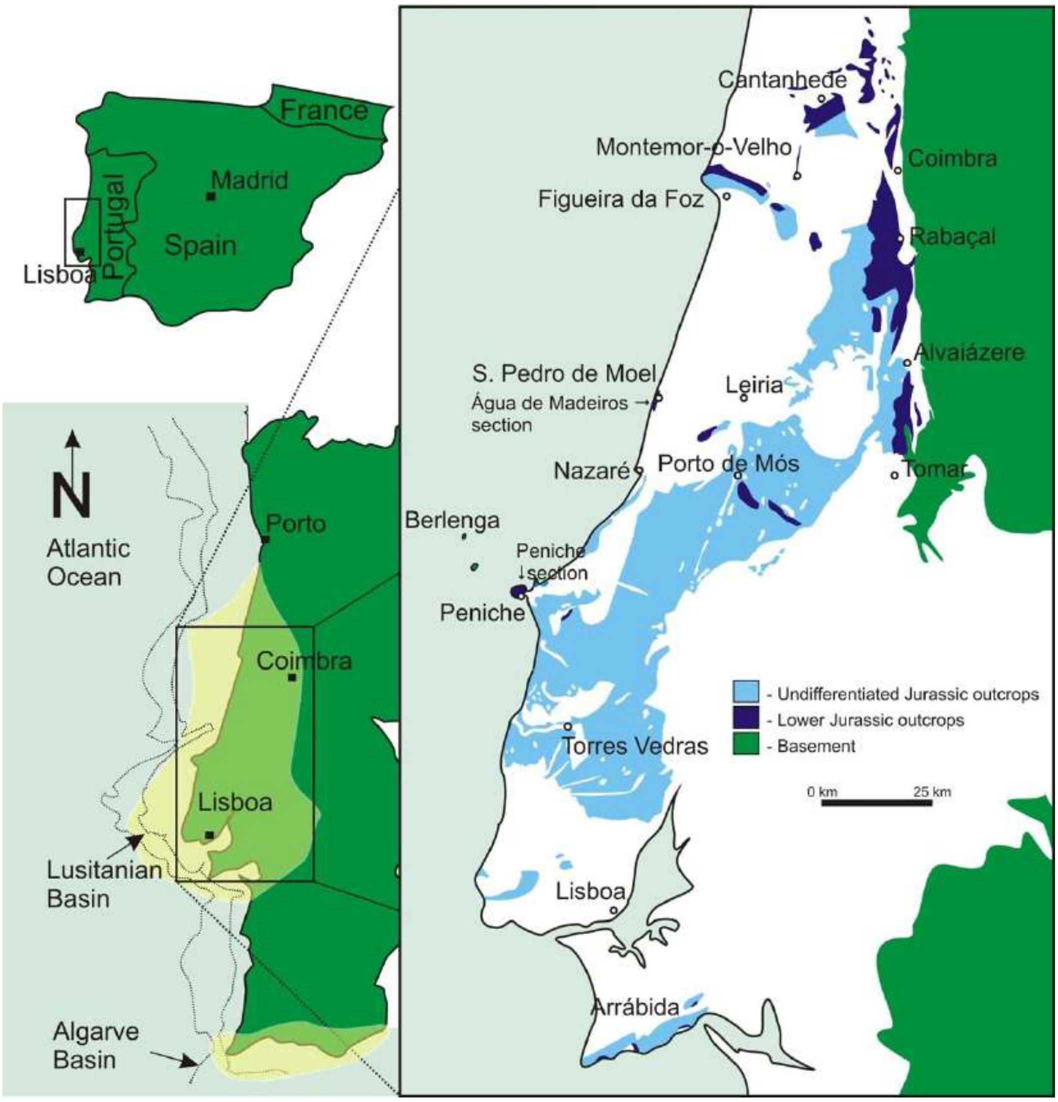

Figure I.2. Simplified geological map of the central-northern part of the Lusitanian Basin (Portugal) and distribution of the carbonate units of Lower Jurassic age. Location of the S. Pedro de Moel and Peniche sections (modified from Duarte et al., 2010).

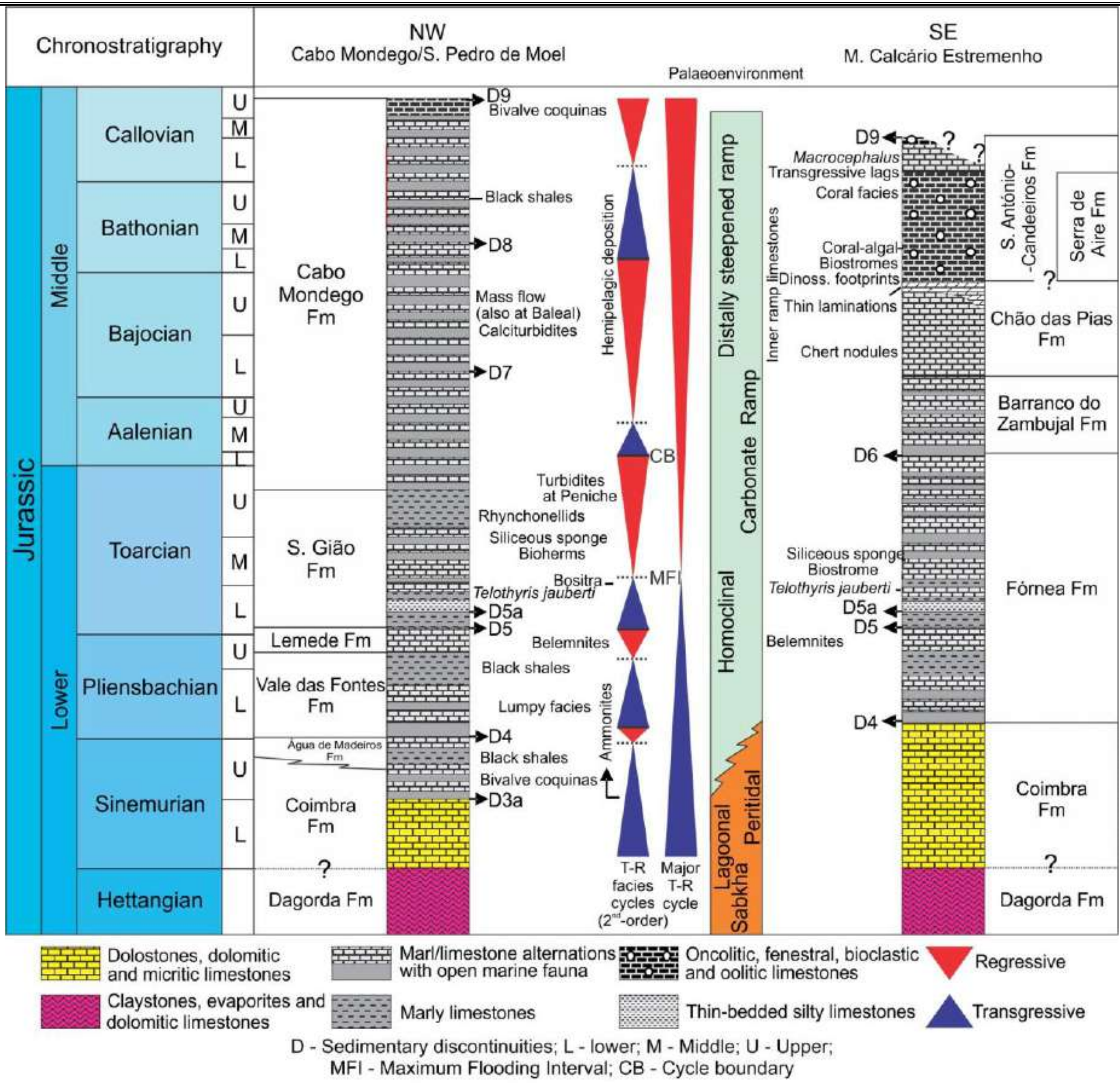

Figure I.3. Stratigraphic units and main sedimentological features of the Lower and Middle Jurassic series in two extreme sectors of the LB (modified from Azerêdo et al., 2003, 2014).

In fact, the Pliensbachian–Toarcian interval is characterized by significant marl–limestone deposition, locally displaying a clear rhythmic pattern and yielding abundant benthic macrofossils (bivalves, brachiopods, crinoids and siliceous sponges) and nektonic macrofossils (ammonites and belemnites). The ammonites and calcareous nannofossils recorded in these units provide a high-resolution biostratigraphic framework for the succession (e.g., Phelps, 1985; Perilli and Duarte, 2006; Correia et al., 2018; Rocha et al., 2016; Ferreira et al., 2019; Vitón et al., 2026; and references therein). The limited lateral facies variation observed across the basin suggests that these sediments were deposited in a marine carbonate-ramp system dipping towards the west–northwest and controlled by N–S and NE–SW tectonic trends (Duarte, 1997, 2007; Silva et al., 2015) (Figure I.4). Despite the general hemipelagic nature of the sedimentation, distinctive sedimentary features can be recognized at several locations in the southern half of the LB, including Arrábida (Meia Velha Formation), Tomar (Prado Formation) and Peniche (Cabo Carvoeiro Formation) (Manuppella and Azerêdo, 1996; Duarte, 1997; Duarte and Soares, 2002) (Figure I.2). In the latter region, the occurrence of siliciclastic and resedimented oolitic deposits during the Toarcian further supports a palaeogeographic configuration controlled by the uplift of the western igneous Berlenga block (Wright and Wilson, 1984; Duarte, 1997; Suan et al., 2008b; Barata et al., 2021).

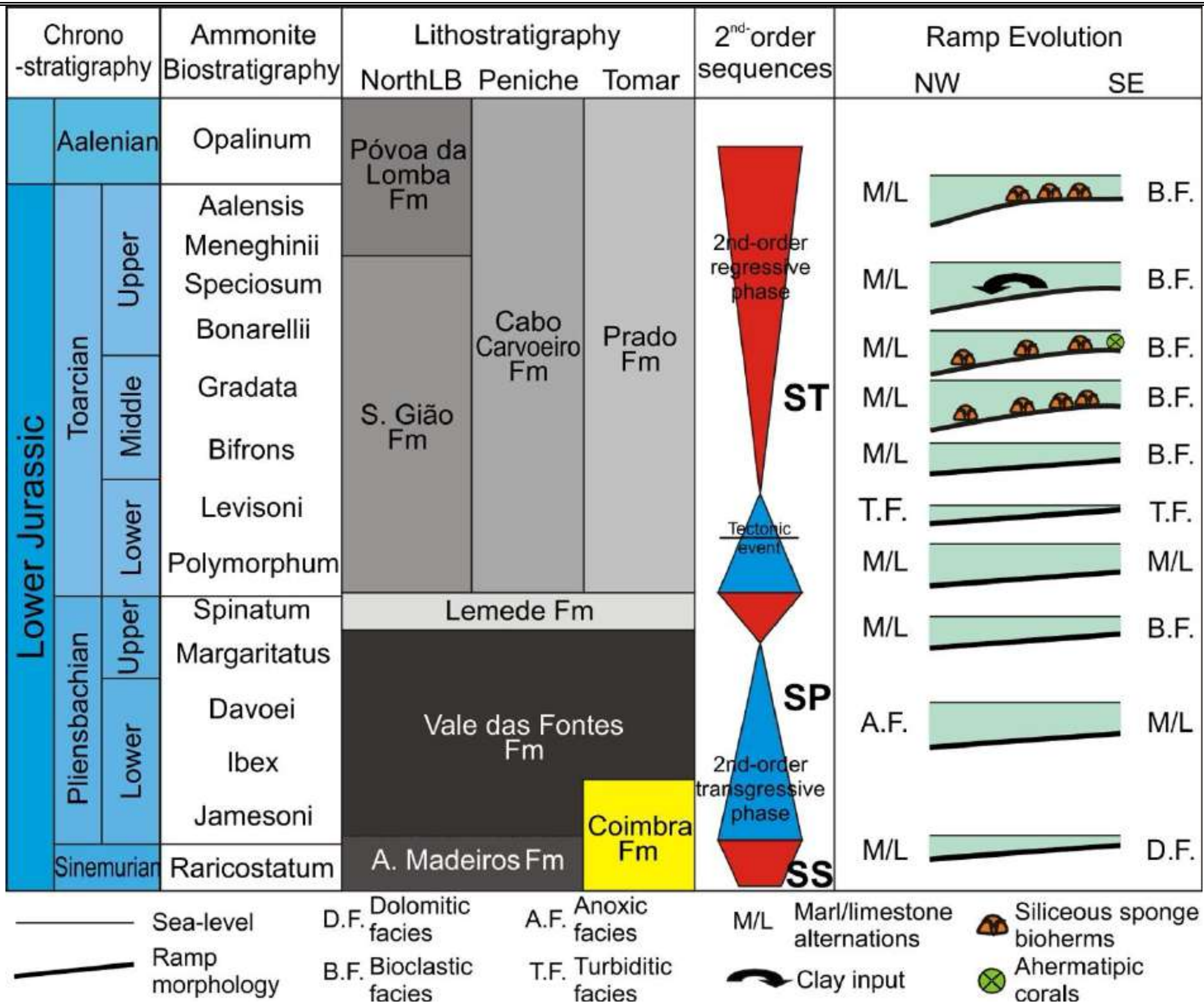

Figure I.4. Stratigraphic chart for the Late Sinemurian – Early Aalenian succession in a great part of the LB (modified from Duarte et al., 2001; Duarte, 2007).

2. The organic-rich facies: characterization and stratigraphic distribution

As stated earlier, the occurrence and preservation of OM are major characteristics of the Lower Jurassic deposits of the LB. In recent years, numerous studies have focused on this feature, particularly on the quantification and characterization of OM in the Coimbra, Água de Madeiros, Vale das Fontes, Lemede and Cabo Carvoeiro formations (see Figure I.4), supported by an increasingly detailed understanding of sedimentological dynamics and a high-resolution stratigraphic framework (see references above). Several papers have addressed the distribution of Total Organic Carbon (TOC) across the basin, palynofacies, biomarkers, Rock-Eval pyrolysis and thermal maturity (e.g., Oliveira et al., 2006; Duarte et al., 2010, 2011a, 2011b; 2012, 2022; Poças Ribeiro et al., 2011; Silva et al., 2011, 2012, 2013, 2021; Brito et al., 2017, 2023).

The organic-rich facies are relatively similar across the basin and are characterized by grey to dark-grey colours, generally with distinct lamination and, locally, abundant pyrite. These organic-rich facies include black shales (Figures I.5a and I.5b), dark-grey marls (Figure I.5c) and thinly laminated limestones (Figure I.5d). Black shales ranging from the Sinemurian to the earliest late Pliensbachian occur in several units of the Coimbra Formation and in all members of the Água de Madeiros and Vale das Fontes formations, but are particularly well developed in the Polvoeira and Marly Limestones with Organic-Rich Facies (MLOF) members

(Figures I.6 and I.7). According to Duarte et al. (2010, 2012) and Silva et al. (2011, 2012, 2021), the highest TOC values exceed 20 wt.% in both units.

Figure I.5. **a**) Black shale level of the Vale das Fontes Formation at Peniche with TOC value of 26.3wt.%; **b)** Thin section of a black shale level of the Vale das Fontes Formation (Peniche), where is possible to observe marked lamination at microscopic scale; **c)** Grey marly facies and black shales levels from the Vale das Fontes Formation at S. Pedro de Moel; **d)** Thin laminated limestone facies of the Polvoeira Member at S. Pedro de Moel with a TOC value of 5.4 wt.%.

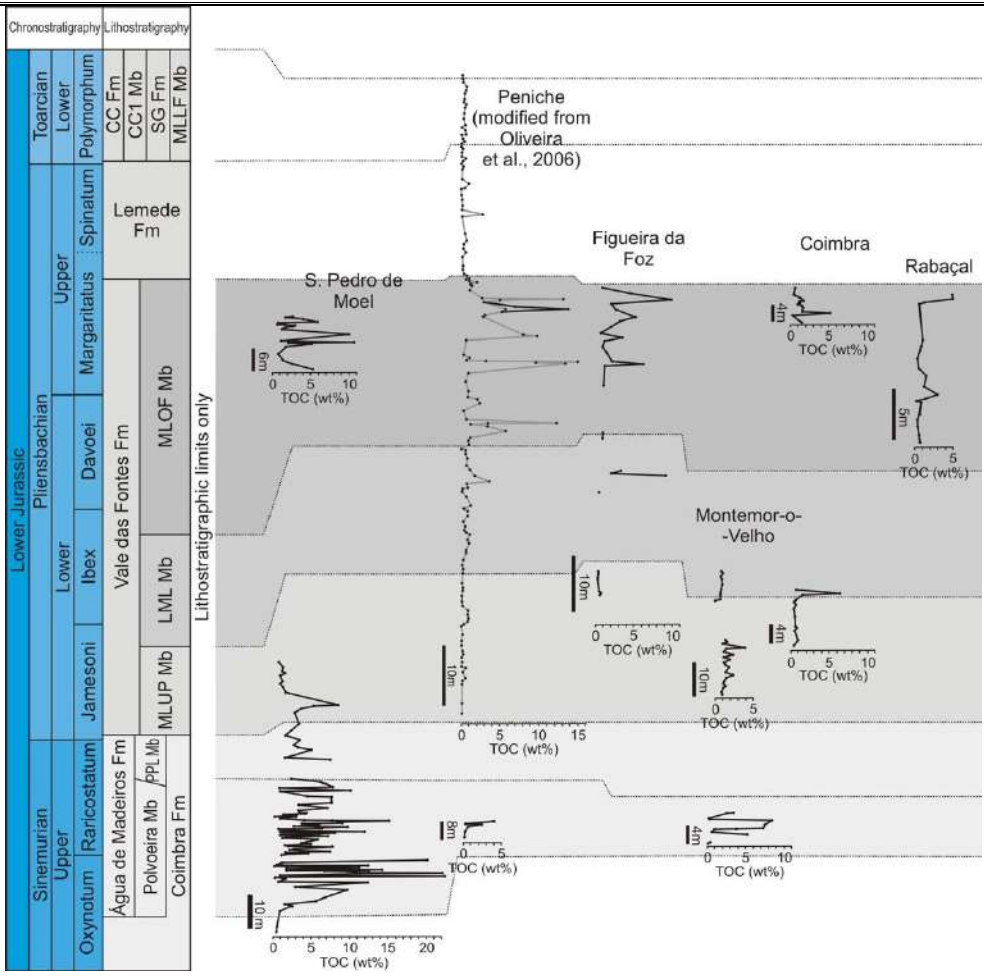

Figure I.6. TOC variation across the Lower Jurassic of the Lusitanian Basin (modified from Duarte et al., 2010).

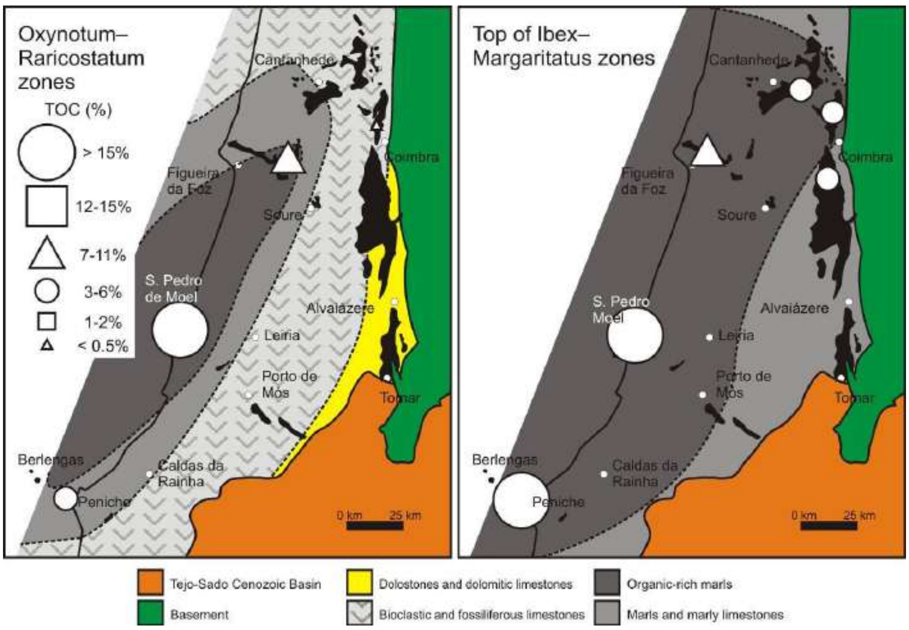

Figure I.7. Facies distribution maps and lateral TOC variation in the two most organic-rich Lower Jurassic intervals of the Lusitanian Basin: Oxynotum–Raricostatum (Polvoeira Member) and top of Ibex–Margaritatus (MLOF member) zone interval (modified from Duarte et al., 2010).

II. The Sinemurian and Pliensbachian organic-rich intervals at São Pedro de Moel

1. Introduction: the Lower Jurassic succession

The village of S. Pedro de Moel is located on the Atlantic coast, approximately 110 km north of Lisbon. Lower Jurassic outcrops in this area extend from Praia Velha to Polvoeira beaches and comprise a thick succession of carbonate and argillaceous (marly) units belonging to the Coimbra, Água de Madeiros, Vale das Fontes, Lemede and S. Gião formations. This succession spans the Lower Sinemurian to Middle Toarcian interval (Duarte and Soares, 2002; Duarte et al., 2008) and is unconformably overlain by Pliocene siliciclastic deposits and Holocene dunes (Zbyszewski and Assunção, 1965) (Figure II.1). Whereas the first three formations display a remarkably complete stratigraphic record, the latter two are poorly exposed owing to the intense fracturing affecting the area. As a consequence of the diapiric structure, the Lower Jurassic succession forms a broad synclinal structure, with the oldest Lower Jurassic unit, the Sinemurian Coimbra Formation, cropping out at both ends of the fold (Figure II.1a). This structural configuration gives rise to a distinctive coastal landscape in western Portugal (Duarte, 2004) (Figure II.2a).

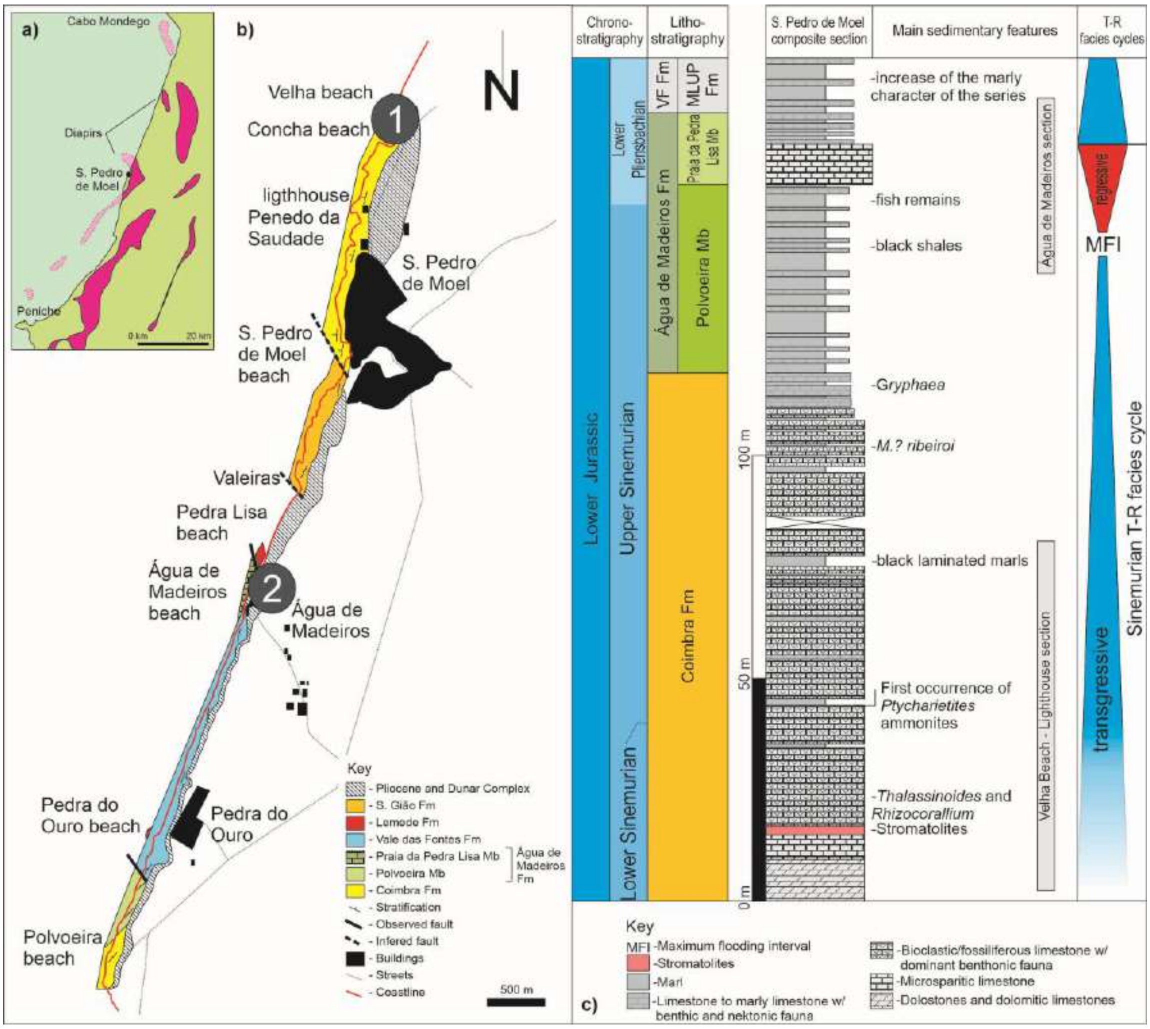

Figure II.1. **a**) Location of S. Pedro de Moel area and approximate geographic extension of the diapiric structures of the North-Central part of the Lusitanian Basin (adapted from Zbyszewski and Faria, 1971; Kullberg, 2000); **b**) Geological map of the Lower Jurassic carbonate units cropping out in the S. Pedro de Moel area and location of the Concha Beach – Lighthouse (1) and Água de Madeiros (2) sections (from Duarte et al., 2008, 2012); **c**) Synthetic stratigraphic log and sequential interpretation of the Sinemurian – lowermost Pliensbachian succession in the S. Pedro de Moel area (adapted from Duarte et al., 2008, 2022; Azerêdo et al., 2010).

One of the most significant stratigraphic features of this sector of the LB is its Sinemurian record. It contains the most complete and continuous succession of the Coimbra Formation (Dommergues et al., 2004, 2010; Duarte et al., 2008, 2022; Azerêdo et al., 2010) and also includes the type section of the Água de Madeiros Formation and its two members (Duarte and Soares, 2002; Duarte et al., 2010, 2014; Boussaha et al., 2014; Vitón et al., 2026; and references therein). Moreover, this area constitutes an important reference section for the LB, particularly for the Sinemurian and Pliensbachian organic-rich marly limestones. Organic-rich deposition, documented by an extensive dataset of organic-geochemical data, including total organic carbon (TOC) and Rock-Eval pyrolysis, together with petrographic data from palynofacies analysis, is the main topic addressed at this stop (e.g., Duarte et al., 2010, 2011, 2012, 2022; Correia et al., 2012; Poças Ribeiro et al., 2011; Silva et al., 2011, 2012, 2013, 2021; Silva and Duarte, 2015; Plancq et al., 2016). These data highlight the potential of Lower Jurassic deposits in the Lusitanian Basin as source rocks (e.g., Duarte et al., 2012; Poças Ribeiro et al., 2013; Brito *et al*., 2017, 2023).

Figure II. 2. Several sedimentary and stratigraphic aspects of the upper Sinemurian – lowermost Pliensbachian carbonate deposits in the S. Pedro de Moel region: **a**) General view of bioclastic limestone succession of the Coimbra Formation (north of S. Pedro de Moel); **b**) Organic-rich marl-limestone alternations in the middle part of Polvoeira Member (Polvoeira section); **c**) General view of the transition between the organic-rich marl-limestone alternations of Polvoeira Member and the calcareous facies of the Praia da Pedra Lisa Member (Água de Madeiros section); **d**) Marl-limestone alternations at the top of Praia da Pedra Lisa Member (Água de Madeiros section).

2. Organic-rich units of the Coimbra Formation (Sinemurian) at S. Pedro de Moel

2.1. The Coimbra Formation: stratigraphic framework and palaeoenvironmental evolution

The Coimbra Formation constitutes a major part of the Sinemurian succession of the LB and represents the first unequivocal evidence of widespread marine influence following the Hettangian deposits of the

Dagorda Formation. At S. Pedro de Moel, the formation is exceptionally well exposed and reaches a minimum thickness of approximately 125 m. In this western sector of the basin, the succession is predominantly composed of limestones, whereas dolostones and dolomitic limestones are much more important towards the eastern and more proximal sectors of the basin (Dimuccio et al., 2016; Sêco et al., 2018; Duarte et al., 2022; Vitón et al., 2024). The Coimbra Formation is overlain by the upper Sinemurian–lowermost Pliensbachian Água de Madeiros Formation. The succession exposed at S. Pedro de Moel can be subdivided into eight informal lithostratigraphic units, UA to UH, which document a clear vertical evolution in lithology, facies and fossil assemblages (Figs. II. 3 and II.4; Duarte et al., 2022).

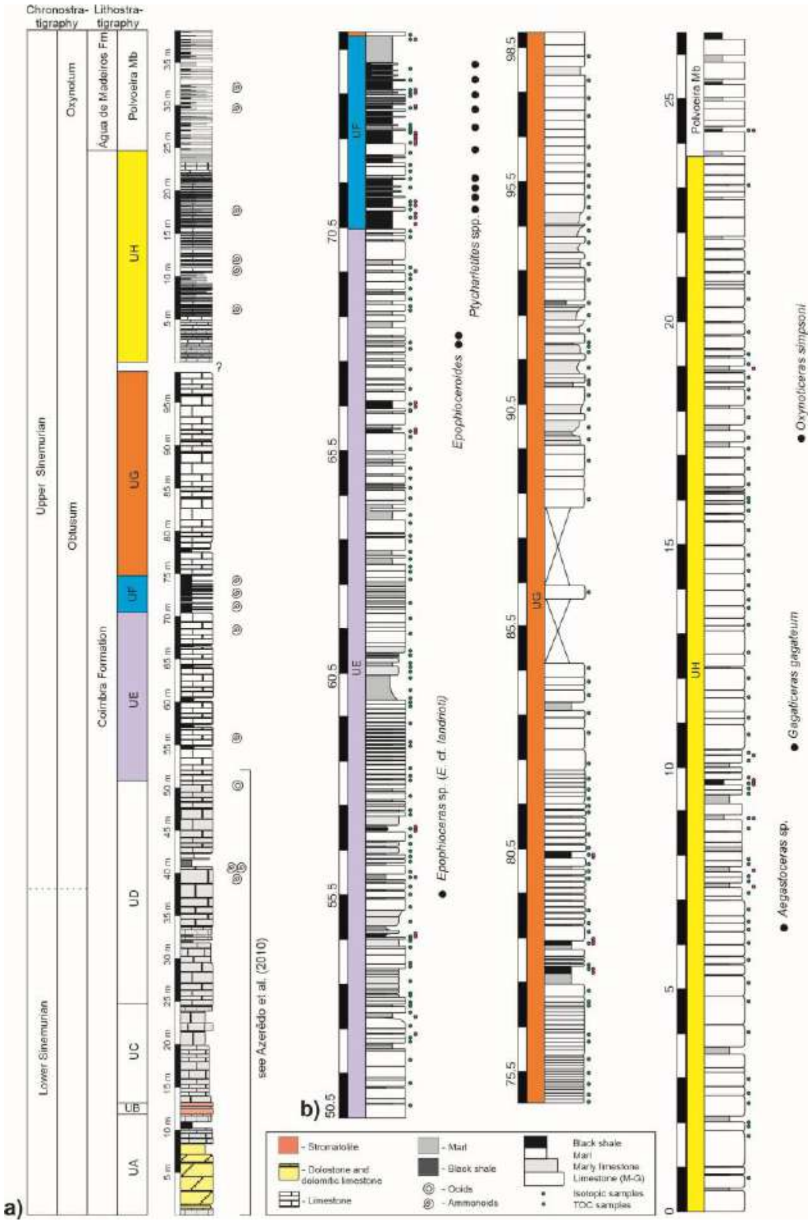

Figure II.3. a) General composite section of the Coimbra Fm (lower to upper Sinemurian) in the S. Pedro de Moel region. **b)** Detailed stratigraphic columns of UE to UG (Lighthouse section) and UH (Polvoeira section). For more information about UA–UD, see Azeredo et al. (2010). *Epophioceroides* occurrences from Dommergues et al. (2010). In Duarte et al. (2022).

The basal unit, UA, comprises a heterogeneous association of dolomitic and limestone facies, ranging from mudstone to grainstone, locally containing bivalves and gastropods. It is followed by UB, which is particularly distinctive because of the occurrence of domal stromatolites. These basal units are succeeded by UC and UD, dominated by micritic, marly and bioclastic limestones, locally intensely bioturbated by *Rhizocorallium* and *Thalassinoides*. Bivalves, particularly *Unicardium*, become increasingly abundant, together with gastropods and ostracods. The first ammonites occur in the upper part of UD, including *Asteroceras* and species of *Ptycharietites* (Dommergues et al., 2004, 2010; Azerêdo et al., 2010; Duarte et al., 2022). The overlying units UE to UG are essentially characterized by limestone–marl alternations. UE comprises bioturbated and bioclastic limestones, locally ranging from micrites to grainstones, whereas UF represents a distinctly more organic-rich marly interval. UG returns to a predominantly carbonate-dominated facies association, with micritic and bioclastic limestones arranged in centimetre- to metre-scale sets. The uppermost unit, UH, exposed at Polvoeira, consists of alternating decimetric limestones and thin marl beds and is distinguished by a marked increase in benthic faunal diversity. Its assemblage includes bivalves, brachiopods, gastropods, crinoids and rare ahermatypic corals, together with ammonites such as *Aegasteroceras*, *Gagaticeras* and *Oxynoticeras* (Duarte et al., 2022; Vitón et al., 2024).

Figure II.4. a) Base of the Coimbra Formation at Praia Velha with stromatolites (UB), see also Azerêdo et al. (2010). **b)** Panoramic view of UC and UD at Concha Beach (white arrow: first level with *Ptycharietites*). **c)** Base of UE showing a discrete level of black shale (white arrow). **d)** Panoramic view of the thick black shale interval of UF, framed by UE and UG (just north of Lighthouse). **e)** Uppermost part of UG around the Lighthouse, and location of Polvoeira Beach (red arrow). **f)** Limestones enriched in brachiopods and bivalves of the base of UH at Polvoeira Beach. In Duarte et al. (2022).

The palaeoenvironmental evolution recorded by the formation is particularly significant. Deposition began under relatively restricted shallow-marine conditions, as indicated by the basal dolomitic and microbial facies, including stromatolites, together with low-diversity benthic assemblages and restricted to brackish ostracods. Upwards, the progressive disappearance of these facies and the increasing abundance and diversity of marine macrofauna indicate a gradual establishment of more open-marine conditions (Azerêdo et al., 2010; Cabral et al., 2013, 2015). Thus, the vertical facies succession records a progressive marine transgression across the Lusitanian Basin. From a sequence-stratigraphic perspective, the Coimbra Formation records a long-term transgressive trend, corresponding to the transgressive part of a second-order transgressive–regressive cycle that reached its maximum flooding around the Sinemurian–Pliensbachian transition. Within this overall transgressive trend, three subordinate third-order flooding phases have been recognized, particularly expressed by increases in marl content and changes in fossil assemblages in the middle–upper part of UD, UF and the lower–middle part of UH (Duarte et al., 2010, 2022). Consequently, the Coimbra Formation records the progressive transformation of a restricted shallow-marine carbonate system into a more open carbonate ramp, with repeated short-term fluctuations in relative sea level and marine connectivity.

2.2. Organic-rich facies and its characterization

TOC data from 34 samples distributed throughout the Coimbra Formation (Units UA–UH) at S. Pedro de Moel show considerable variability, ranging from 0.21 to 9.20 wt.%, and reveal marked differences in organic matter content between the different units (Fig. II. 5). The lower part of the succession (UA–UB) is generally characterized by relatively low TOC contents, although a distinct increase is observed in the upper part of UA. In this unit, TOC values range from 0.36 to 3.64 wt.%, with the highest values associated with samples displaying particularly high insoluble residue (IR) contents of 75–85%. By contrast, the two analyzed samples from UB yield consistently low TOC contents (0.21–0.87 wt.%), accompanied by IR values between 1 and 29%, with the lowest TOC and IR values being associated with a stromatolite sample (Fig. II. 5). Unit C was not sampled for this study.

A pronounced increase in organic matter content occurs upwards in the succession, particularly from UD to UG. Unit UD displays TOC contents up to 8.31 wt.%, with the maximum value associated with a relatively high IR content (68%). The organic-rich character becomes particularly evident in UE and UF, which record the highest TOC contents of the studied succession. In UE, TOC values range from 0.29 to 9.20 wt.%, the latter representing the maximum value recorded in the Coimbra Formation dataset. Unit UF similarly shows relatively high organic matter contents, with TOC values ranging from 1.25 to 8.65 wt.% and four of the six analyzed samples exceeding 4 wt.%. IR contents in this unit range from 8 to 61%. (Fig. II. 5).

Relatively high TOC contents persist into UG, where the three analyzed samples yield values between 2.13 and 6.34 wt.%, with IR contents of 24–48%. This organic-rich interval contrasts markedly with the overlying UH, where TOC contents decrease substantially to values between 0.33 and 2.92 wt.%. Five of the six UH samples contain less than 1 wt.% TOC, while IR contents are consistently low, ranging from 16 to 24% (Fig. II. 5).

Overall, the geochemical profile of the Coimbra Formation reveals a clear stratigraphic variation in organic matter enrichment. The lower units UA and UB are characterized predominantly by low to moderate TOC contents, followed by a major increase from UD onwards and the development of the most organic-rich interval within UE–UF. Organic enrichment remains significant in UG before decreasing sharply in UH. The data also suggest that several of the organic-rich horizons are associated with relatively high IR contents, particularly in UA and parts of UD–UF, indicating preferential organic matter accumulation within the more argillaceous components of the succession.

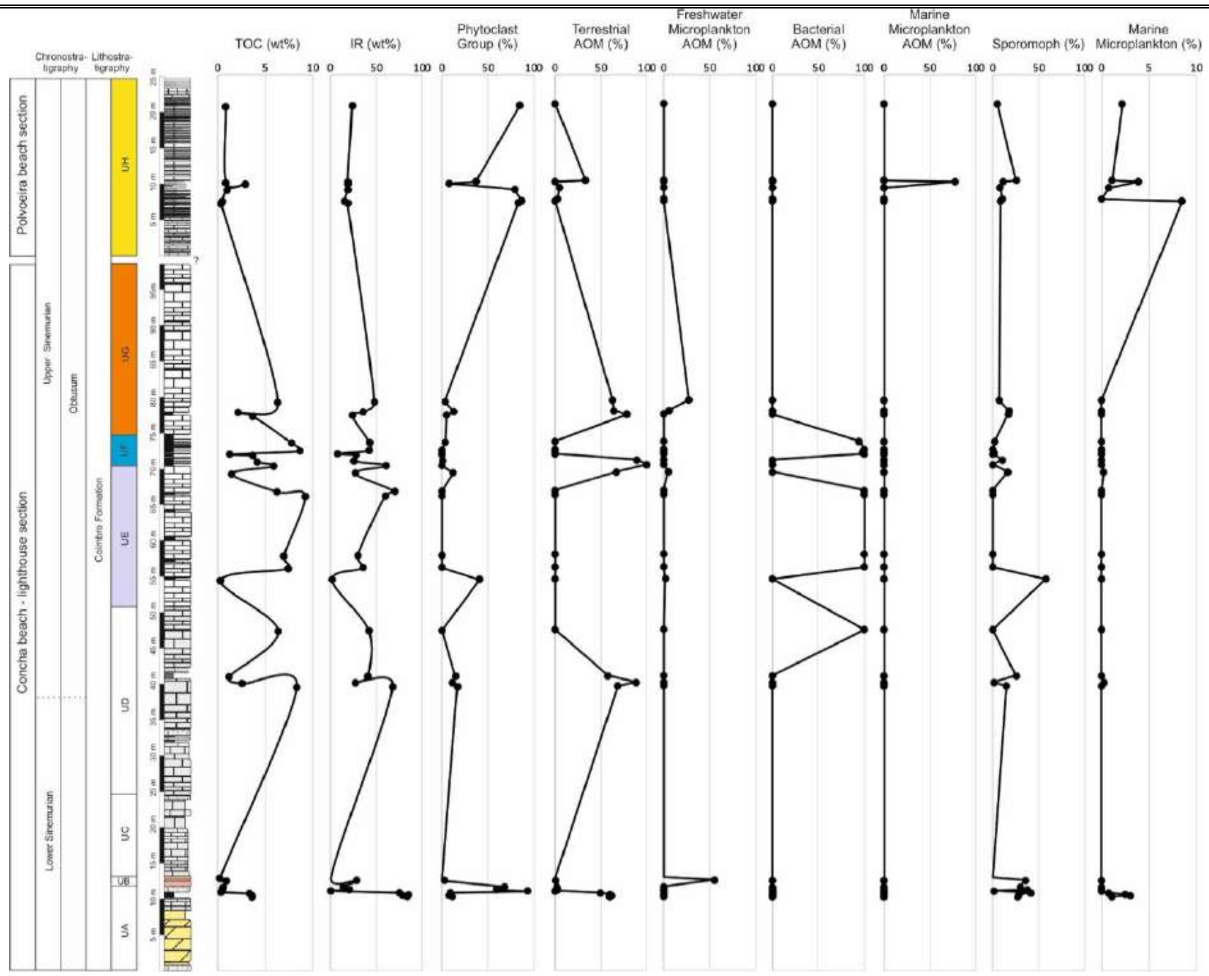

Figure II.5. Total organic carbon (TOC), insoluble residue (IR), and palynofacies data variability throughout the Coimbra Formation at S. Pedro de Moel.

2.3. Palynofacies and biomarkers

Palynofacies and biomarker data from the Coimbra Formation reveal significant changes in organic matter sources, composition and preservation throughout the succession, reflecting variations in continental input, biological productivity, water-column oxygenation and marine influence.

In Unit A, the organic assemblages show considerable variability, associated with marked changes in organic matter content (Fig. II. 5). The intervals with the highest TOC contents, reaching approximately 3.6 wt.%, are characterized by abundant higher plant-derived amorphous organic matter (terrestrial AOM) (Fig. II. 6a) and sporomorphs, accompanied by acritarchs and prasinophytes (Fig. II. 7d-e). These assemblages are associated with bimodal *n*-alkane distributions and Pr/Ph values below 1, suggesting a mixed terrestrial–aquatic organic matter contribution and enhanced preservation under stratified water-column conditions. The occurrence of acritarchs and prasinophytes indicates a marine contribution despite the overall restricted character of the depositional setting. In contrast, carbonate-rich intervals with TOC contents generally below 1 wt.% are dominated by non-opaque phytoclasts (Fig. II. 7a), membranes (Fig. II. 7b) and sporomorphs, including *Classopollis* sp. (Fig. II. 7c), and show a greater contribution of high-molecular-weight *n*-alkanes. These characteristics indicate enhanced terrestrial input and proximity to the continental source area, associated with more oxygenated and higher-energy conditions. The variations in organic matter composition and TOC within Unit A therefore suggest repeated fluctuations in water depth and restriction, with episodes of enhanced marine influence and improved organic matter preservation alternating with phases of stronger continental control and greater water-column oxygenation.

Unit B is characterized by generally low organic matter contents, with TOC values below 1 wt.%. The stromatolitic facies is particularly organic-poor with only remnants of bacterial AOM occurring, whereas the relatively more organic-rich interval contains freshwater microplankton-derived AOM (Fig. II. 6b) and sporomorphs, with the *n*-alkanes displaying a characteristic box-shaped distribution (Fig. II. 5). This unit reflects highly restricted, low-energy environments under strong biogenic control, typical of peritidal to lagoonal settings.

A significant change in organic facies and organic matter abundance is observed in **Unit D**, where TOC contents locally exceed 6 wt.% and reach more than 8 wt.% (Fig. II. 5). Some organic-rich horizons contain terrestrial AOM and sporomorphs associated with acritarchs, together with bimodal *n*-alkane distributions and Pr/Ph values below 1. This association indicates continued continental input combined with increasing marine influence and enhanced organic matter preservation under stratified water-column conditions. Other organic-rich horizons are dominated by plate-like bacterial AOM and short-chain *n*-alkanes, indicating a greater contribution from microbial biomass and enhanced microbial productivity. The occurrence of high TOC contents in association with these different organic facies indicates that organic enrichment resulted from different combinations of organic matter supply, productivity and preservation. Their vertical alternation records fluctuations in water depth and water-column conditions during the progressive flooding of the carbonate ramp.

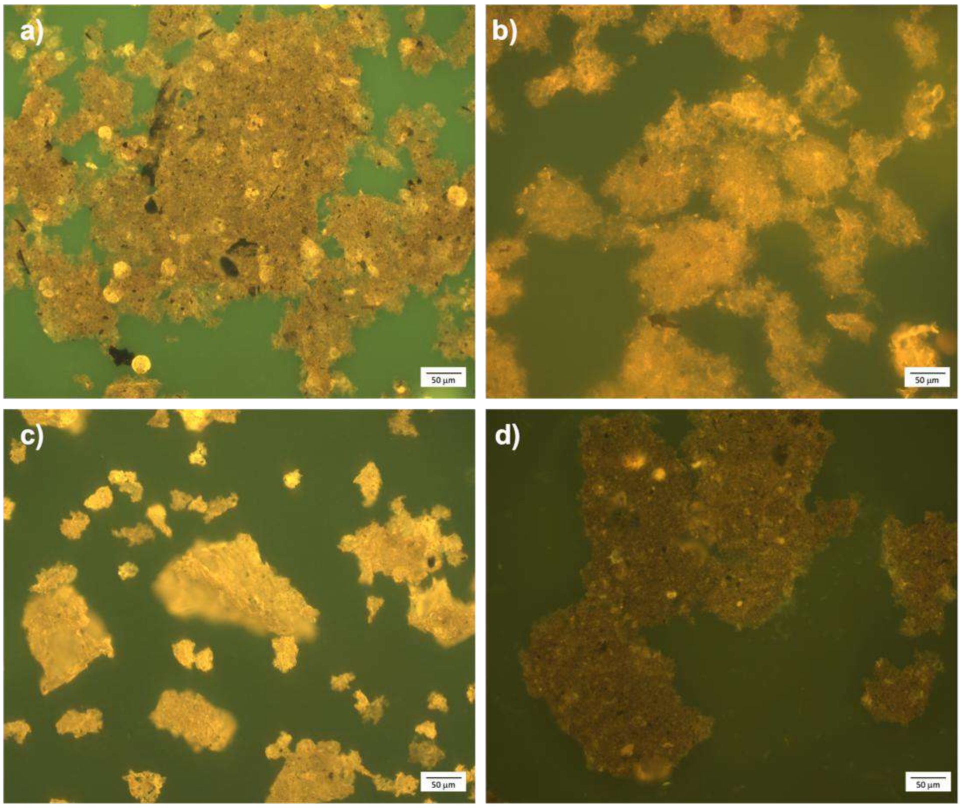

Figure II.6. Photomicrographs of organic particles in samples from the Coimbra Formation (a-d in fluorescence mode illumination): **a**) AOM derived from higher plants (Vegetal AOM) from Unit A; **b**) Freshwater microplankton-derived AOM from Unit B; **c**) Bacterial-derived AOM from Unit F; **d**) Marine microplankton-derived AOM from Unit H.

Units E to G are characterized by pronounced variability in both organic matter abundance and composition and include the highest TOC contents recorded in the studied succession. Unit E reaches a maximum TOC of 9.20 wt.%, whereas Unit F reaches 8.65 wt.%, contrasting strongly with organic-poor carbonate intervals, where TOC may fall below 1 wt.% (Fig. II. 5). In **Unit E**, one of these organic-poor intervals is dominated by membranes and aggregated sporomorphs and displays a bimodal *n*-alkane distribution (Fig. II. 5). This assemblage reflects relatively oxygenated to dysoxic, higher-energy conditions, proximity to the continental source area and increased aridity during a phase of reduced water depth.

In contrast, organic-rich facies occurring throughout the **E–G interval** are characterized by plate-like bacterial AOM (Fig. II. 6c) associated with short-chain *n*-alkanes, indicating enhanced microbial productivity under stratified water-column conditions (Fig. II. 5). Other horizons contain mixtures of terrestrial and freshwater phytoplankton-derived AOM associated with acritarchs, together with approximately bimodal *n*-alkane distributions and Pr/Ph values below 1. The occurrence of acritarchs demonstrates a marine contribution, whereas the simultaneous presence of terrestrial and freshwater-derived components indicates that continental influence remained significant. The association between these organic facies and elevated TOC contents suggests that the **E–G interval** experienced repeated episodes in which increased biological productivity and/or improved preservation under stratified conditions favored organic matter accumulation. These episodes alternated with more oxygenated and higher-energy conditions, emphasizing the highly variable character of the depositional environment during relative sea-level rise.

The most pronounced change towards open-marine conditions is recorded in **Unit H**. In contrast to the underlying organic-rich interval, TOC contents decrease markedly and are predominantly below 1 wt.%, despite the increasingly clear marine signature of the organic assemblages (Fig. II. 5). The lower part of the unit includes facies dominated by phytoclasts, including non-opaque and opaque particles, together with foraminiferal test-linings (Fig. II. 7f). These assemblages are associated with a bimodal *n*-alkane distribution and Pr/Ph >1 and indicate relatively oxygenated, higher-energy conditions under normal marine salinity (gammacerane). Other intervals contain membranes and non-opaque phytoclasts associated with prasinophytes and low-molecular-weight *n*-alkanes, reflecting increased marine influence under relatively oxygenated to dysoxic conditions.

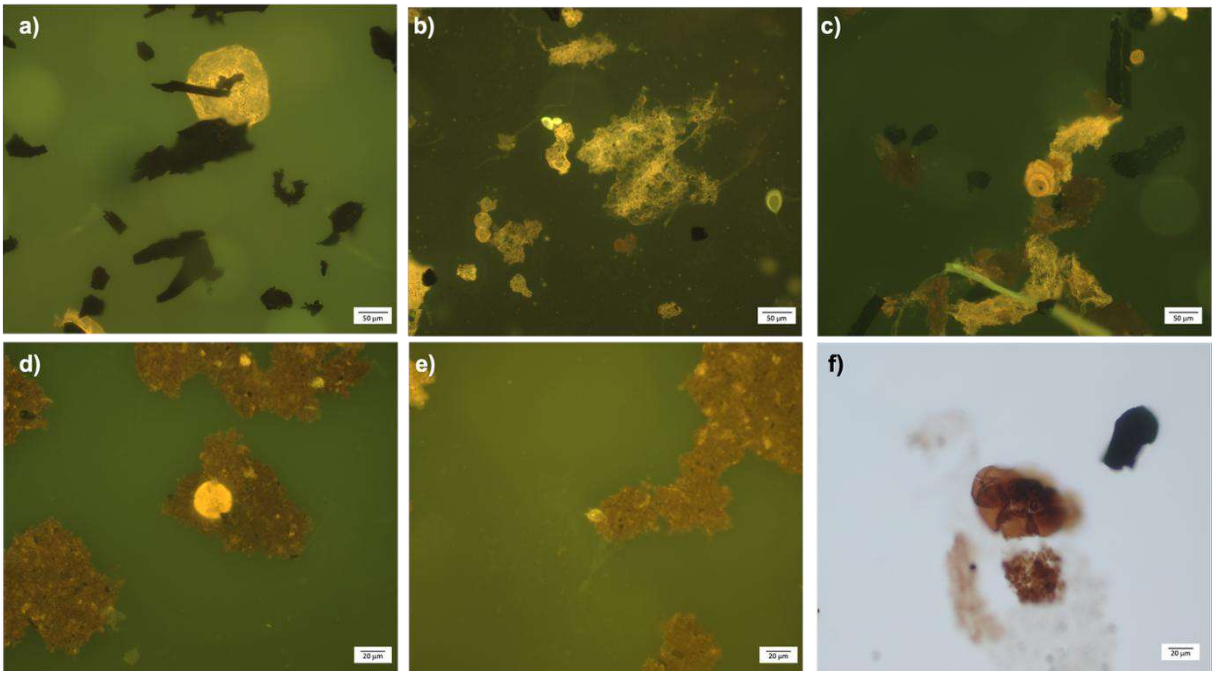

Figure II.7. Photomicrographs of organic particles in samples from the Coimbra Formation (a-e in fluorescence mode illumination; f in transmitted white light): **a**) Non-opaque non-biostructured phytoclasts from Unit A; **b**) Membranes and Sporomorphs from Unit A; **c**) Sporomorphs, Membranes and Phytoclasts from Unit A; **d**) Prasinophytes from Unit A; **e**) Acritarch from Unit A; **f**) Foraminiferal test-lining from Unit H.

Upwards within **Unit H**, an interval with TOC of approximately 2.9 wt.% represents a significant, although moderate, organic enrichment relative to the surrounding facies. In this interval, the organic assemblage becomes dominated by marine phytoplankton-derived AOM (Fig. II. 6d) associated with prasinophytes and acritarchs (Fig. II. 5). Low-molecular-weight *n*-alkanes, Pr/Ph values below 1 and gammacerane accompany this assemblage, indicating enhanced preservation under reducing conditions. This interval represents the clearest particulate organic matter expression of open-marine conditions in the studied succession and is interpreted as recording a maximum flooding surface. Above this interval, TOC decreases again and the association of terrestrial AOM and sporomorphs with acritarchs and prasinophytes, together with a bimodal *n*-alkane distribution and Pr/Ph <1, indicates renewed terrestrial influence while maintaining a significant marine contribution and stratified water-column conditions.

The sterane distribution provides complementary information on organic matter sources throughout the Coimbra Formation. C_{29} sterane, indicative of terrestrial organic matter input, dominates throughout the sequence and is consistent with the recurrent occurrence of phytoclasts and sporomorphs. On the other hand, the C_{30} sterane (indicative of a marine contribution) also occurs in all samples, including intervals where marine-derived particulate organic components, such as acritarchs and prasinophytes, are scarce or absent. Thus, the molecular record demonstrates a persistent marine contribution that is not continuously expressed in the particulate organic matter.

The combined palynofacies, biomarker and TOC records indicate an overall evolution from restricted shallow-water settings towards increasingly open-marine conditions. This transition was not accompanied by a progressive increase in organic matter content: the highest TOC values occur in Units E and F, where enhanced microbial productivity and water-column stratification favored organic matter accumulation and preservation, whereas the more open-marine Unit H generally displays lower TOC contents. The upward evolution of the Coimbra Formation therefore reflects a progressive strengthening of an already established marine influence, rather than the initial onset of marine conditions, culminating in Unit H where the marine signal is clearly expressed in both particulate and molecular organic matter.

Overall, the organic facies variability indicates that this long-term transgressive evolution was punctuated by higher-frequency fluctuations in water depth, hydrodynamic energy, productivity and water-column oxygenation. These changes are consistent with deposition on a shallow carbonate ramp, where predominantly high-energy conditions were periodically interrupted by lower-energy and stratified episodes that favored organic matter preservation, recording higher-frequency flooding events superimposed on the broader transgressive evolution of the Coimbra Formation.

2.4. Thermal maturity

The Coimbra Formation at S. Pedro de Moel exhibits a Spore Coloration Index (SCI) ranging from 3.0 to 4.0, a random vitrinite reflectance of 0.45Rr%, and rock extracts from liquid chromatography mainly represented by the NSO fraction (Poças Ribeiro et al., 2013). C_{29}-steranes are thermally dependent and increase the 20S /(20S+20R) ratio to an equilibrium value of ~0.55, while the αββ/ (ααα+αββ) ratio reaches an equilibrium value of ~0.70 around peak oil generation. For the Coimbra Formation, the ratios are 0–0.09 and 0–0.41, respectively. For homohopanes, the 22S /(22S+22R) ratio usually reaches an equilibrium value of ~0.6 near the main oil generation window. The values from this Formation are 0.12–0.54 (Poças Ribeiro et al., 2013). In most samples, the epimers 20S and αββ from C29 steranes and the 22S from C32 homohopane were not detected. This result and the presence of 17β, 21β-hopanes in the mass chromatography profile is consistent with thermal immaturity. Overall, this data indicates a low degree of thermal maturity for the Coimbra Formation samples (Poças Ribeiro et al., 2013).

3. Organic-rich marly limestones of the Água de Madeiros Formation (Upper Sinemurian–lowermost Pliensbachian) at Água de Madeiros

3.1. The Água de Madeiros section: geological setting and lithostratigraphy

At Água de Madeiros (approximately 1.5 km south of S. Pedro de Moel; Fig. II.1a,b), the outcrops of the Água de Madeiros Formation expose a continuous succession of the upper part of the formation (Fig. II.2). This is the main locality for investigating the Sinemurian–Pliensbachian transition in the LB, which is accurately dated by detailed ammonite (Duarte et al., 2014; Vitón et al., 2026 and references therein), calcareous nannofossil (Mattioli et al., 2013; Plancq et al., 2016; Ferreira et al., 2019) and dinoflagellates (Correia et al., 2018) biostratigraphy. Corresponding to part of the type section of the Água de Madeiros Formation, the Água de Madeiros section includes the upper part of the Polvoeira Member and most of the Praia da Pedra Lisa Member, which together are approximately 58 m thick in this region (e.g., Duarte and Soares, 2002; Duarte et al., 2010, 2012, 2014; Boussaha et al., 2014; Plancq et al., 2016, and references therein).

The upper part of the Polvoeira Member consists of marl–limestone alternations, approximately 14 m thick, containing organic-rich levels (black shale) and decimetre-scale fragments of fossil wood (Silva et al., 2013). The marlstones are grey to black, locally laminated, and rich in organic matter, whereas the limestones generally occur as decimetre-thick beds of fossiliferous wackestone, often containing abundant ostracods and molluscs. Belemnites and ammonites are particularly abundant in the lower part of the member, including reference levels containing echioceratids assigned to the uppermost Sinemurian (Aplanatum Zone; see Duarte et al., 2014; Vitón et al., 2026; and references therein). Upwards, the upper part of the Polvoeira Member shows a significant decrease in the ammonite record (Fig. II.2c).

The Praia da Pedra Lisa Member is predominantly calcareous, consisting mainly of mudstone and wackestone. It begins with approximately 9 m of decimetre- to centimetre-thick microspar limestones (Fig. II.2c), locally displaying lamination and irregular bedding. Despite the occurrence of *Rhizocorallium* and *Thalassinoides*, benthic macrofauna is virtually absent. Nektonic macrofauna is also scarce, although ammonites occur in some horizons. The upper part of the member, approximately 7 m thick, is characterized by a gradual increase in centimetre-scale interbedded grey to dark-grey marls and a marked thickening of the limestone beds (Fig. II.2d). Some marly intervals display lamination and correspond to organic-rich facies. The limestones consist of fossiliferous micrite to biomicrite/wackestone containing molluscs and ostracods. Benthic macrofauna is rare, but belemnites and ammonites are occasionally recorded in the limestone facies. Large specimens of *Apoderoceras* are frequent in the upper limestone beds of the member, dating these beds to the Jamesoni Zone (lowermost Pliensbachian; see Meister et al., 2012; Duarte et al., 2014).

Despite the good outcrop preservation, the boundary between the Água de Madeiros and Vale das Fontes formations is poorly observed in this section. The base of the Vale das Fontes Formation represents the return of marly deposition (marl–limestone alternations), with a stronger marine influence. Some horizons are particularly bioclastic (wackestones), with crinoid ossicles, belemnites, brachiopods and bivalves. Some marly levels correspond to centimetre-thick black shales.

3.2. Organic-rich facies and its characterization

TOC data from approximately 200 samples of the Água de Madeiros Formation at S. Pedro de Moel confirm the organic-rich nature of the Polvoeira Member, with TOC contents reaching up to 22 wt.%, particularly in the lower to middle part of the unit (Oxynotum Zone) at a nearby outcrop (Polvoeira section; Figs. II. 2b and 3) (Duarte et al., 2010, 2012, 2014).

At the Água de Madeiros section, TOC data from more than 60 horizons show considerable variability, with maximum values of 15.2 wt.% in the Polvoeira Member and a large proportion of the analysed samples yielding TOC contents above 3 wt.% (Fig. II.8). In the Praia da Pedra Lisa Member, TOC contents are relatively high in marls from the upper part of the unit, despite the predominantly calcareous nature of the succession. TOC values reach 3–4 wt.% (Fig. II.2d), with a maximum of 7.3 wt.% recorded in a millimetre-thick horizon (Duarte et al., 2012). Some marly facies at the base of the Vale das Fontes Formation display TOC contents of approximately 9 wt.%. These organic-rich facies, which occur in the lowermost part of the formation, are restricted to the S. Pedro de Moel region (Duarte et al., 2010), further highlighting the importance of this sector of the basin for organic matter accumulation and preservation.

Among the several lithofacies identified in the succession, based on sedimentological and geochemical criteria, particularly TOC content, three main organic-matter-rich lithofacies can be distinguished: dark-grey marlstones (TOC < 6 wt.%), black shales (non-bioturbated, laminated marlstones lacking benthic macrofauna TOC > 4 wt.%, and thinly laminated limestones (maximum TOC content of 8.8 wt.%) (Duarte et al., 2012; Fig. II.9).

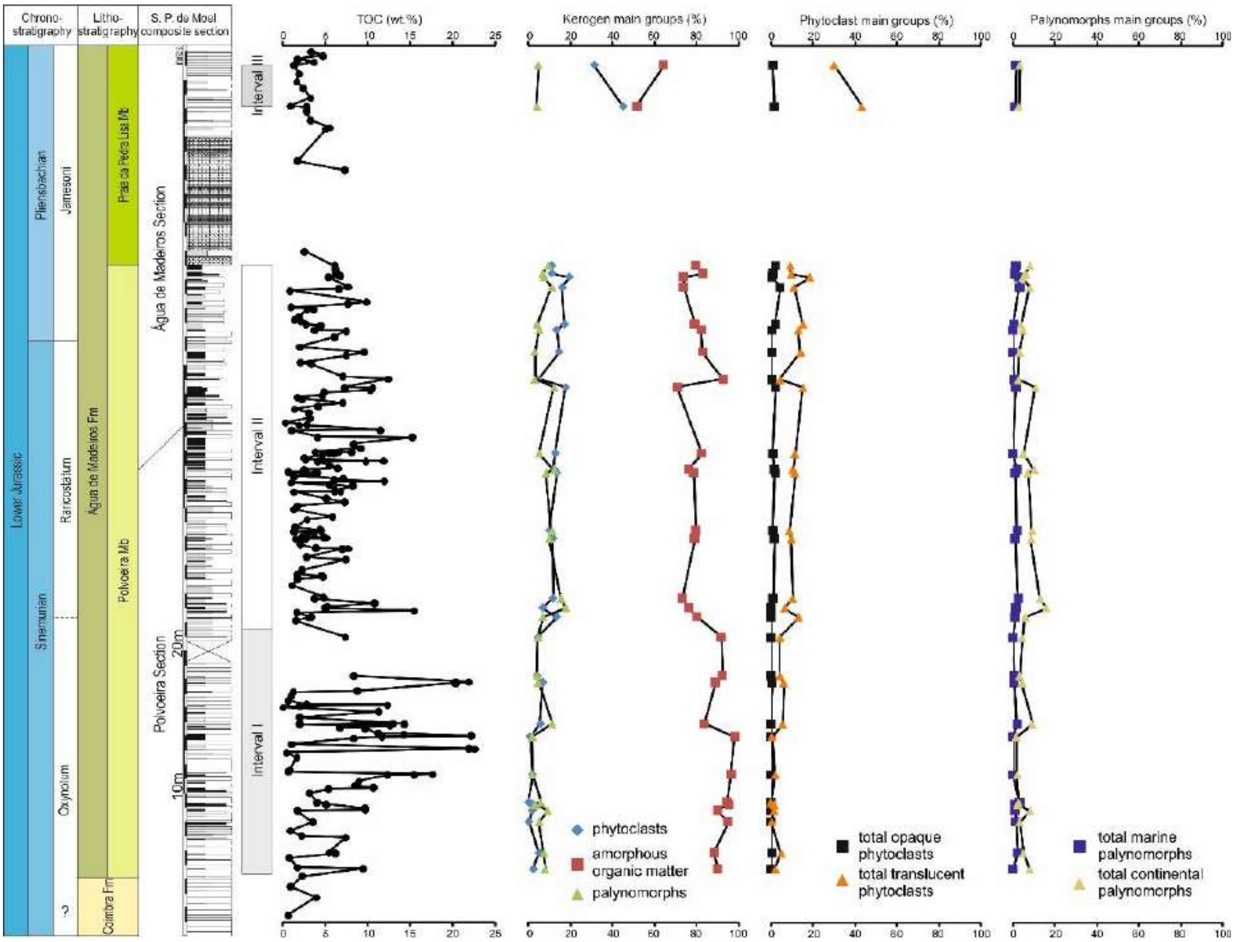

Figure II.8. Variation in TOC content and palynofacies composition through the upper Sinemurian – lowermost Pliensbachian composite section at S. Pedro de Moel (adapted from Duarte et al., 2012). Ammonite biostratigraphic precision from Duarte et al. (2014).

3.3. Palynofacies

The kerogen assemblages of the Água de Madeiros Formation at S. Pedro de Moel are dominated by amorphous organic matter (AOM), consistently exceeding 51.5% (Fig. II.8 and II.10a-c), with some levels containing higher proportions of phytoclasts (up to 45%; Fig. II.10d) and lower abundances of palynomorphs (below 17.5%) (Fig. II.8; Duarte et al., 2012; Poças Ribeiro et al., 2013). The latter are essentially represented by continental sporomorphs (pollen grains and spores, including *Classopollis* in agglomerates and tetrads), with marine palynomorphs (acritarchs and prasinophytes) being very rare. Among the several characteristics of the organic assemblages of the Água de Madeiros Formation, three main intervals can be distinguished (Fig. II.8; Duarte et al., 2012):

i) A high abundance of AOM at the base of the Polvoeira Member, with evidence of a microbial origin (Fig. 5a–c), together with low proportions of phytoclasts (9%) and palynomorphs (11%).

ii) In the middle and upper parts of the Polvoeira Member, black shales become more frequent and thicker, associated with more argillaceous facies (Figs. II.2b and II.9b). This interval also contains the most heterogeneous kerogen assemblage, with increased proportions of phytoclasts (up to 19%) and palynomorphs (3–18%). The increasing argillaceous contribution is accompanied by a gradual disappearance of benthic macrofauna (brachiopods and bivalves), an increase in nektonic organisms such as ammonites and belemnites, and the occurrence of some pelagic bivalves (Duarte et al., 2010, 2014). These sedimentary characteristics are consistent with a deepening phase, interpreted by Duarte et al. (2010) as a second-order transgressive event.

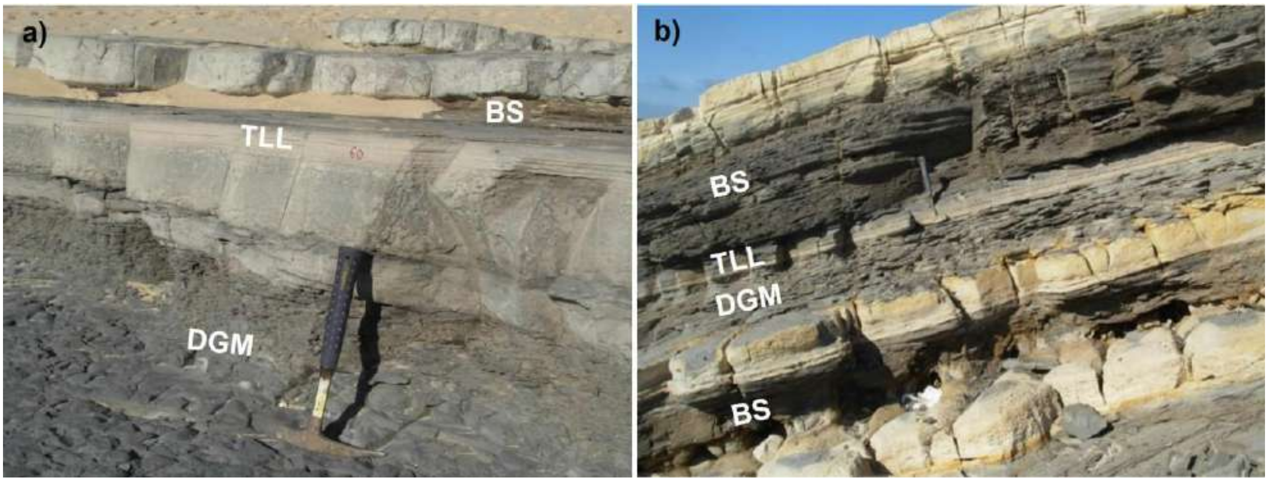

Figure II.9. Field detailed aspects of organic-rich facies in the Polvoeira Member: **a**) base of the unit in the Polvoeira section; **b**) top of the unit in the Água de Madeiros section. DGM – Dark grey marlstone; BS – Black shale; TLL – Thin laminated limestone.

iii) The last interval corresponds to the Praia da Pedra Lisa Member, in which argillaceous deposition and organic matter accumulation are restricted to the upper part of the unit. Palynofacies data indicate that this member represents the most proximal, yet still fully marine, depositional environment recorded in the Água de Madeiros Formation at S. Pedro de Moel. The main feature of this interval is the high proportion of phytoclasts, which account for up to approximately 45% of the kerogen (Figs. II.2d and II.10d). Compared with the Polvoeira Member, the ratio of opaque to translucent phytoclasts decreases significantly, suggesting a shift towards a more proximal, shallow-marine environment. This interpretation is consistent with other sedimentological and stratigraphic evidence, indicating that deposition occurred during a shallowing phase (Duarte et al., 2010; Boussaha et al., 2014). According to these authors, the lower part of the Praia da Pedra Lisa Member records a second-order regressive phase that is also recognized in other parts of the basin (Fig. II.1b).

3.4. Rock-Eval Pyrolysis and thermal maturity

In the Água de Madeiros Formation, 85 samples have been analysed by Rock-Eval pyrolysis (Duarte et al., 2012; see also data from Plancq et al., 2016). The data plotted in Fig. II.11 show high S2 and Hydrogen Index (HI) values, reaching 78.1 mg HC/g rock and 637 mg HC/g TOC, respectively. More than 68% of the analysed samples have S2 values above 10 mg HC/g rock, with the highest S2 values being associated with high HI values. Despite the predominantly calcareous nature of the Praia da Pedra Lisa Member and its relatively low TOC contents, some horizons yield S2 values above 10 mg HC/g rock and HI values of up to 430 mg HC/g TOC.

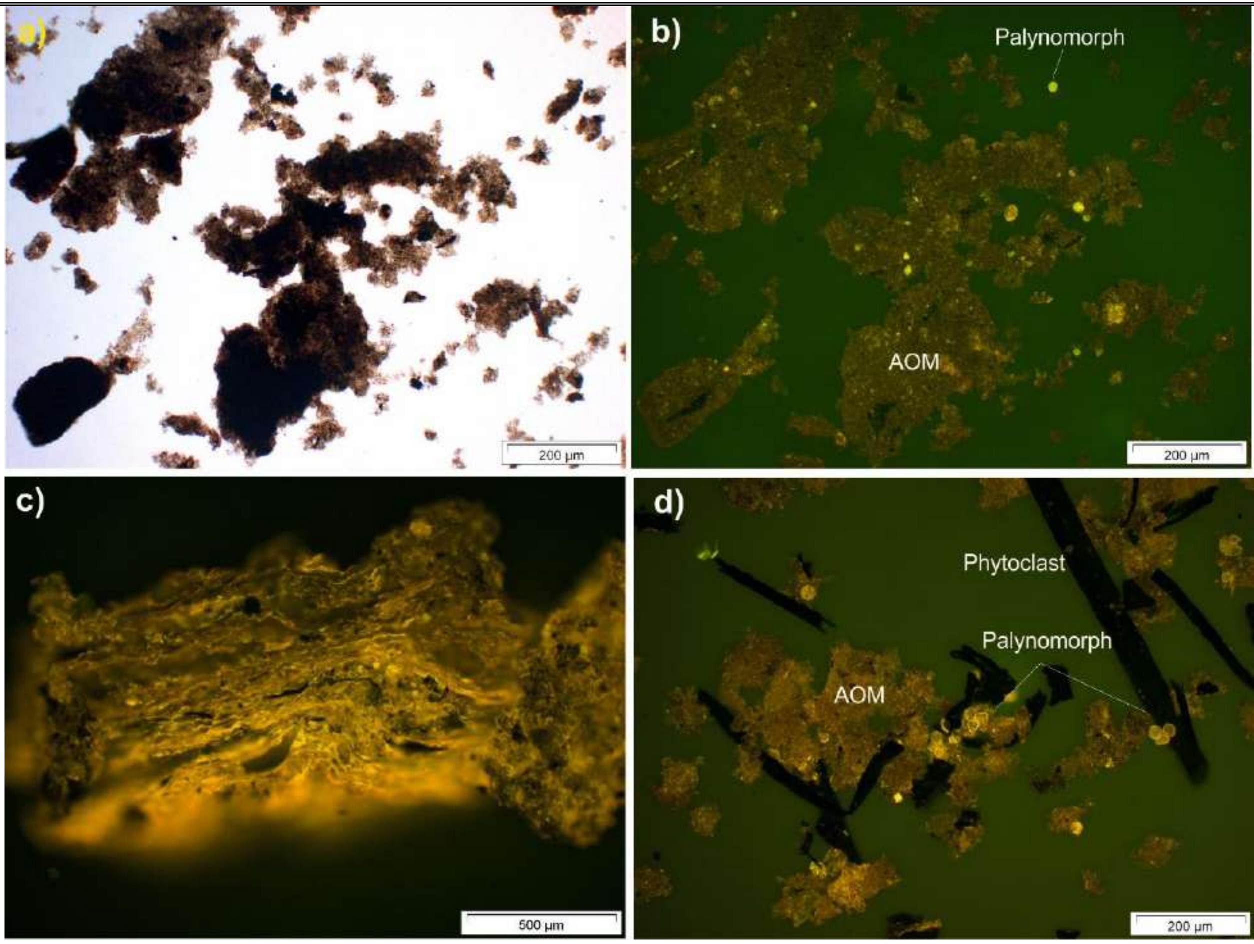

Figure II.10. Photomicrographs of organic particles in samples from the Água de Madeiros Formation (a, in transmitted white light; b, c and d in fluorescence mode illumination): **a**) and **b**) Dominance of AOM in sample from the base of Polvoeira Member); **c**) Amorphous products of primary microbiological productivity, in this case a microbial mat (sample from the base of Polvoeira Member); **d**) Dominance of opaque phytoclasts in sample from the Praia da Pedra Lisa Member. In Duarte et al. (2012).

These results demonstrate the good source-rock potential of the Água de Madeiros Formation in the S. Pedro de Moel region. The sediments are thermally immature, as indicated by Tmax values consistently below 437 °C (Duarte et al., 2012; Plancq et al., 2016). These maturity estimates are consistent with the Vitrinite Reflectance (%Ro) and Spore Colouration Index (SCI) data reported by Poças Ribeiro et al. (2013) for the same section.

Plotting the Oxygen Index (OI) against the Hydrogen Index (HI) in the modified van Krevelen diagram (Fig. II.12) shows that most of the analysed samples fall within the Type II kerogen field, consistent with the palynofacies observations. The few samples with the highest HI values (around 600 mg HC/g TOC) from the Polvoeira Member (Fig. II.11) plot within the Type I kerogen field. Macroscopically, these samples correspond to typical black shales, with TOC contents above 6.7 wt.%. See also Duarte et al. (2013).

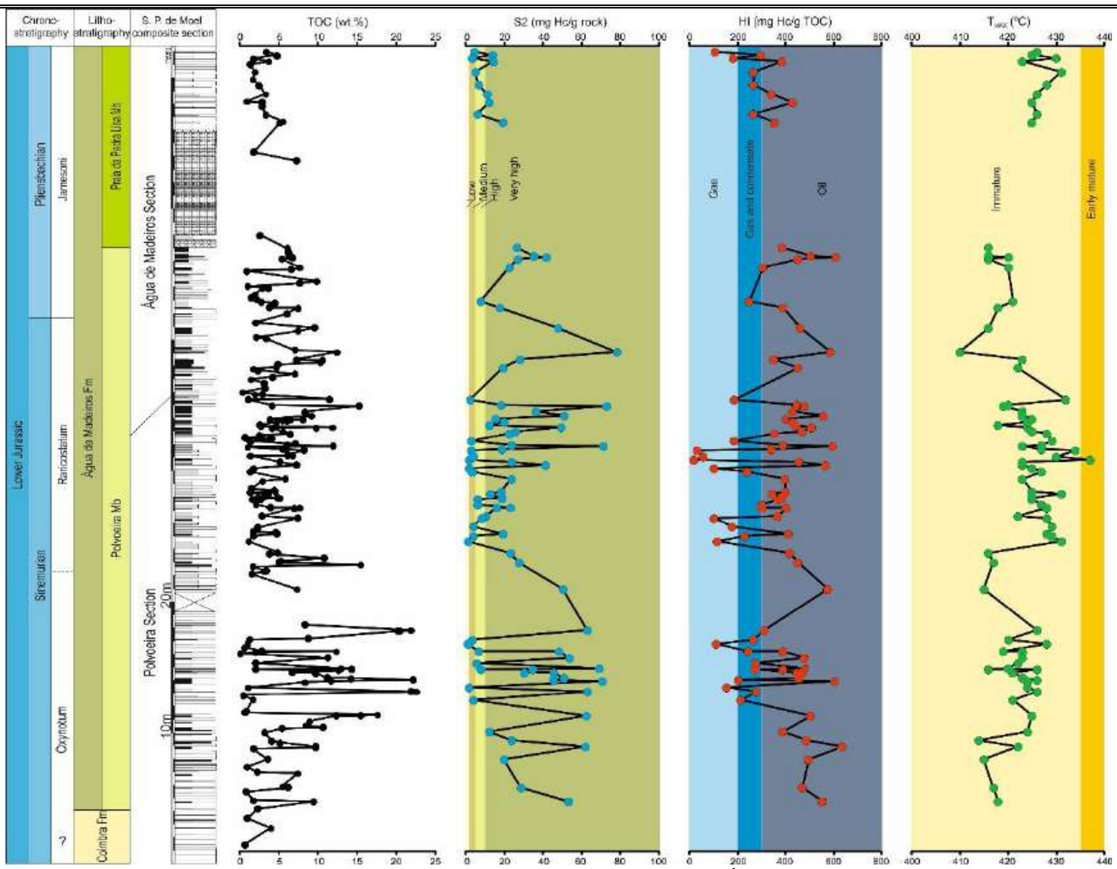

Figure II.11. Stratigraphic variations of TOC, Rock-Eval S_2 and HI across the Água de Madeiros Formation in the S. Pedro de Moel area (adapted from Duarte et al., 2012). Ammonite biostratigraphic precision from Duarte et al. (2014).

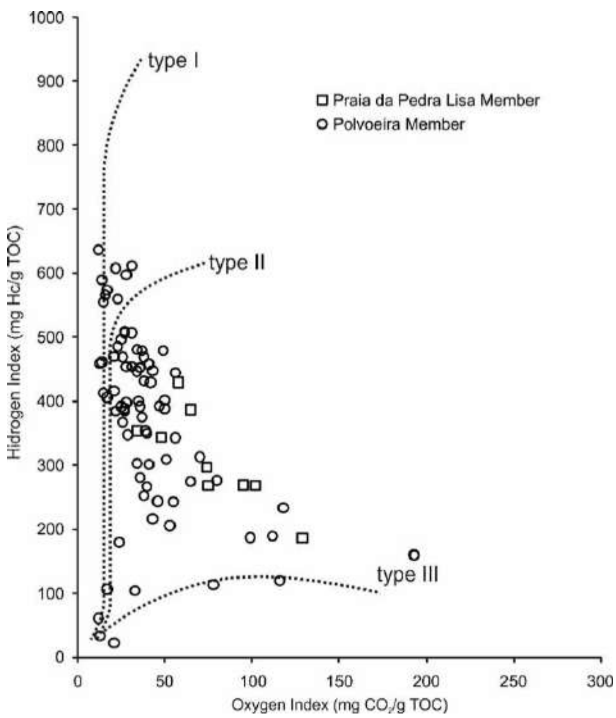

Figure II.12. Plot of Hydrogen Index (HI) versus Oxygen Index (OI) (modified Van Krevelen diagram) for samples from the Polvoeira and Praia da Pedra Lisa members of the Água de Madeiros Formation at S. Pedro de Moel (Duarte et al., 2012).

III. The Lower Jurassic Organic-Rich Facies at Peniche

1. Introduction: The Lower Jurassic succession

The Peniche Peninsula exposes the most continuous carbonate sedimentary succession of the Lower Jurassic in Portugal representing the most important reference section of the LB (Figures I.2 e III.1). The succession is exceptionally well exposed and displays a continuous record of marine carbonate sedimentation, ranging from inner-ramp to hemipelagic settings, from the Sinemurian to the extreme base of the Middle Jurassic (Mouterde, 1955; Wright and Wilson, 1984; Duarte and Soares, 2002; Duarte et al., 2017; Barata et al., 2021). Its excellent exposure conditions, high-resolution stratigraphic control and distinctive sedimentological and geochemical features have made Peniche a key locality for reconstructing the evolution of the Lower Jurassic in the LB and, more broadly, of the Proto-Atlantic Ocean (Duarte, 2004; Duarte et al., 2017). The scientific relevance of the Peniche succession is further enhanced by the definition of the Pliensbachian–Toarcian Global Boundary Stratotype Section and Point (GSSP) at Ponta do Trovão, ratified in 2014 as the formal global reference for the base of the Toarcian (Rocha et al., 2016; Duarte et al., 2017). In addition, the Abalo beach section provides an exceptional record of the base of the Levisoni Zone and the early T-OAE, which has been investigated through high-resolution biostratigraphic, chemostratigraphic and palaeoenvironmental studies (Hesselbo et al., 2007; Suan et al., 2008a, 2008b, 2010; Duarte et al., 2017; Font et al., 2022; and references therein).

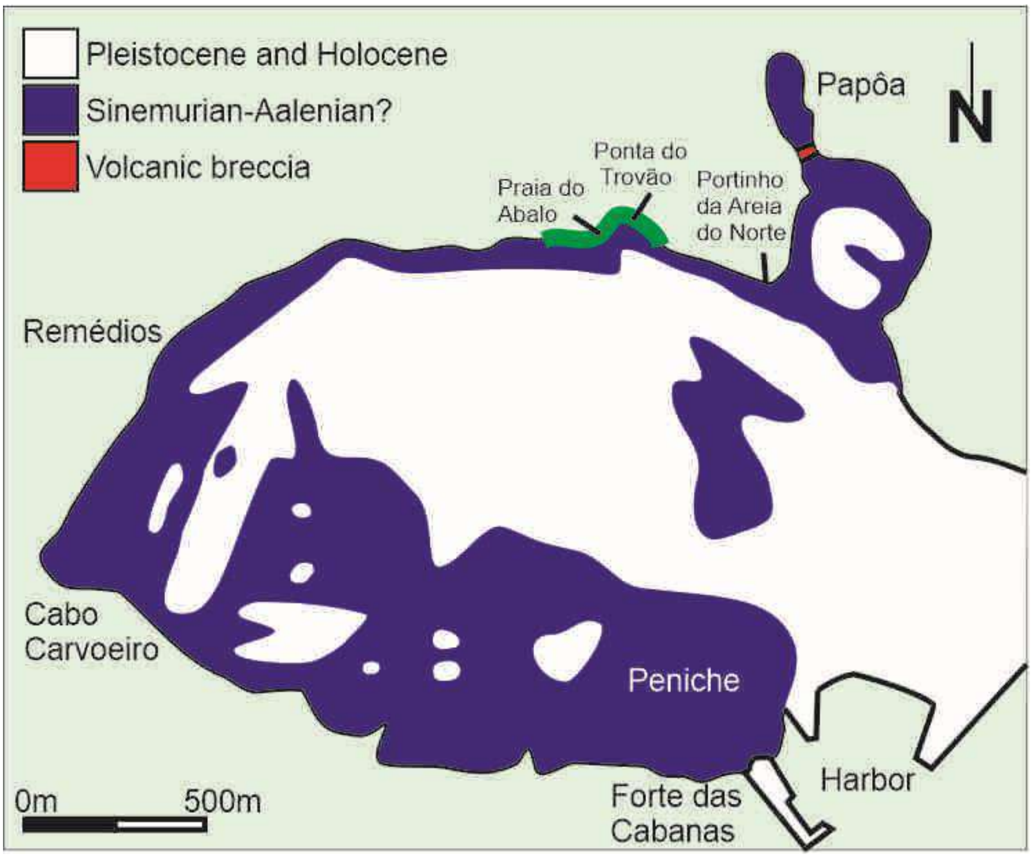

Figure III.1. Simplified geological map of the Peniche Peninsula and locations of the two stops (Portinho da Areia do Norte and Ponta do Trovão) (modified from Camarate França et al., 1960). See Figure I.2 for location.

The Peniche Peninsula exposes a sedimentary succession composed predominantly of carbonate rocks, including marls, locally organic-rich, as well as marly, micritic, dolomitic, bioclastic, oolitic, oncolitic and arkosic limestones, assigned to the Coimbra, Água de Madeiros, Vale das Fontes, Lemede and Cabo

Carvoeiro formations (Figures I.3, I.4, III.2 and III.3). The latter three formations have their type sections in the Peniche area (Duarte and Soares, 2002; Duarte, 2007). In addition, owing to its distinctive geological features and the occurrence of turbiditic sedimentation evolving into peri-marginal environments (see Wright and Wilson, 1984; Duarte, 1997; Barata et al., 2021), the Cabo Carvoeiro Formation is exclusive to the Peniche area. The entire succession exceeds 450 m in thickness (Fig. III.2).

The Coimbra Formation, the oldest unit exposed at Peniche, crops out mainly at Papôa and is dated to the Sinemurian. It consists predominantly of micritic, bioclastic, oncolitic and oolitic limestones, with minor marly intercalations. Bioturbation, particularly by *Thalassinoides*, and abundant bivalves and gastropods are characteristic. Owing to intense fracturing, its thickness is difficult to establish but is estimated at less than 50 m (Fig. III.3a-b).

The overlying Água de Madeiros Formation comprises calcareous and laminated marls, locally organic-rich, alternating with marly, micritic and bioclastic limestones. It is highly fossiliferous, with abundant ammonites, belemnites, brachiopods and bivalves, and is subdivided into the Polvoeira and Praia da Pedra Lisa members. The Polvoeira Member, dated from the Raricostatum Zone, is characterized by marl–marly limestone alternations and marks an important change in sedimentary facies (Fig. III.3b). The Praia da Pedra Lisa Member is predominantly calcareous and bioclastic, although its detailed characterization is hindered by intense fracturing.

The Vale das Fontes marks the return to marl–limestone sedimentation following the predominantly calcareous episode of the Praia da Pedra Lisa Member (Fig. III.3c). At Peniche, it is approximately 76 m thick and is subdivided into three informal members: Marls and Limestones with *Uptonia* and *Pentacrinus* (MLUP), Lumpy Marls and Limestones (LML), and Marly Limestones with Organic-Rich Facies (MLOF). The MLUP Member comprises bioturbated marl–marly limestone alternations rich in benthic and nektonic macrofauna and is dated to the Jamesoni Zone. The LML Member, ranging from the Jamesoni to the Ibex zones, is characterized by distinctive micritic, commonly subspherical “lumpy” concretions, locally displaying microbial or cryptalgal structures. The MLOF Member, extending from the uppermost Ibex Zone to the upper Margaritatus Zone, is more strongly marly and contains abundant benthic macrofauna together with ammonites and belemnites.

The Lemede Formation is predominantly calcareous and extends from the uppermost Gibbosus Subzone of the Margaritatus Zone to the extreme base of the Toarcian (Fig. III.3d). At Peniche, it crops out along the southwestern cliff of Portinho da Areia do Norte and is approximately 23 m thick. It is particularly rich in ammonites and belemnites, and its uppermost part at Ponta do Trovão contains the Toarcian GSSP.

The Cabo Carvoeiro Formation records a marked change in sedimentary conditions, with the development of detrital, oolitic and bioclastic facies. It is subdivided into five members (CC1–CC5), with a cumulative thickness exceeding 210 m (Figs. III.3e-f). CC1 is predominantly marly and rich in macrofauna. CC2, corresponding to the *Levisoni* Zone, is characterized by marls containing lenticular siliciclastic beds, wood fragments and typical turbiditic structures, including groove marks and load casts. CC3 records the disappearance of siliciclastic input and consists mainly of marl–limestone alternations, with abundant ammonites. CC4 contains carbonate grainstones, including oosparites and oopelsparites, locally associated with siliciclastic material and erosional surfaces. Finally, CC5 is characterized by thicker carbonate beds, an increasing siliciclastic component and shallow-water fossil assemblages including bivalves, gastropods, crinoids and ahermatypic corals. This uppermost part records the progressive establishment of shallower-water conditions and is interpreted as corresponding to the final stages of a second-order regressive phase.

In summary, the Peniche succession records a long-lived marine sedimentary system that evolved from predominantly shallow-water carbonate deposition during the Sinemurian to more marly and hemipelagic conditions during the Pliensbachian–early Toarcian, followed by the development of more differentiated peri-marginal environments during the late Toarcian.

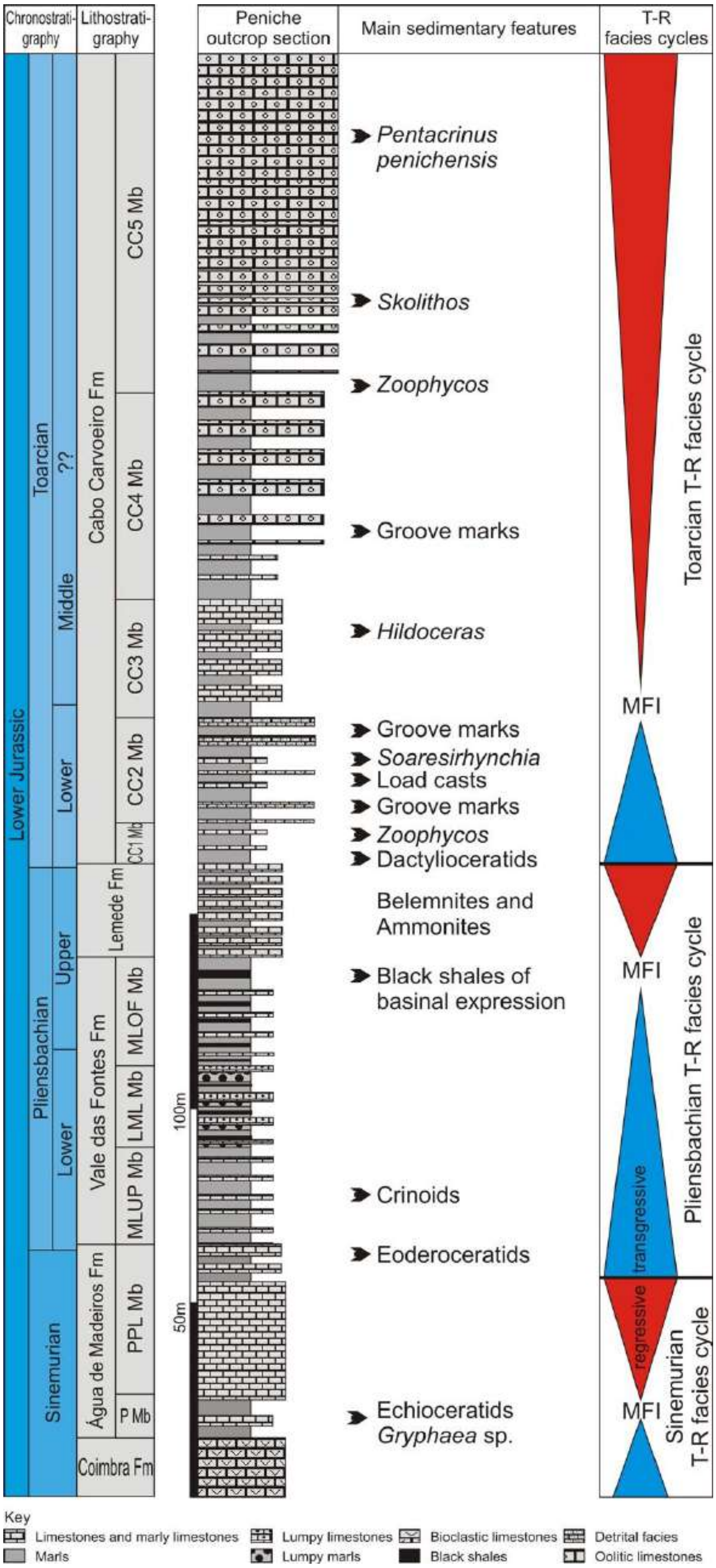

Figure III.2. Stratigraphic chart of the Sinemurian–Aalenian (?) succession of Peniche (modified from Duarte et al., 2004b and Duarte, 2007, 2017). See also Barata et al. (2021).

Figure III.3. General aspects of the different formations exposed on the Peniche Peninsula: **a)** Calcareous facies of the Coimbra Formation cropping out in the northern part of the Peniche Peninsula; **b)** Intra-Sinemurian discontinuity (dotted line) between the Coimbra and Água de Madeiros formations at Peniche; **c)** Part of the Vale das Fontes Formation at Portinho de Areia do Norte; **d)** Cyclic limestone–marl alternations of the Lemede Formation; **e)** Calciclastic limestone–marl alternations of the CC4 Member of the Cabo Carvoeiro Formation at Baixa do Outeiro; **f)** Calciclastic succession, with a strong siliciclastic component, of the uppermost member (CC5) of the Cabo Carvoeiro Formation, exposed at Cabo Carvoeiro.

2. Pliensbachian organic-rich deposits of the Peniche section (Lusitanian Basin, Portugal): Sedimentary characteristics and palaeoenvironmental significance

2.1. Introduction

One of the main characteristics of the Pliensbachian series of the LB is the occurrence of several organic-rich intervals (e.g., Duarte and Soares, 2002; Oliveira et al., 2006; Duarte et al., 2010; Silva et al., 2011, 2012; 2015; Silva, 2013; Silva and Duarte, 2015). Duarte et al. (2010), based in a detailed biostratigraphic framework (especially complete in the Peniche section (Figs. I.3-4 and III.2) sedimentological data, and TOC variation, present a consolidated 2nd-order transgressive–regressive facies cycles scheme for the Lower Jurassic carbonate series of the LB. These organic-rich levels are currently intensively studied throughout the basin, using several innovative techniques, including conventional isotope geochemistry in kerogen (Silva et al., 2011), 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), sequence stratigraphy (Silva et al., 2015), and elemental geochemistry (Silva and Duarte, 2015).

Based on sedimentological criteria, it is possible to distinguish three main sedimentation domains in MLOF Mb (Silva et al., 2012, 2015; Silva, 2013), relating to different environmental subdivisions as predicted for carbonate ramp systems (see Burchette and Wright, 1992 and references therein) (Fig. III.4). 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 (Duarte et al., 2010; Silva et al., 2011, 2012, 2015; Silva, 2013; Silva and Duarte, 2015) (Fig. I.2). Palaeobathimetric estimates based on microfossil data suggest that water column thickness averaged around 100-200 metres (e.g., N'zaba-Makaya et al., 2003; Reggiani et al., 2010). 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 (Silva, 2013; Silva et al., 2015). Locally, organic-rich facies are observed, although these are not that relevant when compared with the Western domain. The Tomar sector, in the Southeastern domain, represents the shallowest of the studied environments (Silva, 2013; Silva et al., 2015).

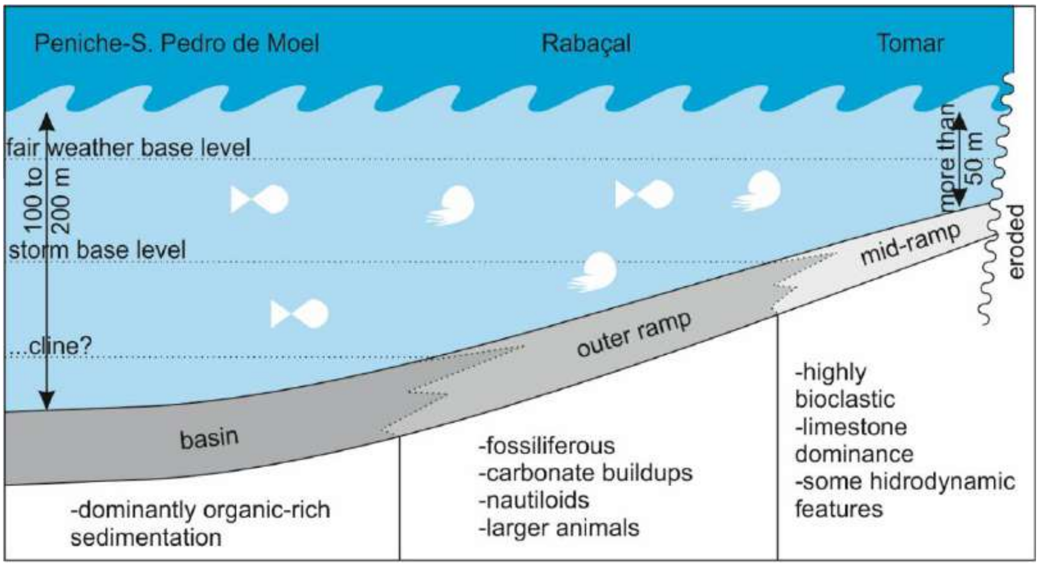

Figure III.4. Schematic diagram showing inferred paleoenvironmental settings (homoclinal ramp) during deposition of the studied Pliensbachian carbonate successions (in Silva et al., 2015).

2.2. The MLOF Member at Peniche

At Peniche, the MLOF Member crops out at Portinho da Areia do Norte (Fig. III.1) and comprises approximately 30 m of marl–limestone alternations, locally rich in both nektonic macrofossils, including ammonites and belemnites, and benthic forms such as brachiopods, bivalves, crinoids and gastropods (Fig.

III.5). The succession is particularly characterized by the widespread occurrence of organic-rich facies, ranging from dark marls and marly limestones to true black shales. These facies are commonly bioturbated, mainly by *Phymatoderma* and *Chondrites* (Fig. III.6a) and are frequently associated with abundant pyrite (Duarte and Soares, 2002; Oliveira et al., 2006; Duarte et al., 2010; Silva et al., 2011, 2012, 2015).

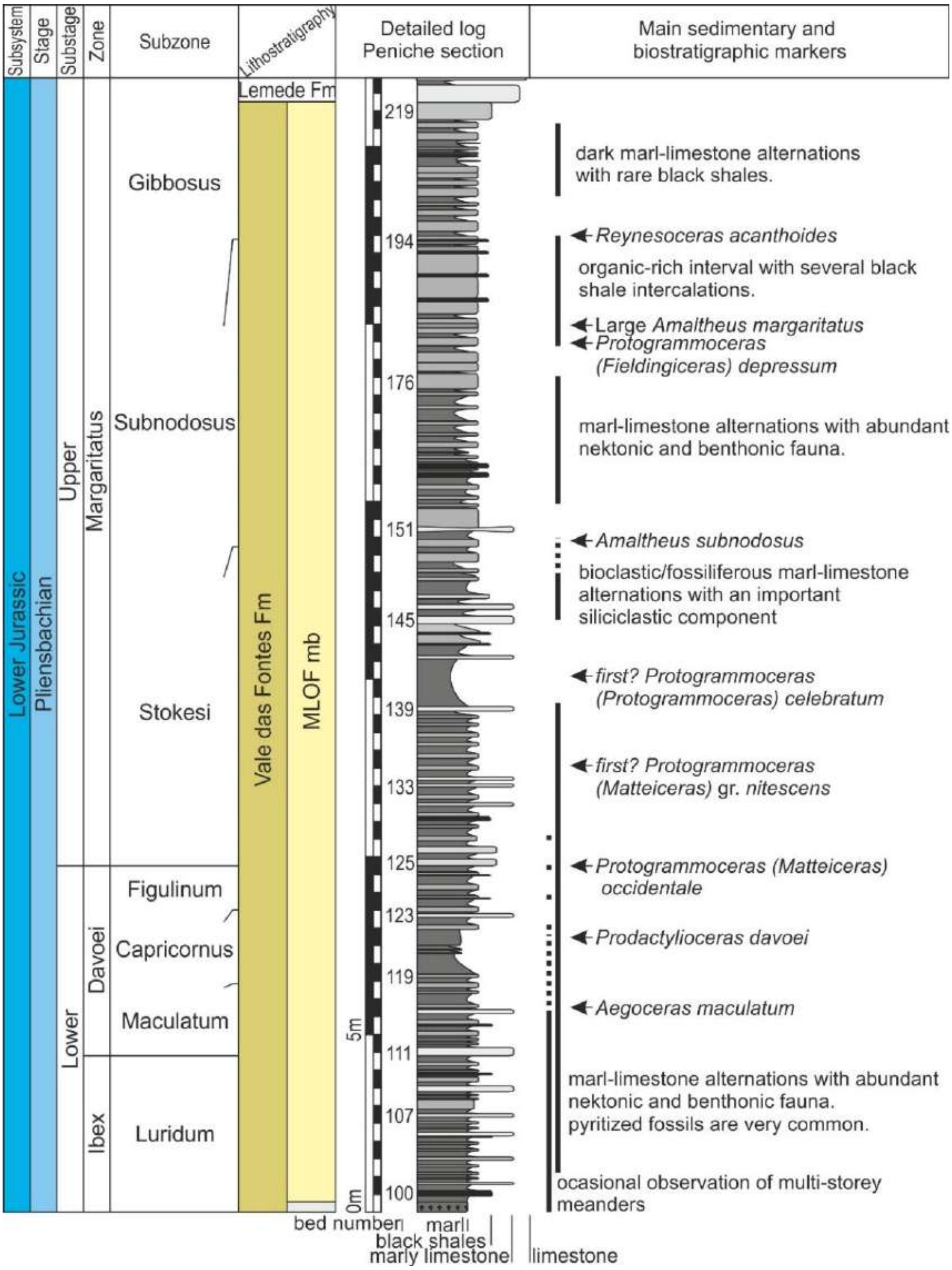

Figure III.5. Detailed log of the MLOF Member and base of Lemede Formation in the Peniche reference section of the LB (modified from Silva et al., 2011; Silva, 2013) (in Silva et al., 2015, 2018).

The lower part of the member, corresponding to the Ibex Zone, consists of regular marl–limestone alternations that gradually pass upwards into a more irregular, marl-dominated interval attributed to the Davoei Zone (Figs. III.5–III.6b). Its lower boundary with the underlying MLM Member is sharp and coincides with the disappearance of the characteristic "lumpy" facies, represented by subspherical micritic concretions, locally displaying cryptalgal structures (see Coimbra and Duarte, 2020). Organic-rich intervals are particularly common at marl–limestone interfaces, while pyrite occurs dispersed, as nodules and as infillings of fossil and ichnofossil moulds (Silva et al., 2011, 2012, 2015).

The Margaritatus Zone is characterized by relatively regular marl–limestone couplets, locally interrupted by thin coarse bioclastic beds. A distinctive interval occurs within the Stokesi Subzone, where two black-shale layers are overlain by a more carbonate-rich interval comprising three mud–wackestone beds (Figs. III.5–III.6c). Higher in the succession, the marly interval becomes particularly rich in bioclasts and contains a significant terrigenous and coarse bioclastic fraction. Towards the upper part of the member, at approximately 25 m above its base, a thick limestone–marl–black shale package develops (Fig. III.6d). The MLOF Member is sharply overlain by the Lemede Formation. High-resolution, bed-by-bed ammonite data (Silva et al., 2011, 2015; Silva, 2013) broadly confirm the established Pliensbachian biozonation of the LB. These data indicate that the base of the Lemede Formation falls within the uppermost Gibbosus Subzone of the Margaritatus Zone, with a distinctive level containing *Arieticeras* gr. *algovianum* occurring approximately 3 m above the formation base.

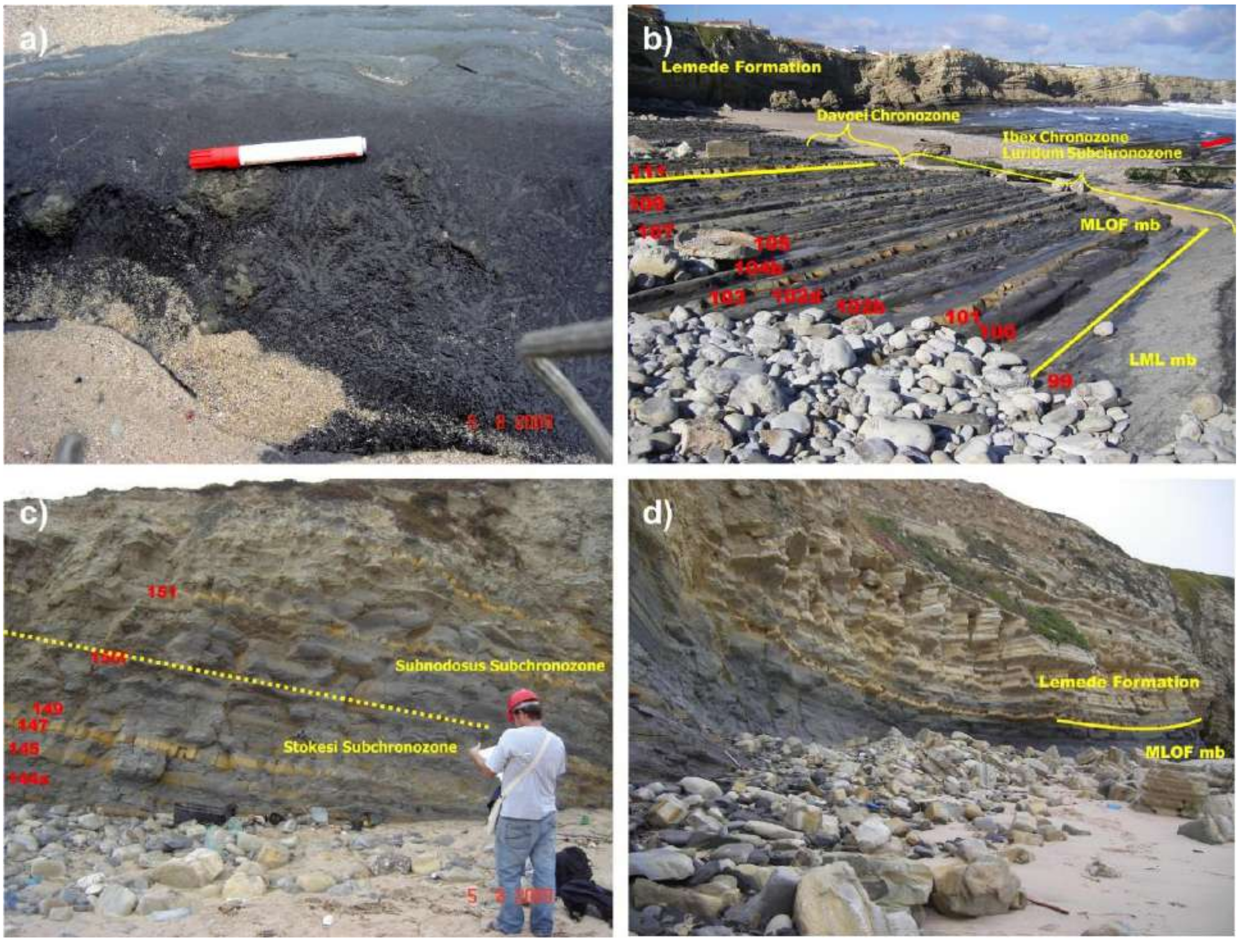

Figure III.6. Field details of the MLOF Member (Vale das Fontes Formation) and Lemede Formation at Peniche: **a)** *Chondrites* sp. in an organic-rich interval; **b)** base of the studied section; **c)** middle portion of the studied section; **d)** limit between the Vale das Fontes and Lemede formations (in Silva et al., 2015).

2.3. Organic-rich facies: origin, preservation and palaeoenvironmental constraints

Basin-wide, the organic-rich facies of the MLOF Member vary between massive dark marls to true black shales (see Duarte et al., 2010; Silva et al., 2011, 2012, 2015; Correia et al., 2013; Silva, 2013; Silva and Duarte, 2015). The former is 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 benthic and nektonic macrofauna is abundant (Silva, 2013; Silva et al., 2015). 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 (Fig. III.7).

Palynofacies analysis and origin-related biomarkers from the Peniche section show that kerogen assemblages in this interval consist of 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; Silva and Duarte, 2015) (Fig. III.8a-b). The black shales of the LB are interpreted to correspond to short-lived basinwide development of mucilaginous aggregate blooms and microbial mats (*s.l.*), promoted by mixing of the water column and preserved in anoxic (occasionally euxinic) sediments (Silva and Duarte, 2015).

Biogeochemical studies show that lipid contents in black shales range from 197.67 to 8446.36 µg/g rock; the maximum value was determined at Peniche. High lipid contents seem to correlate with low [O_2] time intervals, suggesting selective lipid preservation under oxygen-depleted and hydrogen sulfide-rich environments (Silva et al., 2012) (Fig.III.9).

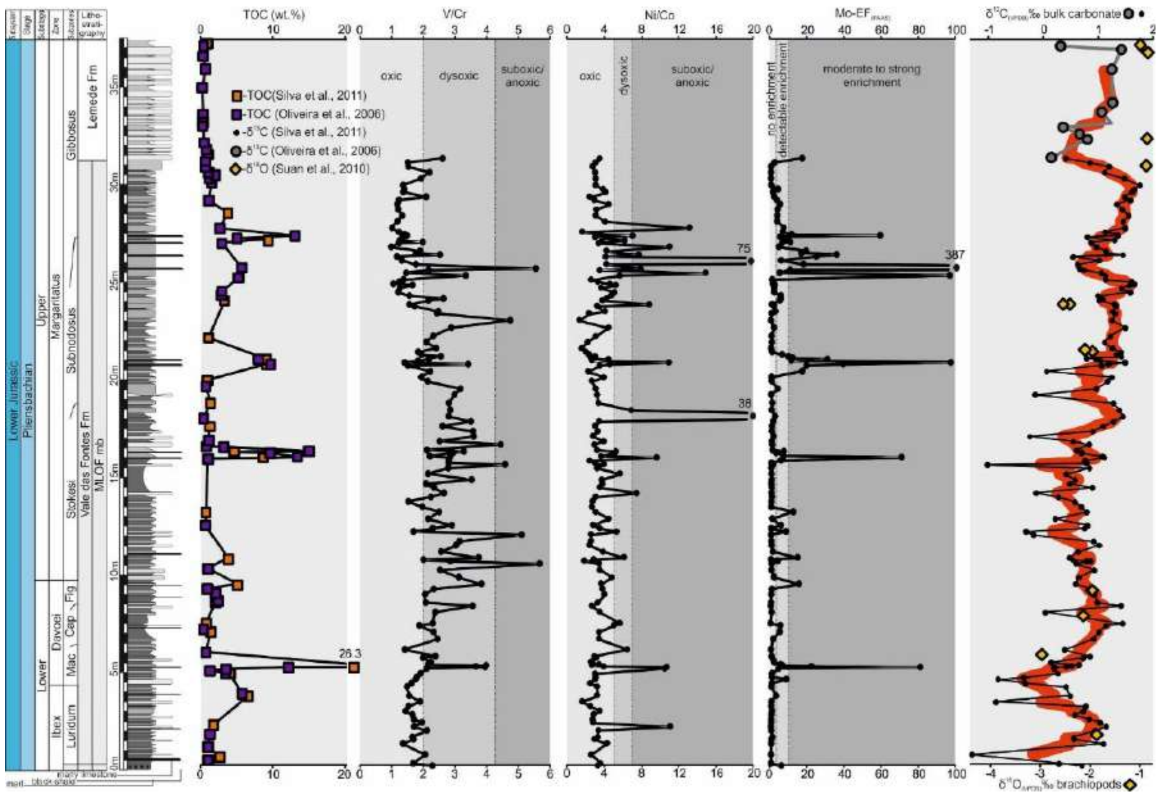

Figure III.7. TOC, $\delta^{13}C$, V/Cr, Ni/Co and Mo-$EF_{(PAAS)}$ for the Pliensbachian MLOF mb of the Vale das Fontes Formation at Peniche (Lusitanian Basin, Portugal) (stratigraphic column and TOC projection modified from Silva et al., 2011) (in Silva and Duarte, 2015, 2018).

Carbonate and kerogen carbon isotopic data from the Peniche section (Silva et al., 2011) allow demonstrating a relationship between accumulation and preservation of organic matter in the LB and several global perturbations of the carbon cycle (e.g., Jenkyns and Clayton, 1986) (Fig. III.7). Comparing the LB with several other basins worldwide, Silva et al. (2011, 2021) 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 (Schlanger and Jenkyns 1976, see below).

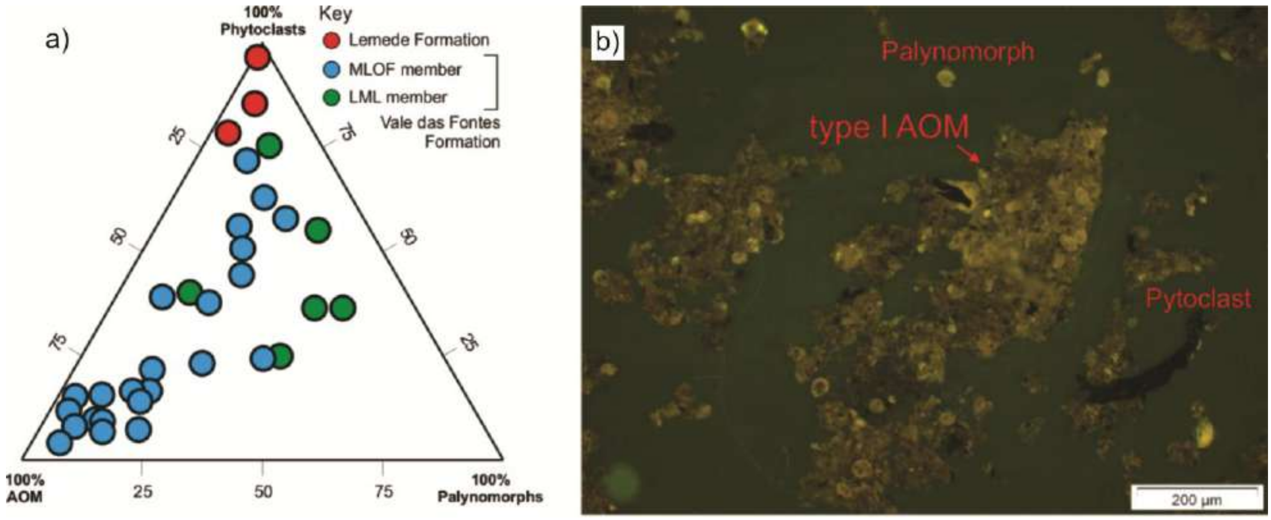

Figure III. 8. **a)** Amorphous Organic Matter-Phytoclasts-Palynomorphs ternary plot for part of the Pliensbachian series at Peniche (modified from Ferreira et al., 2010); **b)** Palynofacies sample evidencing the dominance of marine Amorphous Organic Matter (AOM) (modified from Silva et al., 2012).

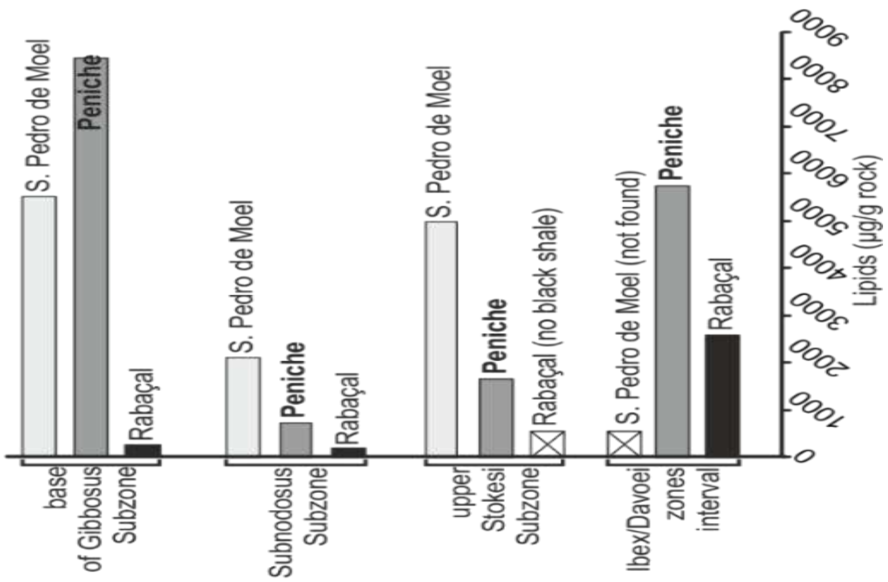

Figure III. 9. Lateral and temporal variation of the lipid content in the Rabaçal, Peniche and S. Pedro de Moel outcrop sections (modified from Silva et al., 2012).

3. The Toarcian GSSP and the Toarcian Oceanic Anoxic Event

The uppermost Pliensbachian–Lower Toarcian succession at Peniche, exposed between Ponta do Trovão and Praia do Abalo (Figs. III.1-2), constitutes the main reference section for this stratigraphic interval in the LB and has attracted considerable international attention (e.g., Duarte et al., 2017), owing to the definition of the Toarcian GSSP (Figs. III.10 and III11a-b; Rocha et al., 2016) and the extensive scientific debate surrounding the TOAE (e.g., Hesselbo et al., 2007; Suan et al., 2008a, 2008b, 2010; Mattioli et al., 2009; Littler et al., 2010; Pittet et al., 2014; Comas-Rengifo et al., 2015; Rita et al., 2016; Baker et al., 2017; Correia et al., 2017; Duarte et al., 2018; Fantasia et al., 2019; Müller et al., 2020; Rodrigues et al., 2021; Font et al., 2022; and references therein). Included within the Lemede and Cabo Carvoeiro formations (Figs. III.10-12; Duarte and Soares, 2002; Duarte, 2007), this stop focuses on the biotic and abiotic parameters investigated across the uppermost Pliensbachian–Lower Toarcian succession at Peniche, as well as on the main stratigraphic markers associated with the TOAE. Particular emphasis will be placed on the distinctive sedimentological and organic matter record of this interval in this sector of the western Iberian margin.

3.1. The Pliensbachian–Toarcian Boundary

The Toarcian GSSP is defined at this locality, at Ponta do Trovão, at the transition between the uppermost two beds of the Lemede Formation exposed in this sector of the LB (Figs. III.10-11a-b; Rocha et al., 2016; Duarte et al., 2017, 2018). Historically, the boundary was placed at the base of micritic limestone bed 15E, corresponding to the first appearance of several species of the genus *Dactylioceras* (*Eodactylites*) (Elmi, 2006; Rocha et al., 2016). The upper part of what is now designated the Lemede Formation, together with the stratigraphic distribution of ammonite taxa, was described by Mouterde (1955) as a distinctive unit termed “Couches de passage” (transition beds). The formalization of this chronostratigraphic boundary by the International Commission on Stratigraphy was achieved using palaeontological criteria (ammonites, brachiopods, ostracods and calcareous nannofossils), sedimentological and geochemical criteria (stable carbon isotopes), and cyclicity (see Rocha et al., 2016 and references therein). More recent and detailed information, covering sedimentological, stratigraphic and palaeontological aspects (ammonites, belemnites, ostracods, foraminifera, calcareous nannofossils and dinoflagellates), can be found in Comas-Rengifo et al. (2016), Correia et al. (2017, 2018), Duarte et al. (2018), Cabral et al. (2020), and Rita et al. (2016, 2021). Collectively, these studies, which are of major scientific relevance, highlight the international significance of both the locality and the Pliensbachian–Toarcian boundary (Duarte et al., 2017).

In addition to the chronostratigraphic boundary, this locality exposes the transition between the Lemede and Cabo Carvoeiro formations, two units formally defined at the Peniche section (Duarte and Soares, 2002; Duarte, 2007). The Lemede Formation is exceptionally fossiliferous, containing both nektonic organisms, such as belemnites and ammonites, and benthic organisms, particularly bivalves and brachiopods. The transition to the Cabo Carvoeiro Formation marks a deepening of the depositional system. The transition is dated to the extreme base of the Toarcian (Polymorphum Zone) and is represented by a predominantly marly succession assigned to its CC1 Member (approximately 11 m thick; Figs. III.10-11). This unit is also highly fossiliferous and contains a distinctive assemblage of small-sized macrofauna. This includes brachiopods, such as the genera *Koninckella*, *Liospiriferina*, *Nannirhynchia* and *Pseudokingena* (Comas-Rengifo et al., 2015) (Fig. III.11c), bivalves, ammonites (including several species of Dactylioceratidae, with numerous specimens preserved as pyritized internal moulds) and belemnites, particularly *Catateuthis longiforma* and *Passaloteuthis bisulcata* (Rita et al., 2021). Another relevant feature of this basal Toarcian unit is its trace-fossil assemblage, which comprises the ichnogenera *Planolites*, *Chondrites*, *Thalassinoides* and *Zoophycos* (Fig. III.11d) (see also Duarte, 1997; Duarte et al., 2018 and references therein).

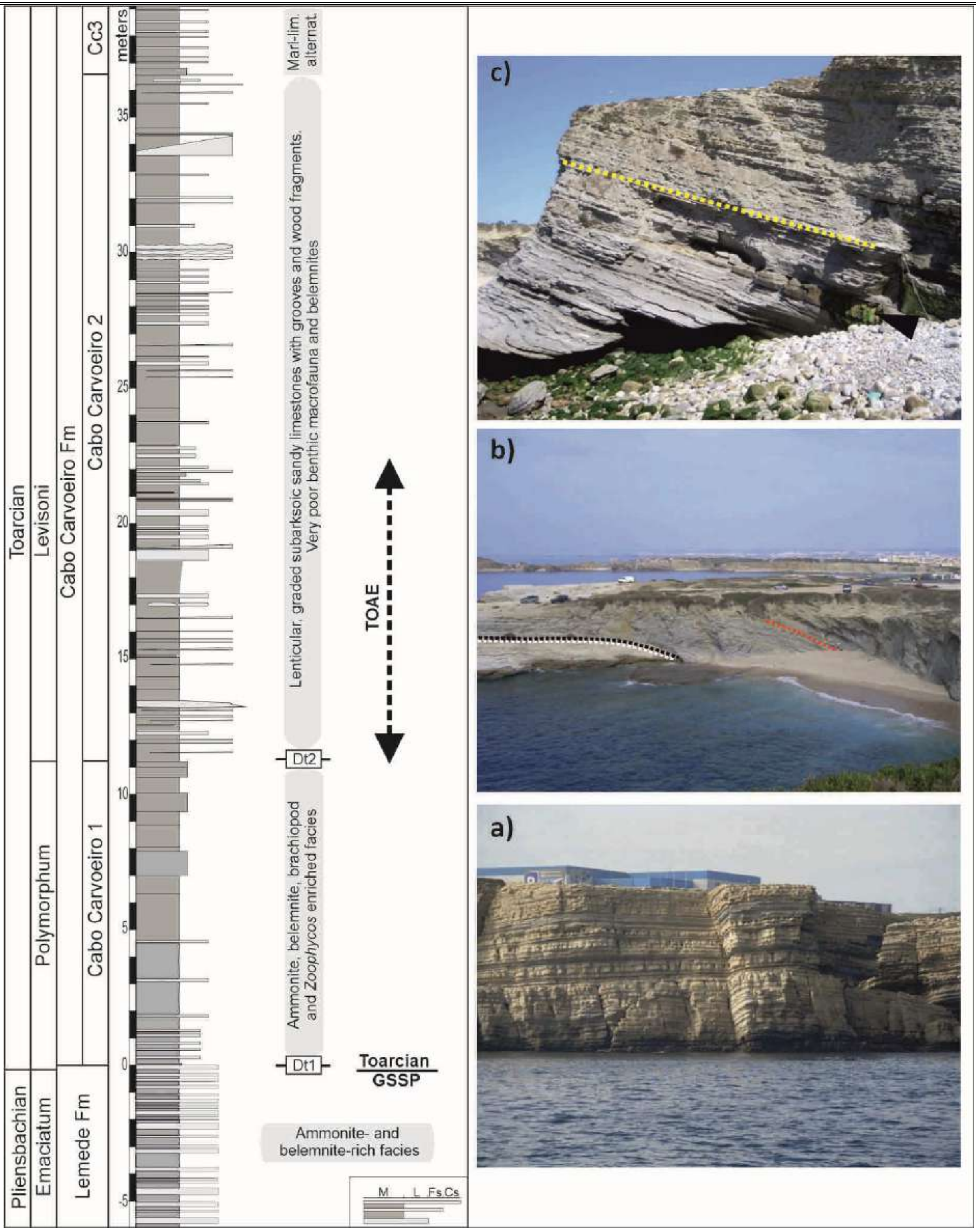

Figure III.10. Detailed log showing some of the most relevant sedimentary and stratigraphic features of the uppermost Pliensbachian–lower Toarcian (top of the Lemede Formation–base of the Cabo Carvoeiro Formation) at Peniche (M – marl; C – limestone; Fs – fine-grained calcarenite; Cs – coarse-grained calcarenite; DT – Discontinuity; in Duarte et al., 2018). **a)** General view of the marl–limestone alternations of the Lemede Formation; **b)** General view of the sedimentary succession at Praia do Abalo: white line – Toarcian GSSP; black line – transition between the Lemede and Cabo Carvoeiro formations; red line – transition between CC1 and CC2 members, marking the boundary between the Polymorphum and Levisoni zones and the onset of the TOAE; **c)** Transition between CC2 and CC3 members (yellow line), highlighting the thickest lenticular siliciclastic bed in the entire succession (arrow). Adapted from Duarte et al. (2018)

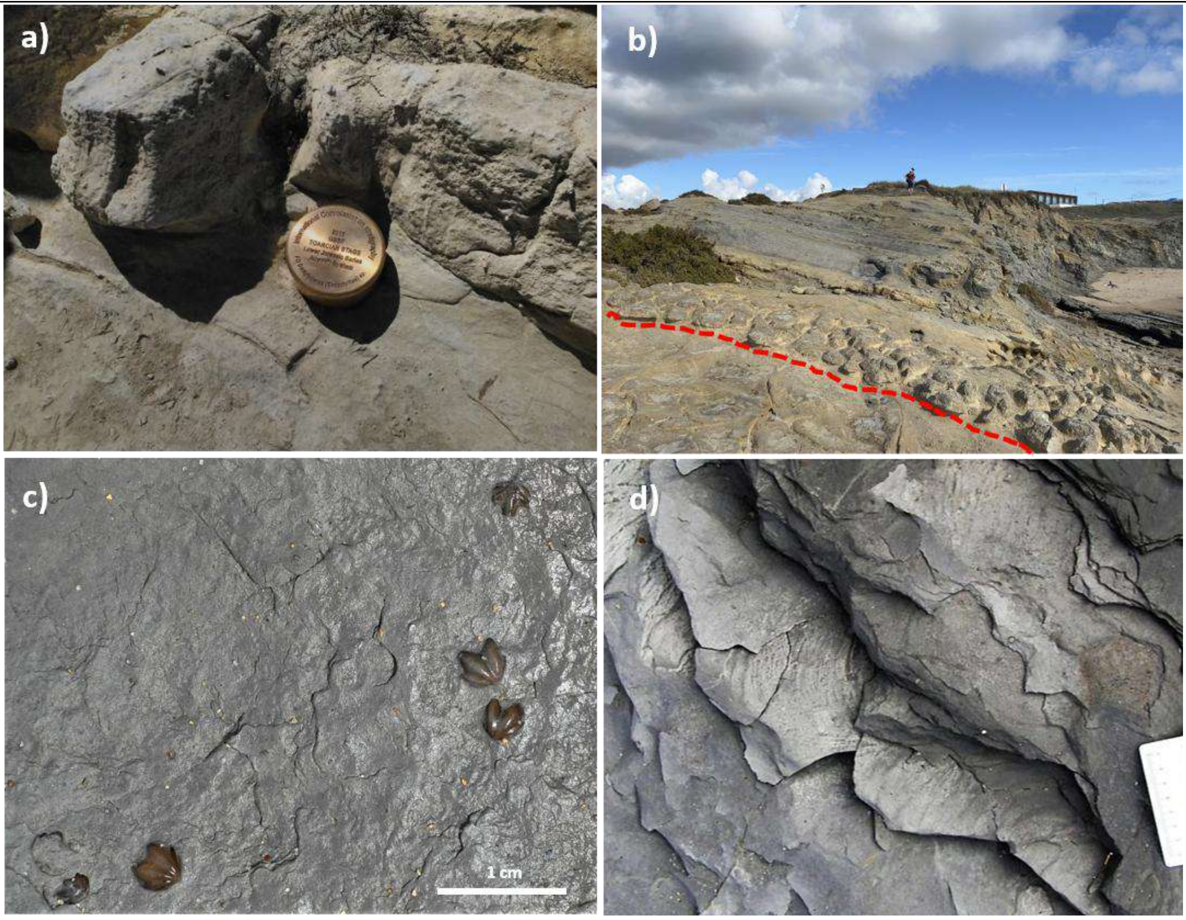

Figure III.11. Stratigraphic and facies features of the Pliensbachian–Toarcian transition at Ponta do Trovão. **a)** The Global Boundary Stratotype Section and Point (GSSP) for the Pliensbachian–Toarcian boundary, marked by the classic "Golden Spike"; **b)** Pliensbachian–Toarcian boundary (red line) and the boundary between the Lemede and Cabo Carvoeiro formations; (just above) **c)** Several specimens of *Nannirhynchia pygmaea* from a marly bed of the CC1 Member; **d)** Occurrence of *Zoophycos* sp. in marly limestone facies of the CC1 Member.

3.2. The Toarcian Oceanic Anoxic Event/Jenkyns Event recorded at Peniche

The Abalo beach provides an exceptional record of the early T-OAE and constitutes a global reference locality for the study of this event (e.g., Hesselbo et al., 2007; Suan et al., 2010; Duarte et al., 2018; Font et al., 2022, and references therein). The T-OAE, which occurred around 183 Ma, is characterized by widespread organic-matter accumulation and major perturbations to the global carbon cycle, expressed by a pronounced negative carbon-isotope excursion (CIE) recorded in both marine carbonate and terrestrial organic matter (e.g., Hesselbo et al., 2007; Fantasia et al., 2019, and references therein) (Fig. III.12).

At Peniche, the high-resolution isotopic geochemical study of Hesselbo et al. (2007) documented a significant negative $\delta^{13}C$ excursion across the Polymorphum–Levisoni Zone transition, recorded both in the marine carbonate component and in terrestrial carbonaceous fragments (Fig. III.12). This excursion was subsequently corroborated by $\delta^{13}C$ data obtained from dispersed organic matter (Fantasia et al., 2019; Rodrigues et al., 2020), providing strong evidence for a major perturbation of the global carbon cycle. This record is particularly significant given the relatively low abundance of dispersed organic matter in the early Toarcian succession at Peniche and elsewhere in the LB. The Peniche succession also provides evidence that the early Toarcian environmental perturbation extended well beyond oceanic anoxia. Oxygen-isotope data indicate a hyperthermal episode (Suan et al., 2008a), while other studies have documented additional environmental and geochemical changes associated with the event (Suan et al., 2008b, 2010; Baker et al., 2017; McArthur et al., 2020). Boron-isotope data suggest that seawater acidification may also have occurred

(Müller et al., 2020). In contrast, mercury data provide evidence for a strong link between the event and magmatic activity associated with the Karoo–Ferrar Province (Font et al., 2022). Together, these observations point to a complex Earth-system perturbation involving interactions between volcanism, climate, the carbon cycle and marine environments.

The biological consequences of this event are also exceptionally well documented at Peniche. Evidence for the associated second-order extinction is provided by changes in the record of spiriferinid brachiopods (Comas-Rengifo et al., 2015) and Metacopina ostracods (Cabral et al., 2020), as well as by major disruptions in the distribution of belemnites (Rita et al., 2021), foraminifera (Rita et al., 2016), dinoflagellates (Correia et al., 2017) and calcareous nannofossils (Mattioli et al., 2008, 2009) (Fig. III.12). Collectively, these palaeontological records document major changes in marine biotic communities across the event and provide evidence of its profound biological impact.

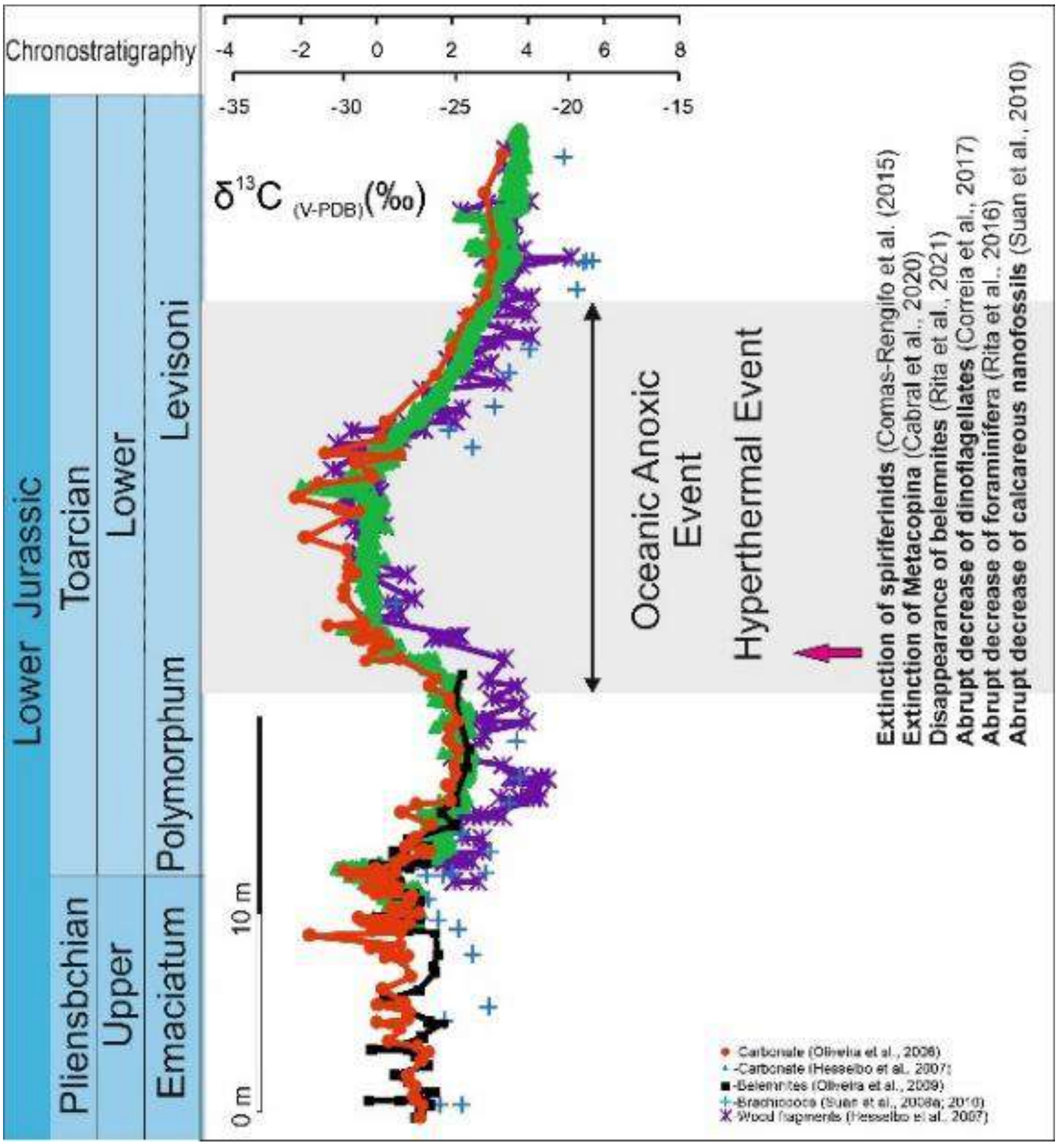

Figure III.12. Some of the main geochemical and palaeontological signatures associated with the Jenkyns Event recorded at Peniche (see text) (adapted from Duarte et al., 2017).

The term Jenkyns Event has therefore been increasingly used to encompass this broader set of environmental and geological changes, rather than referring solely to the development of anoxic conditions (e.g., Reolid et al., 2020). At Peniche, the combination of an exceptional sedimentary record, high-resolution biostratigraphic control, carbon-cycle perturbations, evidence for climatic and oceanographic change, and major biological turnovers makes this succession particularly valuable for understanding the global significance of the Jenkyns Event. It represents a global event expressed in an exceptionally distinctive sedimentary, geochemical and palaeontological record (Fig. III.12).

3.2.1. Sedimentological aspects and depositional dynamics

The Toarcian succession at Peniche displays one of the most significant sedimentary changes recorded throughout the Lower Jurassic of the basin, expressed by the transition between CC1 and CC2 members of the Cabo Carvoeiro Formation (Duarte, 1997; Duarte and Soares, 2002; Duarte et al., 2018). Overlying the predominantly marly and fossiliferous deposits of CC1 Member is a marl–limestone succession containing several intercalations of quartzose, feldspathic and micaceous siliciclastic sediments, occurring as lenticular beds of highly variable thickness (≤110 cm) (Wright and Wilson, 1984; Duarte, 1997; Fantasia et al., 2019). Throughout CC2 Member, which is approximately 25 m thick, a wide range of lithofacies is recognized, from brown to grey marls, locally rich in organic matter, to calcarenites and subarkosic microconglomerates (Figs. III13a–c) (e.g., Wright and Wilson, 1984; Duarte, 1997; Duarte et al., 2018; Rodrigues et al., 2020; Font et al., 2022). The unit is poor in macrofauna, represented mainly by ammonites and a few brachiopods, and contains frequent carbonaceous fragments and pyrite nodules (Fig. III13d). The ichnofacies is characterized by the frequent occurrence of *Thalassinoides*, together with *Planolites* and *Rhizocorallium* (Fig. III.13e). Fining-upward microsequences, together with erosional structures such as groove marks and load casts, represent typical turbiditic features (Figs. III.13a-c and III.13f), suggesting a direct relationship with the granites of Berlenga (see Wright and Wilson, 1984; Duarte, 1997). This sedimentary variability, synchronous with facies displaying paleoseismites recorded in the Arrábida region (Kullberg et al., 2001; Fig. I.2), appears to coincide with intense tectonic activity responsible for the displacement of the Berlenga Block, as previously proposed by Duarte (1997).

The transition from CC2 to CC3 Member is marked by the disappearance of siliciclastic facies and a return to marl–limestone sedimentation, with a clear dominance of the carbonate component towards the top (Fig. III.10). This unit, approximately 30 m thick, contains a scarce benthic macrofauna despite intense bioturbation, notably represented by *Chondrites* and *Planolites*. Ammonites, more frequent in the upper part of the unit, allow its assignment to the Levisoni–Bifrons zones. As observed elsewhere in the basin, the marly interval at the base of CC3 Member is interpreted as corresponding to the maximum flooding interval of the second-order transgressive–regressive cycle that characterizes much of the Toarcian (Figs. I.4 and III.1; see Duarte, 2007; Duarte et al., 2017).

3.3. Organic-matter variability at Peniche

Rodrigues et al. (2020) investigated the variability of sedimentary organic matter (OM) across the uppermost Pliensbachian–lower Toarcian interval of the LB, focusing on the Peniche and Rabaçal reference sections and complemented by data from other sections (Figueira da Foz, Cantanhede, Coimbra and Porto de Mós) (Fig. I.2). The study combines TOC, $\delta^{13}C$ of kerogen ($\delta^{13}C_{kerogen}$) and palynofacies analyses to assess changes in the origin, transport and preservation of OM across the Pliensbachian–Toarcian transition, encompassing the Pliensbachian–Toarcian Event (Pl–Toa Event) and the TOAE (Hesselbo et al., 2007). At Peniche, the uppermost Pliensbachian–lower Toarcian succession is characterised by generally low organic-carbon contents (TOC averaging 0.6 wt.%, still the highest of the basin, whose overall average is 0.4 wt.%) and a predominantly terrestrial origin of OM (Fig. III.14). The kerogen assemblage is strongly dominated by phytoclasts (~86%), with opaque phytoclasts (OP) averaging ~60%. Terrestrial palynomorphs, mainly sporomorphs and *Classopollis*, are subordinate, whereas amorphous organic matter (AOM) and marine palynomorphs are generally scarce. $\delta^{13}C_{kerogen}$ values range from −21.6 to −29.2‰ (Figs. III.14-15).

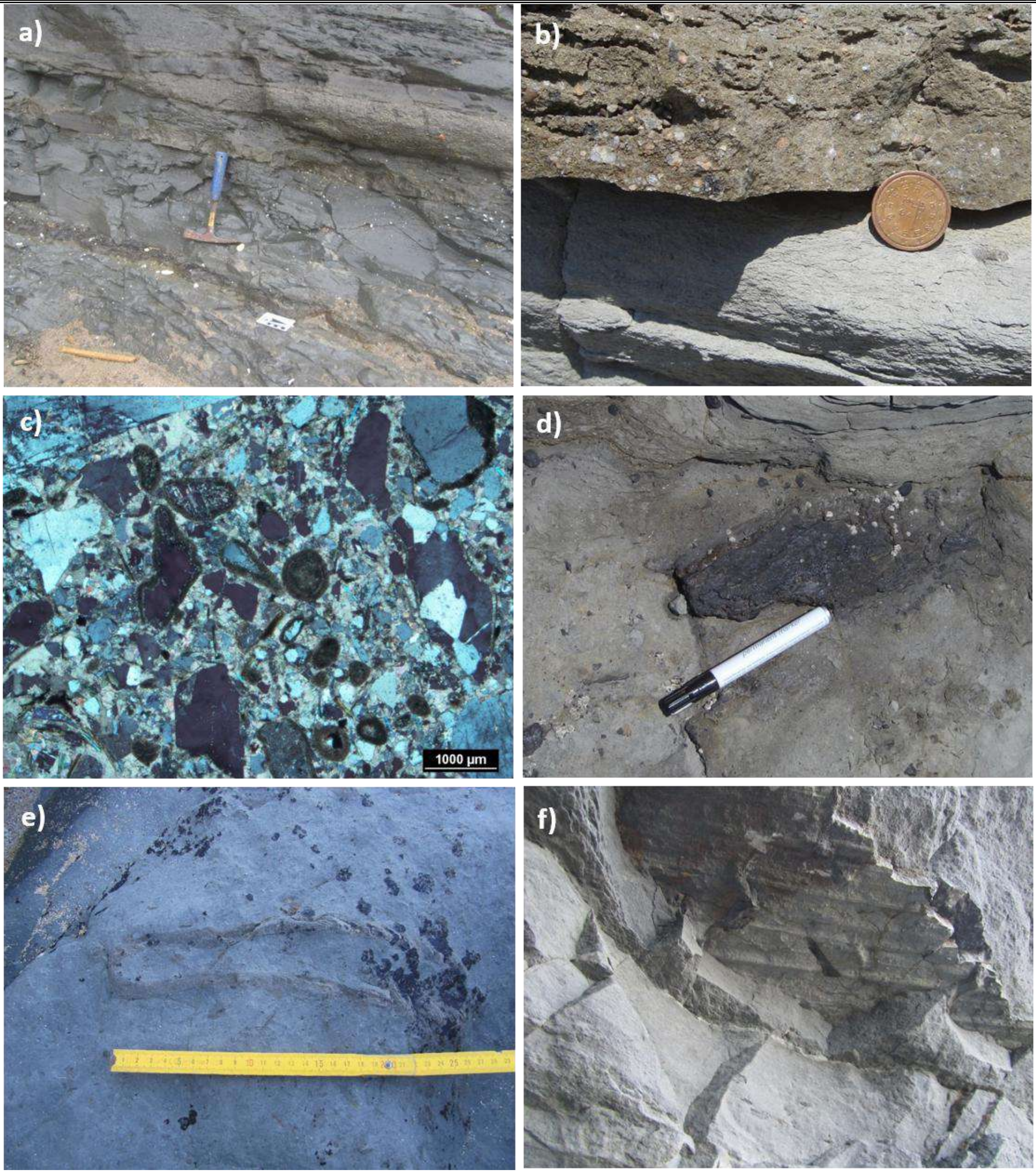

Fig. III.13. Facies characteristics of the CC2 Member exposed at Praia do Abalo: **a)** Lenticular siliciclastic beds (including microconglomerate rich in potassium feldspar) of turbiditic origin alternating with bioturbated marly beds in the lower part of the CC2 Member; **b)** Very coarse-grained, subarkosic sandy bed showing a fining-upward structure (upper part of the CC2 Member); **c)** Very coarse-grained calcarenitic facies containing some allochems; **d)** Detail of a relatively large carbonaceous fragment within marly facies; **e)** Detail of *Rhizocorallium* sp.; **f)** Groove marks at the base of a centimetre-thick subarkosic calcarenite bed (upper part of the CC2 Member). Adapted from Duarte et al. (2018).

In the uppermost Pliensbachian (Emaciatum Zone), the kerogen assemblages are typical of oxygenated proximal settings with a strong continental influence, including freshwater algae (*Botryococcus* sp.); a slight increase in non-opaque phytoclasts (NOP) at the base of the Polymorphum Zone then marks the first evidence of enhanced fluvial runoff, linked to the Pl–Toa Event (Hesselbo et al., 2007; Fantasia et al., 2019).

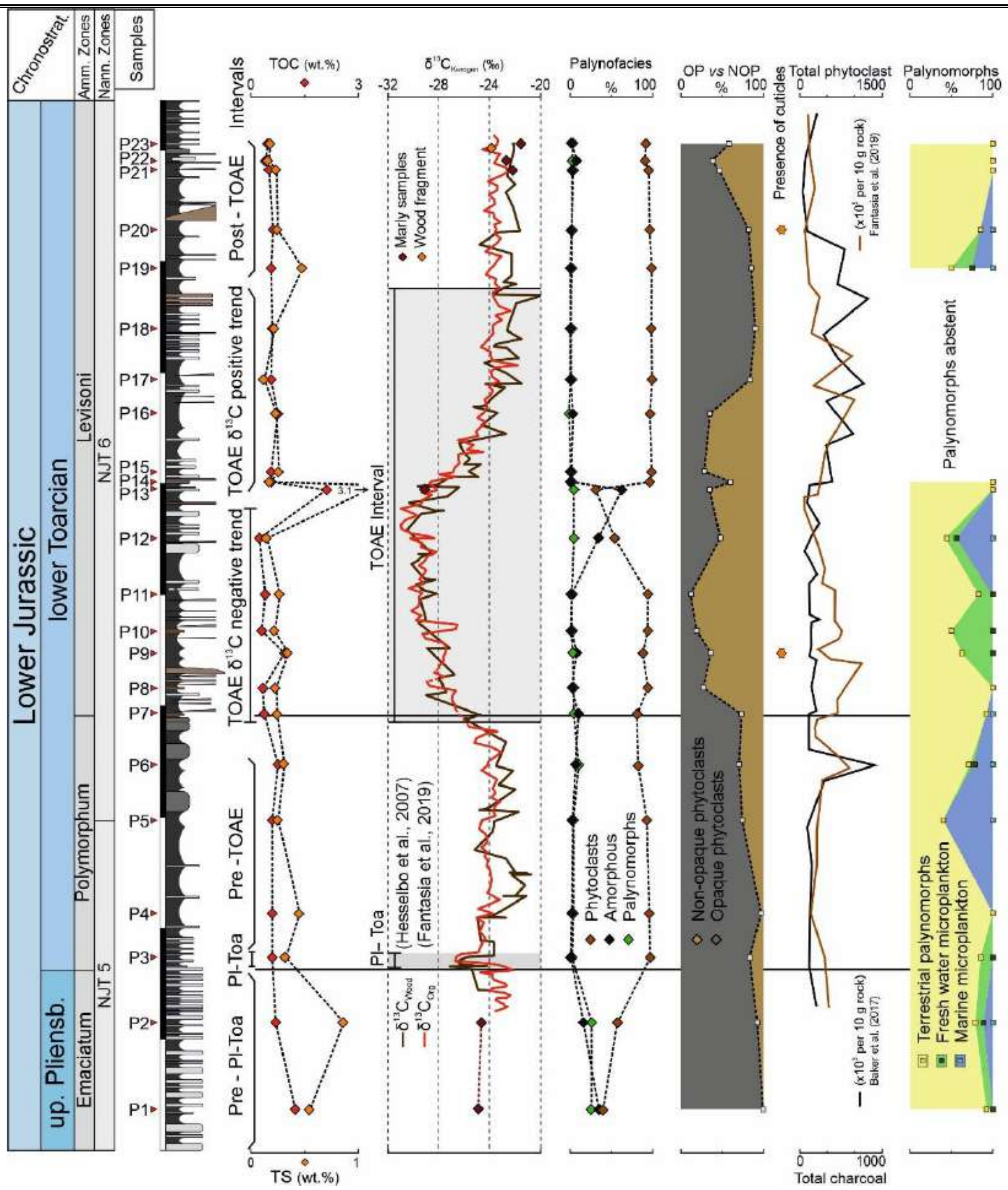

Figure III.14. TOC, TS, $\delta^{13}C_{Kerogen}$, $\delta^{13}C_{Org}$, $\delta^{13}C_{Wood}$, palynofacies associations and main intervals. $\delta^{13}C_{Wood}$ and $\delta^{13}C_{Org}$ data from the supplementary information of Hesselbo et al. (2007) and Fantasia et al. (2019), respectively. Total charcoal and phytoclast abundance from Baker et al. (2017) and Fantasia et al. (2019), respectively. The record of the Pl–Toa Event and TOAE interval is based on Hesselbo et al. (2007) and Fantasia et al. (2019). up. Pliensb. – upper Pliensbachian. Modified from Rodrigues et al. (2020).

During the pre-TOAE interval, particularly the Polymorpum Zone, the dominance of OP and relatively positive $\delta^{13}C_{kerogen}$ values are consistent with a semi-arid, strongly seasonal climate. Up-section, however, there is a progressive increase in NOP, interpreted as evidence for increasing riverine transport of relatively fresh terrestrial OM in response to progressive warming and increasing humidity. Towards the top of the Polymorphum Zone, an increase in the relative abundance of marine palynomorphs (mainly *Nannoceratopsis gracilis*) coincides with a brief peak in charcoal abundance (Baker et al., 2017), suggesting that large fires in the emerged areas of the basin promoted surface runoff and nutrient export to the marine environment.

The most significant change occurs at the base of the Levisoni Zone, the onset of the TOAE. The negative $\delta^{13}C$ excursion documented at Peniche in $\delta^{13}C_{carb}$, $\delta^{13}C_{wood}$ and $\delta^{13}C_{org}$ (Hesselbo et al., 2007; Fantasia et al., 2019) is accompanied by an abrupt increase in NOP (averaging 67%) and in the size of these particles. This shift indicates enhanced continental runoff and delivery of terrestrial OM to the marine environment under warmer and wetter conditions. Terrestrial palynomorphs also increase, whereas marine palynomorphs decrease. The same interval is further marked by a decrease in charcoal (Baker et al., 2017), attributed to the suppression of fire activity under increasingly humid conditions. During the initial phase of the positive $\delta^{13}C$ trend, Peniche records the highest TOC values of the studied succession, reaching 2.1 wt.%, together with a marked increase in AOM. This interval is interpreted as reflecting enhanced freshwater and nutrient input, potentially promoting locally dysoxic conditions and improving OM preservation. Subsequently, NOP abundance decreases towards pre-TOAE values, broadly coinciding with an increase in charcoal. This is interpreted as a progressive return to cooler and drier conditions, favouring renewed wildfire activity and the transport of oxidised terrestrial organic matter. After the TOAE, the organic assemblage gradually returns towards its pre-event composition, although there is a slight increase in terrestrial palynomorphs and NOP suggests renewed continental runoff.

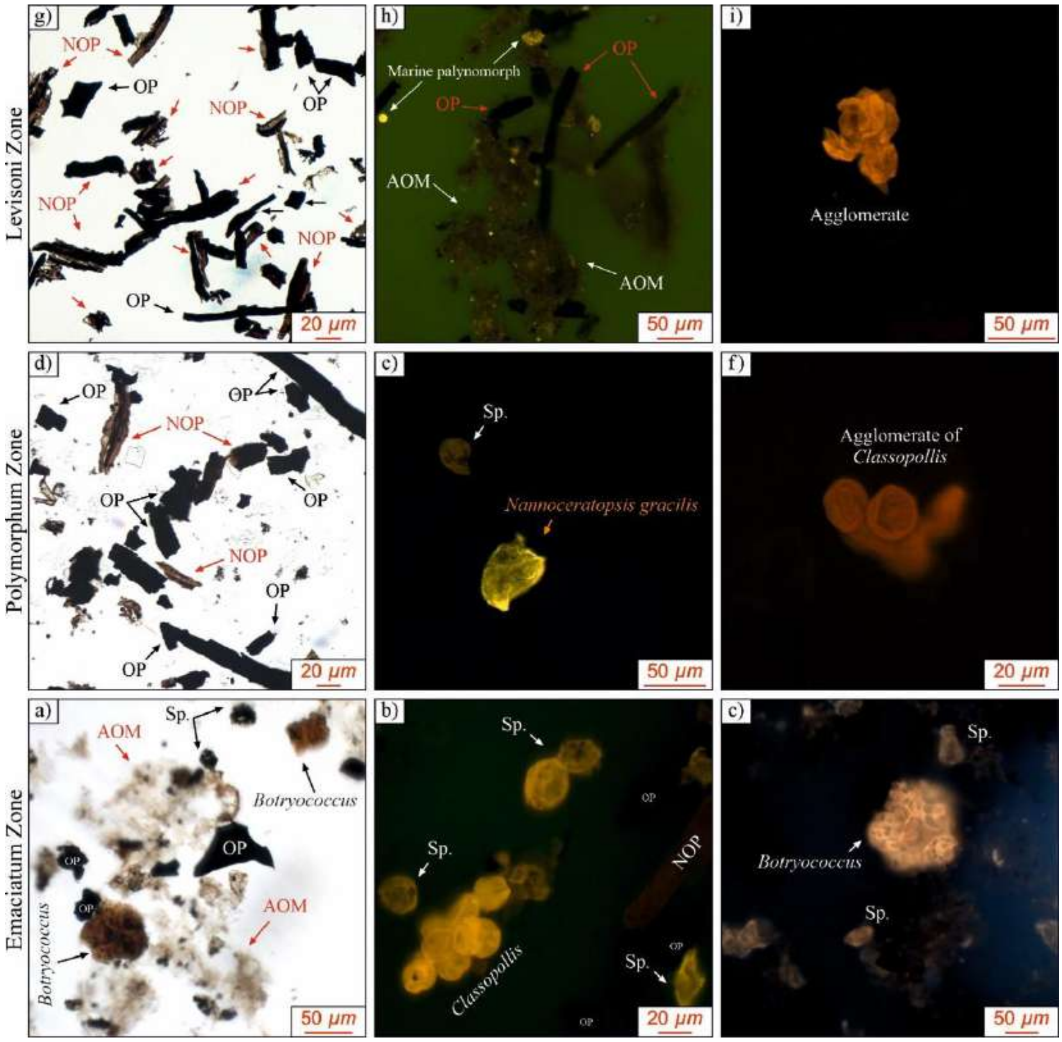

Figure III.15. Photomicrographs of the kerogen assemblages, arranged by ammonite zone: **a)** Amorphous organic matter (AOM), opaque phytoclasts (OP), sporomorphs (Sp.) and *Botryococcus* sp.; **b)** sporomorphs, *Classopollis*, non-opaque phytoclasts (NOP) and OP; **c)** *Botryococcus* sp. and sporomorphs; **d)** OP and NOP; **e)** Sporomorph and the dinoflagellate cyst *Nannoceratopsis gracilis*; **f)** Agglomerate of *Classopollis*; **g)** Dominance of NOP with subordinate OP; **h)** AOM with OP and a marine palynomorph; **i)** Pollen agglomerate. Transmitted white light (TWL): a, d, g. Fluorescence mode (FM): b, c, e, f, h, i.

Overall, the Peniche record documents a clear shift in the nature and supply of organic matter: from predominantly oxidised terrestrial OM under relatively dry conditions, towards increasing fresh terrestrial input with progressive warming and humidification, followed by maximum OM accumulation and AOM during the TOAE, and finally a return towards pre-TOAE conditions.

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This field guide is dedicated to the memory of Professor Deolinda Flores, a leading figure in the study of organic matter and coal geology in Portugal. Her scientific contributions were fundamental to the development of these fields and to the training of successive generations of researchers. As organizer of the 77th Annual Meeting of the ICCP, she also played an important role in strengthening international collaboration and promoting Portuguese research. Her passing represents a profound loss to the scientific community. This field guide pays tribute to her legacy and to her lasting contribution to the study of organic matter.

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