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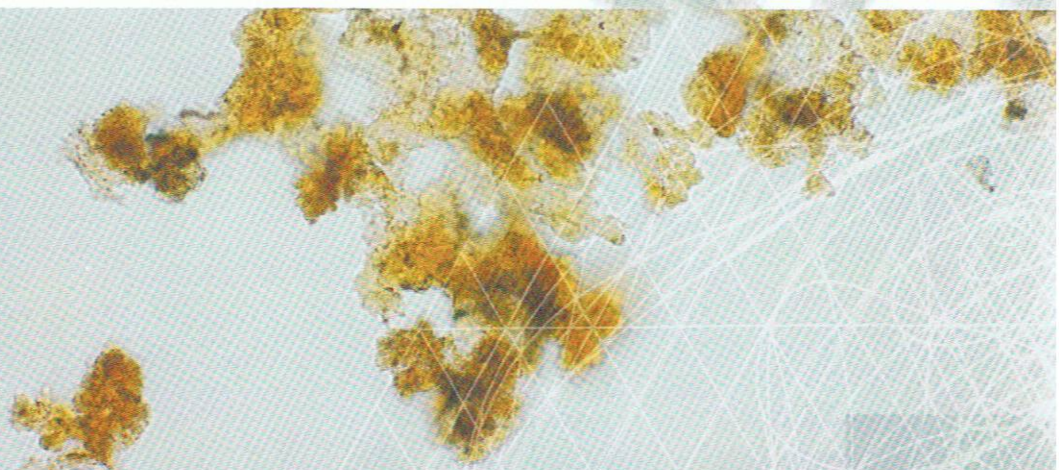
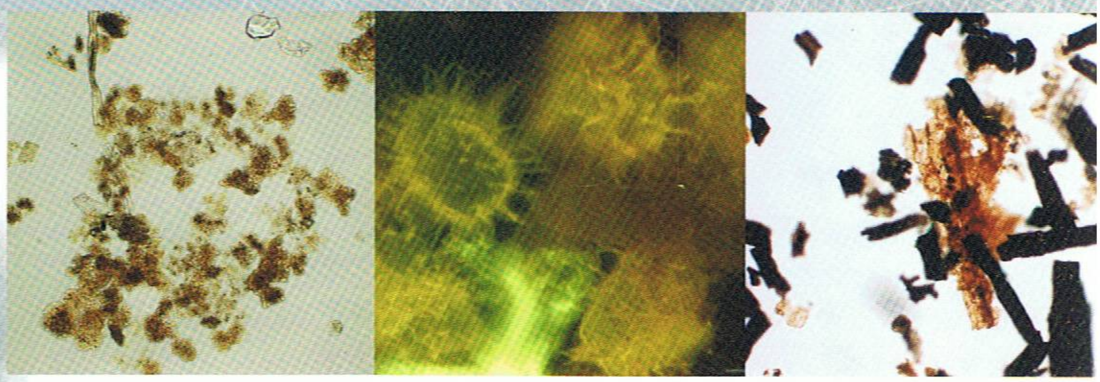


ICCP Training Course on Dispersed Organic Matter



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Chapter 8: Case Studies (Dispersed Organic Matter)

Lusitanian Basin: Geological setting, stratigraphy and organic matter record in the Lower Jurassic hemipelagic deposits of the Lusitanian Basin, Portugal

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8.1. Introduction

The Lower Jurassic it is particularly well represented in the Lusitanian Basin (hereinafter referred as LB), located on the occidental sector of the Iberian Peninsula, and mostly corresponding to a thick marine carbonated series (Soares *et al.*, 1993; Azerêdo *et al.*, 2003; Duarte, 2004, 2010b; Duarte *et al.*, 2004b). Part of that succession, namely the interval comprised between the Sinemurian and the Toarcian Stages, is dominated by marl–limestone alternations. According to the lithostratigraphic scheme proposed by Duarte and Soares (2002) for the Central/North sector of the basin, this period includes the Coimbra, Água de Madeiros, Vale das Fontes, Lemede, S. Gião and its lateral equivalents, the Cabo Carvoeiro and Prado formations. In recent years, these units have been the focus of an intense scientific activity, related to sedimentological, stratigraphic and geochemical (e.g. elemental, carbon and oxygen stable isotopes and organic geochemistry) studies. The specificity of the Sinemurian and Pliensbachian sedimentation, rich in organic matter (OM), and the observed sedimentological changes between the Pliensbachian and the Middle Toarcian (see Duarte, 1997, 2007), have been the ground for several publications, mostly on a chemostratigraphic and palaeoenvironmental perspective (e.g. Duarte, 1997, 1998, 2010a; Duarte *et al.*,2004a, 2004b, 2005, 2007a, 2010a, 2010b; Oliveira *et al.* 2005, 2006, 2009; F. Silva *et al.*, 2006, 2007, 2010; Hesselbo *et al.* 2007; Rocha, 2007; Tedeschi *et al.* 2007; Matiolli *et al.*, 2009; R. Silva *et al.*, 2009, 2010a, 2010b, 2010c, 2010d, 2011a, 2011b, 2011c; Suan *et al.*, 2008a, 2008b, 2010; Reggiani *et al.*, 2010a, 2010b; Azerêdo *et al.*, 2010; Ferreira *et al.*, 2010a, 2010b; Poças Ribeiro *et al.*, 2011a,b). Some of these works have a worldwide impact, specifically those associated with the Toarcian Oceanic Anoxic Event (T-OAE). This importance is clearly enhanced due to the high quality of the outcrops and to the privileged palaeogeographic location of the LB, between the Atlantic and Tethyan domains (Figure 8.1).

Considering the importance and role of the OM in the carbonate sedimentation during the Early Jurassic in the LB, we present here a brief characterization of the stratigraphic units and the palaeoenvironmental evolution of the series, emphasizing the main aspects related to organic geochemistry studies developed in the basin. This work is based in the detailed survey of several key-sections of the LB, such as the world renowned stratigraphic section of Peniche (see Duarte *et al.*, 2004b; Rocha, 2007) (Figure 8.2).

8.2. The Lusitanian Basin

In Portugal, the main Mesozoic onshore records are located in two very distinct geostructural contexts, one to the west (LB) and other to the south (Algarve Basin) of the Hesperian Massif (Figure 8.2).

The LB is a narrow and small North–South elongated basin, limited to the west by the Variscan (granitic and metamorphic) Berlenga Horst (see, for example, Wilson *et al.*, 1989, Pinheiro *et al.*, 1996). To the east, is bounded by the Porto–Tomar shear zone, which constrains the actual eastern limit of the LB. It has it origin in the Triassic, as the result of the extensive phase that preceded the genesis of the North and Central Atlantic Ocean. 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, corresponding to the Silves Group (red beds; Palain, 1976; Soares *et al.*, 1993). The vertical and lateral successions, observed in the whole basin, comprise a great variety of sediments, facies and palaeoenvironmental changes, involving the Triassic to late Cretaceous interval. 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). The first one, corresponding to the Triassic-Callovian, includes the stratigraphic interval here presented and discussed (Figure 8.3).

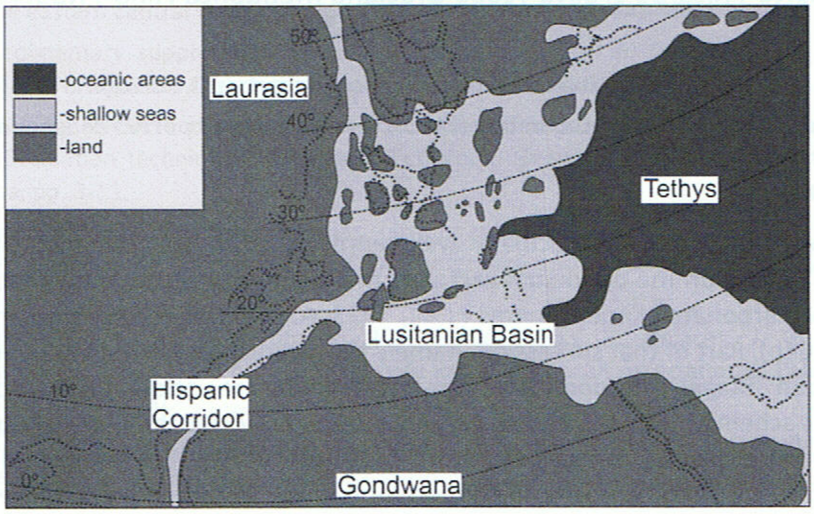

Figure 8.1: Western Tethys palaeogeography and location of the Lusitanian Basin during the late Early Jurassic (modified and simplified from Bassoulet *et al.*, 1993).

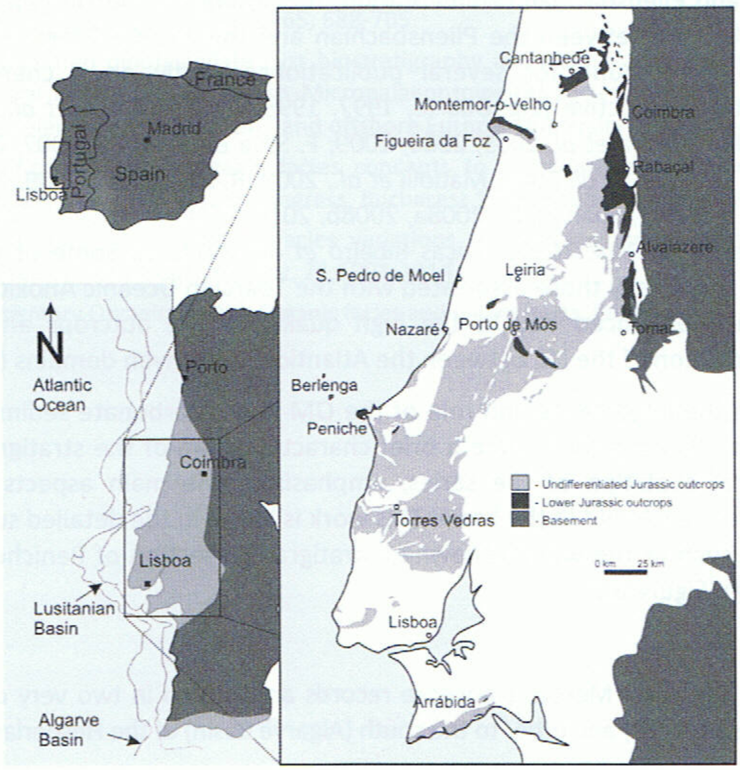

Figure 8.2: Simplified geological map of the central-northern part of the Lusitanian Basin (Portugal) and distribution of the carbonate units of Lower Jurassic age (modified from Duarte *et al.*, 2010b).

8.3. The Lower Jurassic in the Lusitanian Basin

In the LB, the Lower Jurassic is mainly composed of 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 dated from the Hettangian and show a typical set of lagoonal environments of arid climate. These Hettangian facies are capped by the Coimbra Formation (Sinemurian), which is the first truly carbonated unit representative at a basinal scale (Figure 8.3). It is composed of a succession of dolostones and limestones, being the later lithotype more expressive at the top of the unit and in its most western sectors, and corresponds to a marginal-marine palaeoenvironmental setting. During the Upper Sinemurian, namely in the western sectors of the basin (Peniche, S. Pedro de Moel and Figueira da Foz), the sedimentation is characterized by a marl–limestone series with ammonites, rich in organic matter (Água de Madeiros Formation), marking the onset of the development of open marine conditions in the basin (Duarte and Soares, 2002). This fine grained sedimentation extends throughout the basin during the Lower Pliensbachian–Upper Toarcian interval, corresponding to the Vale das Fontes, Lemede, S. Gião and Póvoa da Lomba formations. In fact, this interval is characterized by significant marly limestone deposition, locally with a clear rhythmic pattern and very rich on benthonic (bivalves, brachiopods, crinoids and siliceous sponges) and nektonic (ammonites and belemnites) macrofossils. Ammonites and calcareous nannofossils recorded in these units allow a high biostratigraphic control of the series (e.g, Phelps, 1985; Elmi, 2006; Perilli and Duarte, 2006; Oliveira *et al.*, 2007; Rocha, 2007; Mouterde *et al.*, 2007).

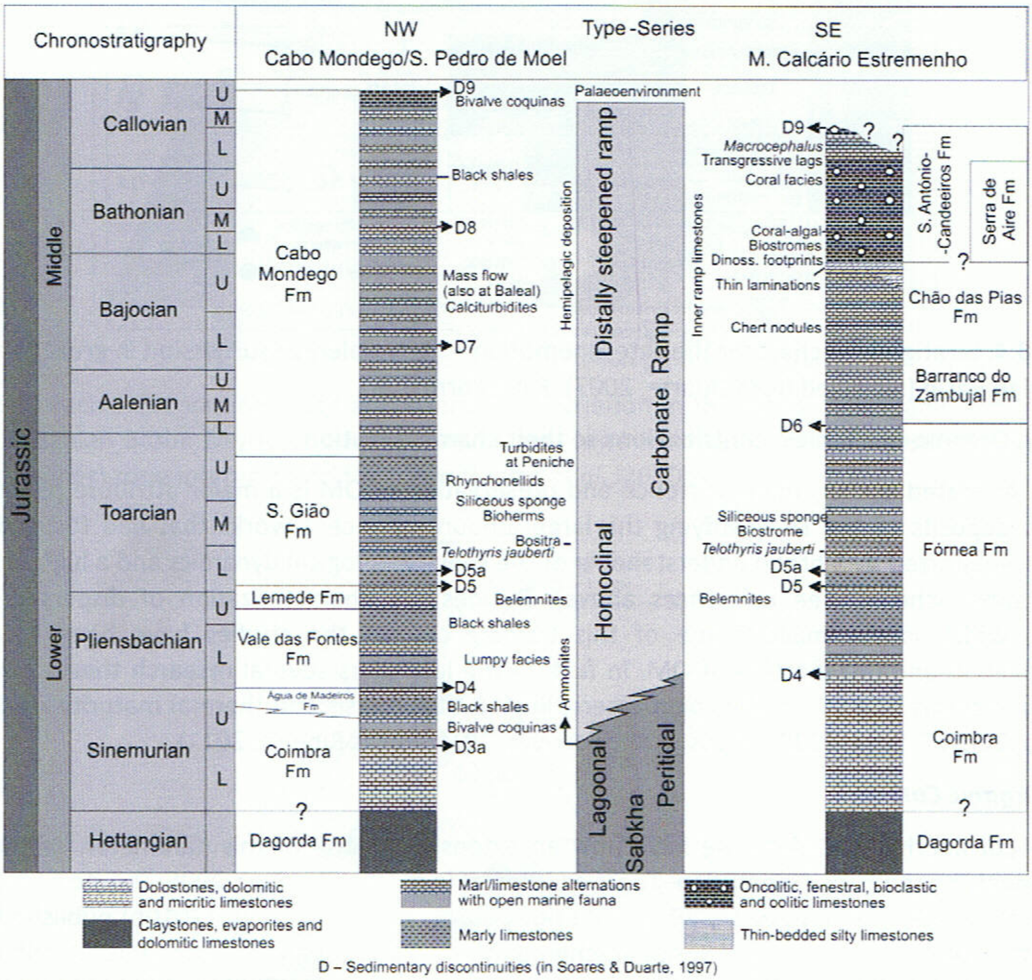

Figure 8.3: Stratigraphic units and main sedimentological features of the Lower and Middle Jurassic series in two extreme sectors of the LB (modified from Azerêdo *et al.*, 2003).

The weak lateral facies variation observed all over 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) (Figure 8.4). Despite this general hemipelagic sedimentation, some particular and differentiated sedimentary aspects can be recognized at several locations in the southern half of the LB, like Arrábida (Meia Velha Formation), Tomar (Prado Formation) and Peniche (Cabo Carvoeiro Formation) (Manuppella and Azerêdo, 1996; Duarte 1997; Duarte and Soares, 2002) (Figure 8.2). During the Toarcian, the deposition of siliciclastic and resedimented oolitic sediments, observed in this last region, confirm a palaeogeography controlled by the uplift of the western igneous Berlenga blocks (Wright and Wilson, 1984; Duarte 1997; Duarte *et al.*, 2004b; Suan *et al.*, 2008b).

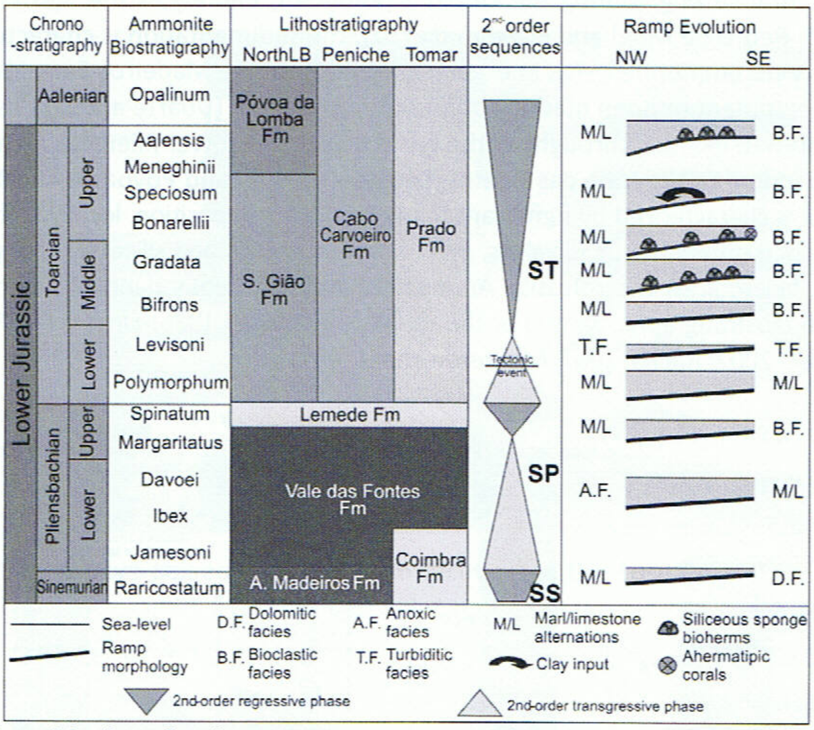

Figure 8.4: Stratigraphic chart for the Late Sinemurian – Early Aalenian succession in great part of the Lusitanian Basin (modified from Duarte, 2007). Fm – Formation.

8.4. The Organic-rich Facies: contributions to their characterization

As stated earlier, the occurrence and preservation of OM is a major attribute of the Lower Jurassic deposits of the LB, justifying the large amount of recent works that had focused in this feature, supported by a broad understanding of the sedimentological dynamics and a high-resolution stratigraphic scheme (see references above). Besides the characterization of dispersed organic matter, which is the main theme of this training course, the studies have been focused in quantification and qualification of OM. In fact, in the last years several research theses have been centred in terms of palynofacies, biomarkers, Rock-Eval pyrolysis and thermal maturity studies (see Oliveira, 2007; F. Silva, 2008; Matos, 2009; Ferreira, 2010; Poças Ribeiro, 2011).

Total Organic Carbon

Considering TOC data, we have now an extensive control of this parameter for the entire basin, involving the Early Sinemurian–Toarcian interval (e.g. Oliveira *et al.*, 2006; Duarte *et al.*, 2010b; F. Silva *et al.*, 2010; R. Silva *et al.*, 2011; data not published). Duarte *et al.* (2010b) published a work where they presented a four-dimensional scheme for the Total Organic Carbon (TOC) distribution for most the LB during the Early Jurassic. In terms of stratigraphic distribution, the organic-rich facies occur preferentially in the Polvoeira and Marly limestones with organic-rich facies (hereinafter MLOF) members of the Água de Madeiros and Vale das Fontes formations, respectively (Figure 8.5). The highest TOC values exceed 20 wt. % in both units (Duarte *et al.*, 2010b; R. Silva *et al.*, 2011b). The organic-rich facies are macroscopically quite similar in all the studied series and are characterized by a grey to dark colour, generally with a net lamination and, locally, abundant pyrite. These facies include black shales, dark grey marls and thin laminated limestones.

Palynofacies

The palynofacies studies have been conducted in the Água de Madeiros and Vale das Fontes formations (Matos, 2009; Ferreira, 2010; Ferreira *et al.*, 2010a, 2010b, Poças Ribeiro, 2011; Poças Ribeiro *et al.*, 2011a, 2011b; R. Silva *et al.*, *in progress*). Regarding the studied units in the Peniche (Figure 8.6) and S. Pedro de Moel areas the Polvoeira and MLOF members are characterized by a palynofaciological assemblage characteristic of oxygen deficient environments, while the framing units correspond to more oxic environments. In the richest TOC samples, the dominant kerogen group is the amorphous organic matter (AOM), presenting variable amounts of Phytoclasts and Palynomorphs, while in the lowest TOC samples, the kerogen assembly show a dominance of the Phytoclast group, as the case of the Lemede Formation (Ferreira *et al.*, 2010a, 2010b).

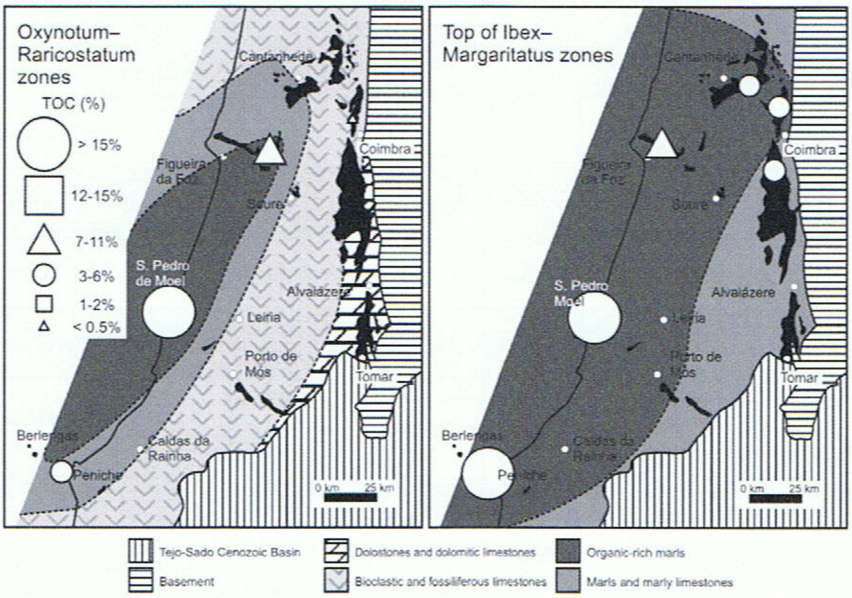

Figure 8.5: Facies distribution maps and lateral TOC variation in the two most organic-rich intervals of the Lusitanian Basin: Oxynotum–Raricostatum (Polvoeira Member) and top of Ibex–Margaritatus (MLOF member) zone interval (modified from Duarte *et al.*, 2010b).

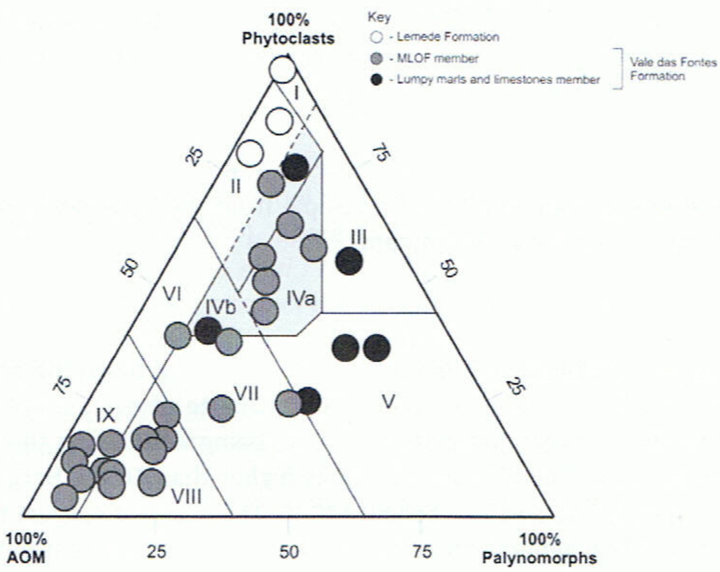

Figure 8.6: AOM-Phytoclasts-Palynomorphs ternary plot for the Peniche section. See chapter 5, item 5.3 for key and significance of the projection fields (modified from Ferreira *et al.*, 2010a).

Biomarkers

The biomarker data shows a good agreement with the optically determined kerogen assemblages and thermal maturity studies (Ferreira *et al.*, 2010a, 2010b; R. Silva *et al.*, 2010c). For example, source-related biomarkers from the MLOF member, like the *n*-Alkane distribution pattern and the C_{27}-C_{28}-C_{29} ααα (20R) ternary plot, show that organic matter consists of a mixture of marine and continental components, preserved in a marine depositional environment and under distinct redox conditions (Figure 8.7). Moreover, when correlated at a basinal scale, some biomarkers allow the distinction of several domains in what would be an apparently homogeneous depositional environment (see R. Silva *et al.*, 2010c; R.Silva *et al.*, *in progress*).

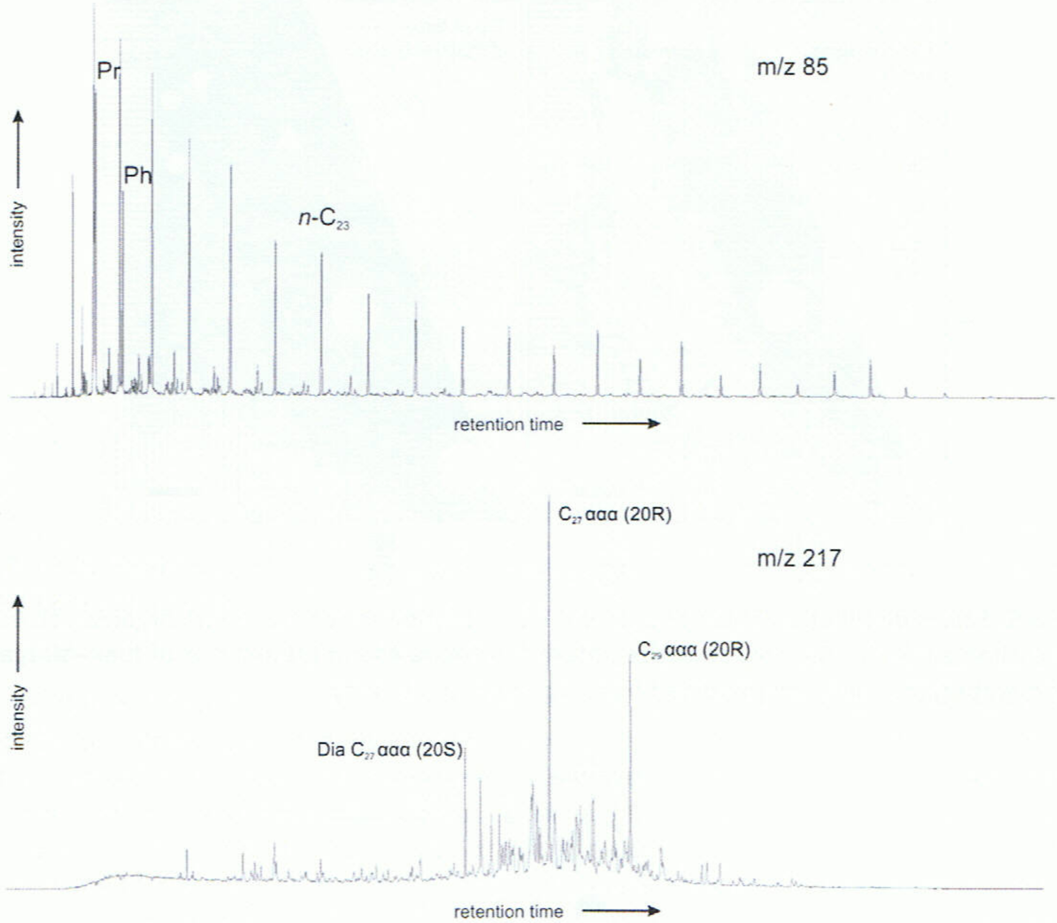

Figure 8.7: Chromatograms m/z 85 and 217 of a sample from the Vale das Fontes Formation of the Peniche reference section. Pr-pristane; Ph-Phytane.

Rock-Eval Pyrolysis

Rock-Eval pyrolysis studies have been conducted systematically in the organic richer series of the LB (Oliveira *et al.*, 2006; F. Silva *et al.*, 2007; 2010; Duarte *et al.*, 2011). The most interesting values follow the same stratigraphic distribution as TOC, being localized in the Polvoeira and MLOF members. In these units, several levels have S2 values higher than 10 mg Hc/g rock, with Hydrogen Index (HI) above 200 mg Hc/g TOC and T_{max} bellow 440 °C. These values suggest that the series have a high potential for hydrocarbon generation, although thermally immature in outcrop (Oliveira *et al.*, 2006; Duarte *et al.*, 2011; Duarte *et al.*, *in progress*). In the remaining units, S2 values rarely exceed 2 mg Hc/g rock, with the exception of the CC2 member of the Cabo Carvoeiro Formation, whose TOC richest sample (2.6%) shows S2 and HI of 8.52 mg Hc/g rock and 327.7 mg Hc/g TOC, respectively (Oliveira *et al.*, 2006).

Table 8.1: S2 and T_{max} values determined in several sectors of the Lusitanian Basin for the Pliensbachian-Toarcian time interval.

Table I – S2 and T_{max} values determined in several sectors of the Lusitanian Basin for the Pliensbachian–Toarcian time interval										
	Peniche*		Figueira da Foz[‡]		Coimbra[‡]		Murterde[‡]		Anadia[‡]	
Lithostratigraphical unit	S2	T_{max}	S2	T_{max}	S2	T_{max}	S2	T_{max}	S2	T_{max}
	aver	max	aver	max	aver	max	aver	max	aver	max
Cabo Carvoeiro Fm										
CC2 mb	1.85	443	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CC1 mb	0.47	488	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lemede Fm	0.50	440	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Vale das Fontes Fm										
MLOF mb	11.87	435	7.14	438	3.83	430	**4.31**	428	n.d.	n.d.
LML mb	0.87	497	**14.06**	434	**13.90**	426	0.35	438	**0.30**	436
MLUP mb	0.83	434	n.d.	n.d.	**0.13**	432	n.d.	n.d.	n.d.	n.d.
The values in bold do not have statistical significance; Fm - Formation; mb - member; n – number of samples; aver – average; max - maximum; n.d. – not determined. * - Oliveira *et al.*, 2006; [‡] - Silva *et al.*, 2007.										

Thermal maturity

In the Peniche and S. Pedro de Moel sections, the thermal maturation studies have been conducted by Vitrinite Reflectance (Ro), Spore Coloration Index (SCI) and fluorescence spectra (Ferreira *et al.*, 2010b; Mendonça Filho *et al.*, 2010; Poças Ribeiro *et al.* 2011b). Regarding the later technique, it is worthy to mention that one of the samples used in the Organic Matter Concentration Working Group of the International Committee for Coal and Organic Petrology (ICCP) during the years 2008 and 2009 was taken from the MLOF member at Peniche (Mendonça Filho *et al.*, 2010). The obtained data indicate that the studied parts of these sections are thermally immature, reaching the final stages of diagenesis or barely entered catagenesis (Table II).

Table 8.2: Spore Coloration Index (SCI), Vitrinite reflectance (Ro) and equivalent Vitrinite reflectance (Rr_{eq}) derived from fluorescence spectra average values for the Peniche and S. Pedro de Moel sections.

Lithostratigraphic unit	Number analyzed levels	SCI	Ro	Rr_{eq}
Peniche				
Lemede Fm	1*	3-3.5*	0.48*	n.d.
Vale das Fontes Fm				
MLOF mb	4*‡	3-3.5*‡	0.47*‡	0.49‡
LML mb	1*	3-3.5*	0.48*	n.d.
Água de Madeiros Fm				
Polvoeira Mb	2§	3-3,5§	0,45§	n.d.
S. Pedro de Moel				
Água de Madeiros Fm				
Polvoeira Mb	2§	3-4§	0,45§	n.d.
Coimbra Fm	1§	3-4§	0,45§	n.d.

Fm - Formation; mb - member; n.d. - not determined; * Ferreira, 2010, Ferreira *et al.*, 2010a, 2010b; § Poças Ribeiro, 2011; Poças Ribeiro *et al.*, 2011b; ‡ Mendonça Filho *et al.*, 2010;

8.5. Concluding remarks

The scientific research in the LB is allowing a deeper insight about the palaeoenvironmental conditions that operated during the Lower Jurassic in the carbonate epeiric seas that characterized the western part of the Tethys Ocean. Many of these works are the outcome of the intersection between several "classical" geological disciplines with the most innovative techniques in the study of OM in sediments. This resulted on an unprecedented constrain of the palaeobiotic and palaeoceanographic conditions contemporaneous of deposition.

Supported by a broad understanding of the sedimentological dynamics and a high-resolution stratigraphic scheme, it has been demonstrated that the organic-rich intervals observed throughout the basin correspond to important events, with significant implications in how we perceive the biological dynamics in the geological record and, perhaps more importantly, in the modern world. The main point is that some of these specific bioevents correspond to important palaeoenvironmental changes, responding actively to major sea-level rises or to O_2 depletion, for example.

Acknowledgements

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