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Stratigraphy, sedimentary patterns, and reservoir characteristics of Jurassic carbonate successions in the Lusitanian Basin

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Abstract

The Jurassic of the Lusitanian Basin (LB) is instructive for interpreting reservoir and source potential in carbonate ramp successions. Selected examples from the Lower, Middle, and lower Upper Jurassic of the LB are used here to illustrate a complete range of carbonate facies across the ramp system, from outer-ramp (Rabaçal), inner–mid-ramp (Maciço Calcário Estremenho and S. Pedro de Moel), and mixed non-marine, paralic and shallow-marine (Cabo Mondego) settings. Each example is used to demonstrate the interaction of tectonics and eustasy in controlling depositional facies, diagenesis, sedimentary patterns, and stratigraphic evolution. Emphasis is placed on the reservoir and/or source-rock potential of each major depositional system. Outcrops are visited in the regions of: i) Maciço Calcário Estremenho (limestone hills in the eastern part of the LB); ii) Rabaçal, near Coimbra, also in the eastern part of the LB; and iii) Cabo Mondego and S. Pedro de Moel, both located in the western part of the basin (shoreline). In the Maciço Calcário Estremenho region, Middle Jurassic shallow-water facies (oolite- and skeletal-dominated sandbodies, coral–algal biostromes, and lagoonal, peritidal, and calcrete sediments) are examined. At Rabaçal, a Lower Jurassic hemipelagic succession is presented, supported by an integrated and detailed stratigraphic analysis emphasizing aspects related to the evolution of the Lower Jurassic series at the basin scale. At the coastal section of Cabo Mondego, the main features of interest are the Middle–Upper Jurassic basinwide disconformity, which shows the effects of a major forced regression, and various marginal- to non-marine Oxfordian facies, including source rocks. At S. Pedro de Moel, the focus is on Sinemurian restricted-marine facies with text-book examples of stromatolites.

Keywords: carbonate successions, reservoir rocks, source rocks, Jurassic, Lusitanian Basin

Resumo

O Jurássico da Bacia Lusitânica (BL) proporciona evidências para a interpretação do potencial como rochas-reservatório e como rochas-geradoras de sucessões de rampa carbonatada. Exemplos selecionados do Jurássico Inferior, Médio e Superior inicial da BL serão utilizados para ilustrar vasto leque de fácies carbonatadas ao longo do sistema de rampa, abrangendo desde rampa externa (Rabaçal), a rampa interna-intermédia (Maciço Calcário Estremenho e S. Pedro de Moel) e ambientes mistos não-marinhos, parálicos e marinhos pouco profundos (Cabo Mondego). Cada exemplo será usado para mostrar a interacção tectónica/eustasia no controlo das fácies deposicionais, diagénese, padrões sedimentares e evolução estratigráfica. Será dada ênfase ao potencial enquanto reservatório ou rocha mãe de cada sistema deposicional principal. Visitar-se-ão afloramentos nas regiões de: i) Maciço Calcário Estremenho (relevos calcários na zona leste da BL), ii) Rabaçal, perto de Coimbra, também zona oriental da BL, iii) Cabo Mondego e S. Pedro de Moel, ambos a oeste (no litoral). No Maciço Calcário Estremenho observar-se-ão fácies de pequena profundidade do Jurássico Médio (corpos arenosos oolítico-bioclásticos, biostromas de corais e algas, depósitos lagunares, peritidais e pedogénicos). Em Rabaçal, será apresentada uma sucessão do Jurássico Inferior, com suporte de análise estratigráfica detalhada e integrada, enfatizando aspectos relacionados com a evolução sequencial da série à escala da bacia. Nos afloramentos litorais do Cabo Mondego, os principais focos serão a desconformidade bacinal Jurássico Médio-Jurássico Superior (que reflecte os efeitos de uma regressão forçada) e diferentes fácies margino-marinhas a não-marinhas, do Oxfordiano, incluindo rochas geradoras. Em S. Pedro de Moel, o foco serão fácies marinhas restritas com excelentes exemplos de estromatólitos, do Sinemuriano.

Palavras-chave: sucessões carbonatadas, rochas reservatório, rochas geradoras, Jurássico, Bacia Lusitânica

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1. Introduction

The Lusitanian Basin (LB) is located in the Western Iberian Margin and is a marginal basin associated with the opening of the North Atlantic Ocean. Most of the basin fill is Jurassic in age, but Upper Triassic to Upper Cretaceous sediments occur, with a Tertiary cover (Fig. 1). Two main episodes of extension and rifting are recorded in the LB, one during the Late Triassic followed by a more major episode during the Late Jurassic–Early Cretaceous (e.g., Wilson *et al*. 1989; Leinfelder & Wilson,1998; Rasmussen *et al*. 1998, Reis *et al*., 2000; Alves *et al*., 2002). The post-Triassic rift stage (Early–Middle Jurassic) was characterized by deposition that became increasingly marine over time, chiefly shallow- to deep-marine limestones and marls, dolostones, and bituminous shales, developed on a carbonate ramp depositional system (Soares *et al*., 1993; Azerêdo, 1998, 2007; Duarte *et al*., 2001, 2004, 2010; Azerêdo *et al*., 2002, 2003, 2010; Duarte & Soares, 2002; Azerêdo & Wright, 2004; Duarte, 2007). The Middle Jurassic is separated from the Upper Jurassic by a basinwide disconformity (e.g., Azerêdo *et al*., 1998, 2002; Leinfelder & Wilson, 1998). The Triassic to Upper Jurassic lithostratigraphy of the LB is rather complex; a simplified scheme, in which some of the units are informal, is presented in Figure 2. Regarding the Lower and Middle Jurassic, formal units have been defined and described by Duarte & Soares (2002) and Azerêdo (2007), respectively, and are used throughout this guidebook.

Selected examples from the Lower, Middle, and lower Upper Jurassic of the LB are used to illustrate carbonate facies across the ramp system. These LB Jurassic series rocks are instructive for interpreting reservoir and source potential in carbonate ramps.

The examples are used to show the interaction of carbonate factory behaviour, tectonics, and eustasy in controlling depositional facies, diagenesis, sedimentary patterns, and stratigraphic evolution. Emphasis on reservoir and source-rock potential is made as appropriate.

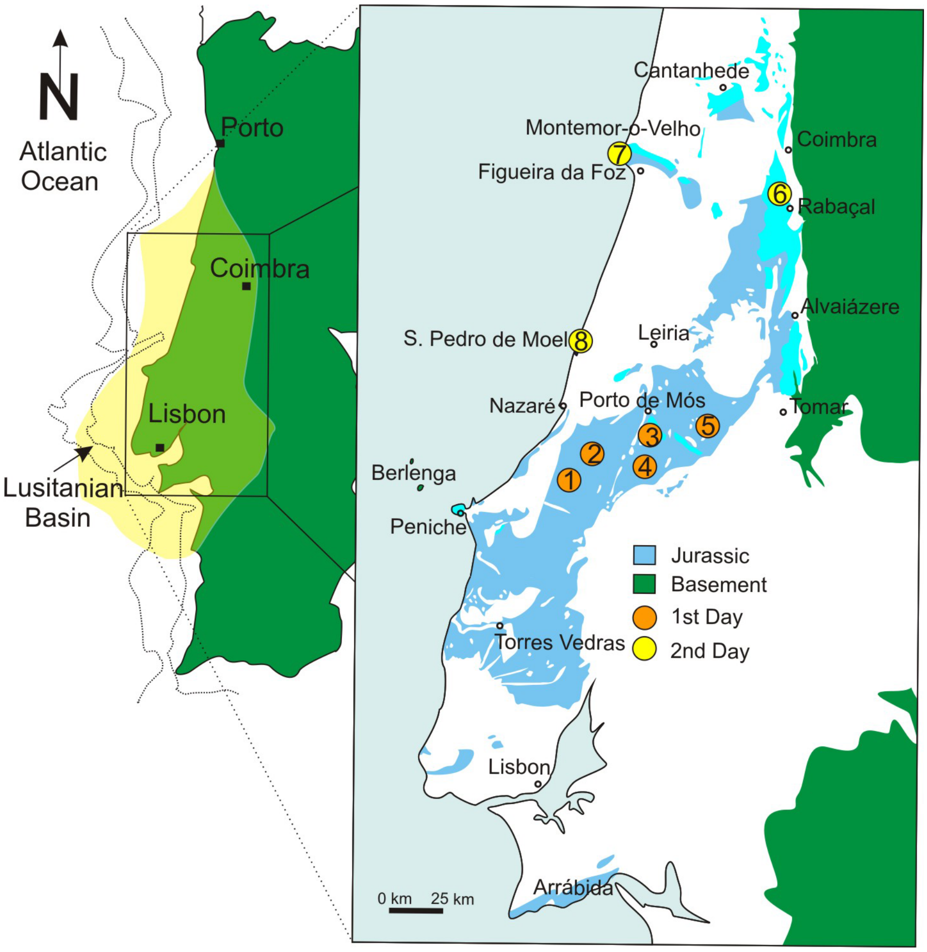

Fig. 1 – Simplified map of the Lusitanian Basin Jurassic (adapted from Duarte *et al*., 2010), also showing the locations of the field-trip stops (1–8). Stops 1–5 are located in the region of Maciço Calcário Estremenho (limestone hills).

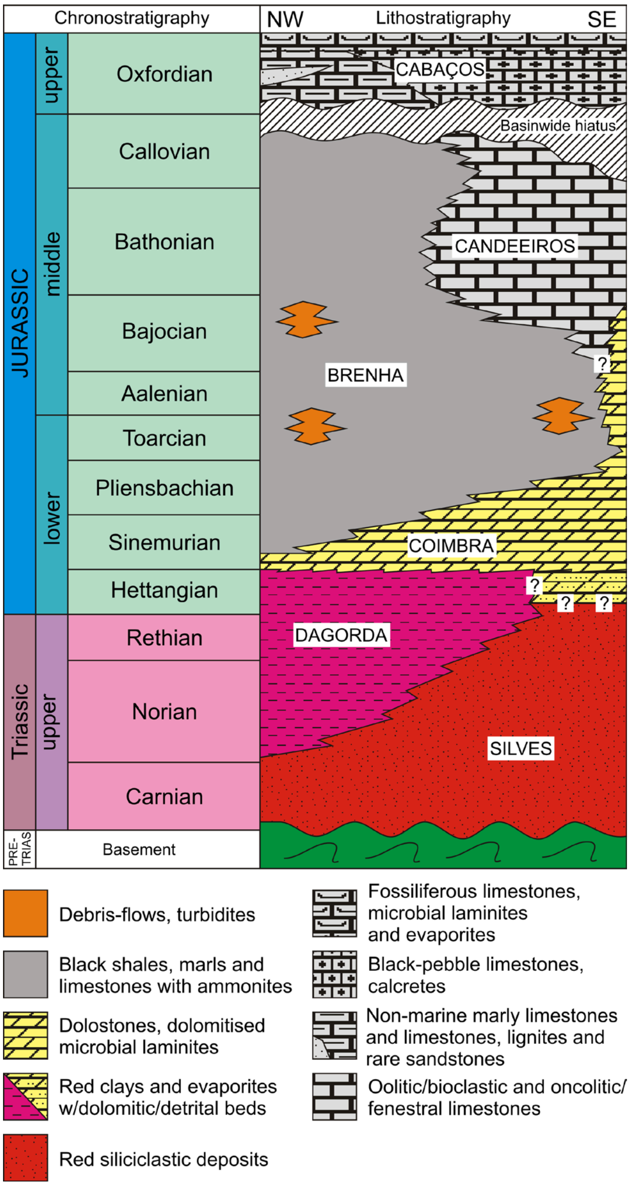

Fig. 2 – Simplified synthetic lithostratigraphic column showing the Upper Triassic to basal Upper Jurassic succession of the Lusitanian Basin (with broad informal units commonly used by oil companies; see text). Adapted from Azerêdo *et al.* (2002).

Outcrops are visited in the regions of: i) Maciço Calcário Estremenho (MCE, limestone hills in the eastern part of the LB); ii) Rabaçal, near Coimbra, also in the eastern part of the LB; and iii) Cabo Mondego (CM) and S. Pedro de Moel (SPM), both in the western part of the LB (shoreline). The outcrops are visited according to the plan given below (Fig. 1).

First Day: Lisboa – Rio Maior – Maciço Calcário Estremenho (MCE)

Middle Jurassic shallow-ramp successions in the MCE region: sedimentary dynamics, sequence patterns, and diagenetic and reservoir features.

Stop 1. Southern Serra dos Candeeiros (upper Bajocian–lower Bathonian): progradational pattern evidence, limestone and dolomite facies types, and porosity/permeability potential.

- **1.1.** "Parque eólico" station grainstones and rudstones.
- **1.2.** Vale de Chã Quarry dolomites.

Stop 2. Vale de Ventos-Portela das Salgueiras (Serra dos Candeeiros): high-energy and lagoonal facies (Sto. António-Candeeiros Fm and Serra de Aire Fm, upper Bathonian).

Stop 3. Fórnea: A panoramic view over an outer-ramp marl–limestone succession.

Stop 4. Vale Florido oolitic–skeletal limestones and coral biostromes: Facies, geometric configuration, and diagenetic features examined from a reservoir perpective (Sto. António-Candeeiros Fm, lower Bathonian).

Stop 5. Galinha Quarry: A pedogenic, organic-matter-rich, peritidal carbonate succession (Serra de Aire Fm, lower Bathonian).

Second Day: Maciço Calcário Estremenho (MCE) – Rabaçal – Cabo Mondego – S. Pedro de Moel – Lisboa

Stop 6. Stratigraphic setting, facies variation, and sequence stratigraphy of the Toarcian carbonate deposits in the Rabaçal–Coimbra region.

Stop 7. Cabo Mondego: Evidence of Middle–Late Jurassic forced regression and basinal disconformity. Oxfordian marginal- to non-marine source rocks and facies characteristics (Cabaços Fm).

Stop 8. São Pedro de Moel region: Stromatolites within a restricted marine succession (Coimbra Fm, Sinemurian).

2. Stops 1 to 5. Middle Jurassic shallow-ramp successions at Maciço Calcário Estremenho: Sedimentary dynamics, sequence patterns, and diagenetic and reservoir features (A. C. Azerêdo)

One of the main aims of this excursion is to examine some examples of well-exposed Middle Jurassic deposits in the east of the basin, namely, in the MCE region, an area of limestone hills (Fig. 1). The lithostratigraphic arrangement of the MCE successions as defined by Azerêdo (2007) is shown in Figure 3. Previous mapping work by Manuppella *et al.* (2000) has helped in arriving at this lithostratigraphic organization.

The field stops focus on parts of the following formations. **The Chão das Pias Formation**, including the **Calcários de Vale da Serra Member** and the

Dolomitos de Furadouro Member (Stop 1), features graded grainstones/rudstones and dolomitic facies types. The **Serra de Aire Formation** is characterized mainly by lagoonal and peritidal lithofacies (Stops 2 and 5). The **Santo António-Candeeiros Formation** is composed of high-energy barrier facies (Stops 2 and 3). A view of the landscape will also be made (Stop 4) encompassing the open-marine **Barranco do Zambujal Formation** and extending to the mid-ramp deposits of the lower **Chão das Pias Formation** (Fig. 3).

In particular, inner-ramp oolite- and skeletal-dominated sandbodies, coral–algal biostromes, and lagoonal and peritidal sediments occur, defining several lithofacies and facies associations (Azerêdo, 1998). These shallow-water carbonate facies form successions measuring several hundreds of metres thick, representing a high-energy carbonate ramp depositional system under the influence of storms but dominated by wave activity. The sandbodies most commonly crop out as thick units of superimposed sets of oolitic and bioclastic grainstones, with rare intercalations of other facies types. The cross-sets comprise multistorey units, with common lateral and vertical variations in cross-stratification types and scales (Azerêdo, 1998, 2004, 2007). The barrier sandbodies are thought to have developed under a microtidal regime dominated by waves and longshore drift currents with frequent storm influence.

The scale of the peritidal cyclothems associated with these sandbodies suggests a microtidal regime (Azerêdo, 1998). The peritidal facies association occurs in close association with the lagoonal facies association, and this entire range of deposits may be interbedded with storm layers. The thick inner-ramp succession was deposited as the result of a strong progradational stage, exhibiting pedogenic carbonates in the eastern part of the LB (see Stop 5) and well-exposed peritidal and dolomitic facies in the western part (Stops 1.1 and 1.2; Fig. 5). In addition, the evolution of the system was chiefly progradational–aggradational, with a high rate of production by the shallow-water carbonate factory (Figs 4 and 6) and rarer retrogradational episodes.

2.1. Stop 1. Southern Serra dos Candeeiros (upper Bajocian–lower Bathonian): evidence for a progradational pattern of sedimentation, limestone and dolomite facies types, and porosity-permeability potential

2.1.1. Stop 1.1. “Parque eólico” station grainstones and rudstones

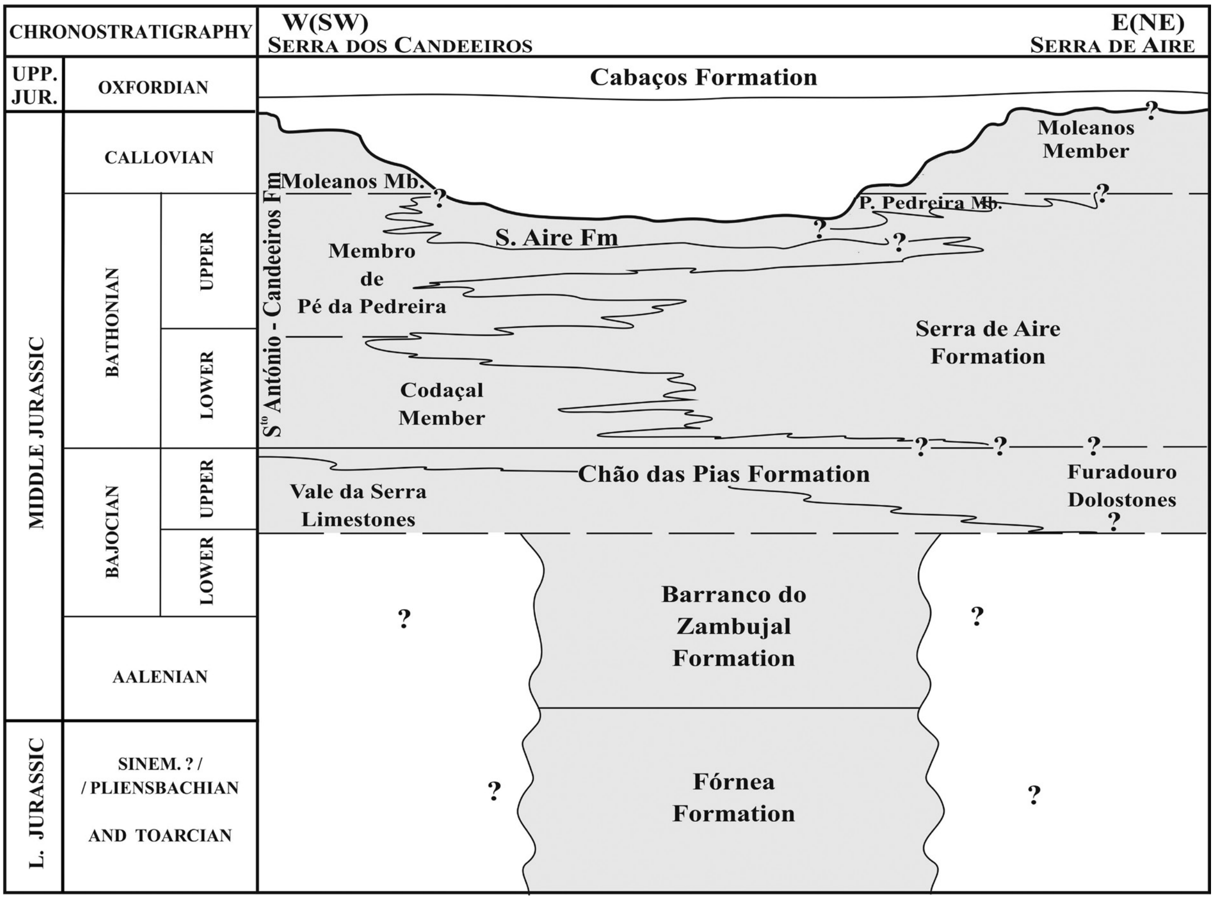

Fig. 3 – Formal lithostratigraphic units defined at Maciço Calcário Estremenho (Azerêdo, 2007).

At this stop, white, commonly graded, oolitic and coarser-grained oncolitic–intraclastic grainstones and rudstones, also exhibiting skeletal material (corals, algae, and molluscs), may be observed (Fig. 5). These limestones, which belong to the Calcários de Vale da Serra Mb of the Chão das Pias Fm, show good examples of low to moderate, heterogenous secondary porosity, namely, intraparticle, oomoldic, vuggy, and fracture porosity types. Dolomites and dolomitic limestones with good examples of recrystallization, fracturing, brecciation, and very large late calcite crystals may also be seen.

2.1.2. Stop 1.2. Vale de Chã Quarry Dolomites

The Vale de Chã Quarry (the Dolomitos de Furadouro Mb of the Chão das Pias Fm) contains good examples of dolomite rocks as well as porosity and permeability features to be examined (Fig. 5). These dolomites, cream to reddish in colour, range from massive dolomites and dolomitized, recrystallized coral limestones (mainly in the upper part of the quarry) to fenestral dolomicrites with oncoidal lenses showing vadose cements and microbially laminated dolomicrites (the lower part of the quarry). Porosity occurs at different scales, namely, well-developed vuggy, fracture, channel, and mouldic porosity. However, several low-porosity zones are also present, and faulting and later karstification further contribute to a complex permeability pattern.

2.2. Stop 2. Vale de Ventos–Portela das Salgueiras (Serra dos Candeeiros) high-energy and lagoonal facies (Sto. António-Candeeiros Fm and Serra de Aire Fm, upper Bathonian)

Several contrasting types of depositional facies may be examined in the nearby outcrops and quarry blocks at this stop (Fig. 6). A group of different micritic lithofacies (Serra de Aire Fm) and another dominated by grain-supported limestones (Sto. António-Candeeiros Fm) can be recognized here. The first facies group includes: oncoidal/algal nodule/porostromate-rich wackestones to floatstones, with a few ostracods, mollusc fragments, common iron-enriched grains, and iron staining; fossiliferous peloidal wacke/packstones, with diverse benthic foraminifers, ostracods, dasyclads, porostromates, gastropods, and

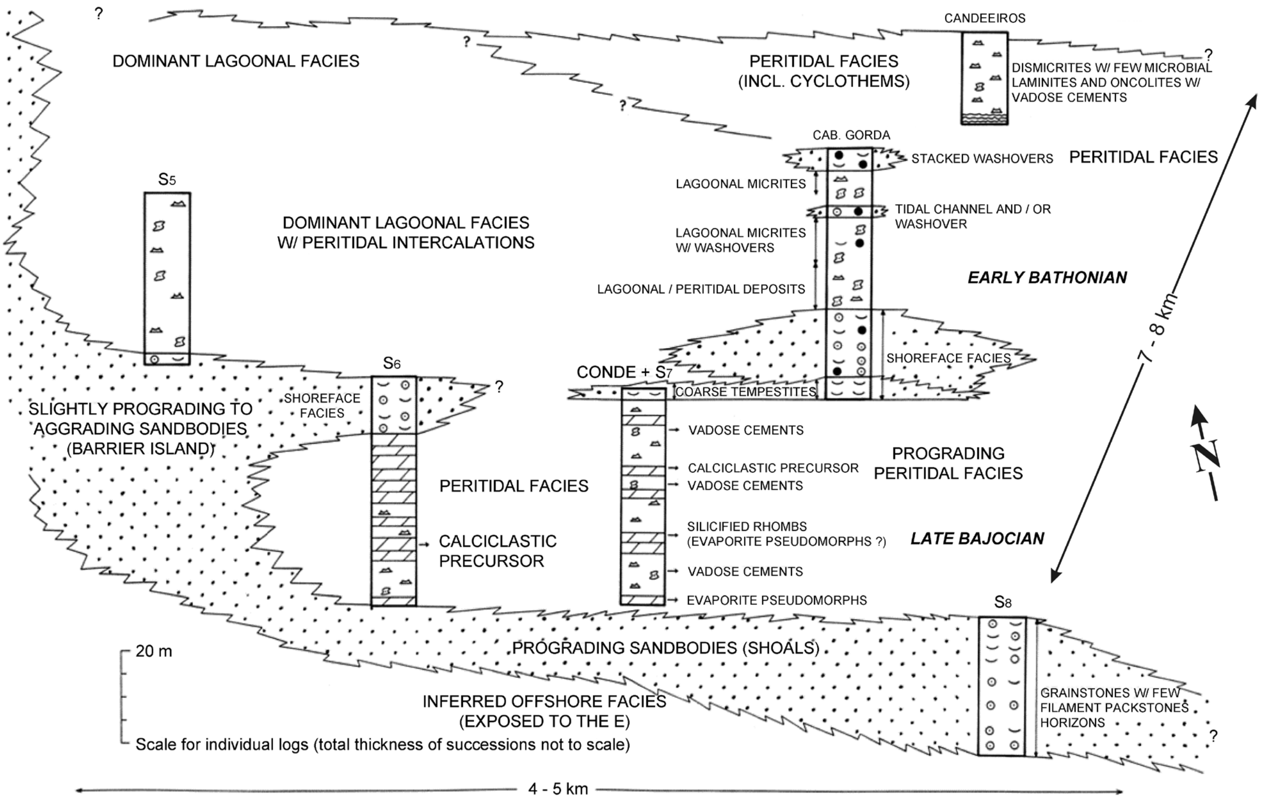

Fig. 4 – Schematic representation of the facies architecture and interpreted evolutionary pattern of the carbonate ramp system during the late Bajocian–early Bathonian, based on the Maciço Calcário Estremenho region (slightly mod. from Azerêdo, 1998). S5 to S8 correspond to boreholes. See also Fig. 9.

bivalves, also locally with ferruginization; and fenestral mudstones, locally with ferruginized/blackened grains and staining. The second group is represented by usually thick-bedded, ooid-skeletal-intraclastic-peloidal grainstones and rudstones, rarely pack/grainstones, with echinoids, crinoids, corals, algae, molluscs, and other skeletal material, interbedded with strongly bioturbated wacke/packstone levels. The grainstones/rudstones exhibit a range of sedimentary structures, namely, cross-stratification, parallel laminations, shell lags, erosional/reactivation palaeosurfaces, and hardground layers, locally bored.

Brief palaeoenvironmental interpretation: The micrite-supported facies association reflects a lagoonal or marginal-marine environment, with episodes of intermittent, rapid subaerial exposure but usually favouring the development of shallow-water benthic faunal and floral communities. The grain-supported limestones reflect wave- and storm-associated depositional conditions. The amalgamated pattern of

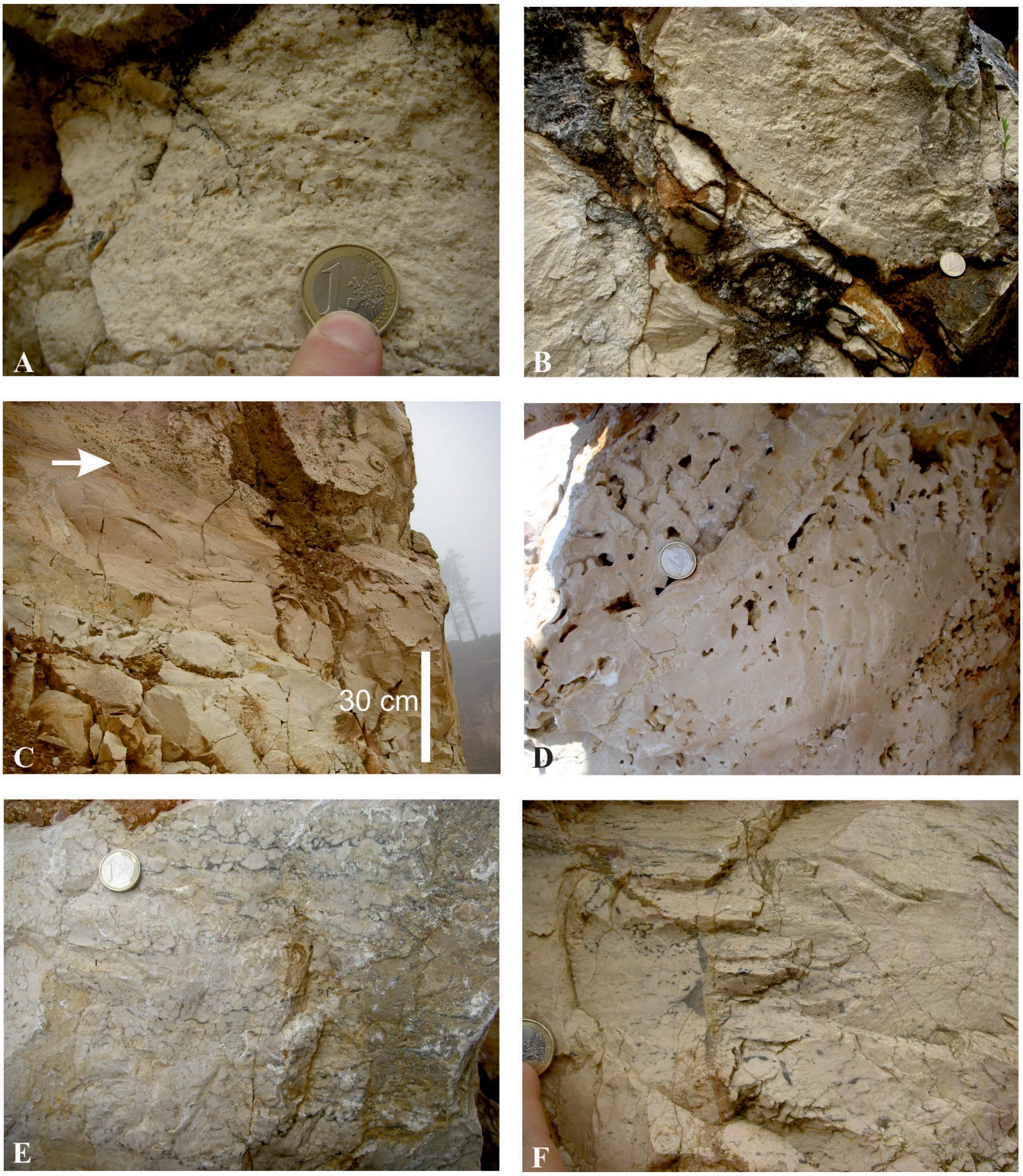

Fig. 5 – Field aspects of shallow-water/peritidal carbonates in the western Maciço Calcário Estremenho region, corresponding to a marked progradation of the ramp system and illustrating lithofacies and diagenetic features: A – Grain-supported bimodal limestones; B – A fracture with associated recrystallization; C – A layer with very high porosity (arrow) overlying a low-porosity zone (laminar dolomicrites), and late fracturing; D – Layers with high vuggy porosity alternating with massive layers; E – Fenestral dolomicrites with oncoidal lenses showing vadose cement; F – Detail of fenestral limestones with late fracturing and veins.

many of these layers and their lateral discontinuity are also features commonly reported in shallow-water storm deposits. The bioturbated wacke/packstones represent sedimentation lag-time intervals between the dominant high-energy intervals.

2.3. Stop 3. Fórnea: a panoramic view over an outer-ramp marl–limestone succession

A spectacular large-scale geomorphological landform can be observed here, namely, the deep and wide Fórnea "amphitheatre", formed by the Fórnea Creek in a marly limestone succession of the Lower to Middle Jurassic (Fig. 7). This site allows a good perspective to be gained over the furthermost outer-marine units in this region, known in the stratigraphic literature as the Barranco do Zambujal section. This section is important for its palaeontological content, namely, ammonoids, which makes it a biostratigraphic reference section for the Lower–Middle Jurassic transition through the Aalenian and Bajocian (Ruget-Perrot, 1961; Henriques, 2000; Manuppella *et al.*, 2000). The section corresponds to a thickening- and shallowing-upwards outer-marine succession, the middle part of which comprises siliceous nodules.

2.4. Stop 4. Vale Florido oolitic–skeletal limestones and coral biostromes: facies, geometric configurations, and diagenetic features from a reservoir perpective (Sto. António-Candeeiros Fm, lower Bathonian)

Along the road that links the two small localities of Vale Florido and S. Bento (Fig. 1), lithofacies and biofacies typical of high-energy, high-sedimentation-rate settings crop out, namely (Azerêdo, 1998, 2004): coral-rich biolithites, bearing large in situ branched corals, smaller cup-shaped corals and coral fragments, associated with calcareous algae and other abundant skeletal material, and locally interspersed with peloidal–intraclastic packstones as internal sediment; finer-grained, mainly oolitic grainstones, with fewer bioclasts and other allochems, exhibiting planar and small-scale low-angle cross-sets, wave ripple cross-laminations, and gradations of these into low- or higher-angle cross-laminations; and massively bedded, crudely graded, coarse-grained, bioclastic-dominated grainstones and rudstones, with intraclasts and oncoids as well as planar or slightly undulatory laminae. The prominent biostrome units may be draped by, or grade laterally into, amalgamated, uneven bioclastic–intraclastic grainstones, and all the lithofacies may interfinger with each other (Fig. 8).

Most of the sandbody and biostrome deposits show low porosities but likely had varied primary porosities as indicated by the range of allochem types and sizes and the depositional fabrics. These deposits were subsequently affected to varying degrees by diagenesis, so there are also cases of higher porosity, even locally excellent (though usually poorly connected), in these lithofacies. These examples of high-porosity correspond to multi-phase, late secondary dissolution, usually, but not necessarily, associated with dolomitization (mouldic, intraparticle/intracrystal, and vuggy porosity; Fig. 8). Mechanical and chemical compactional features do occur, though rarely, as a result of dominant and significant early or multi-generation cementation. These issues can be exemplified and discussed by examining the outcrops at this stop, coupled with petrographic information and other relevant data introduced during the excursion.

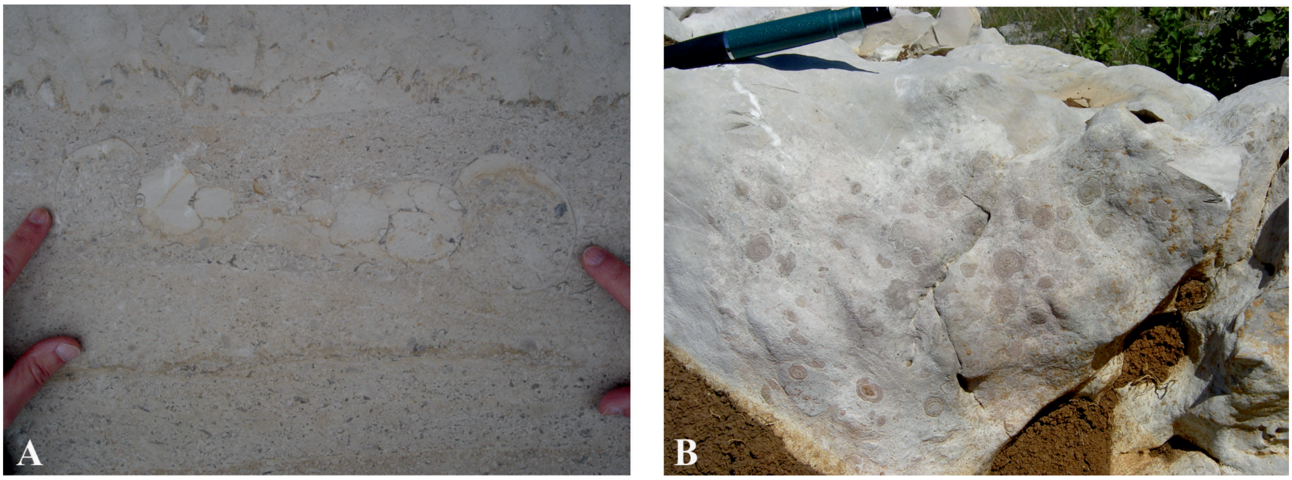

Fig. 6 – Examples of two contrasting lithofacies in the Portela das Salgueiras region: A – Storm-dominated sandbody, with a reworked ammonoid (centre), sharply overlying a bioturbated packstone (stylolites can also be seen); B – Lagoonal floatstone exhibiting large cyanobacteria/algal nodules (brownish structures).

Fig. 7 – Panoramic view over the Fórnea valley, where the Aalenian–Bajocian marl–limestone outer-marine series is exposed.

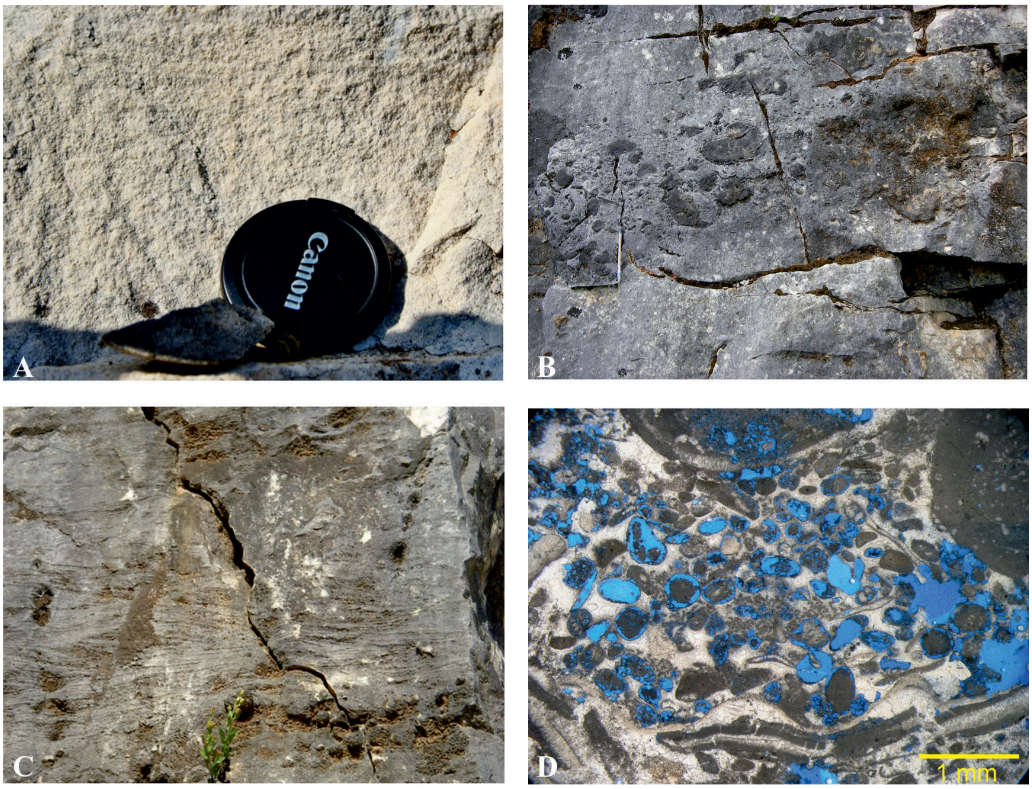

Fig. 8 – Barrier lithofacies of the Sto António-Candeeiros Fm.: A – Cross-laminated oolitic grainstones; B – Coral biostromes interbedded with grainstones and rudstones; C – Planar horizontal/undulatory laminations with climbing ripples in ooid-dominated grainstones, also with coarser-grained coral and algal fragments (the outcrop face is approximately 2 m high); D – Thin-section photograph showing high intraparticle and vuggy porosity.

Brief palaeoenvironmental interpretation: the sandbody and biostromal units are interpreted as typical barrier and peri-barrier deposits, with the biostromes having been formed mainly on the outermost side of the barrier, grading into oolite and skeletal sand sheets deposited between and on the flanks of the biogenic accumulations and small bioconstructions, in a highly dynamic sedimentary setting (Fig. 9). The cross-bedded, mainly oolitic grainstone clearly implies deposition from wave-dominated processes, above the fair-weather wave-base (upper shoreface). In contrast, the coarser-grained, massive to crudely graded planar laminated beds of skeletal grainstones/rudstones suggest a powerful, mainly unidirectional flow, influenced by storms, above the storm wave-base (lower shoreface). The peloidal–intraclastic interstitial sediment is interpreted as washed-in material from storm clouds.

2.5. Stop 5. Galinha Quarry: pedogenic, organic-matter-rich, peritidal carbonate succession (Serra de Aire Fm, lower Bathonian)

The previously active Galinha Quarry, which is located in the Fátima region (~30 km southeast of the Porto de Mós; Fig. 1), is nowadays a conservation site classified as a natural monument because of the excellent examples of sauropod trackways (Santos *et al*., 1994). These tracks are recorded in very shallow marginal–restricted lagoonal carbonate beds, towards the upper part of a pedogenic–peritidal–lagoonal marine carbonate succession assigned to the latest Bajocian?–lower Bathonian transition. The succession contains macrofossils (gastropods and bivalves) and microfossils (foraminifers, ostracods, calcareous algae, and cyanobacteria), several layers of microbial laminites, and fenestral structures (Azerêdo *et al*., 1995, 2013, 2015). The stop focuses mainly on the lower part of the section, which is characterized by pedogenic–peritidal deposits.

This lower part of the section exhibits clear calcretes (massive, laminar, nodular, and brecciated, all with black clasts) interbedded with, and grading laterally or vertically into, a range of other deposits. Limestones and marly–clayey limestones, ranging from massive to nodular or laminar macrofabrics, and composed of clotted micrite, peloidal–intraclastic sediment, black clasts, fenestral carbonate, and scattered bioclasts, are seen either interbedded with or grading laterally into organic- or coal-rich, marly/clayey seams and lenses, locally with carbonate nod-

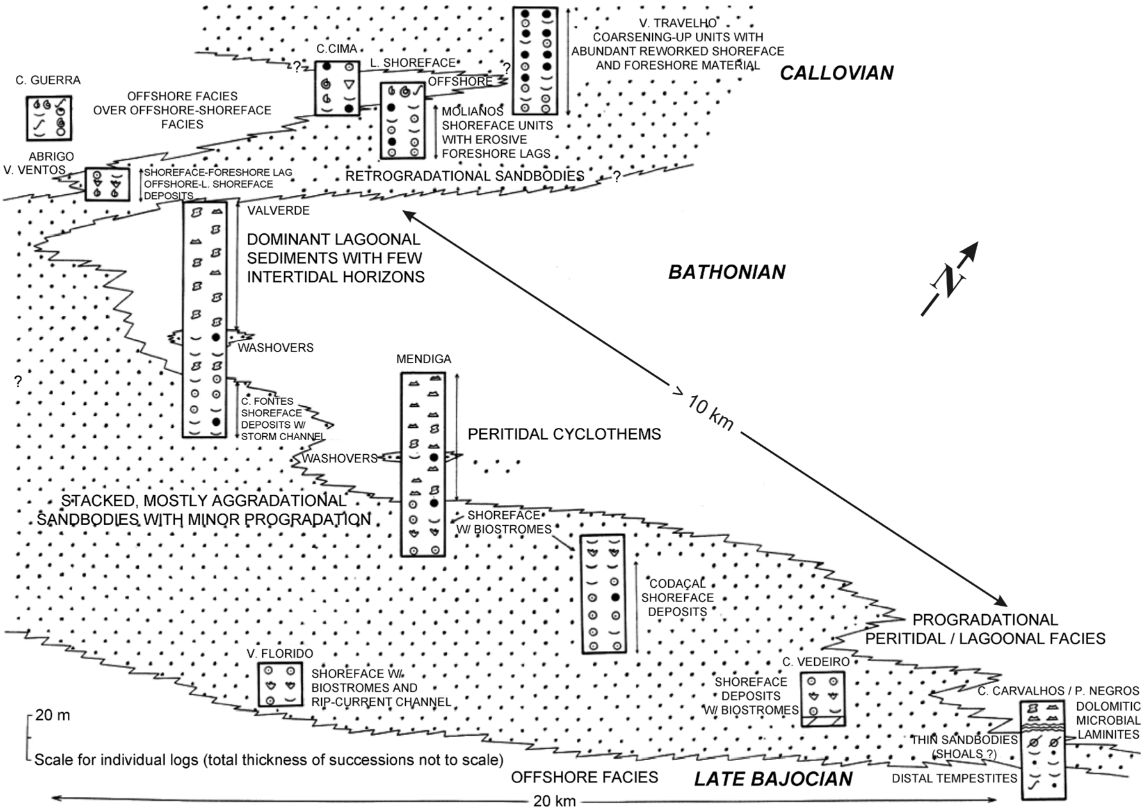

Fig. 9 – Schematic representation of the facies architecture and interpreted evolutionary pattern of the carbonate ramp system for the Bathonian and Callovian, based on the Maciço Calcário Estremenho region series (slightly mod. from Azerêdo, 1998); see also Fig. 4.

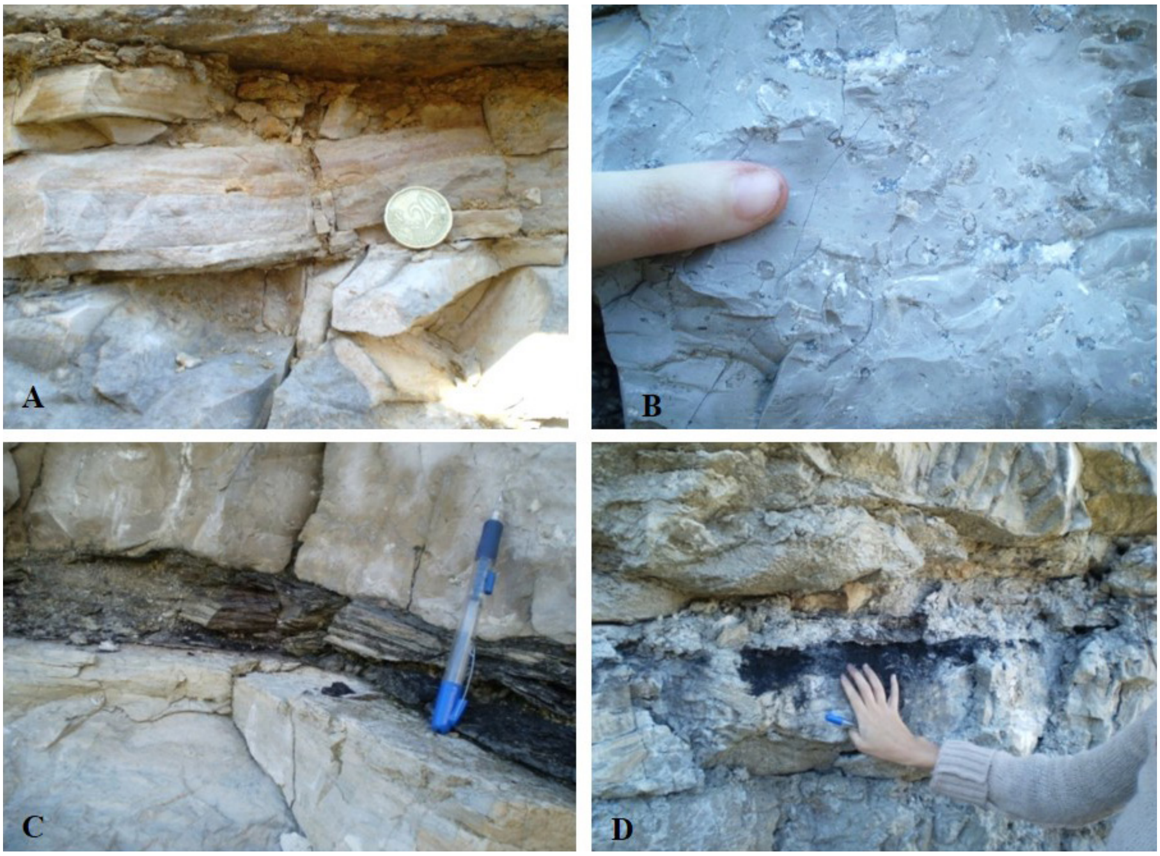

Fig. 10 – Exposures of the lower part of the Serra de Aire Fm at Pedreira do Galinha: A – Microbial laminites; B – Fossiliferous micritic limestone, including gastropods; C – Microbial laminite interbedded with organic-matter-rich layers; D – Marly limestone level with coal lenses and seams.

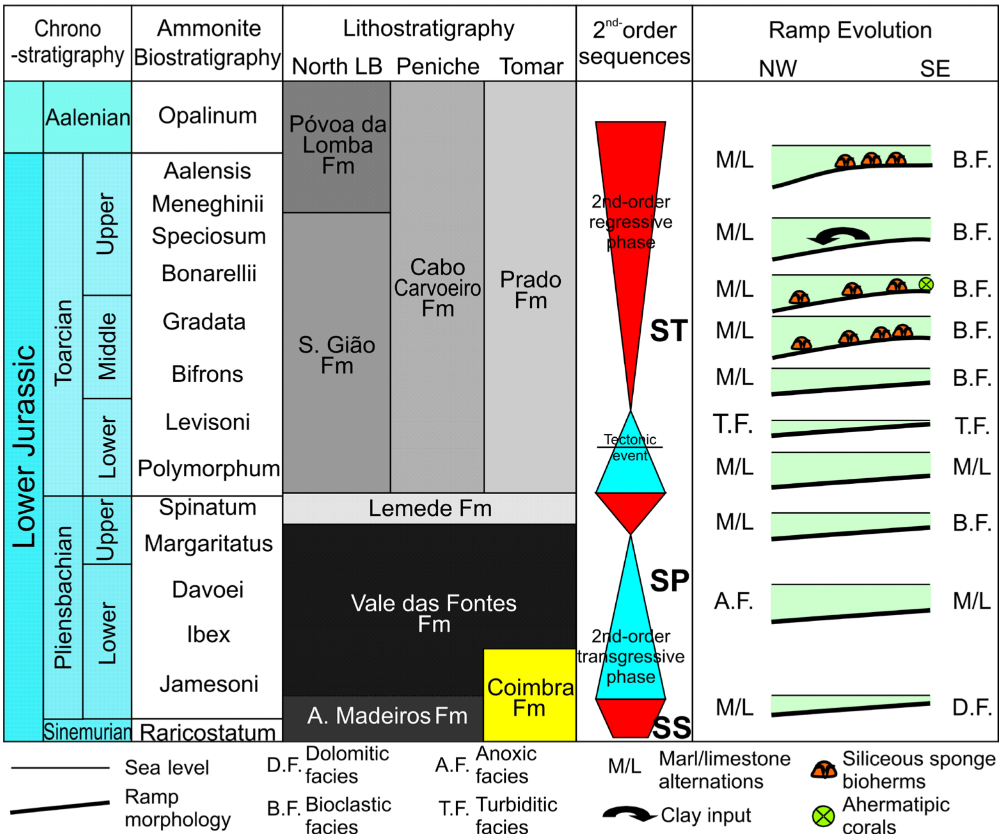

Fig. 11 – Stratigraphic chart for the upper Sinemurian–lower Aalenian succession across most of the LB (modified from Duarte, 2007). The placement of the Sinemurian–Pliensbachian boundary is from Comas-Rengifo *et al.* (2013b).

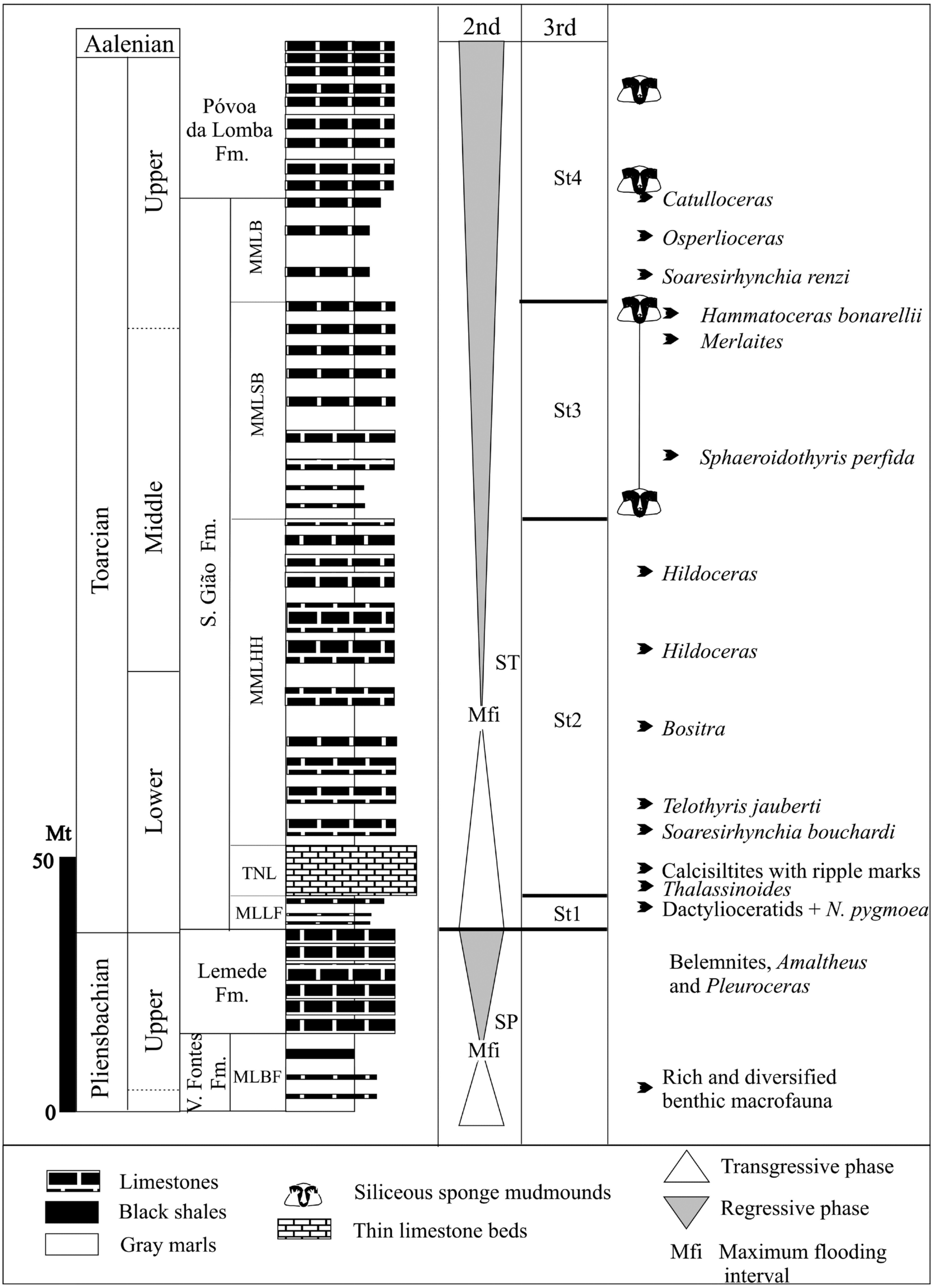

Fig. 12 – Summary stratigraphic log of the upper Pliensbachian–lower Aalenian succession at Rabaçal, showing lithostratigraphy, sequence stratigraphy (second- and third-order sequences), and some sedimentary characteristics (from Duarte, 2007). The ammonite biostratigraphic data are from Mouterde *et al*. (1964–65), Rocha *et al*. (1987), and Henriques (1992).

ules and microbial laminites (Fig. 10). Hardgrounds are also observed. Microscopic examination shows a range of typical calcrete fabrics and a few evaporite traces (Azerêdo *et al*., 2013, 2015). This pedogenic-dominated facies association grades upwards into peritidal cyclothems and lagoonal limestones with gastropods, ostracods, and other fossils. Only very rarely have freshwater ostracods and charophytes been found, at the base of the section. Many beds are bounded by undulated surfaces, and late compaction effects are also recorded. The upper part of the section corresponds to more fossiliferous limestones, with bivalves, gastropods, rare solitary corals, and ostracods, as well as microbial laminites, but no pedogenic evidence is recorded (Azerêdo *et al*., 2013, 2015).

Brief palaeoenvironmental interpretation: The palaeoenvironment resembles more the modern strongly seasonal Coorong setting, perhaps with less marked aridity, rather than a seasonal wetland setting (Azerêdo *et al*., 2013). The organic facies and overall sedimentary characteristics, including evaporites, suggest small ponds and subaerial terrestrial zones in a low-relief landscape subjected to seasonally sub-arid–sub-humid climatic conditions, affected by wildfires, that later evolved to peritidal and restricted lagoonal settings as a result of gradual marine inundation of the previous lowstand system (Azerêdo *et al*., 2015).

2.6. Stop 6. Stratigraphic setting, facies variation, and sequence stratigraphy of the Toarcian carbonate deposits in the Rabaçal–Coimbra region (L. V. Duarte)

2.6.1. Introduction

The Lower Jurassic in the LB is well exposed in almost all sectors of the basin (Fig. 1). Generally, the upper Sinemurian–upper Toarcian is dominated by hemipelagic deposits, represented by marl–limestone alternations, rich in nektonic and benthic macrofauna and controlled by an accurate ammonite biostratigraphy. The vertical facies variation observed between the Jamesoni and the Aalensis zones allows four main formations to be defined: the Vale das Fontes Fm (Jamesoni to Margaritatus Zone), the Lemede Fm (top of Margaritatus Zone to lowermost Polymorphum Zone), the S. Gião Fm (Polymorphum Zone to lowermost Meneghinii Zone), and part of the Póvoa da Lomba Fm (Duarte & Soares, 2002) (Fig. 11). The integration of several stratigraphic and sedimentological parameters (e.g., lithofacies analysis, stratonomy, microfacies, sequence evolution, ichnofossils, and palaeontological evolution) at the basin scale leads to the conclusion that the deposition occurred in a carbonate ramp setting (homoclinal ramp) dipping towards the northwest (e.g., Duarte, 1997, 2007) (Fig. 11).

The Rabaçal–Coimbra region, located in the northeastern part of the LB (Soares *et al*., 2005; Fig. 11), is one of the most important sectors for the study of the Lower Jurassic in Portugal (e.g., Mouterde 1964–65; Duarte, 2004). In this region, most of the Toarcian belongs to the S. Gião Fm and to the base of the Póvoa da Lomba Fm. The S. Gião Fm has its type-section at Rabaçal (Fig. 12), a succession that has been analysed in detail over the last two decades in the different domains of stratigraphy and sedimentary geology (e.g., Duarte, 1997; Duarte *et al*., 2001, 2007; Perilli & Duarte, 2006; Suan *et al*., 2010; Cabral *et al*., 2013a; Comas-Rengifo *et al*., 2013a). Therefore, this stop is focused on examining this section at different scales, including the high diversity of hemipelagic facies and their vertical and lateral arrangement in terms of cyclicity and sequence evolution. Particular attention is paid to the sedimentary and geochemical record observed in the lower Toarcian and the related discussion of the Toarcian anoxic event.

2.6.2. The Rabaçal section (Pliensbachian–Toarcian)

The Lower Jurassic succession observed in the Rabaçal section contains marly limestones exceeding 200 m in thickness extending through the Vale das Fontes, Lemede, S. Gião, and Póvoa da Lomba formations (Fig. 12).

The **Vale das Fontes Fm** (Jamesoni to Margaritatus Zone) is composed of alternations of decimetre- to metre-scale marl and centimetre-scale limestone, particularly rich in brachiopods, bivalves, ammonites, and belemnites. This unit comprises several facies, such as black shales and lumpy bioclastic marls and limestones. In the Rabaçal type-section, only the upper part of the succession is observed, being composed mainly of greyish marls locally enriched in organic matter.

The **Lemede Fm** (top of Margaritatus(?) Zone to the extreme base of the Polymorphum Zone) is composed of bioturbated alternations of centimetre-scale marl and decimetre-scale limestone. The unit is very rich in belemnites and ammonites, amongst other benthic macrofauna (bivalves and brachiopods). This formation reaches around 20 m in thickness in the Rabaçal section (Fig. 13A).

The **S. Gião Fm** is dominated by marly facies and ranges in age from early Toarcian (lowermost Polymorphum Zone) to late Toarcian (Meneghinii Zone). The formation is subdivided into five informal members, as outlined below: the marly limestones with "Leptaena" facies (MLLF) Mb.; the thin, nodular limestones (TNL) mb; the marls and marly limestones with *Hildaites* and *Hildoceras* (MMLHH) mb; the marls and marly limestones with sponge bioconstructions (MMLSB) mb; and the marls and

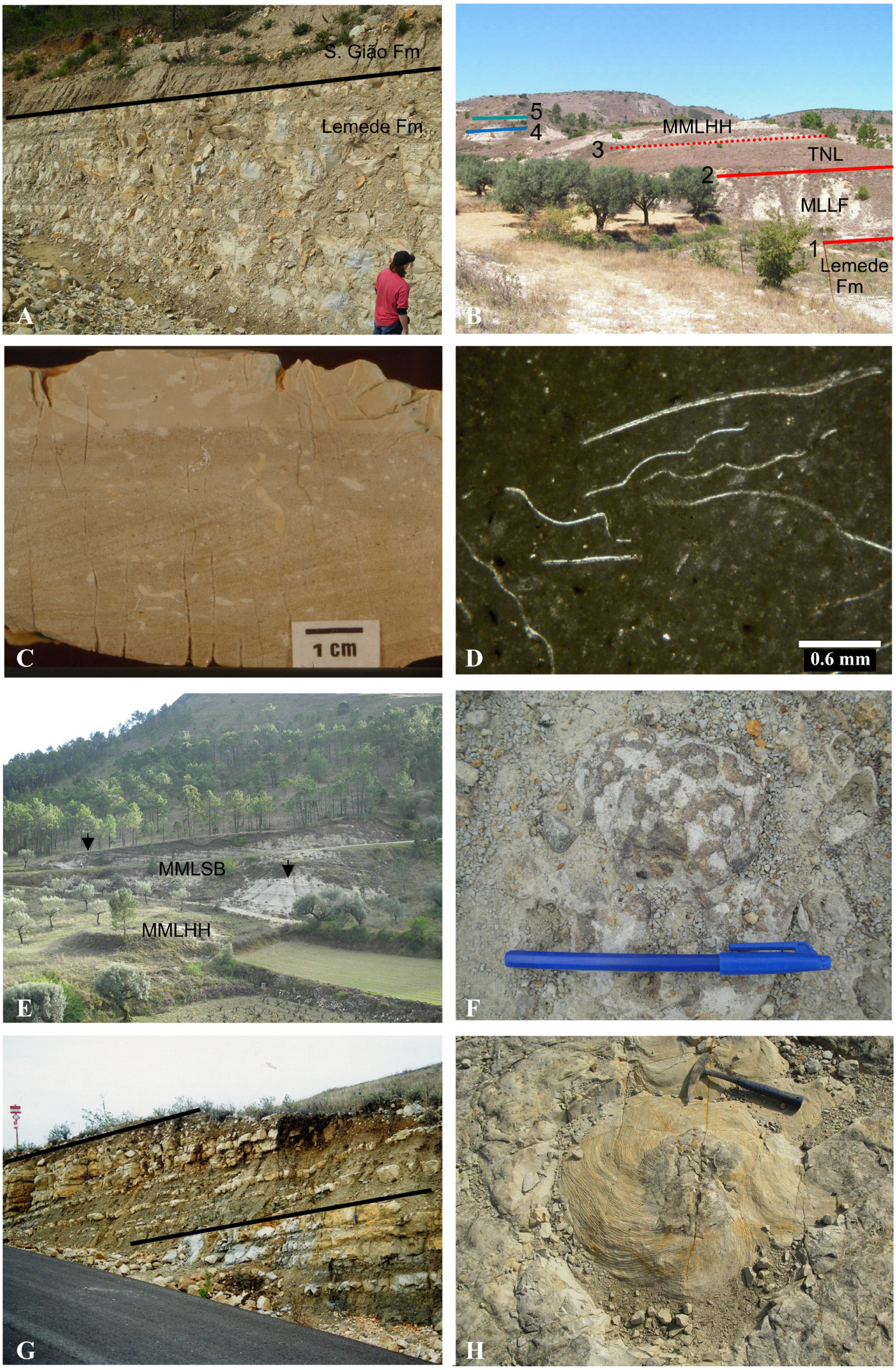

Fig. 13 – Sedimentary and stratigraphic features of the upper Pliensbachian–Toarcian deposits at Rabaçal. A – Calcareous facies at the top of the Lemede Fm; B – Lithostratigraphic, biostratigraphic, and sequence boundaries at the base of the Toarcian deposits; C – Bioturbated sandy limestone with cross-laminations of the TNL mb; D – Photomicrograph of a biomicrite–wackestone facies with thin bivalve shells (such as *Bositra* sp.); E – Landscape view of the marly base of the MMLSB mb (arrows show locations of siliceous sponge mud mounds); F – Detail of a small siliceous sponge bioconstruction (base of the MMLSB mb); G – Detail of fourth-order sequences (black lines: tops of the sequences) composed of marl–limestone alternations observed at the base of the Póvoa da Lomba Fm (Meneghinii–Aalensis transition); H – *Zoophycos* sp. typical record of the Póvoa da Lomba Fm (Aalensis Zone).

marly limestones with brachiopods (MMLB) mb. The S. Gião Fm is easily recognizable across a large area of the LB and is defined in terms of different stratonomic, sedimentological, and palaeontological (macrofauna and ichnofauna) characteristics (Duarte & Soares, 2002; Fig. 12). The formation at Rabaçal is around 145 m thick and is well controlled by ammonites (Mouterde *et al*., 1964–65; Rocha *et al*., 1987).

The **MLLF mb** (7 m; Polymorphum Zone) is characterized by alternations of decimetre- to metre-scale marly beds and centimetre-scale marly limestones, greyish in colour (Fig. 13B). This member contains a very rich benthic and nektonic macrofauna, characterized by an abundance of small brachiopods, belemnites, pyritized ammonites (dactylioceratids), bivalves (mainly *Plicatula* sp.), and *Zoophycos.*

The **TNL mb** (7m; base of the Levisoni Zone) is composed of thin (centimetre-scale) alternations of limestones and marlstones, grey to brownish in colour (Fig. 13B). The limestones include calcilutites to fine calcarenites, with irregular surfaces (amalgamated structures), locally with laminations, cross-bedding (Fig. 13C), and symmetrical current ripples. The thin (<14 cm) calcareous levels are usually strongly bioturbated; *Thalassinoides* and *Chondrites* are common, but ammonites are rare (some *Hildaites* sp.).

The **MMLHH mb** (63 m; Levisoni Zone–Bifrons Zone interval) is composed of decimetre- to metre-scale alternations of marls, marly limestones, and micritic limestones, with the micritic limestones increasing towards the top of the unit (Fig. 13B). The nektonic (ammonites) and benthic (brachiopods and bivalves) faunal association is a persistent feature of this unit, but with low diversity throughout. The brachiopods, mainly rhynchonellids (*Soaresirhynchia* sp.*)* and terebratullids (*Telothyris jauberti*), are very rich at the base of the member, corresponding to the Levisoni Zone. Some horizons of the uppermost part of the Levisoni Zone are very rich in thin-shelled bivalves *(Bositra* sp.; Fig. 13D).

The **MMLSB mb** (43 m; Bifrons Zone to the base of the Bonarellii Zone interval), with the exception of the marly base (Fig. 13E), is composed of regular alternations of decimetre- to metre-scale marly beds and centimetre- to decimetre-scale marly limestones. The occurrence of small siliceous sponge mud mounds (Fig. 13F), preferentially associated with calcareous lithofacies, is a typical and dominant feature throughout the member (Duarte *et al*., 2001). The macrofauna shows high diversity, locally with high concentrations of ammonoids, rhynchonellids, crinoids, and bivalves.

The **MMLB mb** (22 m; Bonarellii Zone–base of the Meneghinii Zone interval) is composed primarily of marls with very rare limestone levels. The occurrence of brachiopods is the most important palaeontological feature of this unit.

The base of the Póvoa da Lomba Fm is composed of bioturbated marl–limestone alternations, with an upward increase in the proportion of calcareous (biomicrite–wackestone, locally packstone) facies. This part of the unit (MST4B in Duarte, 1997), ranging in age from the Meneghinii Zone to the Opalinum Zone, is indicated by the occurrence of siliceous sponge bioconstructions (Duarte *et al*., 2001), preferentially associated with the tops of fourth-order sequences (Fig. 13G). Another important feature that characterizes this unit in this area is the ichnofacies composed of the association of *Chondrites, Zoophycos* (Fig. 13H), *Planolites*, and *Thalassinoides.*

2.6.3. Sequence stratigraphy of the Toarcian succession

The Pliensbachian and Toarcian deposits of the LB are subdivided into two second-order transgressive–regressive facies cycles (SP and ST; Figs 11 and 12). The thickness of these sequences is highly variable, dependent on the palaeogeographic position of each sector in the basin, controlled by the ramp profile and accommodation space. In both second-order sequences, the thickness increases from the southeast (Tomar region) to the northwest (Figueira da Foz–Cantanhede sectors), following the dip direction of the ramp (Fig. 11).

ST is dated from early Toarcian to early Aalenian and includes the S. Gião Fm and the lowermost part of the Póvoa da Lomba Fm, and it is subdivided into four third-order depositional sequences (ST1 to ST4; Duarte *et al*., 2001, 2004a, b), each one bounded by regional discontinuities, recognized over most parts of the LB (Figs 12 and 13B). The base of ST corresponds to an abrupt flooding event and is represented by a generalised marly accumulation across the whole basin (Fig. 13A). The marly dominance observed at the top of the Levisoni Zone marks the peak transgression of the Toarcian second-order sequence, coupled with the occurrence of *Bositra* sp. (Fig. 13B and D). The upper Toarcian–lower Aalenian succession shows a regressive trend, with the sequence ending with an upward increase in calcareous and bioclastic content (Fig. 13G). The discontinuity is dated from the Opalinum Zone and shows different sedimentary records in the basin (Duarte, 1997; DA1 in Duarte *et al*., 2001).

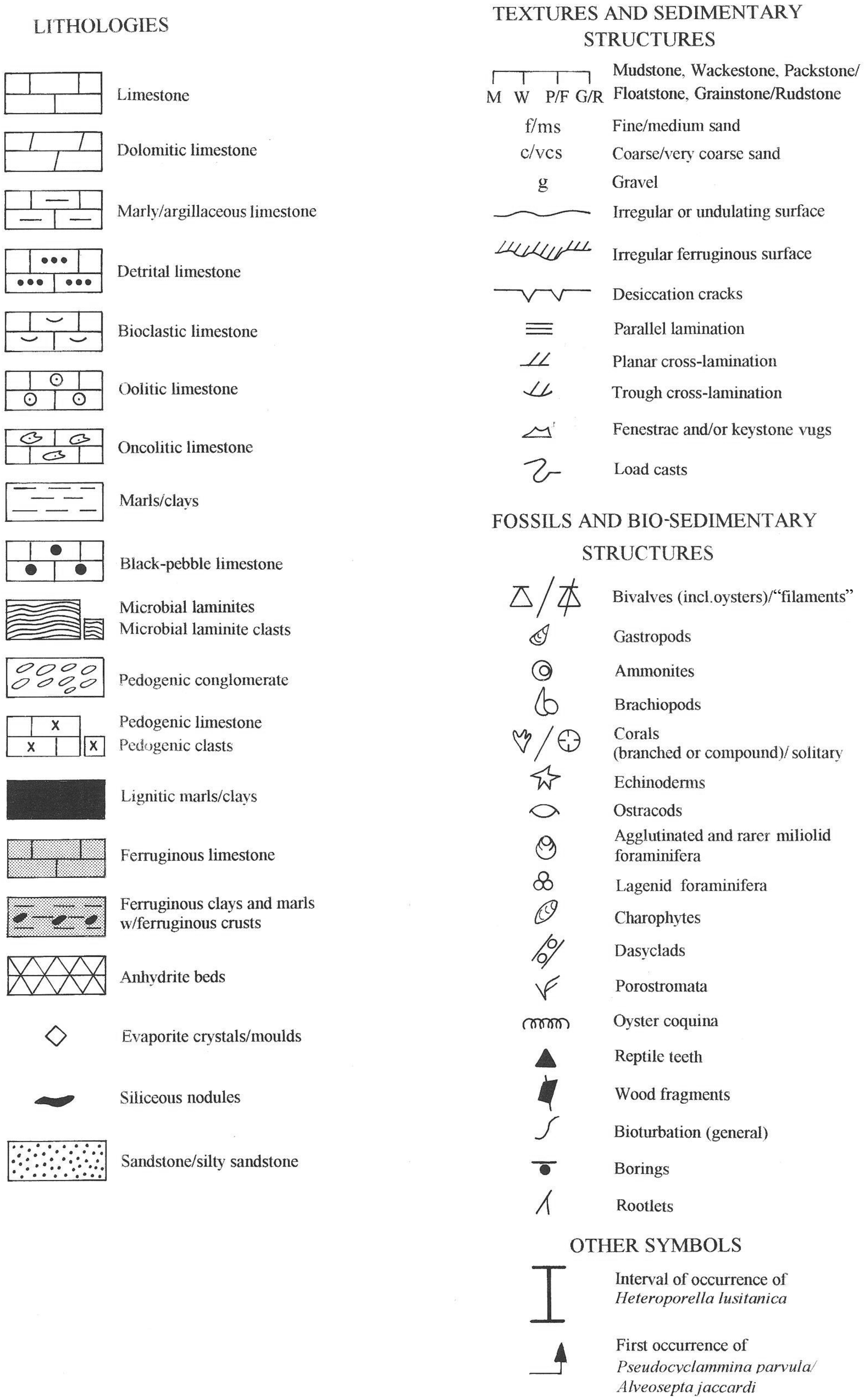

Fig. 14 – Key to the symbols used in the columns of Fig. 15, representing the Callovian–Oxfordian disconformity and succession at Cabo Mondego (from Azerêdo *et al*., 2002).

In this sedimentary context, we emphasize the facies change observed between the MLLF and TNL members (DT2; across the Polymorphum–Levisoni chronozone boundary) (Fig. 13B). This disconti-

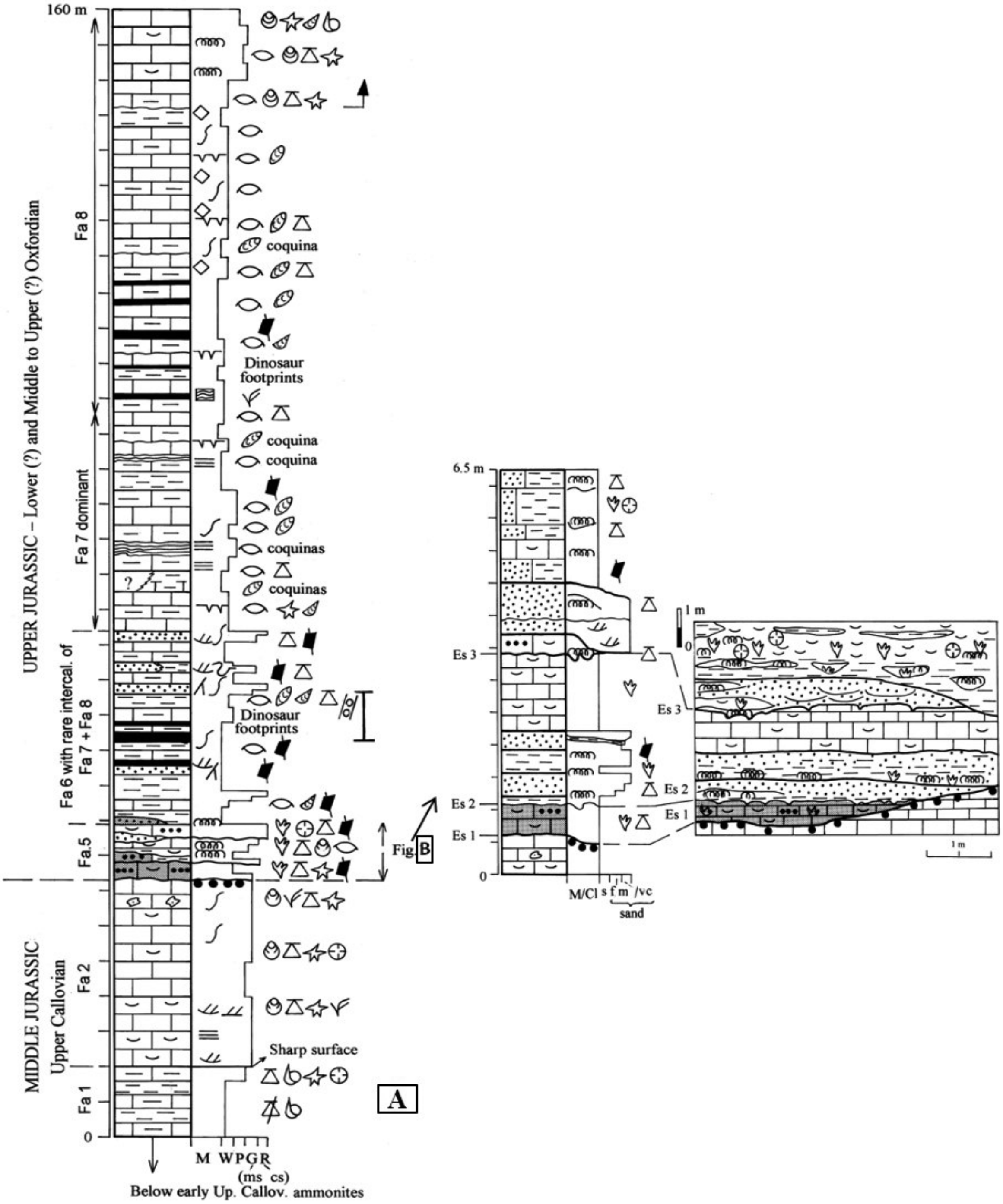

Fig. 15 – A – Synthetic column of the topmost Callovian–Oxfordian disconformity and succession at Cabo Mondego. B – Detail of the interval with mixed corals, oysters, sandstones, and detrital limestones (from Azerêdo *et al*., 2002, partially based on Wright, 1985). Fa: facies associations of Azerêdo *et al.* (2002); Es: erosion surfaces (Wright, 1985). The key is given in Fig. 14.

nuity defines the most important sedimentological and palaeontological change recorded in the whole Lower Jurassic succession of the LB (Duarte, 1997; Duarte *et al*., 2004a) and reflects significant tectonic activity (e.g., Duarte, 1997; Kullberg *et al*., 2001). Corresponding approximately to the Polymorphum–Levisoni chronozone boundary (Duarte, 1997), this discontinuity marks an abrupt decrease in the evolution of Δ^{13}C (Duarte *et al*., 2004a, 2007; Suan *et al*., 2010).

2.7. Stop 7. Cabo Mondego: evidence of Middle–Late Jurassic forced regression and basinal disconformity, Oxfordian marginal- to non-marine source rocks, and facies variations (Cabaços Fm) (A. C. Azerêdo)

At Cabo Mondego (5 km north of Figueira da Foz), cliff sections expose a wide range of Jurassic deposits. This field stop covers only a small part of the coast, near Pedra da Nau, where Callovian out-

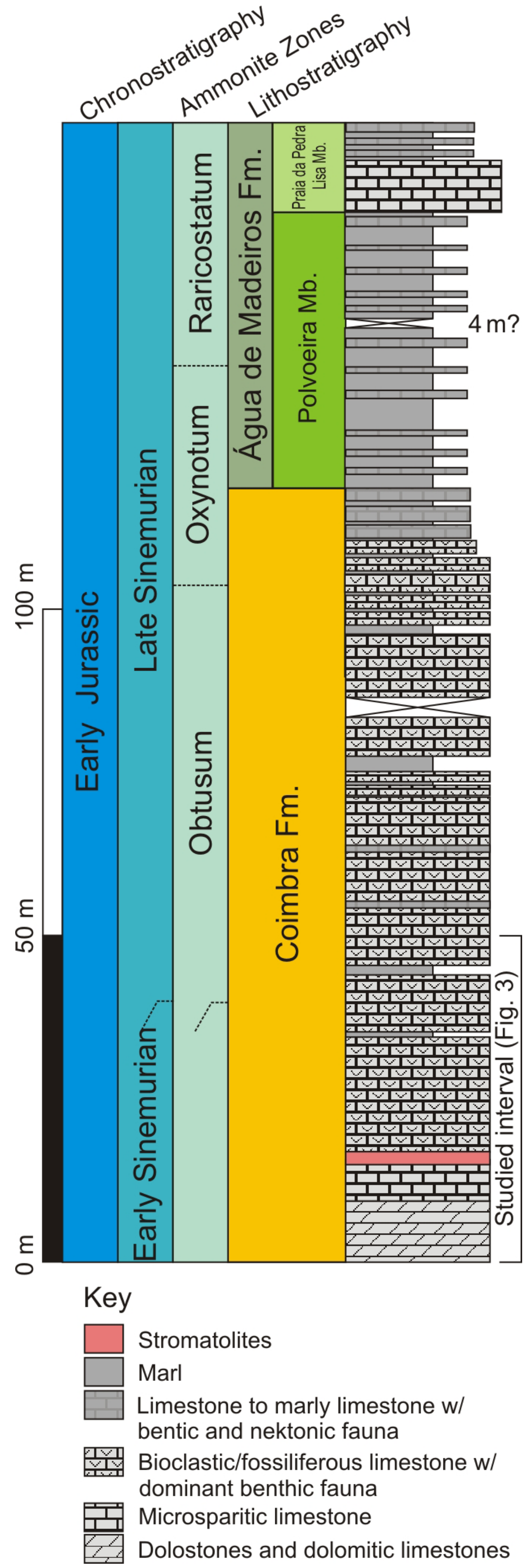

Fig. 16 – Lithostratigraphy and bio-chronostratigraphic framework of the Sinemurian succession cropping out in the S. Pedro de Moel region, western-central Portugal (modified from Duarte & Soares, 2002; Duarte *et al*. 2008). The studied interval corresponds to the detailed work conducted by Azerêdo *et al.* (2010).

er-ramp facies ("Brenha" in Fig. 2; Cabo Mondego Fm *sensu* Azerêdo *et al.*, 2003) are sharply overlain by a carbonate sandbody and then by mixed non-marine–paralic–shallow-marine facies corresponding to the Cabaços Fm (Wright, 1985, 2004; Azerêdo *et al*. 2002; Azerêdo & Wright, 2004). The sharp-based carbonate sandbody is 28 m thick, with extensive *Thalassinoides*-type burrows, and is overlain by a 6-m-thick package of coral-bearing sandstones, coral rudstones and packstones (locally red in colour with evidence of coral leaching), oyster-rich mudstones, in situ oyster–coral bioherms, and bioclastic limestones (Figs 14 and 15; Wright, 1985, 2004). Upwards into the Cabaços Fm, through a thickness of more than 100 m, sandstones, mudstones, shales, and lignites, as well as micritic–marly limestones with mainly non-marine bivalves, gastropods, abundant ostracods, and charophytes, are found interbedded with microbial laminites, organic-rich marls, and laminites, with local occurrences of thin calcite-replaced gypsum layers. This field-trip visits only the lower part of this thick package.

Some of the organic-rich sediments present high total organic carbon values (reaching 30.7 wt.%), and palynofacies studies indicate that the particulate organic matter is mostly of continental origin punctuated by minor events of marine influence (Silva *et al*., 2011, 2013). The overall features suggest that part of the Cabaços Fm. may be regarded as a potential source rock (e.g., Wright, 1985; Silva *et al*., 2011, 2013).

Brief palaeoenvironmental interpretation: This sharp shift from open-marine to carbonate sandbody and then to non-marine deposits is interpreted as clear evidence for a forced regressive episode marking the Middle–Upper Jurassic transition, which is associated with a disconformity recorded at several locations across the basin (e.g., Azerêdo *et al*., 2002; and references therein). Reflooding led to the development of a complex pattern of depositional conditions throughout the basin from freshwater and brackish lagoonal environments to marginal- and shallow-marine settings. At Cabo Mondego, in particular, the input of siliciclastics (probably from the west) reflects erosion related to tectonism and basement uplift. The combination of oysters and corals, lensoidal sandstones, and coarse coral debris, overlain by carbonate-dominated sediments with non-marine fossils, probably represents mixed coastal marginal fresh to brackish water and restricted marine lagoonal settings, periodically affected by deltaic influxes and storms (Wright, 1985, 2004; Azerêdo *et al*., 2002; Azerêdo & Wright, 2004).

Fig. 17 – Features of the Sinemurian deposits at Praia Velha and Praia da Concha: A – Stromatolite mounds; B – Detail of the laminar fabric of a stromatolite; C – Skeletal tempestite; D – Bivalve coquinas at a bedding surface.

2.8. Stop 8. São Pedro de Moel region: stromatolites within a restricted marine succession (Coimbra Fm, Sinemurian)

This stop examines part of a more than 100 m thick, thin- to medium-bedded Lower Jurassic (Sinemurian) carbonate succession cropping out along the cliffs of two contiguous beaches in the S. Pedro de Moel region (Praia Velha and Praia da Concha; Fig. 1). This succession, belonging to the lower part of the Coimbra Fm (e.g., Mouterde *et al*., 1981; Rocha *et al*., 1987; Duarte *et al*., 2008; Azerêdo *et al*., 2010), is affected by faulting and tectonic deformation and reveals some interesting features, including excellent examples of stromatolitic mounds. The lowermost part of the series has not yet yielded age-diagnostic fossils, but it is overlain by marine marl–limestone deposits bearing the first ammonoid faunas recognized in the basin (Obtusum Zone, earliest late Sinemurian; Mouterde *et al*., 1981; Dommergues *et al*., 2004, 2010).

The sedimentary succession has been described and interpreted in detail (with an emphasis on microbialites) by Azerêdo *et al*. (2010). The succession comprises (Fig. 16): dolomites; marly, argillaceous and/or dolomitic limestones, either massively bedded or laminated, locally with undulating boundaries; stromatolites and a few tabular microbalite layers; fossiliferous/skeletal limestones (bivalves, gastropods, and ostracods), graded in some places, with an erosive base and bioclastic lags and coquinas at the top; and a few marls and shales (Fig. 17). Bioturbation is also common. In contrast to the relatively even-bedded deposits both below and above, the succession contains many decimetre- to metre-scale brownish–reddish microbial structures, whose external and internal morphologies allow them to be classified as stromatolites.

Brief palaeoenvironmental interpretation: The overall depositional setting is interpreted as a mainly low-energy, shallow to moderately deep subtidal marine setting (distal inner- and mid-ramp), punctuated by higher-energy (storm/flooding) episodes, particularly in the middle and upper parts of the section. Some type of physical constraint, coupled with the low gradient of the ramp system, would presumably have defined an embayment environment in which circulation was relatively restricted for most of the time (favouring the microbial community), except when affected by externally induced events. Towards the upper part of the succession, progressive environmental openness leading to a gradually stronger marine influence, alternating with frequent environmental restriction, is inferred from the composition of palaeobiota and changes in diversity (Azerêdo *et al*. 2010; Cabral *et al*., 2013b).

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