Post-Meeting Field Trip P1

Early Jurassic carbonate evolution in the Lusitanian Basin (Portugal): facies, sequence stratigraphy and cyclicity

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1. INTRODUTION

The Lusitanian Basin (Central Portugal) has a unique location, between the Atlantic and the Tethyan realm. It constitutes an important and decisive key-study area concerning Jurassic palaeogeographic reconstructions. Besides the local sedimentary particularities of the Lusitanian Basin (LB), several Portuguese outcrops record some of the main events that occurred at the world scale. In the particular case of the middle-upper Liassic series, they are characterised by an expressive marly limestone accumulation (marl/limestone alternations), sometimes with a clear cyclicity. The weak lateral facies variation, generally observed at the basin scale, suggests these sediments were deposited in an epicontinental extensional basin, on a homoclinal carbonate ramp, influenced by eustatic fluctuations and local and regional tectonics. Considering the Late Triassic-late Callovian large cycle (pre-rift phase), those sediments correspond to the maximum transgressive facies, which are observed widely in all the succession.

In this field trip, our aim is to show the main depositional events occurred during the Early Jurassic times. Several kinds of facies such as hemipelagites, turbidites, siliceous sponge mud mounds or black shales, are recognizable in classic and well-exposed outcrops of Rabaçal-Coimbra, S. Pedro de Moel and Peniche (Fig. 1). The main objective of this excursion is to show a sequential scheme interpreted in terms of sequence stratigraphy, and to discuss the hierarchy of the sedimentary cyclicity (second to fourth-order). Nevertheless, some other particular and interesting sedimentological aspects are also presented and discussed, such as the internationally known case of Toarcian carbonate fan turbidites in the Peniche section (Wright & Wilson, 1984), the siliceous sponge mud mounds occurrences in the middle to upper Toarcian series (Duarte *et al.*, 2001) and the ammonite taphonomic features of lower Pliensbachian carbonate facies (Fernández-López *et al.*, 2000). The sequential analysis is also achieved by assembling all the available data on the series, such as lateral and vertical facies evolution, palaeoecological and taphonomic features and mineralogical and geochemical parameters (stable isotopes and total organic carbon).

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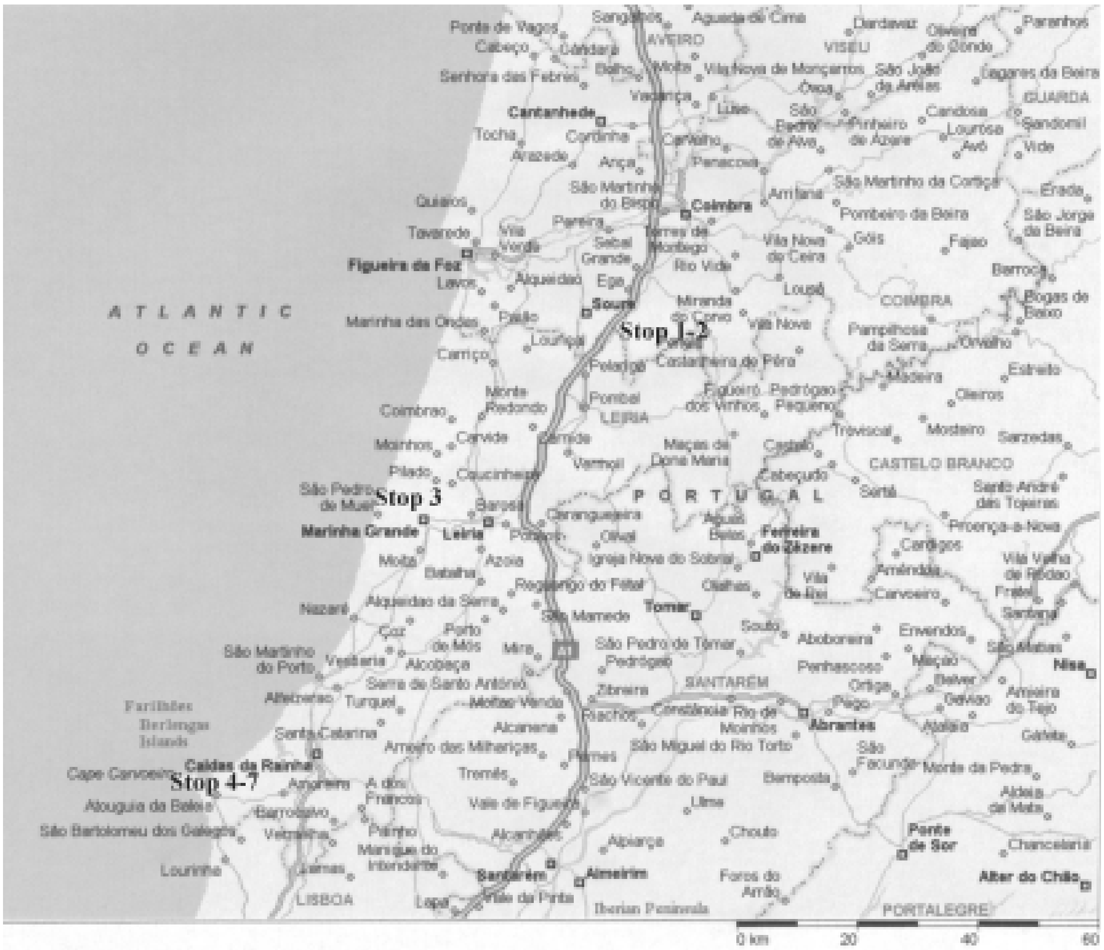

Fig. 1 - Itinerary of the excursion P1. First day: Stops 1-3. Second day: Stops 4-7.

2. STRATIGRAPHIC SETTING, FACIES VARIATION AND SEQUENCE STRATIGRAPHY OF THE LOWER JURASSIC CARBONATE SERIES

L. V. Duarte

The Jurassic in the LB is well exposed, including practically the two extremes of the basin: Figueira da Foz-Cantanhede at the north end and Arrábida at the south end (Fig. 2). Generally, the middle-upper Liassic record is dominated by hemipelagic deposition, represented by marl/limestone alternations, very rich in nektonic and benthic macrofauna. The vertical facies variation, observed between the Jamesoni and the Aalensis zones, allows the definition of four main formations (Duarte & Soares, 2002), previously included in the same informal Brenha Formation (Fm) (Witt, 1977): Vale das Fontes Fm (Jamesoni to Margaritatus Zone), Lemede Fm (Spinatum to lowermost Polymorphum Zone), S. Gião Fm (Polymorphum to lowermost Meneghinii Zone) and, partially, Póvoa da Lomba Fm (Duarte & Soares, 2002) (Fig. 3), each characterized by different marl-limestone relationships. These units display a limited number of distinct lithofacies, consisting generally of marlstones, limestones and more rarely of bioclastic limestones, carbonate nodular facies, black shales and siliceous sponge mud mounds. The Vale das Fontes Fm is sub-divided into three members, whereas the S. Gião Fm is sub-divided into five members (Fig. 3). Despite some macroscopic similarities, all these units are defined in terms of different sedimentological and palaeontological (macrofauna and ichnofauna) characteristics (*vide* Duarte, 1997; Duarte & Soares, 2002). The integration of several stratigraphic/sedimentological procedures (e.g. lithofacies analysis, microfacies, sequential evolution, ichnofossils and palaeontological evolution) allows the conclusion that the deposition occurred on a carbonate ramp setting (homoclinal ramp *sensu* Read, 1982, 1985) dipping towards the northwest (Duarte, 1997).

In spite of this generic geological context, the lateral facies variations across the southern half of the LB, show three major tectono-palaeogeographic settings, with special sedimentological features and, consequently, showing a different lithostratigraphic chart (Fig. 3): these sectors are Arrábida-Sesimbra, Tomar and Peniche.

Arrábida-Sesimbra: in this sector the outcrops are very scarce and the ammonite biostratigraphic control is very poor. The series is composed by dolomitic and bioclastic limestone facies, corresponding to the most shallow marine sediments observed in the whole basin. The sedimentary succession is included in the informal Dolomitic marls and limestones with brachiopods of Meia Velha Fm (Manuppella & Azerêdo, 1996), lacking in this sector all Middle and Upper Toarcian. This sedimentary gap is also observed in the Algarve Basin, in south Portugal (Rocha, 1976; Manuppella *et al.*, 1988), where the Toarcian is restricted to two small outcrops.

Tomar: located in the southeastern part of the Basin, the middle-upper Liassic series is very condensed (Duarte, 1997), when compared to the whole Basin. The facies are bioclastic-rich (essentially benthonics) in calcareous dominated successions belonging to three formal formations: Vale das Fontes Fm and Lemede Fm of Pliensbachian age and Prado Fm, lateral equivalent of S. Gião Fm (Fig. 2) (Duarte & Soares, 2002). In Tomar the series typifies the proximal part of the homoclinal ramp (Duarte, 1997), well developed towards the north and west. The occurrence of ammonites is rare, but locally allows an accurate biostratigraphic control (Mouterde *et al.*, 1971; Mouterde & Rocha, 1983).

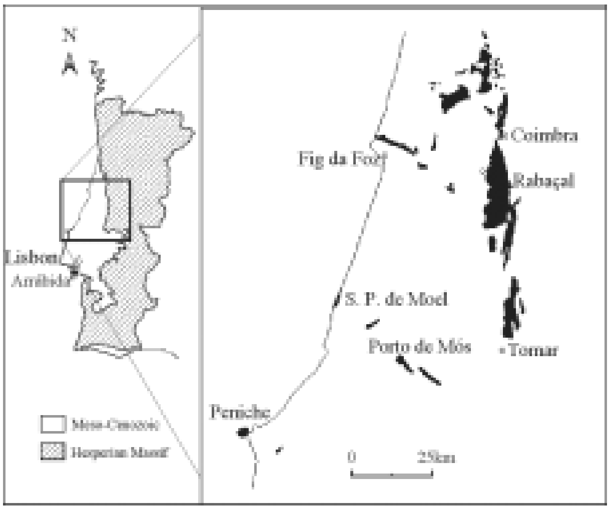

Fig. 2 - Geological map of Lower Jurassic marly limestones in the LB (north of Lisbon). Location of the main outcrops.

Peniche: the unique feature of this sector, located in the southwestern part of the Basin and well exposed along the cliffs of the Peniche peninsula, is the strong siliciclastic and oolitic resedimented accumulation observed in the Toarcian succession (Cabo Carvoeiro Fm, Duarte & Soares, 2002). The influx of these sediments seems to have been related with turbiditic mechanisms (Wright & Wilson, 1984). Despite this sedimentary setting for the upper Liassic, such as observed in other parts of the Basin, the Pliensbachian is here dominated by a thick succession of marl/limestone alternations. This sector shows the type-section of Vale das Fontes and Lemede Fms. (Fig. 3).

2.1. Sequence Stratigraphy

The studied successions of mid to late Liassic are included in the Upper Triassic (Norian?)-Callovian cycle (Wilson *et al.*, 1989; Soares *et al.*, 1993a,b; Soares & Duarte, 1997). This cycle begins with the coarser red siliciclastic facies at the extreme base of Late Triassic and ends with the bioclastic limestones of the late Callovian (Athleta Zone). Generally, the base of this sedimentary package overlies Precambrian metamorphic units (Cristalofilian Complex) and, in the northeastern sector, the Upper Carboniferous/Lower Permian siliciclastic deposits. The great sedimentary facies change, observed between the top of Callovian and the base of the Upper Jurassic successions, is associated to an important emersion phase with sub-aerial exposure (Azerêdo *et al.*, 2002 and references therein).

The first sequential chart applied to the Lower and Middle Jurassic series of LB was presented by Soares *et al.* (1993a,b). In this chart, the Upper Triassic-Callovian succession was sub-divided into eight megasequences (**A** to **H**), bounded by regional discontinuities. The significance of these surfaces was later discussed by Soares & Duarte (1997), in terms of the interplay of eustatic/ /tectonic mechanisms. In spite of restricted analysis (e.g. Duarte, 1997, 2003; Duarte *et al.*, 2001) any sequential scheme was presented to Lias and Dogger series based on sequence stratigraphy fundamentals. The weak lateral facies variation of the series was probably the main reason for this situation. This is valid in the particular case of middle-upper Liassic where, with the exception of Peniche, Tomar and Arrábida, the facies are dominated everywhere by hemipelagic deposits. However, despite this difficulty, the marly limestone succession, presents marl-limestone alternations, in some cases very rhythmic and organised in a hierarchical sequence scheme. In fact, three scales of sequences (second to fourth-order; Vail *et al.*, 1991), equivalent to stratigraphic cycle terminology of Jacquin & De Graciansky (1998a,b), have been distinguished in the Pliensbachian and Toarcian series of the LB: (second-order) transgressive-regressive (T-R) facies cycles, third-order sequence cycles and parasequence (fourth-order) cycles. In some cases, a fifth-order (elementary marl-limestone couplet) can also be recognised.

2.1.1. Second-order Sequences

Concerning the northern sector of the LB, Soares *et al.* (1993a,b) sub-divided the whole Late Triassic-extremely late Mid Jurassic cycle in to eight megasequences (A to H), bounded by regional discontinuities. The duration of these sequences, approximately equivalent to stages, places each megasequence with second-order sequence (*sensu* Vail *et al.*, 1991) or, considering the hierarchy of sedimentary cyclicity, with transgressive-regressive facies cycles (*sensu* Jacquin & Graciansky, 1998a,b; Graciansky, 1999).

In our case study, the Middle-Upper Liassic of the LB series is sub-divided in to two second-order sequences (**SP** and **ST**), with duration equivalents in time to the Pliensbachian and Toarcian stages (Duarte, 2003). The thickness of these sequences is highly variable, depending 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 southeast (Tomar region) towards the northwest (Figueira da Foz-Cantanhede sectors), following the direction of the dipping ramp.

Sequence SP: The Pliensbachian succession of the LB shows a typical second-order transgressive/regressive sequence (megasequence D, *in* Soares *et al.*, 1993a,b), with a dominant marly deposition at the base (Carixian and early Domerian time: Vale das Fontes Fm) and a calcareous dominant facies at the top (late Domerian to extreme base of early Toarcian: Lemede Formation).

The basal discontinuity of the **SP** is particularly well observed in the western part of the LB (S. Pedro de Moel), dated roughly of Sinemurian/Pliensbachian boundary (Duarte, 2003; see Stop 3). The series shows a large transgressive phase, ending in the middle-upper part of Margaritatus Zone (around Subnodosus/ Gibbosus Subzone boundary). The whole basin is marked by organic-rich deposition period (Duarte & Rodrigues, *in progress*).

During the Spinatum Zone the sedimentation returned to a calcareous regime, very rich in benthic macrofauna. In southeastern sectors of the basin, this regressive phase is represented by bioclastic/grainstone facies, representing minimum accommodation space (Duarte, 2003). The upper discontinuity of the **SP**, observed in the whole basin (**DT1** in Duarte, 1997; see Stops 1 and 7), is lowermost Polymorphum Zone (intra-Mirable Subzone) in age.

Considering the nature of the sediments, dominated by hemipelagic marly limestones, without inner ramp facies development, the weak lateral facies variation of the Pliensbachian series does not allow the recognition of third-order sequences.

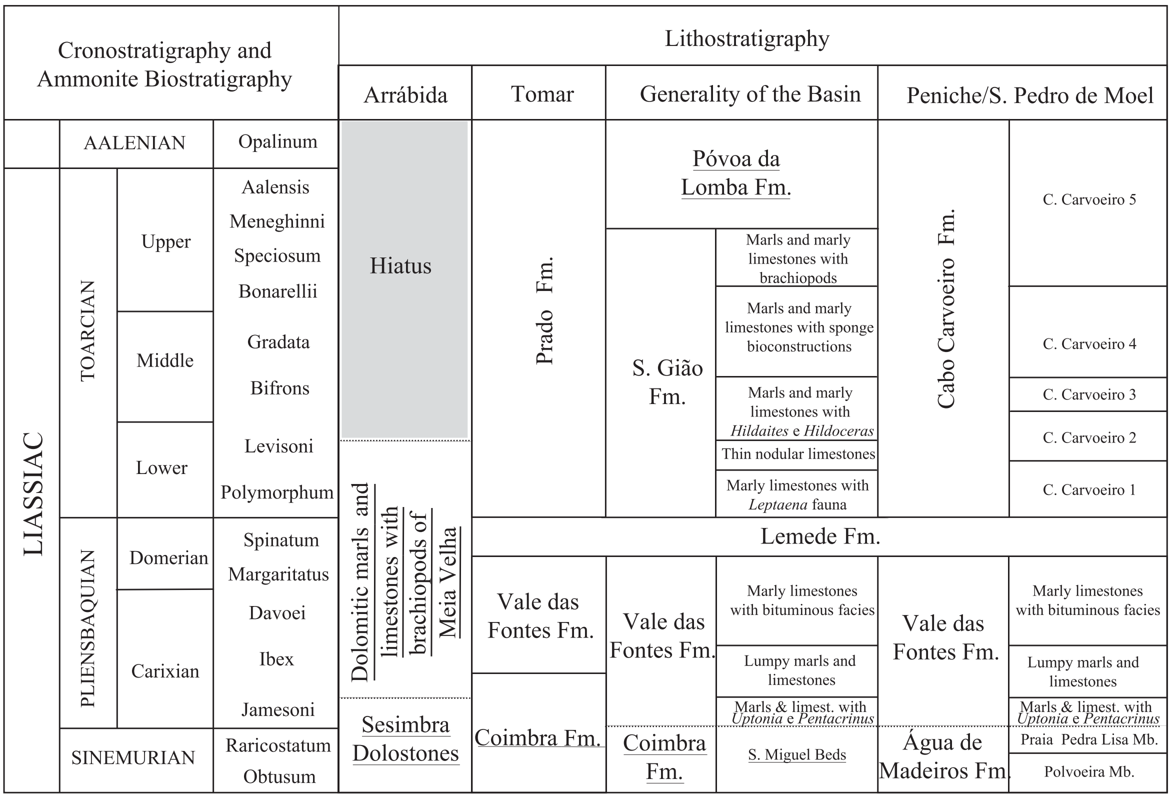

Fig. 3 - Lithostratigraphical chart for the Pliensbachian-Toarcian units of the LB (Duarte & Soares, 2002).

Sequence ST: This second-order depositional sequence is dated of the early Toarcian to early Aalenian and includes the S. Gião Fm and the lowermost part of Póvoa da Lomba Fm. In the stratigraphic chart of Soares *et al.* (1993a,b), this sequential unit corresponds to the megasequence **E** and it is sub-divided into four third-order depositional sequences (**ST1** to **ST4**; MST1 to MST4 in Duarte, 1997), each one bounded by regional discontinuities, recognised over most parts of the LB. The base of **ST** corresponds to an abrupt flooding event, through a generalised marly accumulation in the whole basin. This sequence varies between 75-80 m in Tomar and around 280 m thick in the Coimbra sector.

The marly dominance observed at the top of the Levisoni Zone marks the maximum peak transgression of the Toarcian second-order sequence (Duarte, 2003; Duarte *et al.*, 2003, 2004a; see Stop 1). The upper Toarcian-lower Aalenian succession shows a regressive trend, ending this depositional sequence with an upward increase of calcareous and bioclastic content. The discontinuity is dated of Opalinum Zone and shows different sedimentary records in the basin (Duarte, 1997; **DA1** in Duarte *et al.*, 2001).

3. STOP 1. FACIES VARIATION IN THE LOWER TOARCIAN SUCCESSIONS OF THE NORTHERN LUSITANIAN BASIN: THE RABAÇAL--COIMBRA REGION

L. V. Duarte

The Coimbra-Rabaçal region is located in the northern part of the LB (Fig. 2) and constitutes one of the most important sectors for the study of the lower Toarcian succession. The Lower Toarcian in this region corresponds to the base of S. Gião Fm, and is sub-divided in the following three members: Marly limestones with *Leptaena* fauna (MLLF), Thin nodular limestones (TNL) and base of Marls and marly limestones with *Hildaites* and *Hildoceras* (MMLHH) members (Figs. 4 and 5). It is organised into two third order depositional sequences (**ST1** to **ST2**), bounded by three (**DT1** to **DT3**) isochronous regional discontinuities. Besides the facies (lithofacies and biofacies) changes, in this stop we emphasize the evolution of carbon stable isotope (∂^{13}C) as an important tool for sequence stratigraphic interpretation (Duarte, 1998a; Duarte *et al.*, 2003, 2004a).

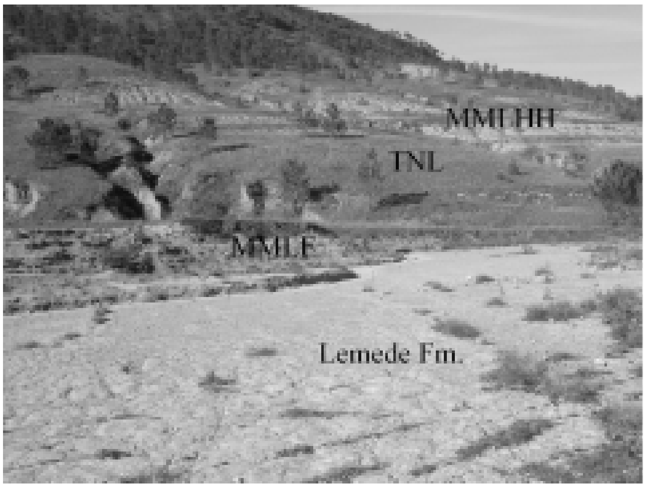

Fig. 4 - General view of S. Gião Fm in Rabaçal showing its first three members. The top surface of Lemede Fm represents a second order sequence boundary (between **SP** and **ST**).

3.1. Third-order depositional sequences

ST1: this sequence corresponds to the MLLF Mb, and is the most argillaceous unit of the entire Toarcian succession. The marl/marly limestone alternations show an interesting rhythmicity at various scales (parasequences and parasequence groups). Usually, several sedimentological and stratinomic aspects show an elementary rhythmic sequential organisation (parasequence), from marl grading to marly limestone (micrite to biomicrite/wackestone). This sequence is very asymmetric, and a large part of it is interpreted as being a transgressive system tract. Hence it is quite difficult to identify the maximum flooding surface although this probably corresponds to a thick limestone bed (0.80m), very rich in Dactylioceratids (a good event/horizon easily recognizable in all the LB). Besides, this transgressive trend is well documented by the ∂^{13}C maximum excursion (Duarte *et al.*, 2004a) observed at the top of MLLF Mb (Fig. 5).

ST2: this sequence begins with brownish clays and marls that characterize the base of TNL Mb. These facies, exclusive to the northern part of the LB, are usually unfossiliferous. Upwards, this sequence grades into thin (centimetre-scale) silty to sandy (quartz and micaceous minerals) limestone alternations with marly clay inter-beds that corresponds to the typical TNL Mb in the whole basin (Fig. 6). The limestone facies include calcilutites to fine calcarenites, with irregular surfaces (amalgamated structures), locally with lamination, cross--bedding, symmetrical and current ripples (Fig. 7). The

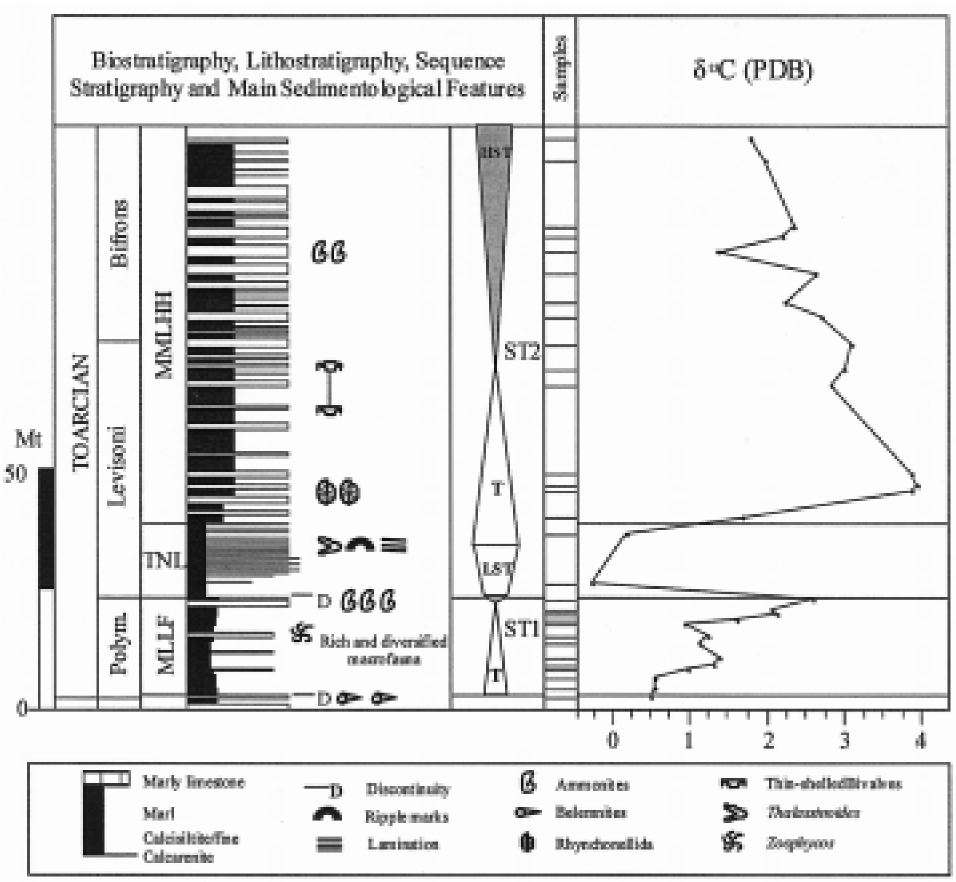

Fig. 5 - Synthetic stratigraphic and sedimentological chart for the lower and base of middle Toarcian of the Lusitanian Basin northern sector (Coimbra region). Third-order sequences and carbon-isotopic record. MLLF – Marly limestones with *Leptaena* fauna; TNL – Thin nodular limestones; MMLHH – Marls and marly limestones with *Hildaites* and *Hildoceras*. T – Transgressive system tract; LST – Lowstand system tract; HST – Highstand system tract (modified from Duarte *et al.*, 2004a).

thin calcareous levels are usually strongly bioturbated; *Thalassinoides*, *Chondrites* and ferruginous tubular burrows are common. Several patterns can characterise the sequential organisation (microsequences), but all of them are fining upward (Fig. 7) and can show a millimetre--scale bioclastic lag, composed of echinoid fragments. These facies, observed in the other sections of the LB, show tempestitic-turbiditic features (Duarte, 1997) and are related to tectonic trigger mechanisms (Duarte & Soares, 1993; Duarte, 1997). Besides, the $\partial^{13}C$ evolution across TNL Mb shows an abrupt decrease, which supports the lowstand interpretation, through the increase of lighter continental ^{12}C in the depositional system.

The overlying part of ST2, coincident with the MMLHH Mb, is composed of marl-limestone decimetric to metric alternations. The base of this thick unit corresponds to a transgressive event, shown by an increase in marly deposits, very rich in brachiopods (terebratulids and rhynchonellids), and by a positive carbon-isotope excursion (values around 4.00‰ in Rabaçal and Coimbra) (Fig. 5). This event ends with some evidences of pelagic deposition (top of the Levisoni Zone). In fact, the maximum flooding surface is shown by thin-shelled bivalve-rich (*Bositra* sp.) horizons (Fig. 8).

The transgressive system tract is overlain by a thick aggrading/prograding package. The series become

Fig. 6 - General view of the stratal pattern of TNL Mb in the Coimbra region. Note the nodular aspect of the thin (centimetric) alternations marl/limestone, very typical of this unit in the whole basin.

Fig. 7 - Microsequential pattern of a limestone bed from TNL Mb showing sandy/lutitic limestone alternations with climbing ripple facies overlain by a bioturbated lime mudstone.

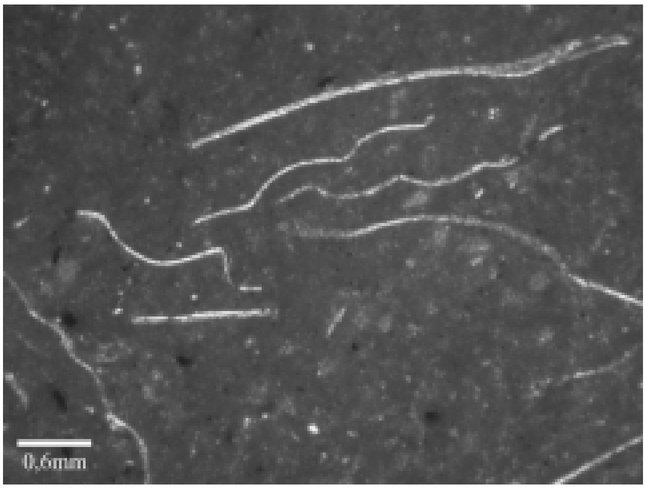

Fig. 8 - Photomicrograph of thin-shelled bivalve (*Bositra* sp.) rich horizon. MMLHH Mb (top of Levisoni Zone) from the Coimbra region.

progressively more calcareous and the vertical facies association, compared with the evolution recognised in other points of the basin (Duarte, 1997), illustrates a shallowing-upward evolution (highstand system tract). This trend is corroborated by the $\partial^{13}C$ record, showing a negative excursion (Fig. 5), interpreted as being more the result of an increase in continental ^{12}C rather than a decrease in marine productivity. With exception of TNL Mb, the vertical distribution and diversity of calcareous nannofossils is very similar in the whole **ST2** (MMLHH Mb; Duarte *et al.*, 2004a).

3.2. Unconformities

*DT1***:** this first Toarcian discontinuity is dated of the earliest Polymorphum Chronozone (intra-Mirabile Subzone). This surface coincides with the boundary between the Lemede and the S. Gião Fms. (Fig. 5), and corresponds to the first Toarcian flooding surface. Compared with the much more calcareous uppermost part of the underlying Spinatum Zone, the base of **ST1** is interpreted as representing a deepening phase.

DT2: this unconformity corresponds to the MLLF/TNL Mbs boundary. It defines the most important sedimentological and palaeontological change observed in the whole Lower Jurassic succession of the LB

Fig. 9 - General view of the **ST2/ST3** third-order boundary (**DT3**) in the Rabaçal section (arrow).

(Duarte & Soares, 1993; Duarte, 1995, 1997; Gahr, 2002), and reflects significant tectonic activity (Duarte & Soares, 1993; Duarte 1995, 1997; Kullberg *et al.*, 2001). Roughly corresponding to the Polymorphum--Levisoni Zone boundary (Duarte, 1997), this discontinuity marks an abrupt decrease in the $\partial^{13}C$ evolution (Duarte, 1998a; Duarte *et al.*, 2003, 2004a; Fig. 5).

DT3: this unconformity is easily recognizable in the superbly exposed Rabaçal section (Fig. 9). The major facies change, corresponding to a flooding surface, occurs between the MMLHH and MMLSB Mbs. (Bifrons Subzone; Duarte, 1997).

4. STOP 2. SILICEOUS SPONGE MUD MOUNDS IN THE MIDDLE-LATE TOARCIAN OF THE ANSIÃO-RABAÇAL REGION

L. V. Duarte and M. Krautter

The marl-limestone alternations of the middle Toarcian/lower Aalenian show the occurrence of small--scale siliceous sponge mud mounds (Duarte *et al.*, 2001). These facies are particularly well documented and preserved in the Rabaçal-Ansião region, belonging to the following two units: Marls and marly limestones with sponge bioconstructions (MMLSB) Mb (S. Gião Fm) and to the lower part of the Póvoa da Lomba Fm (Fig. 10). Both units correspond to very bioturbated (*Chondrites*, *Zoophycos*, *Planolites* and *Thalassinoides*) marl-limestone successions. Between these two units exists the Marls and marly limestone with brachiopods (MMLB) Mb (top of S. Gião Fm) wich corresponds to a marly unit, with rare limestone levels and are very poor in siliceous sponge bioconstructions.

The MMLSB Mb, demonstrably more marly and fossiliferous than Póvoa da Lomba Fm, is dated of the uppermost Bifrons Zone through the base of the Bonarellii Zone. The majority of the siliceous sponge mud mounds occur within this time slice. These mounds are characterized by a great abundance and diversity of benthic macrofauna mainly composed of brachiopods (rhynchonellids and terebratulids), crinoids and bivalves.

The base (Meneghinii-Opalinum interval; MST4B *in* Duarte, 1997) of the Póvoa da Lomba Fm is composed by bioturbated marl/limestone alternations, with an upward increase of calcareous (biomicrite/wackestone, locally packstone) facies. The rhythmicity of the marl//limestone couplets is an important feature, defining elementary sequences (parasequences). The vertical succession of the parasequences is organised into parasequence groups showing a clear asymmetry, with the marls typically thicker at the base (Fig. 11). Besides,

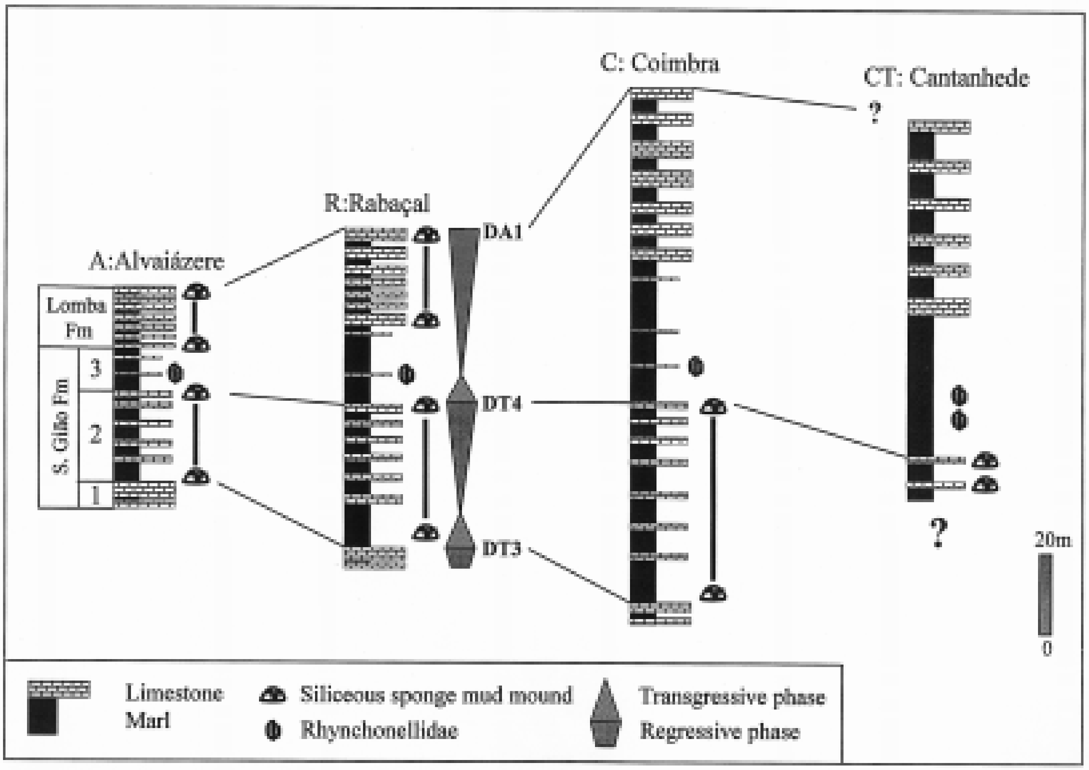

Fig. 10 - Vertical and lateral variation of the uppermost S. Gião and lowermost Póvoa da Lomba formations in the basin. 1 - MMLHH Mb; 2 - MMLSB; 3 - MMLB

Fig. 11 - Partial view of fourth-order sequence pattern in the Póvoa da Lomba Fm (Rabaçal section).

the tops of these fourth-order sequences are marked by a thickening of the limestone beds and, sometimes, by a large density of *Zoophycos*. The siliceous sponge mud mound occurrences are particularly associated with these levels.

4.1. Siliceous Sponge Mud mounds

The Toarcian mud mounds of the LB are usually only a few decimetres thick and most display irregular knob--like to flat lenticular morphologies. Some build-ups are round and can reach 1.5 metres in thickness and ten metres in diameter (Fig. 12). The upper mound surface is normally rough and uneven. In both sequences they are always related laterally with carbonate beds, which correspond preferentially to the tops of fourth-order sequences. The mud mounds consist of mostly brownish, iron-rich calcified siliceous sponges and a greyish, sometimes peloidal allochthonous micritic matrix. In general, the sponges themselves consist of dense leiolitic microbolites (automicrites *sensu* Reitner & Neuweiler, 1993). The sponge spicules are diagenetically transformed into calcite. The great majority of the sponge specimens belongs to the Hexactinosa (Class Hexactinellida) and are unknown and undescribed to date. "Lithistides" (polyphyletic desma-bearing demosponges) are very rare and only occur as forms encrusting Hexactinosan sponges. The benthic macrofauna is abundant and consists of monospecific crinoids, rhynchonellids, terebratulids and bivalves (mainly pectinids and ostreids). Encrusting organisms are serpulids, bryozoans and foraminifera, as well as "Lithistids", mentioned above. They are entirely restricted to the stratal surfaces of the siliceous sponges.

The sponge bioherms consist of several microfacies types (wackestones, packstones, floatstones and boundstones). All of them are micrite dominated and represent low energy environments. They differ mainly in the amount of siliceous sponges, micrite, microbialites, encrusting organisms and the accompanying fauna (Fig. 13).

Fig. 12 - Siliceous sponge mud mound at the base of MMLBS Mb (Ansião section). This bioconstruction shows a stratiform shape and corresponds to one of the most larger mud mounds found in the Portuguese Toarcian.

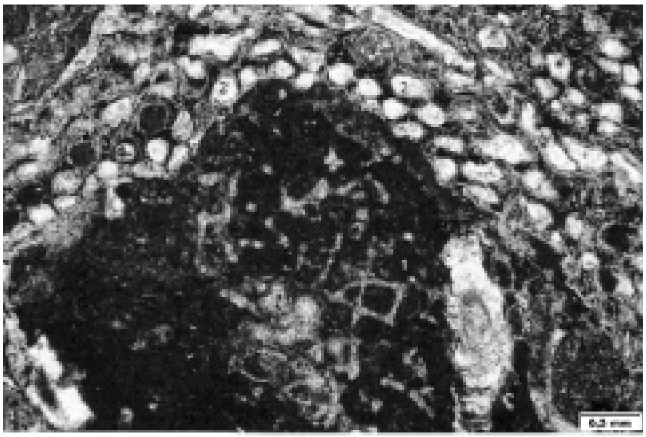

Fig. 13 - Photomicrograph (crossed polars) of siliceous sponge mud mound facies. This boundstone shows a siliceous sponge (1) encrusted by bryozoans (2). Sample from Póvoa da Lomba Fm (upper Toarcian) of the Rabaçal section.

4.2. Palaeoenvironmental Significance

The amount of microbially induced carbonate clearly emphasizes the importance of microbial activity in respect of the reef building potential. Furthermore, three other controlling factors played an important role in the initiation of the siliceous sponge mud mounds of the LB (Duarte *et al.*, 2001): bathymetry, sea-floor morphology and sedimentation rate. The role of the first two factors is evident because the siliceous sponge mud mounds are particularly important (abundance and volumetric expression) in the eastern part of the basin (Rabaçal-Alvaiázere region). They are practically absent towards the west (essentially in the base of Póvoa da

Lomba Fm) where the series shows hemipelagic features (Figs. 14 and 15).

Reduced sedimentation rate was a precondition for the settlement of siliceous sponges and Hexactinosa in particular. Compared to all other Toarcian units, MMLSB Mb and Póvoa da Lomba Fm are the thinnest and therefore reflect the lowest sedimentation rates (Fig. 15). The preferential occurrence of these bioconstructions at the top of fourth order sequences seems to be related with sediment-starved intervals.

5. STOP 3. FACIES AND SEDIMENTARY CHANGES ACROSS THE SINEMURIAN/PLIENSBACHIAN BOUNDARY IN THE S. PEDRO DE MOEL REGION

L. V. Duarte, A. Azerêdo, S. Fernández-López, R. Rodrigues and N. Perilli

In the LB the Lower/Middle Liassic series corresponds to an important change in the depositional conditions within the carbonate ramp system, as the

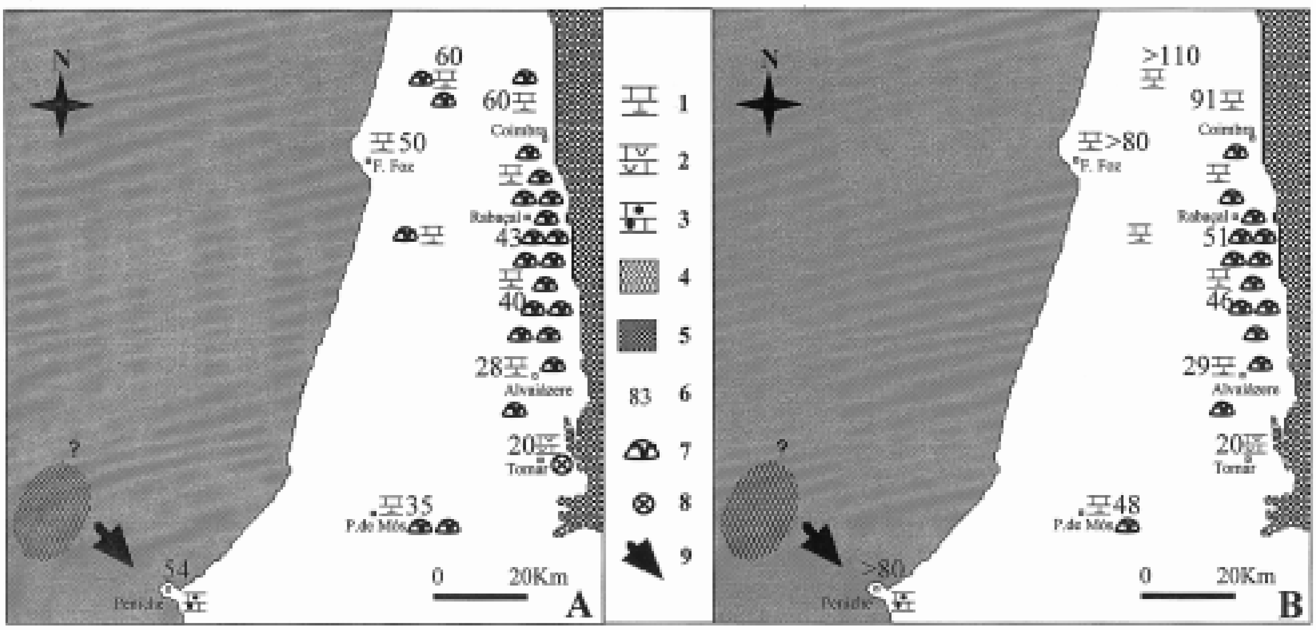

Fig. 14 - Facies distribution and palaeogeographic reconstruction for the units with siliceous sponge facies (**A**: MMLSB Mb; **B**: MMLB Mb and base of Póvoa da Lomba Fm; MST4 in Duarte, 1997). Legend: 1 - Marly-limestone facies; 2 - Bioclastic facies; 3 - Oolitic and sandy limestone facies; 4 - Emerged block; 5 - Hesperic Massif (partially submerged during the middle Toarcian-Lower Aalenian); 6 - Thickness (meters); 7 - Siliceous sponge mud mounds; 8 - Solitary corals; 9 - Palaeocurrent. Modified from Duarte *et al.* (2001).

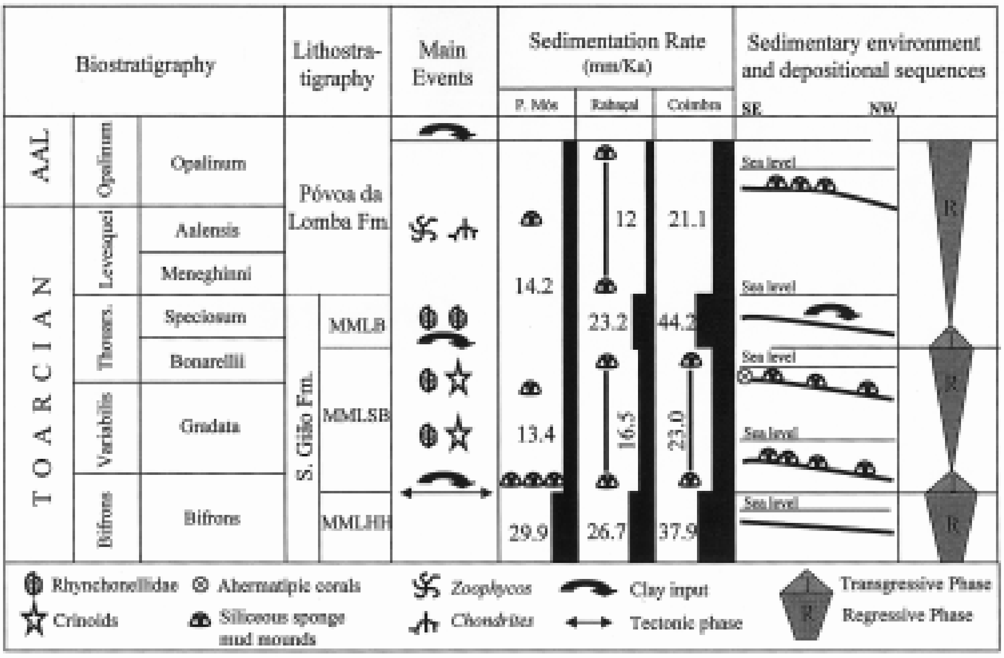

Fig. 15 - Sedimentary evolution in the middle Toarcian-lower Aalenian carbonate ramp of the LB. Vertical and lateral distribution of the siliceous sponge mud mounds in the ramp and its relation with the sedimentation rate, sea bottom morphology and bathymetry (modified from Duarte *et al.*, 2001).

succession evolved from peritidal facies (Coimbra Fm) into hemipelagic deposits (Água de Madeiros Fm and Vale das Fontes Fm) (Fig. 3). In the eastern part of the basin, the upper Sinemurian series is composed of dolomitic and calcareous dolomitic facies, whereas in the western sector it is characterized by a marl (sometimes bituminous)/ limestone succession, which is particularly well recorded and dated at Peniche, Água de Madeiros (near S. Pedro de Moel) and Montemor-o-Velho (Fig. 2). Among all these localities, the Água de Madeiros section displays the best exposure of the upper Sinemurian/lower Pliensbachian succession (Duarte *et al.*, 2004b), which is accurately constrained by ammonite biostratigraphy (Mouterde, 1967; Antunes *et al.*, 1981). In fact, in other important sectors of the basin (e.g. Tomar, Alvaiázere, Porto de Mós, Rabaçal Coimbra and Cantanhede), either continuous sections are lacking, condensed series occur or biostratigraphic references are missing. For these reasons, in those regions it is very difficult to recognize a hierarchical sequence chart based on third-order sequences.

The studied succession belongs to the late Sinemurian (Raricostatum Zone) - early Pliensbachian (Jamesoni Zone) interval. It includes the upper part of the Água de Madeiros Fm (uppermost part of the Polvoeira Mb and the Praia da Pedra Lisa Mb) and the lowermost part of the Vale das Fontes Fm (Fig. 16).

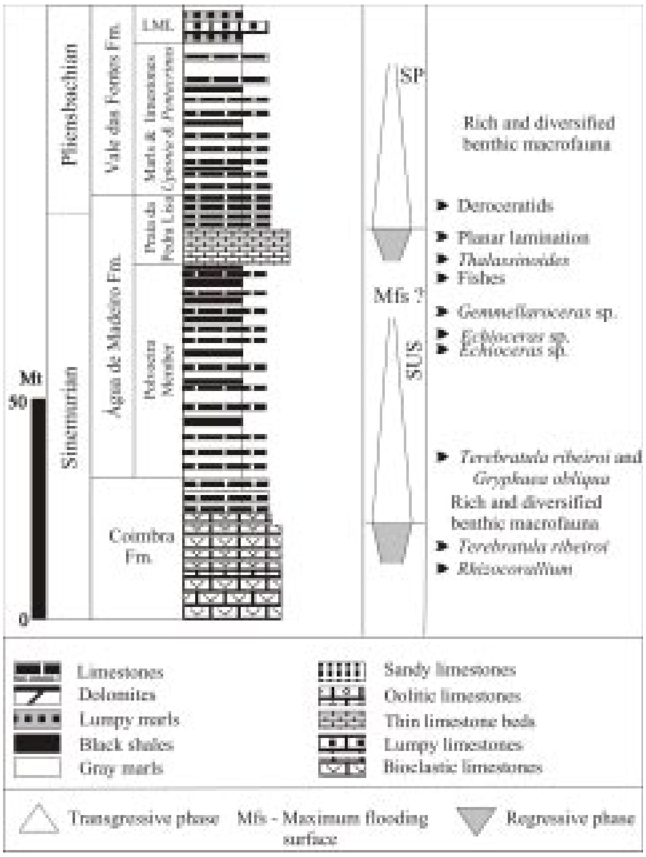

Fig. 16 - Stratigraphy, sequence evolution (second-order) and sedimentary variations across the Sinemurian/Pliensbachian boundary in Água de Madeiros (LML - lumpy marls and limestones Mb).

5.1. Facies and Sequence Stratigraphy

The Polvoeira Mb corresponds to a marl dominated unit, composed of marl/limestone alternations, including some black shale horizons (Fig. 17). The microfacies are dominated by mudstone-wackestone biomicrites, locally very rich in ostracods, echinoid spines and radiolarians. The muddy nature of the deposits, with diverse and well-preserved calcareous nannofossil assemblages (dominated by *Schizosphaerella spp.*, *Tubirhabdus patulus* and *Parhabdolithus liasicus distinctus*), and the local abundance of nektic macrofauna (ammonites and belemnites), coupled with the absence of storm- or wave-generated structures, indicate that deposition occurred in a low-energy, open-marine setting, such as an outer-ramp setting. Ammonite fossils usually appear scattered in the sediment, showing planar fabric. Hollow ammonites (*i.e.*, showing no sedimentary infill in the phragmocone) and hollow phragmocones (*i.e.*, without septa) are dominant. The aragonitic shells have been dissolved and moldic porosity is filled by calcite spar cement. The abundant resedimented and reoriented shells, implies some form of current flow or winnowing affected the burial of shells (Fernández--López *et al.*, *in progress*).

The strong occurrence of bituminous facies in the series shows that the palaeoenvironment was controlled by significant oxygenation oscillations. In fact, black shales show high TOC values (reaching maximum values up to 10%), confirming some anoxic intervals (Duarte *et al.*, 2004b). The clear increase in the mud and TOC contents, observed towards the top of this

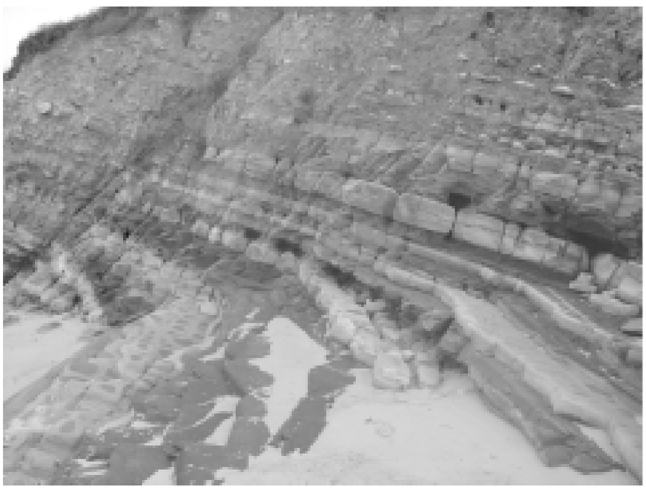

Fig. 17 - Marl-limestone alternations of Polvoeira Mb in the Água de Madeiros section. Some of the marly levels correspond to black shale facies.

member, are interpreted as being the result of a second-order transgressive event.

In the Praia da Pedra Lisa Mb, which is a limestone-dominated unit (Fig. 18), several facies variations are observed. The base of this member (about 8m-thick) consists of centimetre-thick microsparitic limestones with planar lamination, *Rhizocorallium* and *Thalassinoides*. The microfacies are characterised by mudstones and wackestones, whose fossil content is dominated by ostracods (Fig. 19) and radiolarians. Some horizons are ferruginous and rich in tiny ammonites (*Eoderoceras* sp.; Antunes *et al.*, 1981). Despite the absence of benthic macrofauna, these facies are indicative of a shallow marine palaeoenvironment, in a regressive depositional context. They are organized in to several parasequences, characterised by a thickening-upwards calcareous component, bounded by ferruginous and tiny ammonite-rich surfaces (Fig. 20). The last level with this kind of facies marks the top of the upper Sinemurian second-order sequence (top of **SUS**). This surface is overlain by decimetre-thick argillaceous limestones interbedded with centimetre-thick grey shales, showing a gradual upward increase in the clay and bioclastic contents (base of **SP**).

Fig. 18 - General view of Praia da Pedra Lisa Mb in the Água de Madeiros section. Arrow indicates second-order sequence boundary (**SUS**/**SP**).

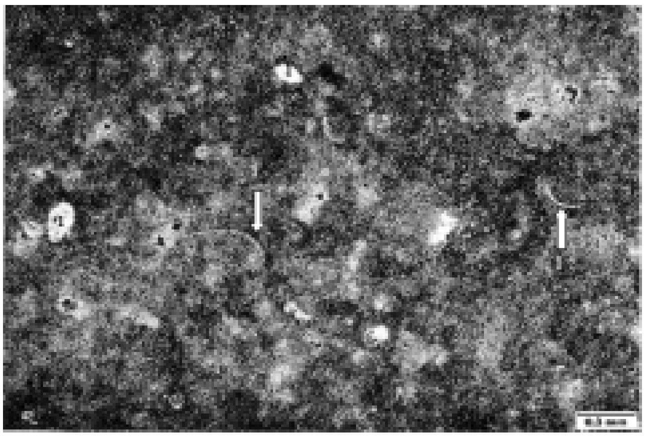

Fig. 19 - Photomicrograph of fossiliferous microsparitic/ wackestone with ostracods (1) (crossed polars). Praia da Pedra Lisa Mb.

The base of the Vale das Fontes Fm (Marls and limestones with *Uptonia* and *Pentacrinus* Mb) shows a return to marl/limestone alternations, with marly dominance and more marine influence. Some horizons are particularly bioclastic-rich (wackestones), being composed of crinoid ossicles, belemnites, brachiopods and bivalves. Some marl levels show centimetre-thick black shales, with TOC values reaching around 9% (Duarte & Rodrigues, *in progress*). These anoxic facies, observed in the lowermost Jamesoni Zone beds, are exclusive of the S. Pedro de Moel region.

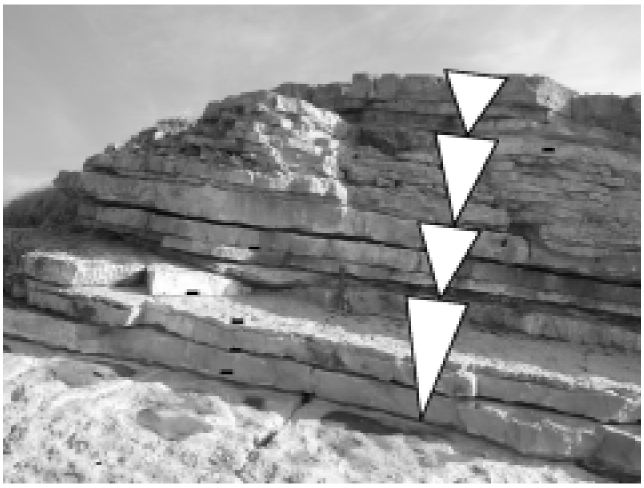

Fig. 20 - Parasequence stacking pattern in the Praia da Pedra Lisa Mb (Água de Madeiros section). Facies are very bioturbated, showing *Thalassinoides* and *Rhizocorallium*.

6. STOP 4. THE UPPER SINEMURIAN-UPPER TOARCIAN SUCCESSION IN THE PENICHE PENINSULA. LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY - INTRODUCTION

L. V. Duarte

The Peniche Peninsula shows the most representative Liassic succession for the LB (Fig. 21). This section, more than 450 m thick, ranges in age from the early Sinemurian (dolomitic limestones and limestones of

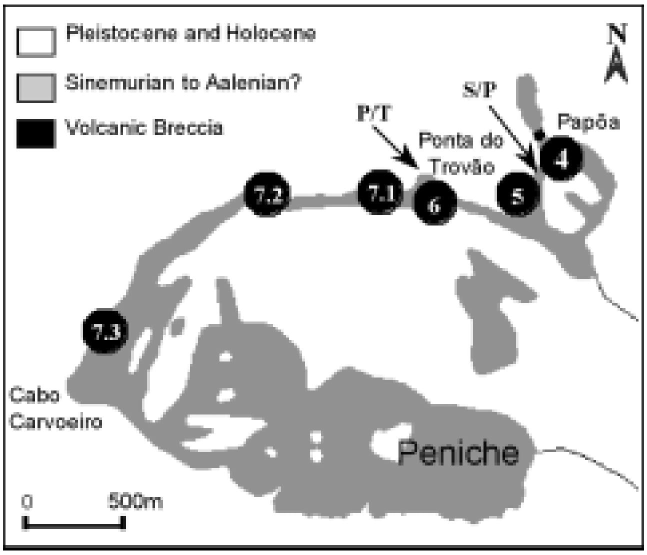

Fig. 21 - Geological map of Peniche Peninsula and location of stops 4 to 7. S/P – Sinemurian/Pliensbachian boundary; P/T – Pliensbachian/Toarcian boundary.

Coimbra Fm) to the oopelsparites/ grainstones of early Middle Jurassic (Aalenian?; top of Cabo Carvoeiro Fm). Good exposure and biostratigraphic data (Mouterde 1955; Phelps 1985; Dommergues 1987; Elmi *et al.*, 1996) allowed the definition in Peniche of three type-locality formations: Vale das Fontes, Lemede and Cabo Carvoeiro (Duarte & Soares, 2002; Fig. 22).

The analysis of vertical facies variation in this section allows the recognition of the main discontinuities observed in the LB during the Sinemurian/Toarcian interval (Duarte, 1997, 1998b, 2003; *in progress*). In relation to these facies we refer the reader to the works of Dommergues *et al.* (1981), Guery (1984), Wright & Wilson (1984), Dromart & Elmi (1986), Elmi *et al.* (1988), Fernández-López *et al.* (1999, 2000, 2002) and Duarte (1995, 1997, 1998a).

6.1. Second-order sequences

For the upper Sinemurian-lower Aalenian succession in the LB, three second-order sequences have been identified (**SUS**, **SP**, **ST**; Duarte, *in progress*), bounded by regional discontinuities and particularly well observed in Cabo Carvoeiro cliffs.

6.1.1. Sequence SUS

This sequence is particularly well recognized in western sectors of the LB. In Peniche this sequence is dated from the uppermost Sinemurian (Oxynotum?-Raricostatum Zone) and starts with bioclastic centimetre-thick marl/decimetric limestone alternations (Polvoeira Mb), very rich in benthic macrofossils (brachiopods and bivalves). The basal part of this unit is delimted by a ferruginous bioturbated oobiosparite/ /grainstone surface (top of Coimbra Fm), which represents a sharp transition in the intra-Sinemurian of Peniche (Fig. 23). The transgressive event, very condensed, ends with a marly dominated interval (mudstone/ / wackestones), rich in ammonites (*Echioceras* sp.). The increase of bioclastic carbonate facies (packstones) observed towards the top of uppermost Sinemurian is indicative of shallowing (highstand system tract).

6.1.2. Sequence SP

This sequence is bounded by a transgressive surface, particularly well observed in Água de Madeiros (Fig. 18; Stop 3), dated to the latest Raricostatum Chronozone. In the western part of the LB, the base of the Pliensbachian (Jamesoni Zone) consists of thick marl--limestone series organised into deepening-upward

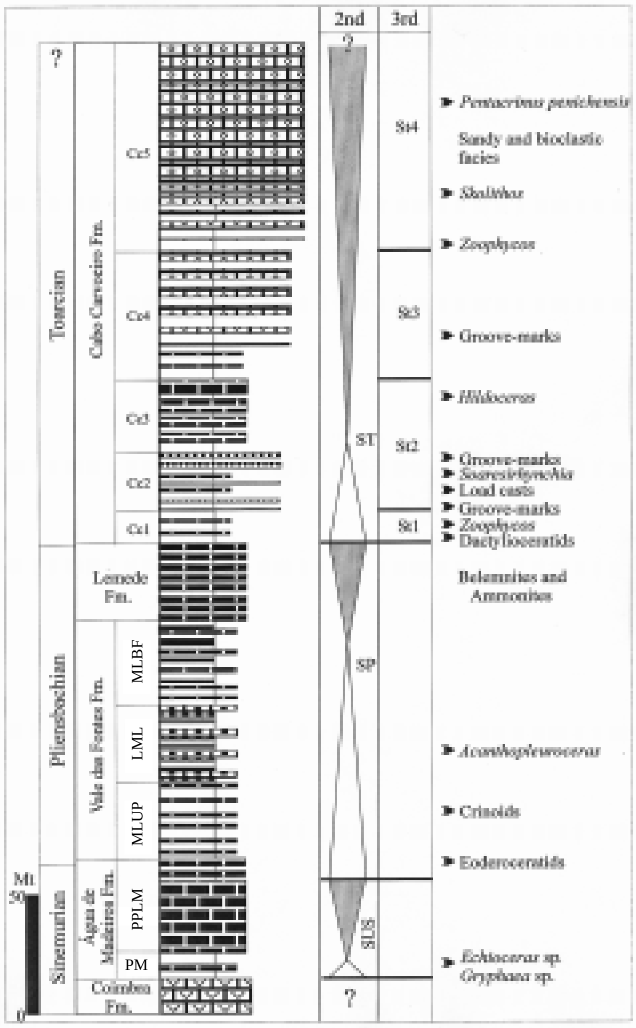

Fig. 22 - Upper Sinemurian - upper Aalenian (?) succession at Peniche: Lithostratigraphy, sequence stratigraphy (second and third--order sequences; Duarte *in progress*) and main events (see legend in Fig. 16).

Fig. 23 - Intra-Sinemurian discontinuity (arrow) between Coimbra Fm and Água de Madeiros Fm in the Peniche section.

parasequences. In Peniche this transgressive event was well expressed, corresponding to the Jamesoni-Margaritatus Zone interval (around 70m thick). The marly facies of Margaritatus Zone, which include several black shale horizons (with TOC values reaching 15%), mark the peak transgression phase of **SP** (Duarte, 2003; Duarte & Rodrigues, *in progress*).

A sharp increase of calcareous facies towards the top (Lemede Fm) marks the regressive trend of this sequence. This shallowing-upward event is particularly evident in the Tomar sector, at the southeastern part of the basin, represented by condensed benthic bioclastic grainstones (Duarte, 2003). In Peniche, the series consist of bioturbated centimeter-thick marl/decimetric limestone alternations, very rich in nektonic macrofauna (belemnites and ammonites). The cycle ends with transgressive surface dated to the early Polymorphum Zone (Lower Toarcian).

6.1.3. Sequence ST

Despite the knowledge of the Toarcian sedimentary organization and evolution in this sector of the LB (Wright & Wilson, 1984), with special autogenetic sedimentary conditions (discussed in Stop 7), the series shows strong similarities with the sequential organization, admitting to the others sector of the basin (Duarte, 1997, 1998b, 2003). Thus, four third-order depositional sequences (MSTP1 to MSTP4 in Duarte, 1995, 1997) are identified to the Toarcian series of Peniche (Fig. 22), bounded by regional discontinuities: **DT1** – lowermost Polymorphum Zone (intra Mirabile Subzone; **DT2** – Polymorphum-Levisoni Zone boundary; **DT3** – intra Bifrons Zone; **DT4** – around Bonarellii-Speciosum Zone boundary (Fig. 24).

Fig. 24 - **ST3/ST4** third-order boundary (**DT4**; arrow) in the Peniche section (Cerro do Cão; locality 7.2 in the Fig. 21). In the whole basin, the base of **ST4** is characterised by a thick marly accumulation (MMLB Mb; see Figs. 3 and 15). More discussion in Stop 7.

7. STOP 5. AMMONITE TAPHOFACIES AND PALAEO-ENVIRONMENTAL CYCLES IN LOWER PLIENSBACHIAN LUMPY LIMESTONES AND BLACK SHALES OF PENICHE

S. Fernández-López, L. V. Duarte and M. H. Henriques

Lumpy limestones and bituminous shales occur within the lower Pliensbachian deposits of the LB, particularly well developed in Peniche, S. Pedro de Moel and Brenha (Hallam, 1971, Dommergues *et al.*, 1981; Dromart and Elmi, 1986; Elmi *et al.*, 1988; Fernández-López *et al.*, 1999, 2000, 2002; Duarte & Soares, 2002). These facies are included in the Lumpy marls and limestones (LML) Mb of Vale das Fontes Fm (Fig. 3).

In this stop attention has been centred on the taphonomic features of the ammonites recorded in the lower Pliensbachian deposits of Peniche, assessing some palaeoenvironmental implications. The analysed stratigraphical succession consists of over 20 m of limestones and shales (Fig. 25), which is exposed in cliffs on the northern side of the Peniche peninsula (Fig. 21).

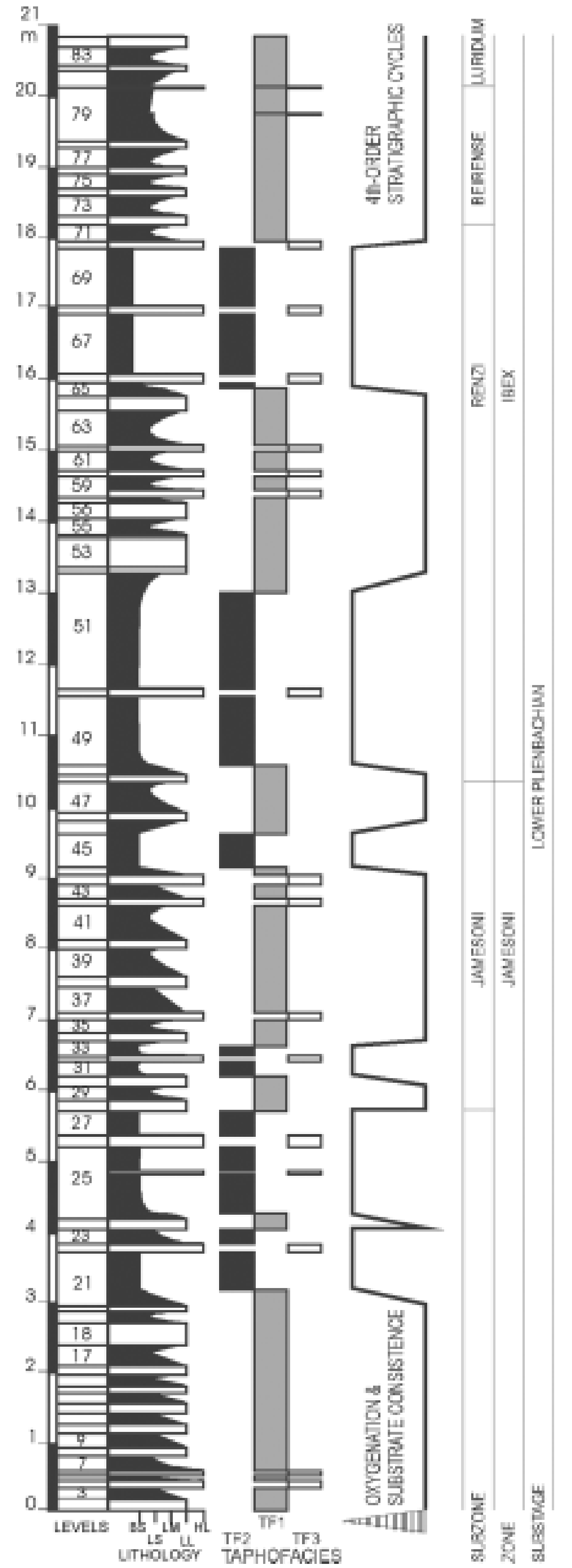

Fig. 25 - Lower Pliensbachian section at Peniche. BS - Bituminous shales; HL - Homogeneous limestones; LL - Lumpy limestones; LM - Lumpy marly intervals; LS - Laminated marls; TF1 - Lumpy limestones and marly intervals with reelaborated ammonites; TF2 - Laminated mudstones and bituminous shales with accumulated ammonites; TF3 - Homogeneous limestones with resedimented ammonites (Fernández-López *et al.*, 2000).

The lithofacies analysed consist of limestones and shales. Thin limestones, heavily bioturbated, alternate with thicker, weaker bioturbated, marly mudstones and some bituminous, laminated shales (with TOC values up to 5%). Limestones are mudstone to wackestone with very recrystallized bioclasts (ammonoids, brachiopods, belemnites, thin shelled gastropods, spicules of sponges, bivalves, radiolaria, ostracods and equinoderms). *Chondrites* and other biogenic structures are common.

The lumps included in limestone beds and marly intervals are micritic, calcareous concretions, subspherical and angular in shape, millimetric or centimetric in size. Sometimes several concretions are clumped together to form larger masses up to 3 cm diameter. Lumps are not represented in bituminous shales. Contacts between lumps and sedimentary matrix are sharp and well defined in the marly intercalations, but gradational in some limestone levels. They may been aligned on certain sedimentary surfaces. Some lumps are covered by micritic envelops as cryptalgal oncolite structures (Elmi *et al.*, 1988). The concretions are scattered fairly uniformly through limestones. However, they can be sorted in marly intervals.

7.1. Ammonite taphofacies

Ammonites occur throughout the sections, and they show locally little size. The degree of packing of ammonites (estimated by the difference between the number of specimens and the number of fossiliferous levels sub-divided by the number of fossiliferous levels) and the stratigraphical persistence (proportion of fossiliferous levels) display high values. Ammonite shells and internal moulds normally appear dispersed in the sediment, showing no pattern of imbricated or encased regrouping. The aragonitic shells have been dissolved. Moldic porosity is completely filled by spar cement.

These fossiliferous deposits can be sub-divided into three main taphofacies which are distinguished by the preservational features of the ammonites (detailed description and interpretation in Fernández-López *et al.*, 2000): **TF1**) lumpy limestones and marly intervals with reelaborated ammonites; **TF2**) laminated mudstones and bituminous shales with accumulated ammonites; and **TF3**) homogeneous limestones with resedimented ammonites.

TF1: Deposits of this taphofacies are composed by mudstone to wackestone beds ranging in thickness from 5 to 40 cm and marly intervals from 10 to 50 cm, yellowish or greyish, with lump size ranging from 2 to 40 mm

The boundaries of the lumpy beds are commonly gradational, but the bases of some beds are sharper than the tops. The concretions are scattered fairly uniformly through limestones. However, they can be sorted in marly intervals. These concretions show distribution grading, also. Gradual reduction of the size or normally distribution grading of concretions is more common than gradual increase or inversely distribution grading, in these marly intervals (Fig. 26).

Recorded associations of ammonites of this taphofacies are dominated by reworked elements (*i.e.*, reelaborated or resedimented elements). Accumulated elements, showing no evidence of removal, are very scarce or absent. Reelaborated internal moulds, exhumed and displaced before their final burial, may be dominant. Resedimented shells, displaced on the sea-bottom before their burial, are locally common. The degree of removal (*i.e.*, the ratio of reelaborated and resedimented elements to the whole of recorded elements) and the degree of taphonomic heritage (*i.e.*, the ratio of reelaborated elements to the whole of recorded elements) can reach 100%. However, the degree of taphonomic condensation in the ammonite recorded associations reaches very low to zero values in all cases. Ammonite mixed assemblages composed of specimens representing several biozones or biohorizons in a single bed have not been identified. These reworked associations of ammonites are characterized by the occurrence of complete and homogeneous concretionary internal moulds, including juvenile shells, bearing no signs of abrasion (such as rounding facets), bioerosion or encrusting organisms (such as serpulids, bryozoans or oyster). However, ammonite half-lumps is a common preservational type (Fig. 27).

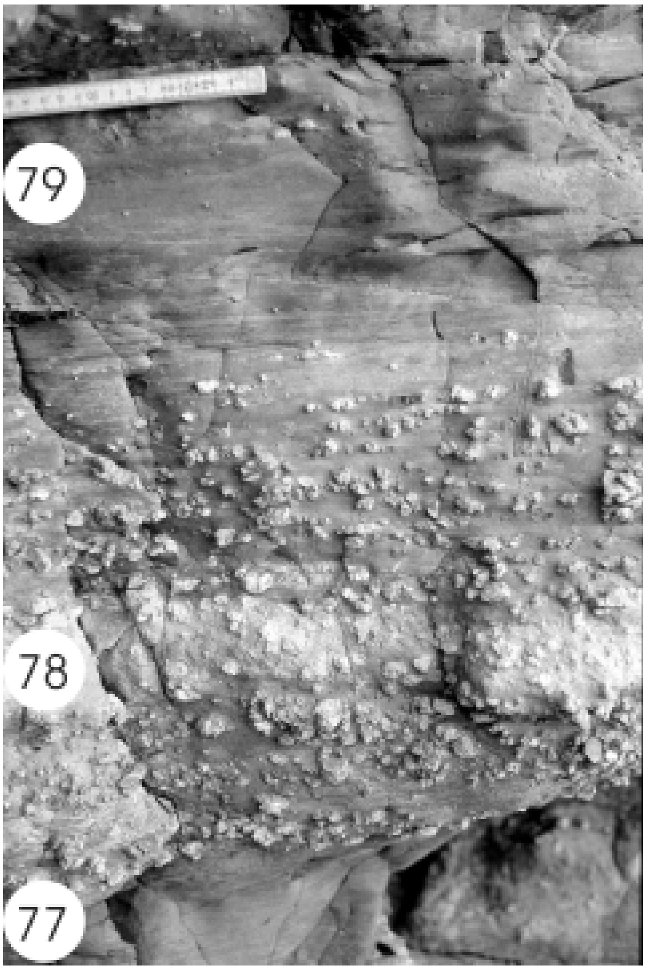

Fig. 26 - Close-up view of lower Pliensbachian deposits in Peniche. The level 78 (taphofacies 1, lumpy limestones and marly intervals with reelaborated ammonites) shows gradational boundaries. Bar for scale is 15 cm long.

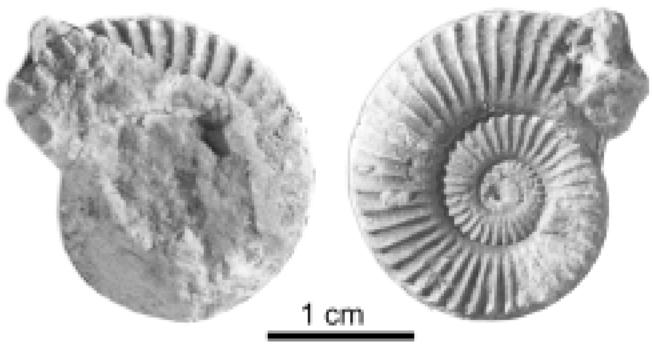

Fig. 27 - Ammonite half-lump (incomplete phragmocone of *Dayiceras* sp., lower Pliensbachian). Specimens of this preservational type are preferentially encrusted by calcareous microbial or stromatolitic laminae on a side (the upper side during reworking). These internal moulds show a structural discontinuity between the sedimentary infilling and the enclosing sedimentary rock, or a disarticulation surface. They are reelaborated, calcareous, concretionary internal moulds, maintaining their original volume and form as a result of rapid early cementation (Fernández-López *et al.* 2002).

Sediments of this lumpy facies are interpreted as having been deposited in an open sea, below wave base, taking into account the absence of sedimentary structures indicating either shallow water or storm deposition. However, the presence of reelaborated ammonites implies that some form of current flow or winnowing affected the burial of the concretionary internal moulds. Currents were slight, but concretionary internal moulds of ammonites were disarticulated and azimuthally reoriented on softgrounds by reelaboration (*i.e.*, exhumation and displacement on the sea-bottom, before their final burial). The concretions must have formed either contemporaneously with the sedimentation or within the sediment in early diagenesis. In this hemipelagic environment, episodes of lower rate of sedimentation and lower degree of accommodation of sediments favour a higher degree of bioturbation and reworking of ammonite shells. The reelaboration processes and the activity of burrowing organisms are the main factors that induced the development of ammonite associations showing a high degree of taphonomic heritage, but the degree of stratigraphic and taphonomic condensation is negligible over geochronological time-scales. Increasing porosity was induced by draught filling in the ammonite shells and bioturbation of the sedimentary matrix, favouring a relatively faster lithification. Concretionary internal moulds of ammonites and lumpy structures were developed on a sea-bottom undergoing oxic to suboxic conditions. Although the calcareous benthos is very scarce, the presence of abundant burrowing structures suggests aerobic to dysaerobic biofacies.

TF2: this taphofacies is composed by dark, organic rich, marly mudstones and bituminous shales, commonly showing millimetric scale, bedding-parallel lamination (Fig. 28). Structures of bioturbation of centimetric size are sparse but some marly intervals contain abundant, small *Chondrites* and pyrite-filled tubular (1-3 mm diameter), burrows. Finely disseminated pyrite occurs locally. The boundaries of the laminated intervals are commonly gradational.

Ammonite associations of this taphofacies are dominated by non-reelaborated elements (*i.e.*, resedimented or accumulated elements). Reelaborated internal moulds are virtually absent. Accumulated shells, showing no signs of removal, are locally common. Resedimented shells are dominant. The degree of removal (*i.e.*, the ratio of reelaborated and resedimented elements to the whole of recorded elements) can be variable, but the degree of taphonomic heritage (*i.e.*, the ratio of reelaborated elements to the whole of recorded elements) can reach 0%. There is no biostratigraphic evidence of taphonomic condensation in the ammonite recorded associations.

The fine-grained nature of the mudstones suggests deposition in a low-energy setting. Laminated mudstones and bituminous shales were developed on a sea-bottom undergoing suboxic to anoxic conditions. Despite the absence of calcareous benthos, active-burrowing, soft-bodied infauna is present. The abundant pyrite at some horizons suggests that reducing conditions extended to very near the sediment-water interface, allowing unrestricted diffusion of seawater sulphate to occur.

TF3: Homogeneous limestones of this taphofacies represent less than 41% of the whole of beds. They are normally under 20 cm thick, yellowish or greyish. Accumulated shells are virtually absent in this taphofacies. Reelaborated elements are scarce, the resedimented shells being dominant. The degree of removal can be variable, but the degree of taphonomic heritage will be from very low to zero. There is no biostratigraphic evidence of taphonomic condensation.

These homogeneous beds show several features indicative of rapid deposition, in contrast to the slow rates of sedimentation and accommodation inferred for the lumpy limestones of the **TF1**. Burrowing is not evenly distributed throughout the beds, as **TF1** shows, but it is concentrated in the last few centimetres of each bed. The bases of the beds are erosional, nongradational. The decrease in grain-size and bed thickness, seen from **TF1** to **TF3**, also suggests a more distal and deep deposition. The homogeneous limestones of this facies are interpreted as expanded deposits and distal sedimentary products of gravity flows (turbidites or tempestites). Distal deposition by gravity flows (**TF3**), carrying homogeneous hemipelagic muds from oxic conditions, interrupted a background sedimentation from

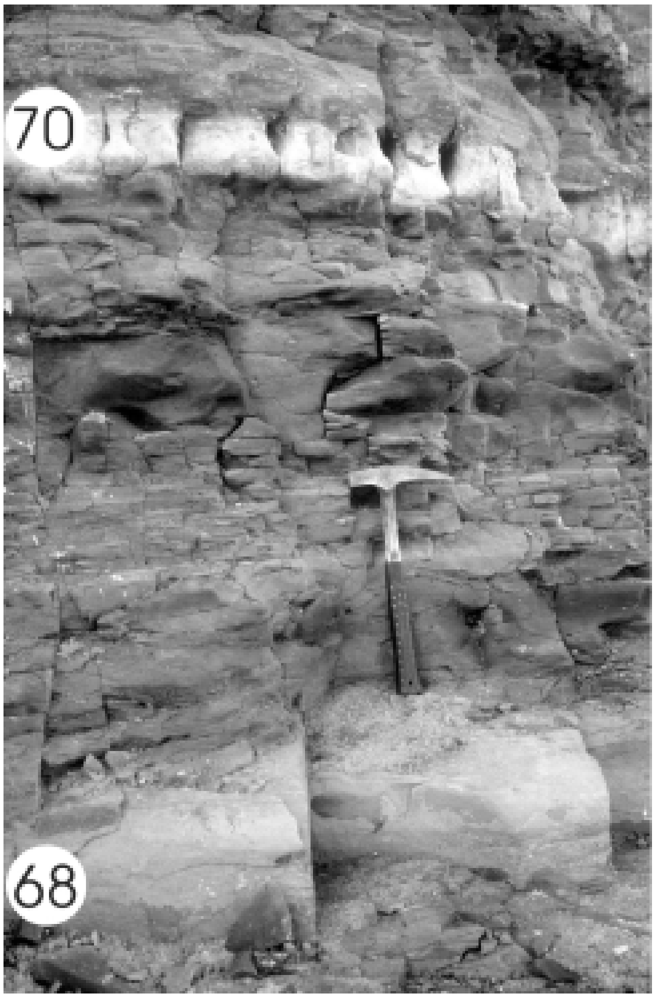

Fig. 28 - Close-up view of lower Pliensbachian deposits in Peniche. Limestone beds 68 and 70 correspond to the taphofacies 3 (homogeneous limestones with resedimented ammonites). The stratigraphic interval between them corresponds to the taphofacies 2 (laminated mudstones and bituminous shales with accumulated ammonites). Hammer for scale is 33 cm long.

suboxic to anoxic conditions changing laterally from dysaerobic, bioturbated lumpy muds (**TF1**) to anaerobic, laminated muds (**TF2**).

7.2. Palaeoenvironmental implications and cyclicity

The background sedimentation (**TF1** and **TF2**) was interrupted by episodes of event sedimentation (**TF3**) during the development of these lower Pliensbachian deposits. A deep, background sedimentation from suboxic to anoxic conditions changing laterally from dysaerobic, bioturbated lumpy muds (**TF1**) to anaerobic, laminated muds (**TF2**) was interrupted by episodes of distal deposition by gravity flows (**TF3**) (Fig. 29). Lumpy limestones with reelaborated ammonites, showing gradational boundaries and inversely distribution grading, are condensed deposits developed in deep marine environments, induced by sedimentary starving. The stratigraphic intervals of this taphofacies represent the lowest values of sedimentation rate and the minimum degree of accommodation of sediments.

TF1 alternate with **TF2** composing stratigraphic cycles which have metric scale. According to the geochronological and geochronometric data published by Dommergues *et al.* (1997) and Odin *et al.* (1994) the stratigraphic cycles identified in these lumpy limestones resulted from cyclical environmental modifications of 4/5 hundreds of thousands of years. In accordance with this hypothesis, fourth-order deepening episodes led to the development of dysaerobic to anaerobic environments, while during the subsequent shallowing episodes increased the levels of bottom oxygenation (Fig. 25).

8. STOP 6. TOARCIAN GSSP CANDIDATE: THE PENICHE SECTION

S. Elmi

In Portugal, the Pliensbachian–Toarcian transition is well exposed in several localities yielding Tethyan ammonites associated with some NW European classic species. These assemblages give good markers for worldwide correlations. Moreover, the transition beds often indicate a relatively continuous sedimentation, contrarily to the frequent gap recorded in NW Europe. The best Portuguese section is located along the Atlantic coast at Ponta do Trovão, in the Peniche Peninsula (Fig. 30). In this locality, the upper Pliensbachian (Domerian) series consists of regular marl-limestone alternations (Lemede Fm), dipping gently to the South. The uppermost part of this formation (around 1m thick), was described by Choffat (1880) and Mouterde (1955) as a particular unit called “couches de passage”. They have yielded a continuous and diversified fossil material, which has been strongly collected. Shells are often accumulated and gathered, forming irregular heaps. Some belemnite accumulations have been interpreted as coprolites remnants. *Harpax* and serpulids are fixed on ammonite shells or casts. The “couches de passage” indicate a low sedimentation rate and they are capped by hard ground (top surface of level 15E; D5, Soares *et al.*, 1993; **DT1**, Duarte, 1995, 1997, 2003). The last bed (15E) has yielded a characteristic association of Dactylioceratids that is classically interpreted as marking the beginning of the Toarcian. In consequence, the chronostratigraphic boundary differs from the lithologic one, the latter being situated between the “couches de passage” (levels 15, topmost of Lemede Fm) and the base of the Cabo Carvoeiro Fm (level 16, base of Cabo Carvoeiro 1 Mb; = “Couches à Leptaena”). The biostratigraphic boundary is located within a succession showing a progressive sedimentary evolution, without noticeable interruption. The time recording can be considered good enough to give an international reference.

The detail of the “couches de passage” succession will be shortly described (Fig. 31).

Bed 15A (0,15m).*Canavaria* bed. Bioturbated micritic limestone with some lumps. *Canavaria* is associated with *Emaciaticeras* and *Lioceratoides*. This assemblage indicates the Emaciatum Subzone.

Bed 15B (0,25/0,30m). Calcareous laminated marls with belemnites, gastropods and bivalves (*Harpax*).

Bed 15C (0,25/0,30m). *Taurومeniceras* bed. Bioturbated micritic limestone with *Taurومeniceras*, *Lioceratoides*, *Tiltoniceras* and *Paltarpites*.

Bed 15D (0,20/0,30m). Marly limestones rich in belemnites and spiriferinids. *Taurومeniceras mazetieri, Leioceratoides* aff. *hoffmani*. Beds 15C and D are related to the last “Domerian” Subzone (Elisa Subzone).

Bed 15E (0,20m). *Eodactylites* bed. Micritic limestone with numerous ammonites (including at top of the bed), generally corresponding to oxidized pyritic casts. Shows the first appearance of *Eodactylites* and disappearance of Arieticeratinids. *Eodactylites* are abundant and

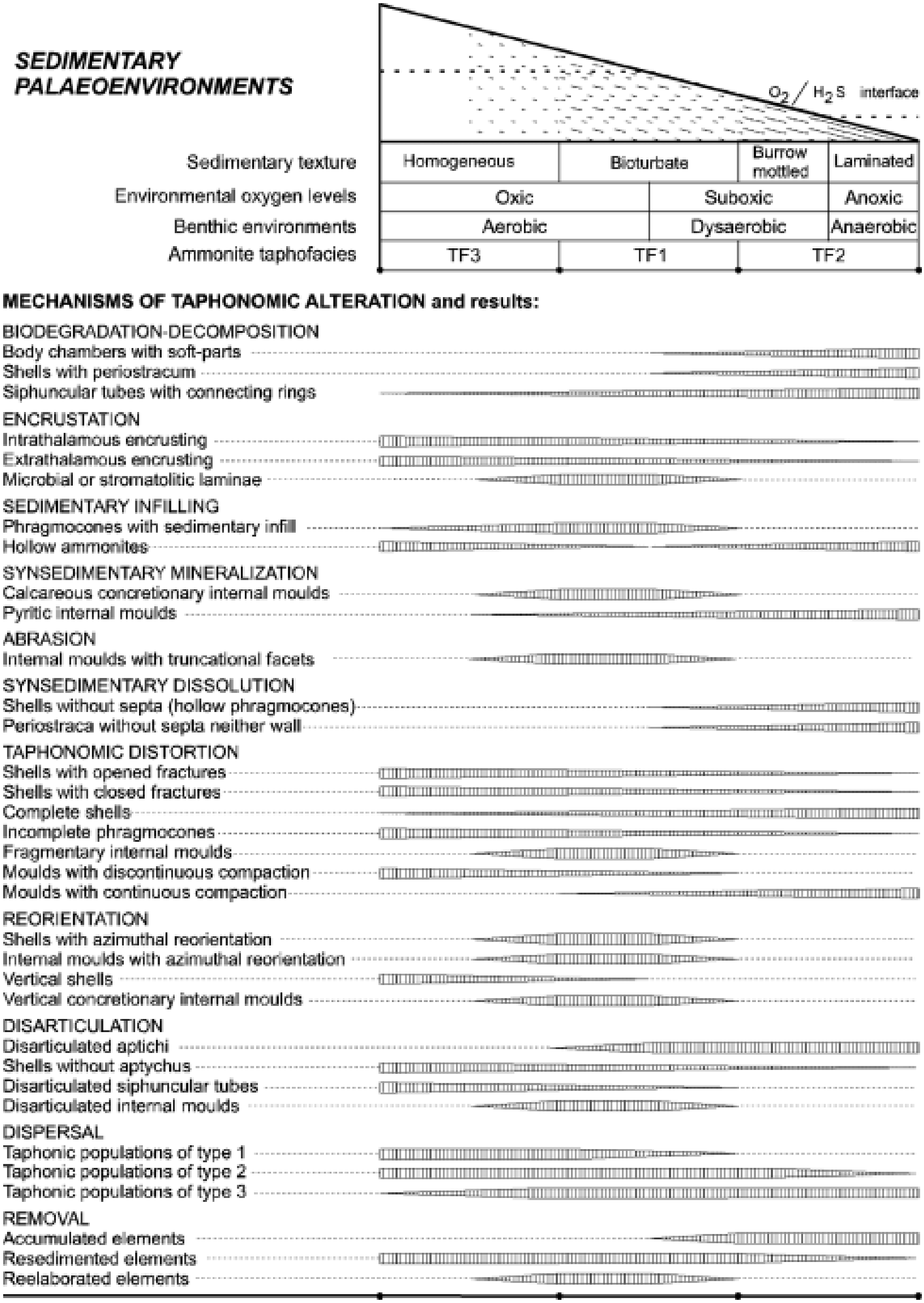

Fig. 29 - Taphonomic gradients observed on ammonites from the three taphofacies recognized in the lower Pliensbachian deposits of the LB (TF1 = Taphofacies of type 1; TF2 = Taphofacies of type 2; TF3 = Taphofacies of type 3).

Fig. 30 - General view of the Pliensbachian/Toarcian boundary in the Peniche section (Ponta do Trovão). Detailed view, see Fig. 32.

varied: *Dactylioceras (Eodactylites) simplex, D. (E.) pseudocommune, D. (E.) polymorphum.* The association *simplex – pseudocommune* can indicate a slight condensation, according to Iberian Ranges data, which requires larger confirmation. Other ammonites are also remnants of Domerian stocks such as *Tiltoniceras capillatum* and *Lioceratoides ballinense*. The presence of *Protogrammoceras (Paltarpites)* cf. *paltus* is a good indicator for correlations with the NW Europe. This bed (Fig. 32) marks the beginning of the Toarcian (Paltus/Mirabile Subzone of the Tenuicostatum/Polymorphum Zone).

Upward, the level 16 marks the lower part of the Cabo Carvoeiro 1 Mb (Fig. 31). The basal two meters of this marl dominated unit contain small pyritous casts of representatives of NW european species of *Orthodactylites*: *D. (O.) crosbeyi, D. (O.) clevelandicum* associated with *Paltarpites*. Their presence allow a tentative correlation with the Clevelandicum horizon (or Subzone) of Britain and document the hypothesis that the absence of *Eodactylites* in many classic sections is due to a sedimentologic gap rather than to a palaeogeographic differential

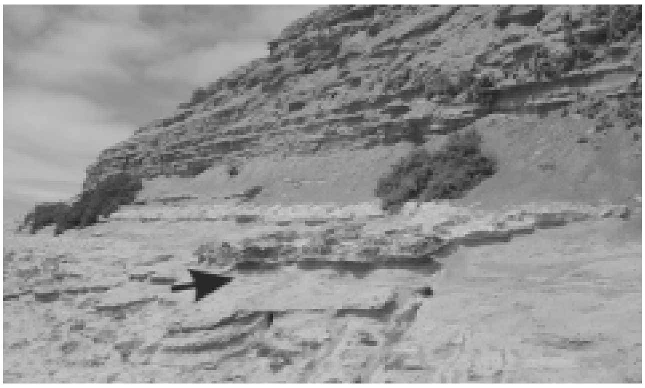

Fig. 32 - Close-up view of Pliensbachian/Toarcian boundary at Ponta do Trovão (arrow at the base of bed 15E).

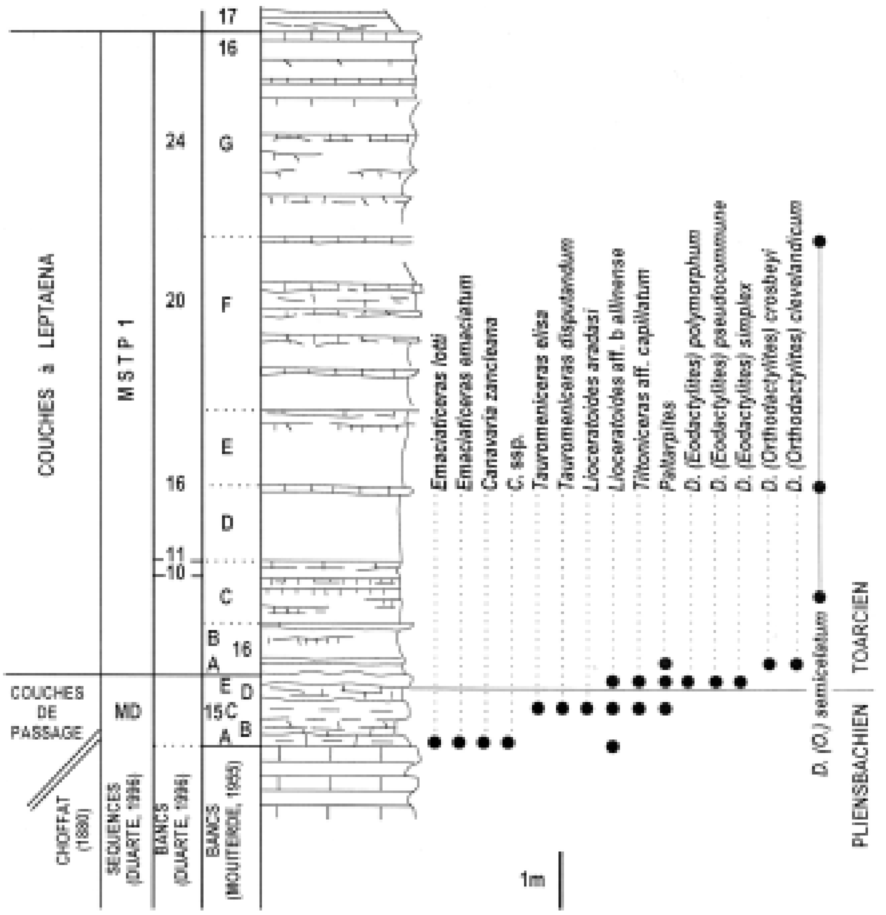

Fig. 31 - Lithology, stratigraphy and ammonite distribution across the Pliensbachian/Toarcian boundary at Peniche.

distribution. The same levels yield an abundant assemblage of belemnites, gastropods and brachiopods. These small faunas can be, partly, dwarf or miniaturized communities that have lived in an environment rich in organic matter and poorly oxygenated. Bioturbation is important (*Zoophycos* and ferruginous tubular burrows).

The upper part of level 16 contains several fossiliferous beds yielding mainly *D. (O.) semicelatum*. These ammonites can be disorderly disposed, probably as a result of bioturbation.

9. STOP 7. SUBMARINE FAN EVOLUTION OF THE TOARCIAN, PENICHE

V. P. Wright

The Toarcian-Aalenian resedimented (Cabo Carvoeiro Formation) carbonates of the Peniche area are a remarkable example of a carbonate submarine fan, developed during an early rifting phase of Atlantic opening. Most slope carbonates represent apron systems whereby sediment shed from the linear platform margin forms a more-or-less wedge-shaped body either connected to the margin (slope apron) or at the foot of the slope (base-of-slope apron). Much less common are carbonate submarine fan deposits whereby the carbonate sediments are transported into the basin along via a channel system from one or just a few point sources. The few ancient examples known are from tectonically active platform margins. The carbonates at Peniche represent the most accessible example of an ancient carbonate fan so far documented. The overall setting seems to have been that to the east the area passed into a carbonate ramp developed on a westerly dipping hangingwall, with the Peniche fan having been shed off the footwall zone to the west where a carbonate platform formed on an uplifted basement block. The rifting and uplift that created this large half-graben was a precursor of the major rifting phase in the LB in the late Jurassic.

The succession can be sub-divided into 7 major units (Wright & Wilson, 1984).

The base of the Toarcian is exposed in the small bay to the west of Ponta do Trovão (locality 7.1 in Fig. 21), 1km. north of Peniche. The lowermost part of the sequence is exposed on the western headland, while the remainder is exposed on the north facing cliffs of the bay. The succession here (Unit 1, Fig. 33) consists of 32m of green, silty radiolarian mudstones with pyritised

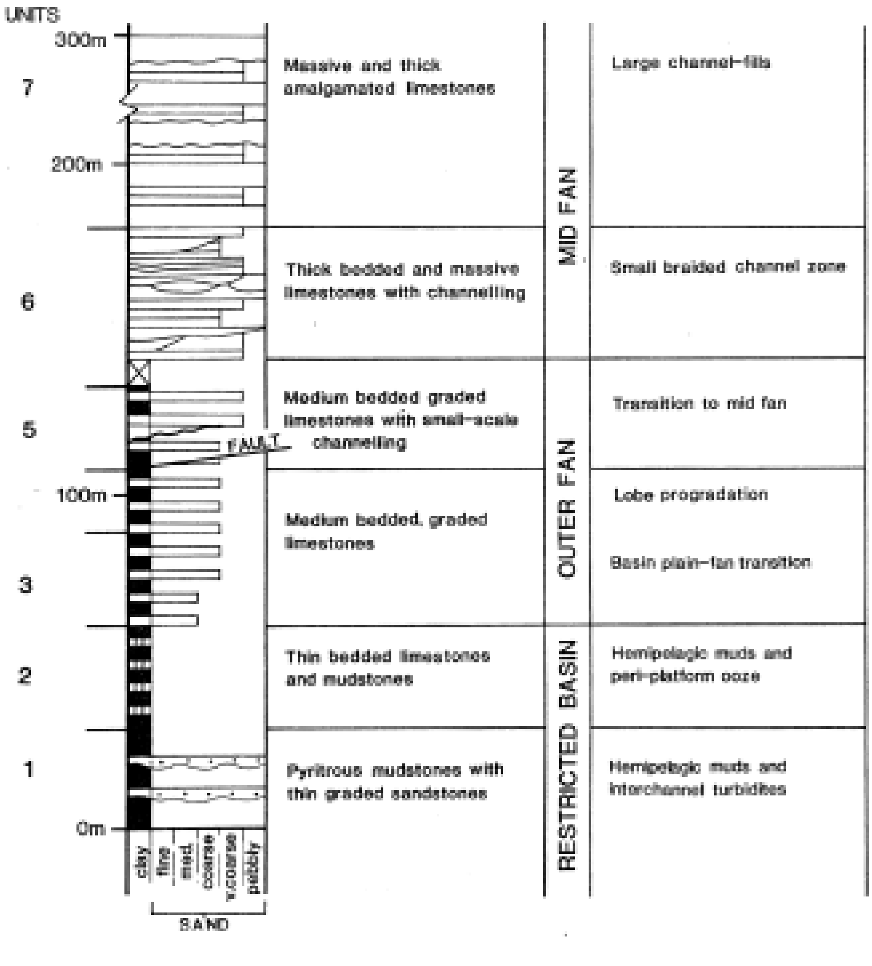

Fig. 33 - Major lithological divisions in the Toarcian-Aalenian resedimented succession at Peniche.

and compressed ammonites, belemnites, common carbonized wood fragments, small, thin shelled bivalves and rare brachiopods. Trace fossils are common and include narrow pyrite-filled burrows, *Zoophycos* and rarer *Chondrites*. There are 12 thin, lenticular, normally graded and very coarse sand-grade, subarkosic sandstones with grooved and fluted bases. These are best exposed on the path leading down to the bay. A 0.5m pebbly mudstone (debris flow?) is exposed at the base of the steps. Thin argillaceous wackestones, pyrite-rich horizons, laminated mudstones and bituminous shales also occur. The top of this unit is taken as the incoming of thinly interbedded limestones and mudstones (Unit 2), which occur a metre or so above the prominent, thick, lenticular brown sandstone visible in the stack in the bay. Unit 2 is visible on the western part of the bay, west of Ponta do Trovão. It can be reached by crossing the bay at low tide, or by descending the cliff. It consists of 32m of alternating, thin, heavily bioturbated wackestones, lime mudstones and silty mudstones. Bituminous shales and pyrite are less common.

Unit 1 represents a deeper water setting with fluctuating oxygen levels, including intervals of sea-floor anoxia. The sandstones are interpreted as turbidites but are striking in being relatively thin bedded but coarse textured, and channelised. One explanation is that these represent overbank deposits on the margins of deep sea channels, although there is no direct evidence for the existence of such channels. The importance of these turbidites lies in that they indicate that a felspar-rich source area was being eroded and that sufficient slopes were being generated to trigger sediment gravity flows. The likely source, borne out by palaeocurrent data from the succession as a whole, was a granitic and high-grade metamorphic Hercynian basement block to the west (likely now represented by the position of the Berlengas – Farilhoes islands, 12km to the WNW), probably a horst block. The fan-like signature of the bulk of the succession (Units 3-7) implies that the resedimented carbonates were being supplied from a point source, and it seems likely that this was inherited from whatever feeder system deposited these Unit 1 sandstones. The limestones of Unit 2 probably represent increased hemipelagic input and a cessation of coarse clastic sediment that might indicate the flooding and drowning of the clastic source followed by carbonate production.

Unit 3 consists of 30m of generally thin to medium-bedded (average of 0.17m) normally graded carbonate grainstones, and mudstones, with a limestone:mudstone of 1:2. The former are siliciclastic-rich, peloidal, oolitic grainstones with prominent grooves on their bases. Those in the lower half of the succession grade from medium to fine sand, whereas those in the upper half grade from medium or coarse sand to fine sand (Fig. 34). These represent turbidites of an outer fan or even basin plain association (see below). The possibility that these resedimented carbonates are distal storm deposits requires comment. Against such an origin would be the complete absence of any characteristic storm features such as hummocky cross stratification in the succession. Furthermore, if these grainstones were simply the products of storm flows on a carbonate ramp, the absence of any parautochthonous material is striking, implying that the storm-generated bottom flows were capable of transporting sediment some distance across a ramp but did not incorporate any sediment other than the very shallow water grains derived from an inner ramp. The regional palaeogeography does not invoke any shallow water ramp to the west of Peniche, and there are no comparable resedimented deposits to the east where a large carbonate ramp did exist: if these carbonates represent distal storm flows from the east, the sediment by-passed the contemporaneous ramp, and some how incorporated coarse siliciclastic material not available from the east. The weight of evidence is for a westerly source from a steep, probably drowned horst.

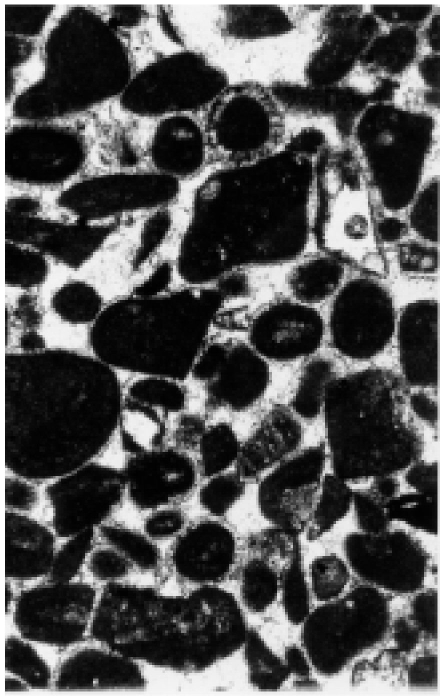

Fig. 34 - Peloidal-oolitic grainstone turbidite from Peniche. Field of view is 2.5mm wide (long axis).

The abundance of peloids might imply that the margin shedding these carbonate sands was a leeward one. The change from hemipelagic input in Unit 2 to carbonate sands might imply that shallowing had taken place over the platform.

The top of Unit 3 and the base of Unit 4 can be examined on the eastern side of a small cove 50m west of the Station of the Cross VIII, some 100m east of the Cerro do Cão headland (locality 7.2 in Fig. 21). The top of Unit 3 is a 6m thick mudstone, and the top of Unit 4 is faulted against Unit 5. Unit 4 consists of some 17m of peloidal grainstones (graded coarse to medium or fine sand) with a limestone:mudstone of 1.3:1. A small (3m) thickening-&-coarsening-up sub-unit is exposed. Overall this unit is more proximal to Unit 3 and the thickening-&-coarsening-up sub-unit might be interpreted as a prograding lobe deposit.

Unit 5 consists of 30m of interbedded limestones and argillaceous interbeds. It is exposed on the western side of Cerro do Cão and can be traced in good exposures along the cliff tops around to the west of the headland and towards Remedios (locality 7.3 in Fig. 17). The bulk of this unit consists of grainstones 0.2-0.3m thick, grading from very coarse (with granules) to medium sand. The limestone:'shale' is 4:1. Bed amalgamation is common and small-scale channeling is also present. Unit 6 is exposed in the heavily karsted terrain from 50m west of the Station of the Cross XI to the cliffs north of Remedios, where it is best exposed. It is approximately 50m thick and consists of thickly bedded, amalgamated and massive (up to 4m) very coarse sand to pebbly sand grade limestones. Cobble-sized lithoclasts, rolled corals and coarse criniodal limestones are also present. Many beds are strongly channelised and channel-fills are clearly seen.

These two units continue the clear distal-proximal trend seen up-sequence from Unit 3. The coarse grain sizes, amalgamation and channeling are reminiscent of a sandy mid fan-type deposystem, although these channel-like features are very small and likely represent either a component of a small fan system or, more likely, distal braided mid fan channels.

Unit 7 is poorly exposed west of Remedios, around to Cabo Carvoeiro and back along the southern coast of the peninsula, and is best viewed in inaccessible cliff sections. It consists of 150-200m of massive, very thickly bedded and amalgamated, coarse to very coarse sand-grade limestones. Pebbly sand-grade limestones are common and limestone boulders occur at the bases of some of the thicker limestones. On the southern side of the peninsula, at Carreiro da Furninha, there are cross-bedded, channel sandstones. These channels were cut into limestones and their bases contain numerous cobble to boulder-sized limestone clasts. On the eastern side of the cove, in the lower part of the cliff, a thick limestone can be seen cut internally by large erosion surfaces. At Carreiro da Joana bipolar, medium-scale cross-bedding can be seen in coarse grade limestones. This unit as a whole continues the proximal-distal trend, and the bipolar cross-bedding suggests tidal flows, which are known to affect deep sea channels. Quite what the depositional context was unclear. These thick limestones could represent major channel-fills but not the main canyon feeder system which presumably would have been cut into the basement high some kilometres away.

There are many uncertainties about the overall depositional setting of this remarkable succession. It is strongly localised, there being no development of such deposits at Serra d'El Rei 12 km to the east. The channeling and lobe-like packages suggest a fan-like (Fig. 35) behaviour and it seems likely that this was inherited from a precursor siliciclastic system once the uplifted block had become flooded, triggering carbonate deposition. It is not possible, with the limited outcrop to categorically show a radial (fan-like) sediment dispersal pattern, so is it correct to refer to the Peniche grainy limestones as a submarine fan? Could this succession not simply represent a spatially restricted apron with extensive channeling? Abbots (1989) reinvestigated the Peniche "fan" with the aim of evaluating if the succession exhibited fan-like cyclicity. She used Runs Test statistics on Units 3-5 and showed that they display a statistically valid number of thickening and thinning-upwards packages. She concluded that Wright & Wilson (1984) has been over cautious in identifying only one such package (in Unit 4). As a result of displaying such packages Abbots reinterpreted Unit 3 as an outer fan lobe-lobe fringe deposit. The case for the Peniche resedimented carbonates being a fan is based on the similarities to sandy fan deposits and that the succession exhibits strong evidence of turbidite lobe and channel deposition, features not well documented from carbonate apron systems.

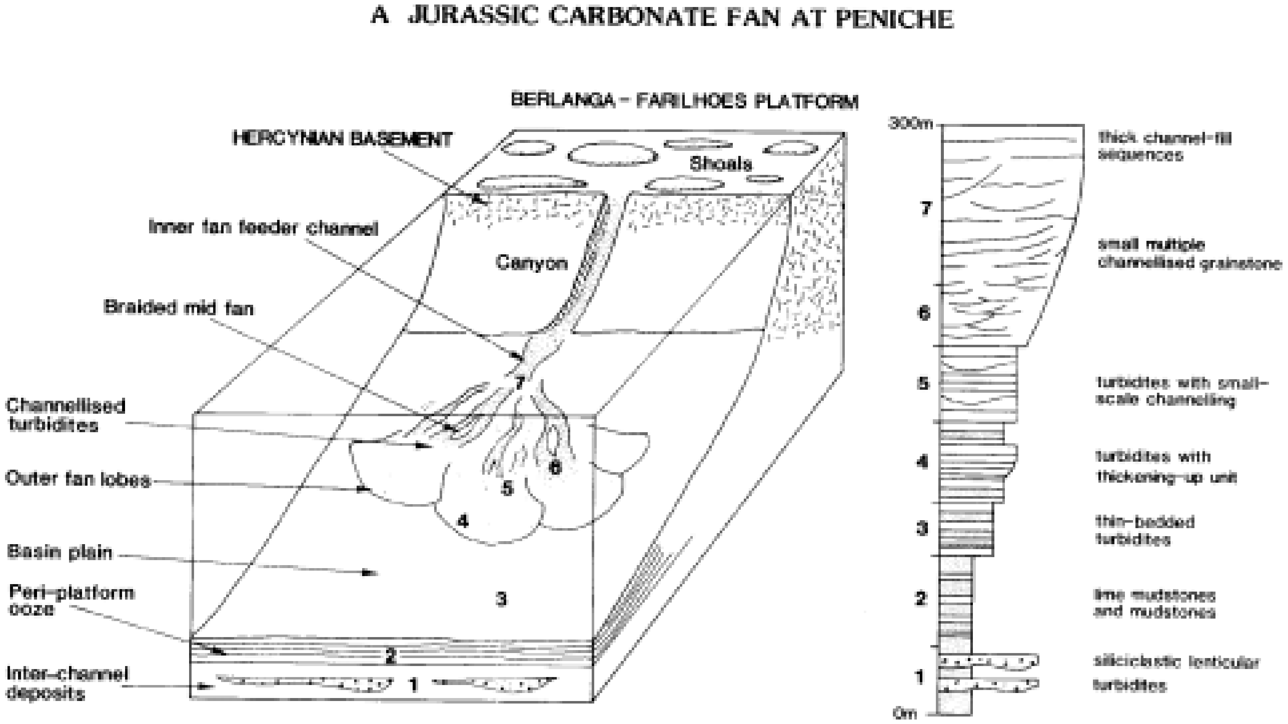

Fig. 35 - Schematic interpretation of the Toarcian-Aalenian carbonate fan at Peniche.

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