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Facies analysis and sequential evolution of the Toarcian-Lower Aalenian series in the Lusitanian Basin (Portugal)

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Key-words: Lusitanian Basin; Toarcian; Lower Aalenian; facies and sequential analysis; unconformities; tectonics; eustasy.

Abstract: In the Lusitanian Basin, the Toarcian-Lower Aalenian series correspond to an important lutitic marly-limestone accumulation with hemipelagic characteristics. Those sediments show sequential organization supported by four depositional sequences, bounded by correlative regional unconformities: **DT1** (Intra Polymorphum Zone), **DT2** (Polymorphum/Levisoni boundary), **DT3** (Intra Bifrons Zone), **DT4** (Intra Bonarellii Zone) and **DT5** (Intra Opalinum Zone). Except for the **DT2** with obvious characteristics of tectonic nature, all the unconformities seem to be connected with allogenetic mechanisms, like the eustatic oscillations defined in the main global eustatic curves.

The depositional sequences (**MST1** to **MST4**) show, in differentiated contexts of a homoclinal ramp, shallowing upward evolutions; these characteristics are particularly evident in the proximal parts of the basin such as Tomar and in the southwest border at Peniche. In this last region a strong siliciclastic and oolitic accumulation is observed in the Peniche section, in straight dependence with the Berlenga igneous massif.

Palavras-chave: Bacia Lusitânica; Toarciano; Aaleniano inferior; análise de fácies; análise sequencial; descontinuidades; tectónica; eustatismo.

Resumo: Análise de Fácies e Evolução Sequencial do Toarciano-Aaleniano inferior da Bacia Lusitânica (Portugal). A série de sedimentos do Toarciano-Aaleniano inferior da Bacia Lusitânica mostra uma importante acumulação margo-calcária com características hemipelágicas. Esta série mostra uma organização sequencial apoiada em quatro sequências deposicionais, limitadas por descontinuidades regionais correlativas: **DT1** (intra Zona de Polymorphum), **DT2** (limite entre as Zonas de Polymorphum e Levisoni), **DT3** (intra Zona de Bifrons), **DT4** (intra Zona de Bonarellii) e **DT5** (intra Zona de Opalinum). Com excepção de **DT2**, com características manifestamente de natureza tectónica, todas as restantes descontinuidades parecem estar associadas com mecanismos alogenéticos, dada a evidente sobreposição com as grandes oscilações eustáticas definidas nas principais curvas conhecidas.

As sequências deposicionais (**MST1** a **MST4**) mostram, em diferentes contextos de uma rampa homoclinal, evoluções regressivas; estas características são particularmente evidentes na parte proximal da bacia (Tomar) e no bordo sudoeste, em Peniche. Neste último sector, observa-se uma forte acumulação siliciclástica e oolítica em estreita dependência com o maciço hercínico da Berlenga.

INTRODUCTION

The Lower and Middle Jurassic of the Lusitanian Basin show an expressive carbonate infilling, sometimes with rhythmic marl/limestone alternations. During this time, we recognize in the basin two main depositional sectors (AZEREDO, 1988, 1993; WATKINSON, 1989; HENRIQUES *et al.*, 1991; SOARES *et al.*, 1993a, b). One, located in the western side (Figueira da Foz-Cantanhede), with a marly-limestone sedimentation rich in cephalopod fauna; the other, today located in southeast part (Tomar-Serra da Arrábida region), very condensed, composed by bioclastic facies very rich in benthic macrofauna (shallow-water facies). This sedimentological configuration suggests a paleogeography controlled by an epicontinental sea sustained by a gently carbonate ramp, dipping towards northwest. This general paleogeography, agreed by all that been worked in the portuguese Lower Jurassic, can be analysed with more detail through the sedimentological features of the Toarcian-Lower Aalenian series.

THE TOARCIAN-LOWER AALENIAN DEPOSITS IN THE CONTEXT OF THE TRIASSIC-CALLOVIAN CYCLE

Like in other atlantic margins the continental red beds of the Upper Triassic (Silves Sandstones) are overlain by dolomitic facies of the Lower Jurassic (Coimbra Beds s. s.). During the Lotharingian a flooding phase began in the west part of the basin with the deposition of the marly-limestone facies with cephalopods in an outer ramp setting. Since the Lower Carixian (megasequence **D**, SOARES *et al.*, 1993a, b), the sedimentary evolution has expressed a combination of megasequences (**D** to **H**, SOARES *et al.*, 1993b; SOARES & DUARTE, 1995, 1997) that represent, in distinct context of the carbonate ramp, transgressive-regressive cycles, explained

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directly by eustasy, locally with tectonic overprint. The megasequences basal surfaces are transgressive, like **MD** (Upper Lotharingian-Lower Carixian), **ME1** (early Lower Toarcian) and **MG** (Intra Lower Bajocian), that in the Hallam eustatic curve (HALLAM, 1988), correspond to a gradual fall/abrupt rise eustatic fluctuations. The large cycle ends in the Late Callovian, with calcareous sandstone facies that corresponds to the ramp cicatrization (SOARES *et al.*, 1993a).

The vertical and lateral facies associations in the basin testify an evolution of homoclinal ramp model during the Middle-Upper Liassic (WATKINSON, 1989; DUARTE, 1991) to a distally steepened ramp during the Bajocian-Lower Bathonian (AZEREDO, 1988, 1993; WATKINSON, 1989; SOARES & DUARTE, 1997). This last model bound in the east (Sicó-Candeeiros-Tomar), the proximal environments composed by reefal, oolitic and other shallow-water facies, from the hemipelagic and pelagic facies of the northwest part of the basin (Figueira da Foz-Cantanhede) that recorded marl/limestone alternations with mass-flow systems (WATKINSON, 1989).

DEPOSITIONAL SEQUENCES

The megasequential evolution of the Liassic and Dogger carbonates of the Lusitanian Basin is well knowledge (*vide* SOARES *et al.*, 1993a, b; SOARES & DUARTE, 1997). In this cycle, the toarcian rhythmic marly-limestone was incorporated in two megasequences (**ME1** and **ME2**) (Fig. 1), in which the last levels belong to the Opalinum Zone (DUARTE, 1991; HENRIQUES, 1992; SOARES *et al.*, 1993a).

The use of the allostratigraphic fundamentals (NACS, 1983) in the Toarcian-Lower Aalenian series of the Rabaçal-Condeixa region (DUARTE, 1991) allowed, for the first time, the recognition of the main intra Toarcian unconformities and the presentation of the rhythmical characteristics and evolution of each sedimentary body (mesosequences = depositional sequences). This sequential framework was resumed in four main phases of sequential infilling (Fig. 1).

The research extended to the whole of the basin brings us to the conclusion that those sequential units

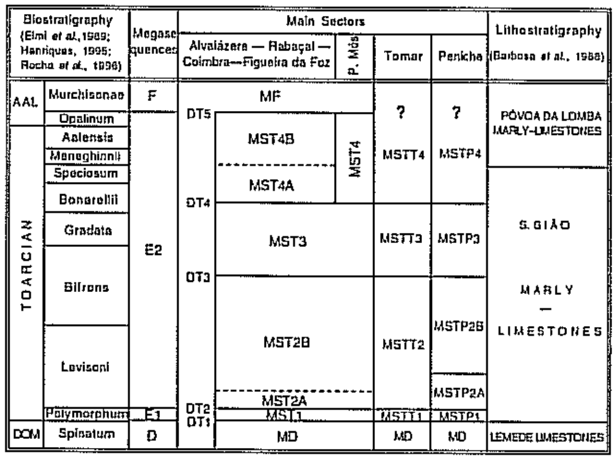

Fig. 1 – Sequential chart of the Toarcian-Lower Aalenian from the Lusitanian Basin: Megasequential units (SOARES & DUARTE, 1995), unconformities, depositional sequences (DUARTE, 1995) and lithostratigraphy (*vide* SOARES & DUARTE, 1997).

are recognized in almost all studied regions, excluding the series materialized in the Tomar and Peniche sectors. The detailed analysis of the marly-limestone succession in the remaining regions, makes possible the construction of a less informal stratigraphical framework and with a more global incidence (**MST** – toarcian mesosequence). Each mesosequence shows a marl/limestone sequential organization observed at two scales with a clear marl to limestone sedimentary evolution (Table 1).

TABLE 1

Sequential hierarchization presented to the Toarcian marl/limestone series of the Lusitanian Basin

SEQUENTIAL ANALYSIS	EQUIVALENT TERMINOLOGY
Megasequence (Decametric to Hectometric)	2nd Order Rhythm (DELFAUD, 1972); Transgressive-regressive sequence (DUVAL *et al.*, 1991; VAIL *et al.*, 1991)
Mesosequence (Decametric)	Rhythm (DELFAUD, 1972); Depositional sequence (VAN WAGONER *et al.*, 1988); Sequential cycle (DUVAL *et al.*, 1991)
Macrosequence (Metric)	Parasequence set (VAN WAGONER *et al.*, 1988)
Elementary Sequence (Decimetric to Metric)	Elementary Sequence (DELFAUD, 1972); Parasequence (VAN WAGONER *et al.*, 1988); Parasequence cycle (DUVAL *et al.*, 1991).

For the Tomar and Peniche sections an individualized nomenclature was applied, considering the particularity of its facies (**MSTT** and **MSTP** respectively) (Fig. 1).

In order to demonstrate the depositional variability in the basin of the Toarcian-Lower Aalenian series, 34 partial sections were studied in detail (*vide* DUARTE, 1995) (Fig. 2), all of them referenced in the biostratigraphic scales of ELMI *et al.* (1989) and ROCHA *et al.* (1996). We can resume this information in seven regional virtual sections, represented in Fig. 3, that show a thickness range from 70 to around 300 meters.

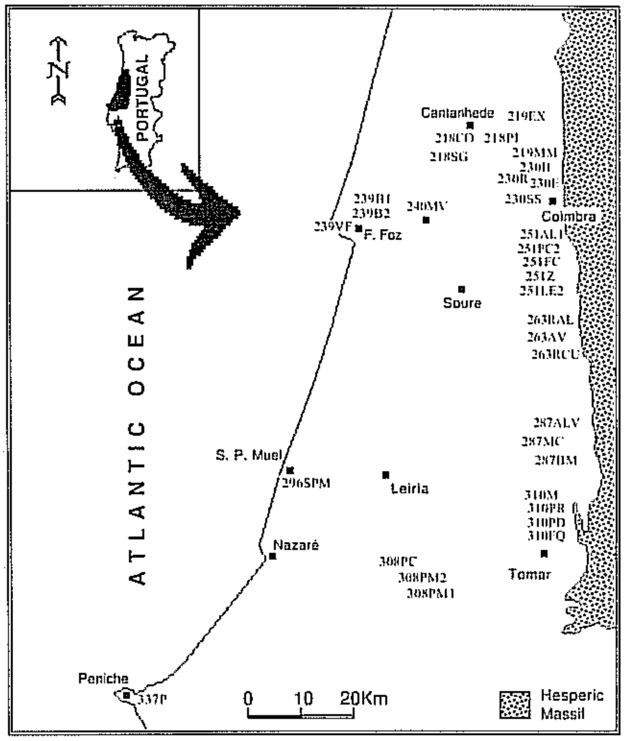

Fig. 2 – Location of the partial stratigraphic sections studied in detail (*vide* DUARTE, 1995).

ALVAIÁZERE-FIGUEIRA DA FOZ-PORTO DE MÓS SECTOR

Top of MD: Is composed in all the basin by a strong calcareous series with thiny marly alternations. The limestone facies, of the decimetric to metric scale, are fundamentally composed by bioturbated bioclastic wackestones, with abundant ammonoids, belemnites, bivalves, and brachiopods. In Tomar, the facies are very bioclastic (packstone to grainstone) and locally dolomitic, with a very diversified macrofaunal component.

MST1 Unit: Like it is shown by Fig. 4, the elementary facies association is formed by greyish decimetric marls which evolve towards marly limestones in centimetric beds, in asymmetric sequential organization (Pl. I, Figs. 1 and 2). The occurrence of tiny brachiopods and pyritized ammonoids (Dactylioceratids), belemnites and bivalves is remarkable. *Zoophycos* and ferruginous tubular burrows are common in the limestone lithofacies. In the Tomar-Coimbra direction, we can see a gradual increase of thickness, where it reaches around 20 meters.

MST2 Unit: Corresponds to a thick series and, similarly to the sequential chart presented in the Rabaçal region (DUARTE, 1991), this sequence can be subdivided in two units.

MST2A Unit: Corresponds to a small succession very poor in macrofauna of marls and sublithographic limestones in centimetric beds, with very irregular surfaces (Pl. I, Fig. 3). The thickness of this unit in all the basin is around 10 meters. By attentive observation of this stratonomy, it is possible to identify a great multiplicity of macrofacies and microsequential patterns. Dominant calcilutitic facies are associated with others, calcarenitic, but the distinction between them is occasionally difficult due to their high degree of recrystallization. The microfacies correspond to a microsparits with radiolarians. In the Mealhada-Condeixa band, the basal part of this unit is composed by a little sequence (maximum thickness of about 7 meters) of unfossiliferous brownish marls. The vertical and lateral facies arrangement show four main sectors (Fig. 5):

Alvaiázere-Rabaçal Sector – **MST2A** consists of a nodulose and ferruginous succession of marls and microsparitic limestones with gutter-casts. The calcarenites facies are rare but the degree of recrystallization is very high. However, the degree of bioturbation is relevant at the top surfaces of limestone beds. The base of this unit is particularly rich in large *Thalassinoides*.

Porto de Mós Sector – The marly component is practically absent in the upper part of **MST2A**, where it corresponds to laminated thin levels. The limestones show two types of stratonomic appearance. At the base, the centimetric layers (1 to 7 cm) show very regular bedding with sharp surfaces. The facies correspond to laminated fine calcarenites (silty to fine sandy); some microfacies show microsparitic cements with micritic intraclasts, bioclasts, sandy quartz and rare oolites. At the top, the marl/limestone ratio decreases gradually upward. Bed surfaces are ferruginous and very irregular but with a homogenous thickness (2 to 4 cm). The high degree of the bioturbation and the occurrence of *Thalassinoides* are typical in this unit.

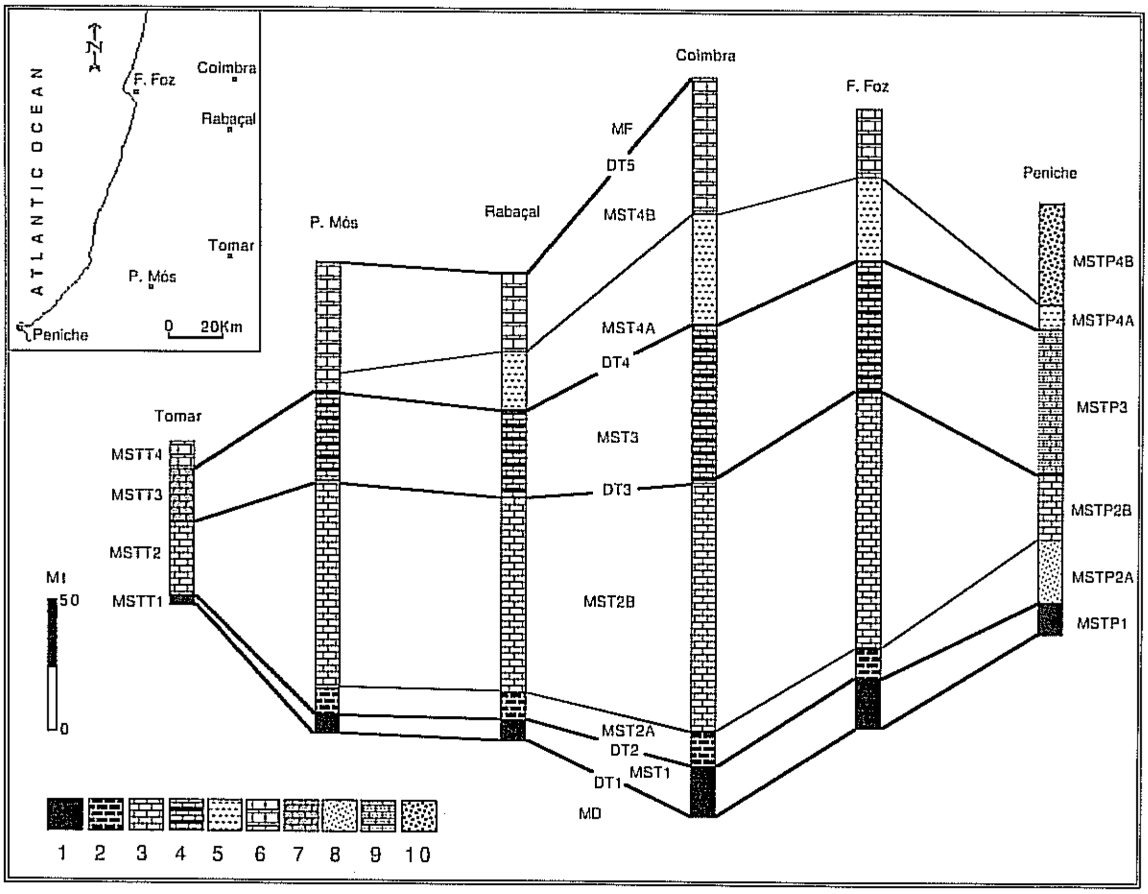

Fig. 3 – Location map of the virtual sections in all the basin. Lateral and vertical repartitions of the depositional sequences (horizontal not to scale). 1 - Marl/limestone decimetric alternations with small brachiopods; 2 - Calcilutitic to calcarenitic facies alternated with marls in centimetric scale; 3 - Metric to decimetric lutitic marl/limestone alternations; 4 - Decimetric marl/limestone alternations with bioconstructions; 5 - Marls and marly-limestones with brachiopods; 6 - Marls and micritic limestones with bioconstructions; 7 - Bioclastic limestones; 8 - Lenticular siliciclastic facies; 9 - Oolitic and peloidal facies; 10 - Oolitic and sandy limestones facies.

Coimbra-Montemor-o-Velho Sector – The thin limestones are very rich in calcarenites with lamination, cross bedding (sometimes with hummocky morphologies) (Pl. I, Fig. 4), and symmetrical and current ripples (Pl. I, Fig. 5). Some microsequences show at the base a milimetric scale bioclastic facies composed by echinoids fragments. The limestone facies show thickness values between 1 and 14 centimetres, with amalgamated structures, irregular surfaces and a strong bioturbation. The trace fossils include *Thalassinoides*, *Chondrites* and ferruginous tubular burrows.

Cantanhede-Figueira da Foz Sector – The detrital component in the limestones is very poor (< 5 % of fine calcarenites). In all **MST2A**, the bioturbation is very strong, with *Chondrites* richer at the top, and *Thalassinoides* in the nodulose facies of the base (Fig. 5). The asymmetric sequential style, very typical of the overlying unit, can be observed. If we compare it with other regions, the stratonomical appearance show a quickly diminution in the limestone thickness.

MST2B Unit: The sedimentological differentiation between the top of **MST2A** and the base of **MST2B** is gradual. At the base, the limestone beds are more argillaceous and with more regular surfaces. Towards the top the series become more calcareous. The necktonic and benthic faunal interposition is a persistent feature in this unit but always with low diversity. The ammonoids and brachiopods (terebratullids and rhynchonellids) are very rich in all the basin being the pectinids and pelagic bivalves less abundant. The vertical facies variation in **MST2B** allows to define three main sectors (Fig. 6):

Alvaiázere-Rabaçal Sector – Despite the considerable diminution of thickness towards south we can see in

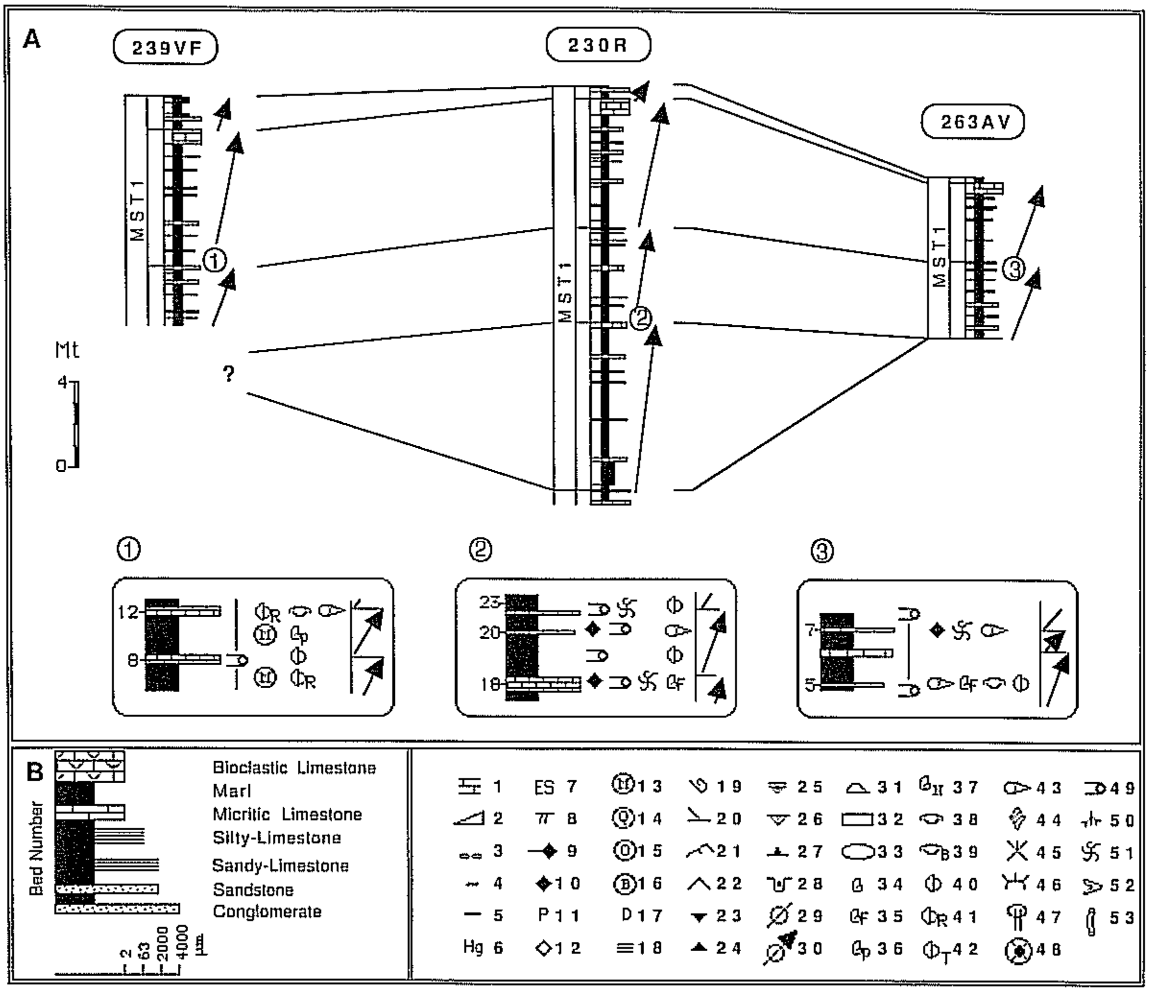

Fig. 4 – A - MST1: Facies analysis and sequential typology (macrosequential and elementary sequential evolution) in the Figueira da Foz (239VF), Coimbra (230R) and Ansião (263AV) regions. B - General legend: 1 - Marl/limestone thin alternations, 2 - Lenticular stratification, 3 - Nodular stratification, 4 - Irregular stratification, 5 - Strong facies variation, 6 - Hardground, 7 - Erosive surface, 8 - Perforation, 9 - Ferruginous surface, 10 - Iron oxides and hydroxides nodules, 11 - Pyrite, 12 - Carbonized wood fragments, 13 - Mica flakes, 14 - Sandy quartz, 15 - Oolitic limestone, 16 - Bioclastic limestone, 17 - Dolomitic limestone, 18 - Lamination, 19 - Convolute lamination, 20 - Planar cross-bedding, 21 - Asymmetric ripples, 22 - Symmetric ripples, 23 - Finning upward sequence, 24 - Coarsenning upward sequence, 25 - Load structures, 26 - Gutter-casts, 27 - Tool-marks, 28 - Groove-marks, 29 - Paleocurrent direction, 30 - Paleocurrent azimuth, 31 - Mud mounds, 32 - Bioherms, 33 - Lenticular bioclastic wackestone to grainstone, 34 - Ammonites, 35 - Fragments of ammonites, 36 - Pyritized ammonites, 37 - Nautiloids, 38 - Bivalves, 39 - Thin-shelled bivalves, 40 - Brachiopods, 41 - Rhynchonellid brachiopods, 42 - Terebratullid brachiopods, 43 - Belemnites, 44 - Gastropods, 45 - Crinoids, 46 - Echinoids, 47 - Siliceous sponges, 48 - Corals, 49 - Tubular burrows (includes *Planolites*), 50 - *Chondrites*, 51 - *Zoophycos*, 52 - *Thalassinoides*, 53 - *Skolithos*.

all this band the same type of sequential organization, with very rhythmic styles (DUARTE, 1994). The elementary sequences correspond to the evolution of decimetric/metric marls facies to limestones in more homogeneous thickness beds (Pl. II, Fig. 1).

Porto de Mós Sector – The elementary sequences of **MST2B** are not rhythmic in this area. At the base, the facies association are very similar to the **MST2A**, but with calcilutitic levels. At the top, the marls are practically absent in the series.

Coimbra-Figueira da Foz Sector – The base of **MST2B** is composed by centimetric lutitic marl/limestone alternations, very similar to **MST2A** but very rich in rhynchonellids. This configuration is marked, by a rhythmic thick level of marls, that corresponds to the basal part of the parasequences.

In the upper part of **MST2B** the facies are more calcareous. The bases of the parasequences show yellow decimetric marls that evolve to a metric assemblage

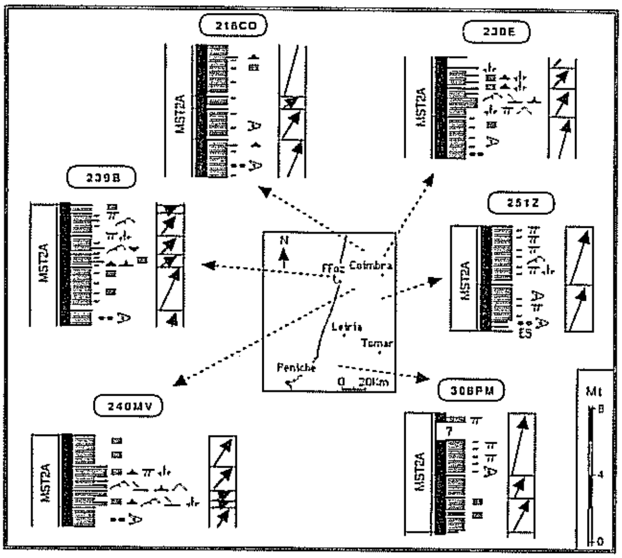

Fig. 5 – MST2A: Facies analysis and sequential typology in Figueira da Foz (239B), Cantanhede (218CO), Montemor-o-Velho (240MV), Coimbra (230E), Rabaçal (251Z) and Porto de Mós (308PM).

of thin marl/limestone alternations (Pl. II, Fig. 2). These facies are particularly rich in thin-pelagic bivalve shells (Pl. II, Fig. 3). The elementary sequence ends with bioturbated and ferruginous limestones.

MST3 Unit: Shows in all the sections large similarities of facies and sequential arrangements, with a strong marly infill at the base (Pl. II, Fig. 4). Contrarily to MST2B, this unit is composed by a large diversity of paleontological elements (Fig. 7). The macrofauna is very rich in ammonoids, rhynchonellids, crinoids, bivalves being less abundant echinids and gastropods.

The elementary sequential organization shows regular alternations, composed by deci to metric marls facies that evolve to the top to centi to decimetric marly limestones, sometimes with bioclastic features (Fig. 7). Despite this apparent uniformity of lithofacies associations, the marl/limestone couplets are often affected by small syndepositional structures, materialized by lenticular and tabular bioclastic buildups, particularly rich in crinoids and brachiopods. Other preponderant and typical aspect of whole MST3 and observed in all the regions, is the occurrence of small (decimetric to metric scale) biohermes (Pl. II, Fig. 5) and mud-mounds, always associated with the top of the elementary sequences. In both these buildups, the facies are composed by bioclastic wackestones and packstones with siliceous sponges (Pl. II, Fig. 6), these ones, sometimes in a good preservation state. The typology and density of these bioconstructions show a geographic control, with a notorious diminution in the west sectors of the basin.

MST4 Unit: At the base this unit corresponds to a marly sequence (MST4A), very thick in the Coimbra and Cantanhede regions. This strong marly infill evolves to the top, to a more calcareous series (MST4B).

MST4A Unit: The first evidence of this unit corresponds to the marly facies dominance (Pl. III, Fig. 1), but

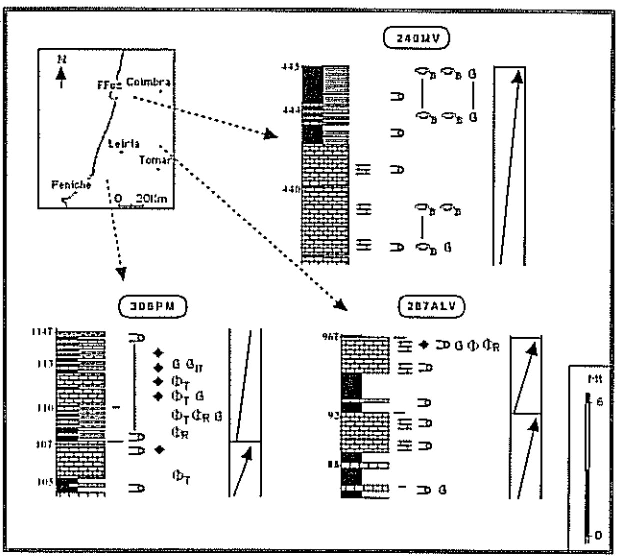

Fig. 6 – MST2B: Facies analysis and macrosequential typology in Montemor-o-Velho (240MV, *vide* DUARTE, 1995, Fig. II.14, p. 64), Porto de Mós (308PM, *vide* DUARTE, 1995, Fig. II. 40, p. 101) and Alvaiázere (287ALV, *vide* DUARTE, 1995, Fig. II.29, p. 87) regions.

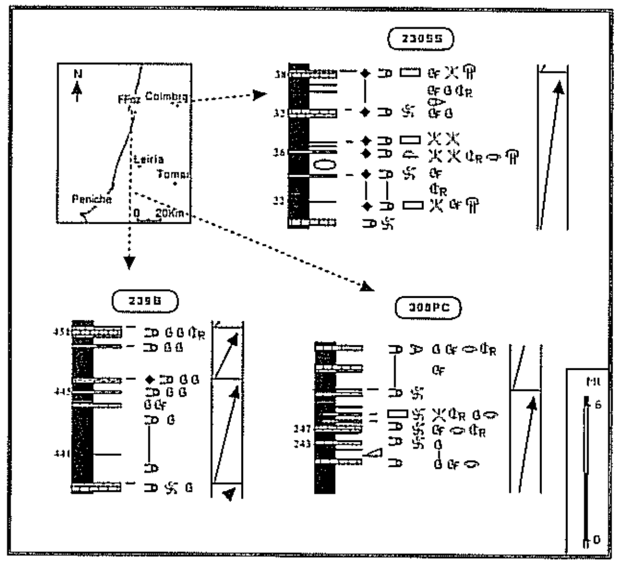

Fig. 7 – MST3: Facies analysis and macrosequential typology in Coimbra (230SS, *vide* DUARTE, 1995, Fig. II.13, p. 61), Figueira da Foz (239B, *vide* DUARTE, 1995, Fig. II.16, p. 68) and Porto de Mós (308PC, *vide* DUARTE, 1995, Fig. II. 42, p. 103) regions.

always with a marl/marly limestone sequential organization (Fig. 8). It is very difficult to show sedimentary breaks in the series but any variations seem to occur in the sediments colours, between grey, brown and greenish. The macrofauna consists of ammonoids, bivalves and tiny brachiopods, being the last ones very rich in some levels. Crinoids are less common, occurring sometimes in small bioclastic buildups. Trace fossils are rare, being exclusively composed by ferruginous tubular burrows.

The thickness variation of **MST4A** shows a gradual decrease towards south (42 m in Coimbra, against less 10 m in Alvaiázere region). In Porto de Mós, the typical marly infill of **MST4A** is absent, showing the series a rhythmic marl/limestone alternation, very similar to the **MST4B** vertical arrangement. However, the facies association increases in carbonate upward.

MST4B Unit: Is composed by bioturbated marl/limestone alternations with an upward increase of calcareous facies. When compared laterally, the elementary marl/limestone sequences are very heterogeneous. Although, the macrosequences are always characterized by thickening arrangement of the limestones beds (Fig. 9) (Pl. III, Fig. 2). Some marls are very densely burrowed by *Chondrites* in a green and centimetric beds, a feature that can be seen in all the basin. The ichnofacies is very diversified and consists of *Zoophycos*, *Chondrites*, *Thalassinoides*, *Planolites* and ferruginous tubular burrows. The macrofauna is predominantly composed by ammonoids and pectinid bivalves.

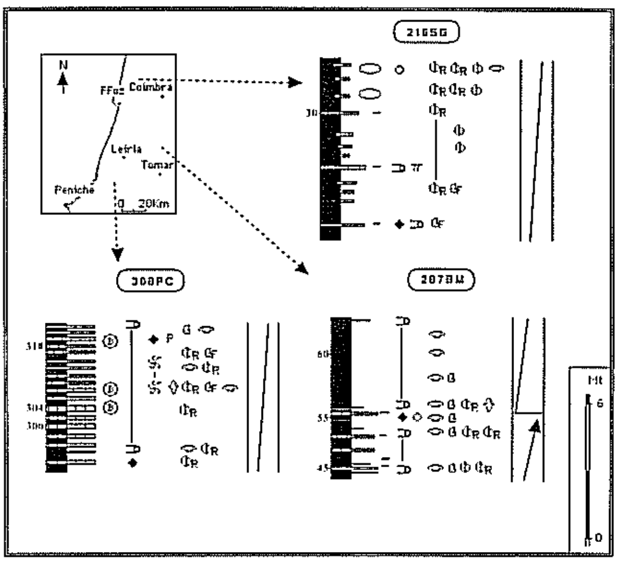

Fig. 8 – MST4A: Facies analysis and macrosequential typology in Cantanhede (218SG, *vide* DUARTE, 1995, Fig. II.5, p. 49), Porto de Mós (308PC, *vide* DUARTE, 1995, Fig. II.42, p. 103) and Alvaiázere (287ALV, *vide* DUARTE, 1995, Fig. II.29, p. 87) regions.

Similarly to **MST3** small buildups (decimetric to metric scale), like mud-mounds and biohermes occur in all the sequence. These ones are composed by siliceous sponges spicules and other very diversified benthic macrofauna (echinids, crinoids, brachiopods and bivalves). The bioturbation in these buildups is a very strong feature.

The vertical facies variation in **MST4B** allows to define three main sectors:

Porto de Mós Sector – The vertical facies association shows a large complexity with a not rhythmic style and with an important bioclastic contribution. The top of this sequence is composed by a thick calcareous series (Pl. III, Fig. 3). The bioconstructions are medially common in this sector.

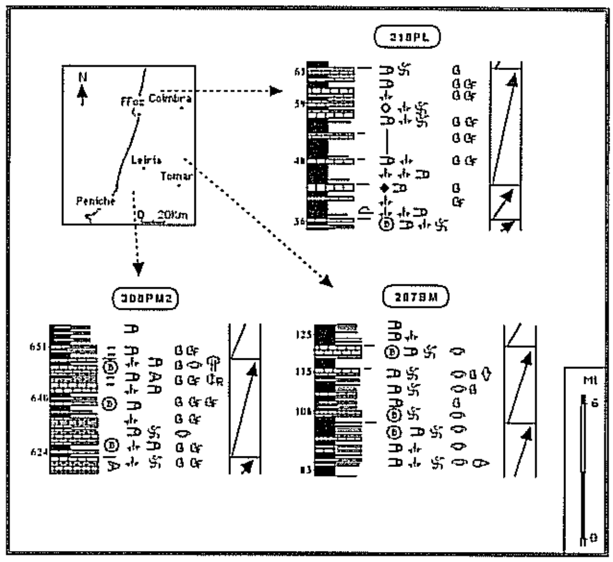

Fig. 9 – MST4B: Facies analysis and macrosequential typology in Cantanhede (218PL, *vide* DUARTE, 1995, Fig. II.6, p. 50), Porto de Mós (308PM2, *vide* DUARTE, Fig. II.41, p. 102), and Alvaiázere (287BM, *vide* DUARTE, 1995, Fig. II.31, p. 89) regions.

Alvaiázere-Coimbra Sector – Despite the large difference in thickness observed in this sector (in Coimbra is three times greater than Alvaiázere region), the marl/limestone alternations are very rhythmic. The asymmetry of the macrosequences is marked by thickening and hardground surfaces at the top of the limestone beds, sometimes with a large density of *Zoophycos*. The bioconstructions are particularly common in the Rabaçal-Alvaiázere band, as well as in the bioclastic facies.

Cantanhede-Figueira da Foz Sector – The rhythmicity of the lutitic marl/limestone couplets is an important feature. The marls are notoriously thicker at the base of the macrosequences. The tops of these sequential units sometimes show hardground and ferruginous surfaces. In this area we did not find any type of bioconstructions.

The basal part of MF: In all the sections studied, the base of MF shows some differences in the vertical facies association. In the southeast part of the basin (Alvaiázere-Porto de Mós region) the series are characterized by a strong unfossiliferous marly infill (Pl. III, Figs. 3 and 4). The Rabaçal-Coimbra sector consists of white decimetric limestones (bioclastic wackestones very rich in filaments), that alternate with marls, particularly thick in the Coimbra region. In Cantanhede--Figueira da Foz sector the series are very rhythmic not being detected any sedimentary rupture between ME2 and MF. In this case, the marl/limestone bedding couplets, very typical of the upper part of ME2, show in the MF the same type of facies association and rhythmic structure. The bioturbation is an important characteristic of limestone facies.

The widespread development of siliceous sponges buildups, very typical of MST4B, are not observed in MF.

TOMAR SECTOR

Along the length of national highway n° 526, between Tomar and Ponte de Milheira, it is possible to make up a series of partial sections (*vide* Duarte, 1995; Figs. II.34 to II.37), whose lateral and vertical integration shows a thickness of about 70 meters for all the series.

In this region the sedimentation during the Late Liassic show individual aspects, being very condensed and characterized by a strong bioclastic infill. The sequential analysis shows the following four depositional sequences (Fig. 10).

MSTT1 Unit (around 1,5 m): To the bioclastic dolomitic limestones of the top of MD follows a small sequence of yellow-brownish marls with few centimetric marly limestones (Pl. III, Fig. 5). These marls are very rich in silty quartz grains. Lateral equivalent to MST1 and MSTP1, MSTT1 shows a macrofaunistic component distinct from those other units by the rarity and very low diversity.

MSTT2 Unit (about 30 m): The facies association shows a bioclastic limestone and thinner (centimetric) bioclastic marl alternations. The base of this unit is characterized by centimetric layers of micritic limestones that alternate, in practically the same proportion, with brown-greyish coloured marls. The nodular appearance of the bedding shows macroscopic similarities with MST2A. Towards the top, there is an evident de-

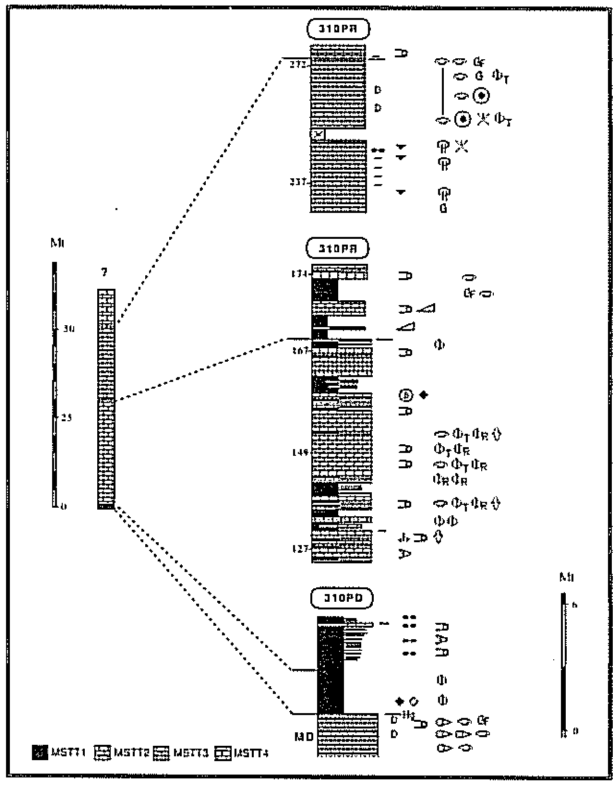

Fig. 10 – Sequential units in Tomar sector. Facies analysis in each depositional sequence (detail *in* Duarte, 1995, Figs. II. 34 to II.37).

crease in marly expression at the same time that there is a gradual increase in calcareous lithologies, with a clear prevalence of bioclastic facies (wackestone to packstone). The ammonoids are very rare in all the unit, but the benthic organisms are very rich with abundant rhynchonellids and terebratullids. The bivalves occurs regularly in MSTT2, being less common the gastropods and crinoids. *Planolites* and *Thalassinoides* are the most obvious trace fossils but they are rare.

MSTT3 Unit (around 22 m): It represents a regressive stacking, reflecting a progressive energy gain in the depositional environment. The marls are restricted to the base of the unit, where they alternate with marly and micritic limestones (around 3,50 m). This body evolves rapidly to a calcareous bioclastic series (Pl. III, Fig. 6), reaching at the top biosparitic limestone facies, slightly dolomitized.

At the base, the macrofaunal record shows rhynchonellids and, less common, bivalves, ammonoids and gastropods. The middle part of MSTT3 is heavily bioclastic but poor in macrofauna. The top is very rich in bivalves, echinids spines, crinoids, gastropods, rhynchonellids, terebratullids and ahermatypic corals. Some Hammatoceratids occur in the bedding interfaces. The ichnofauna is always poor but *Thalassinoides* is common at the bases of limestone beds.

MSTT4 Unit (> 10 m): The macroscopic differentiation between the top of **MSTT3** and the base of **MSTT4** is not clear. The lithofacies of the base of **MSTT4** are characterized by an association of white micritic limestones in decimetric beds. Towards the top the series become more bioclastic with rare ammonoids and large diversity and abundance of bivalves and terebratullids. The top of **MSTT4** is not easily recognizable owing to the absence of uninterrupted outcrops.

PENICHE SECTOR

Despite the good knowledge of the toarcian sedimentary organization and evolution in this sector (WRIGHT & WILSON, 1984; GUERY, 1984), with special autogenetic sedimentary conditions, however we observe large similarity with the sequential style admitting to the others sectors of the basin. The series is well exposed along the cliffs of Peniche peninsula and begins in the small bay of Abalo beach (Fig. 11).

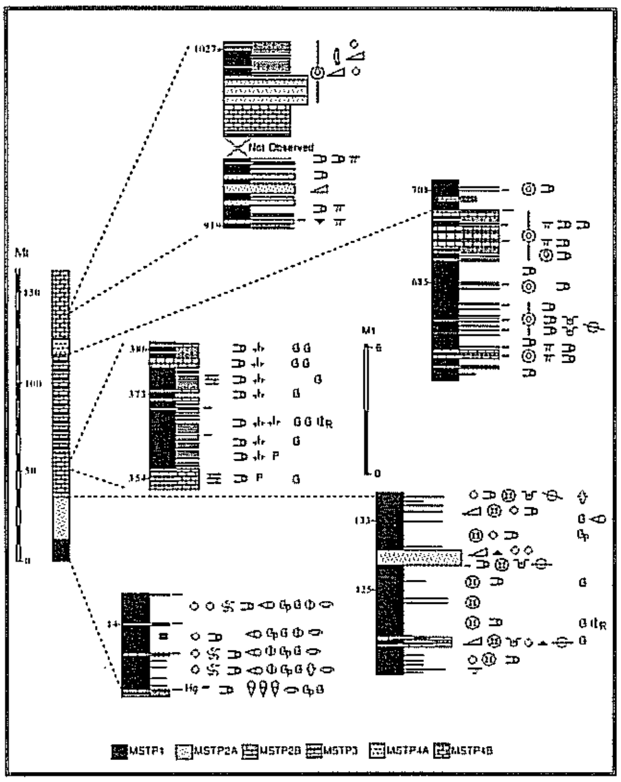

Fig. 11 – Sequential units in Peniche sector. Facies analysis in each depositional sequence (detail *in* DUARTE, 1995, Fig. II.45).

MSTP1 Unit (12,5 m): The facies associations correspond to a small rhythms marl/limestone (Pl. IV, Fig. 1). The centimetric marly limestones (micritic and argillaceous bioclastic wackestones) alternate with decimetric grey-greenish marls, sometimes micaceous and laminated. Like **MST1**, the great particularity in this unit is the diversity and abundance of belemnites, tiny brachiopods, pyritous ammonoids, and bivalves. The ichnofacies is composed by tubular ferruginous burrows, *Planolites* and *Zoophycos*.

MSTP2A Unit (around 24 m): It corresponds to the amplitude recorded of lenticular siliciclastic facies (Pl. IV, Figs. 2 and 3) which interstratify into a marly limestone series, macroscopically similar to that observed in **MSTP1**. The lithofacies are very diversified including greyish marls and micritic limestones, calcareous sandstones/sandy limestones, subarkosic microconglomerates, silty to sandy micaceous marls, and bituminous black shales (milimetric scale). The sandstone facies (26 horizons), with variable thickness (≤ 75 cm) show typical turbidite features (WRIGHT & WILSON, 1984). They are lenticular and show normal grading and, sometimes, load and convolute bedding. The more clastic facies show large quantities of quartz, orthoclase, microcline, sodic plagioclase and micaceous minerals. The base of beds is frequently sharp and can show horizontal tubular burrows and erosive structures like tool and groove-casts (these last with a corrected trend of approximately N 80-130) (Pl. IV, Fig. 3). The top of the beds surfaces are generally very irregular.

The fossil record is very poor. Ammonoids and brachiopods occur in association with more lutitic facies. The ichnofacies is composed by pyritized tubular burrows and *Chondrites*.

MSTP2B Unit (around 30 m): The top of **MSTP2A** is marked by the last truly detritic event of the Lower Toarcian. The series which distinguishes the base of this unit is monotonous, being formed by centimetric marly limestones, finely quartzose and micaceous, which alternate with grey marls in decimetric beds (Pl. IV, Fig. 2). Such as **MST2B** (Porto de Mós and Coimbra-Figueira da Foz sectors), towards the top, a pronounced and gradual increase of the micritic phase is noticeable, by means of the piling up of nodular limestones in beds which rarely exceed a thickness of one decimetre. Pyritization, normally associated with bioturbation, is a dominant feature. Despite the strong degree of bioturbation, the benthic macrofossils are very rare (only some brachiopods), but the ammonoids are common. The ichnofacies consists of *Chondrites* and ferruginous tubular burrows.

MSTP3 Unit (around 54 m): After the rhythmic succession represented by thinly stratified marly limestone beds (top of **MST2B**), an inversion occurs with accumulation of thick bedded marls which alternate with decimetric marly limestones. Progressively, the alternations give place to gradually coarser peloidal oolitic facies (grainstones), in centimetric beds (Pl. IV, Fig. 4), sometimes fining upwards, which alternate with gray-greenish marls in gradually thinner beds. This tendency represents styles of macrosequential organization which configurates its polarization through the overlaying of calcareous beds, gradually coarser and thicker. In the more lutitic segments it is noteworthy the occurrence of mineralized carbonaceous wood remains and small pyritized concretions.

This sequential evolution is an evidence as well in the microfacies. The lithofacies evolve from micrites/mudstone and bioclastic wackestones to oopelsparites and oosparites grainstone (Pl. IV, Fig. 5). Detritic material follows this evolution; particles are fundamentally quartzose, being feldspars (orthoclase and sodic plagioclase) less frequent and micaceous minerals rare. Together with a few organoclasts (mainly echinids and brachiopods) terrigenous elements very often form the nucleus of the oolites.

The oolitic facies show a very regular thickness, with sharp bases, sometimes with cylindrical burrows, gutter and groove-casts. The top surfaces are very irregular, ondulated and mainly bioturbated.

In this unit the macrofauna is very poor. Associated to the marly facies of the base, the ammonoids are particularly common. At the top, some levels show tiny brachiopods, crinoids and rare ammonoids. The ichnofauna shows two assemblages types: *Zoophycos* and ferruginous tubular burrows in the lower part of this sequence, with the first exclusive of the lutitic facies; *Skolithos* preferentially associated to the thinning beds of oolitic limestones, at the top.

MSTP4A Unit (9 m): Few are the lithic and sequential differences between the base of **MSTP3** and this unit. **MSTP4A** starts with a thick grey marly series (5.7 meters), with centimetric oolitic limestones (oosparites/grainstone, detrital and very poorly sorted). Towards the top, the marls gradually become less expressive, acquiring a strong carbonate content and originating a thickening upwards structure of its oolitic facies. This characteristic is followed by an increase of the detritic fraction, gradually coarser, where small quartz pebbles (over 1 cm in diameter) are not rare. The top of the limestones are frequently very irregular; the bases show cylindrical burrows and groove-casts (paleocurrents with W-E trend).

The macrofauna is very rare. The ammonoids are scarse showing remobilization and abrasion surfaces. The ichnofacies is characterized by small ferruginous and cylindrical burrows assemblage; *Zoophycos* is rare and occurred only in lutitic facies.

Analyzing the vertical style of this unit, with a strong marly component at the base, the similarity with the sequential articulation of **MST4A** is notorious.

MSTP4B Unit (> 80 m): The upper levels of the Peniche section are practically devoided of marly intercalations, and great lateral thickness variations are present in the various lithofacies. These are composed by fine oolitic, bioclastic or sandy limestones and calcareous sandstones, occasionally very coarse, reaching locally the conglomeratic pole. To the top it is notorious the thickening trend of the limestone beds. The facies are dominated by oolitic sandy limestones with planar cross bedding (Pl. IV, Fig. 6), channeling and by decimetrical crinoidal sandy limestones. These characteristics are more obvious at the top of this unit.

The macrofauna and the ichnofauna are typical of a very littoral environment. The first is composed by bivalves, echinids, crinoids and coral fragments; the ichnofossils consist of *Skolithos* and horizontal tubular burrows. Due to the great vertical extension of this unit, and despite the absence of biostratigraphic markers, it is admitted that the top of **MST4B** is of Aalenian age.

TOARCIAN-LOWER AALENIAN DEPOSITIONAL PHASES: GENETIC INTERPRETATION

In the sedimentary modeling, the more important parameters can be resumed to three variables: sedimentation rate, accommodation and time. Naturally, each one of these variables will include various others. For example, the accommodation (Jervey, 1988) will be the result between the eustatic oscillations and the vertical movements of the crust (subsidence and uplift) effects. These two parameters are obviously associated to the production carbonate and to the terrigenous supply rates, the fundamental variables in the carbonate platform modeling (Kendall & Schlager, 1981; Read, 1982; Burton *et al.*, 1987; Bice, 1988; Bosence & Waltham, 1990). The conjugation of these ones controls the facies distribution and the internal architecture of the platform.

The strong argillaceous continental supply observed in the series, in all the Lusitanian Basin, seems to be the most responsible for the volume, durability and wideness of the platform. The depositional rates, calculated for the several sectors, show positions in the basin with more accumulation, controlled, obviously, by subsidence.

The integration of all the information (facies, sequential evolution, ichnofossils, paleontological evolution, clay minerals, geochemistry) (Fig. 12), allows to demonstrate the

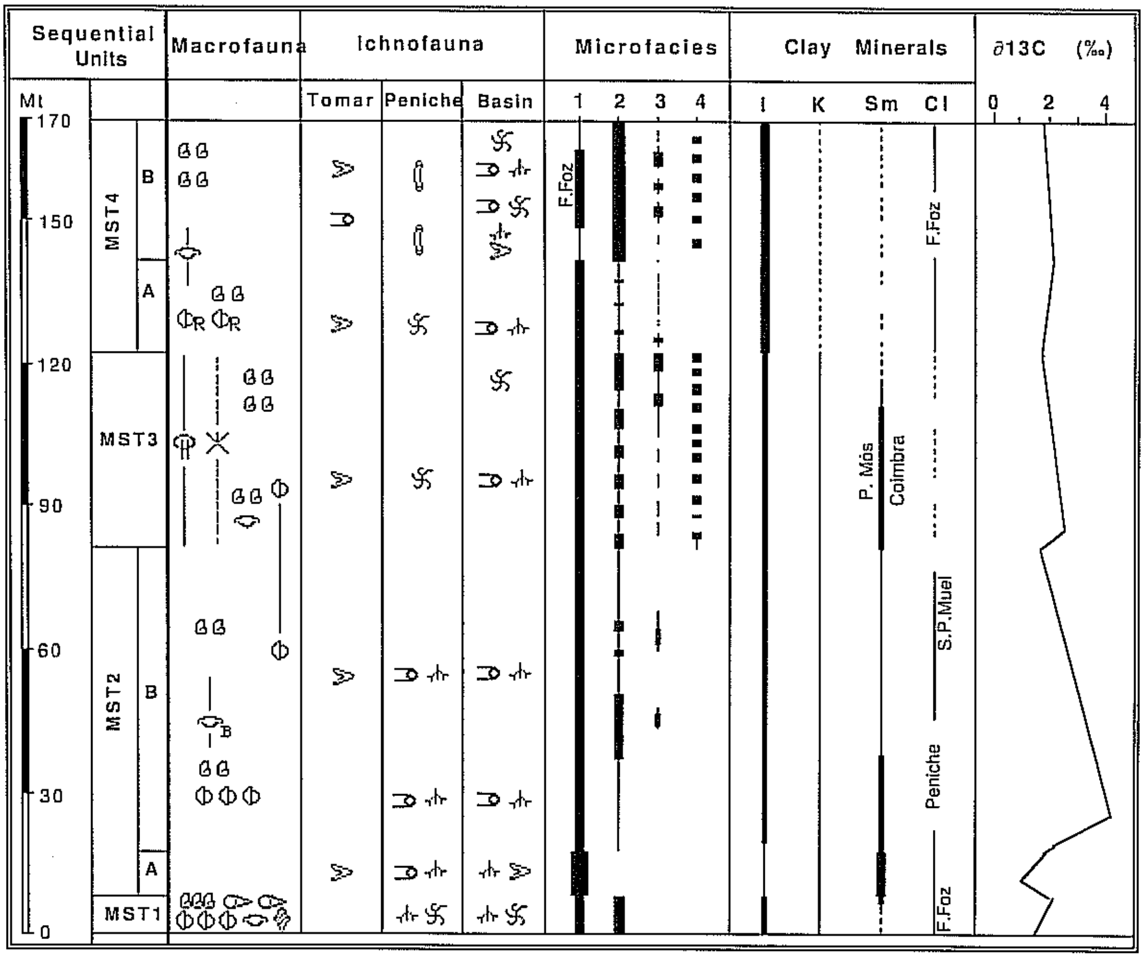

Fig. 12 – Sedimentary general evolution in the Toarcian-Lower Aalenian series of the Lusitanian Basin. Macrofauna (see legend in Fig. 4), Ichnofauna (see legend in Fig. 4), Microfacies (1 - mudstones, 2 - biomicrites and biopelmicrites/wackestone, 3 - biomicrites and biopelmicrites/packstone, 4 - Boundstone), Clay Minerals (I - illite, K - kaolinite, Sm - smectite, Cl - chlorite) and Carbone Isotope Evolution (smoothed curve for Rabaçal region, *vide* DUARTE, 1997).

evolution of the Toarcian-Lower Aalenian sedimentary phase (Fig. 13). It is possible to conclude that the deposition has occurred in a carbonate platform, dipping towards west. According to the mesosequential characterization, the basin is subdivided in three distinct sectors: Tomar, Peniche and the Alvaiázere-Coimbra-Figueira da Foz-Porto de Mós sector. If in this last sector, the facies analysis and the sequential evolution allows to configure for the Toarcian of the Lusitanian Basin, a distal carbonate platform (homoclinal ramp) the other two sectors show particular morphologies.

Tomar Sector – During all the Lower and Middle Jurassic, the sequential evolution of the facies in this region is typical of a shallow carbonate depositional environment. In the Toarcian, the facies show characteristics that tipify a bioclastic carbonate platform (very rich in benthonics organisms), being the proximal part of a homoclinal ramp, well developed towards NW.

Considering the geographic restriction of these facies (only in the southeast border of the basin) and the dolomitic feature of the series in the Sesimbra-Serra de Arrábida sector (with sedimentary gap of Middle and Upper Toarcian), the shoreline at this point would be located in the east of these regions occupying a space far beyond the present limit of the basin. In this case, the facies of Tomar can correspond to the distal part of an inner ramp setting.

Peniche Sector – The great depositional particularity of this region corresponds to the strong siliciclastic and oolitic resedimented accumulation observed in the Peniche section. The influx of these sediments seems to be related with turbiditic mechanismes in the way they are interpreted by WRIGHT & WILSON (1984). All this is the result of the vertical faulting of the Berlengas block, elevated during the Upper Liassic. This morphologie will be the western boundary of the homoclinal ramp (*vide* WATKINSON, 1989).

In this context of homogeneous facies variations, the application of the sequential stratigraphy concepts are very restrictive, particularly, the recognition of the system tracts. However, all the information about the Toarcian-Lower Aalenian series allows to present the first paleobathymetric curve. This one, show the relative bathymetric changes resulted by the vertical facies association observed in each sedimentary infilling phase (Fig. 13).

The Basal Toarcian Transgression (Polymorphum Zone)

To the calcareous facies of the top of MD follows in all the basin a predominantly argillaceous infill, composed by marl/marly limestone alternations (Fig. 14), organized in decimetric-scale elementary sequences, with remarkable occurrence of pyritized ammonoids, tiny brachiopods, belemnites, bivalves and *Zoophycos*. The depositional settings of Tomar (MSTT1), Peniche (MSTP1) and Coimbra (MST1), show a large increase of thickness (1,5 to 20 m) with strong condensation in the proximal region (Fig. 14).

Despite this flooding phase the facies suggest some restriction in the sedimentary conditions, giving the organic matter and the ferruginous nodules occurrence, particularly rich in the sediments. This depositional environment is characterized by very slow rates of sedimentation, despite the large differences in the thickness observed in all the basin.

Instability During the Levisoni Zone

The sedimentary records (MST2A and MSTP2A) known in all the Basin, put the Early Levisoni Zone like a time of great hidrodynamics instability. MST2A corresponds to a small succession (< 10 m), very poor in macrofauna, of marls and calcilutitic to calcarenitic limestones in centimetric beds (Fig. 5). By attentive observation of this stratonomy, it is possible to identify a great multiplicity of macrofacies and microsequential patterns, that represents a typical sequential develop-

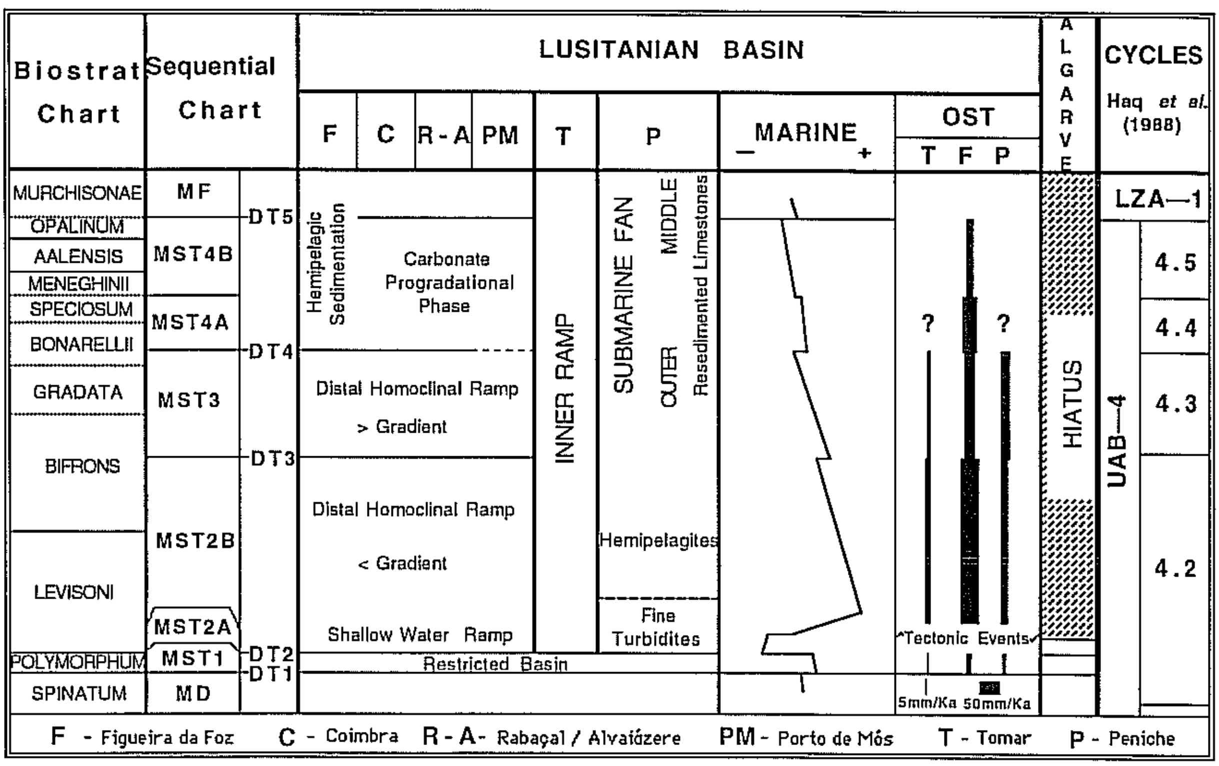

Fig. 13 – Biostratigraphy, unconformities and mesosequential evolution in the Toarcian of the Lusitanian Basin. Sedimentary models (Peniche region according to WRIGHT & WILSON, 1984), paleobathymetric curve, observed sedimentation rate (OST) and correlation with Algarve basin and the third order eustatic cycles (HAQ *et al.*, 1988).

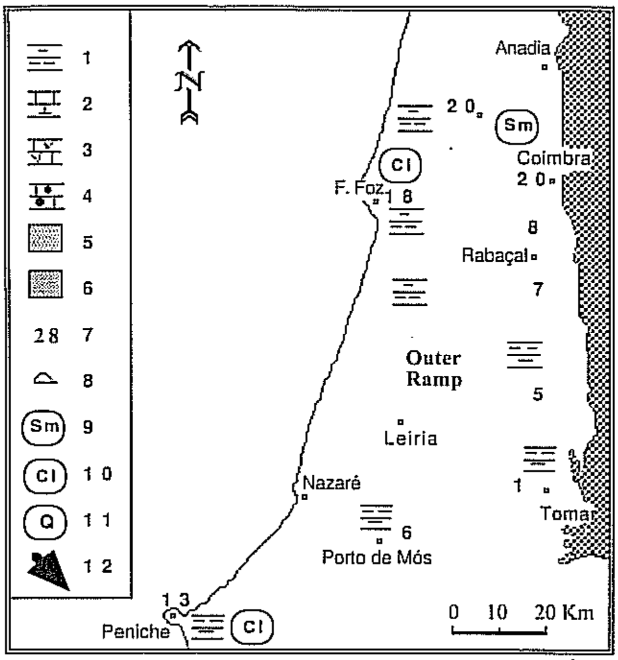

Fig. 14 – Facies and paleogeographic map during **MST1** phase (Polymorphum Zone). 1 - Marly facies; 2 - Marly-limestone facies; 3 - Bioclastic facies; 4 - Detrital and resedimented oolitic facies; 5 - Emerged block; 6 - Hesperic Massif (partially submerged during the Upper Liassic); 7 - Thickness (meters); 8 - Mud mounds and bioconstructions; 9 - Smectite; 10 - Chlorite; 11 - Quartz; 12 - Paleocurrents.

ment of shallowing, with interposition of tempestitic and/or turbiditic processes in a ramp open towards west (DUARTE & SOARES, 1993a, b). In Peniche, it occurs a very coarse detrital series that interstratifies hemipelagic lutitic marl/limestone alternations (**MSTP2A**, Fig. 11), a more thick unit (around 24 meters) that the equivalent **MST2A**. The sandy facies show typical turbidite features (WRIGHT & WILSON, 1984) with sole marks to indicate paleocurrents from WNW. These sediments seem to correspond to gravitic flows (WRIGHT & WILSON, 1984), naturally related with the Berlengas block uplift and denudation (HALLAM, 1971; WRIGHT & WILSON, 1984; DUARTE, 1995).

Considering the genetic discussion of WRIGHT & WILSON (1984) as valid, we have in the basin and during the Early Levisoni Zone, a shallowing phase with the definition of a submarine fan system tract, in a straight relation with the Berlengas igneous block. The lowstand of the deposition is also confirmed by the low values of $\partial^{13}C$ (Fig. 12), verified in **MST2A**, indicative of less marine influence (*vide* DUARTE, 1995, 1997). The emerged block is also responsible by the supply of chlorite, present in the argillaceous sediments of **MSTP2A**, but absent in the clay minerals associations of the equivalent **MST2A** (*vide* discussion in DUARTE, 1997).

Small anoxic episodes (black shales) are also recorded in the Peniche section. These anaerobic conditions, with reflex in the benthic life, are contemporaneous of the anoxic events recorded in northwest of Europe (JENKYNS, 1985, 1988).

Hemipelagic Deposition During the Uppermost Levisoni-Bifrons Zones

MST2B show a sequential organization composed by marl/limestone alternations (Fig. 15), locally with a very rhythmic style (DUARTE, 1994) and always with a necktonic and benthic faunal interposition. The greater marly expression of the base of **MST2B** (also observed in **MSTP2B**), with very rich levels in rhynchonellids, terebratullids (these, fundamentally abundant in the Coimbra-Tomar band), and pelagic bivalves, is interpreted like a deepening phase, where the sedimentation seems to be specially rapid caused by high accommodation rate. This evolution is well confirmed through the carbone isotope values that shows a positive incursion at the base of **MST2B** (more than + 4,00 ‰) (*vide* DUARTE, 1995, 1997).

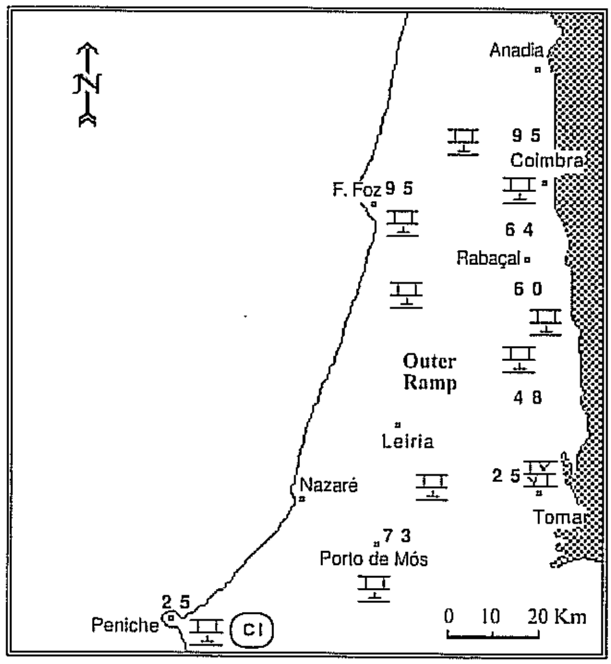

Fig. 15 – Facies and paleogeographic map during MST2B (MSTT2 and MSTP2) phase (Levisoni-Bifrons) (see legend *in* Fig. 14).

In Porto de Mós-Peniche sector it is notorious, at the top of **MST2B** (and **MSTP2B**), the strong carbonate infill, maximum indicative of a regressive phase. In Tomar, the micritic series of the lower part of **MSTT2**, is followed by a bioclastic infill, very rich in brachiopods and echinids, typical of a shallow carbonate ramp (inner ramp). Although, the Berlengas igneous massif persists to carry out influence in the deposition at Peniche with silty quartz and micaceous sediments.

In the Algarve basin and according to MANUPPELLA *et al.* (1988), this infilling phase corresponds to an erosive episode, responsible by a large hiatus between the Middle Toarcian and the Late Aalenian.

Bioconstructions Development in the Ramp

Since the top of the Bifrons Zone the basin shows a mud infill poor in carbonates (base of **MST3**). Subsequently, the vertical evolution of the facies shows, just to the top, a very rhythmic asymmetric style with marl/ /limestone decimetric to metric alternations. The development of small bioherms, mud-mounds and small syndepositional structures (like slumping and lenticular bioclastic facies) in the eastern sectors, and their decreasing trend (quantity and volumetrical expression) observed towards west (Fig. 16), draw a change in the homoclinal morphology, with an increasing in the ramp gradient between those ones. In this paleotopographic configuration, the meridional tectonic axes of Arunca-Montemor (SOARES *et al.*, 1993a) seems to exercise some preponderance.

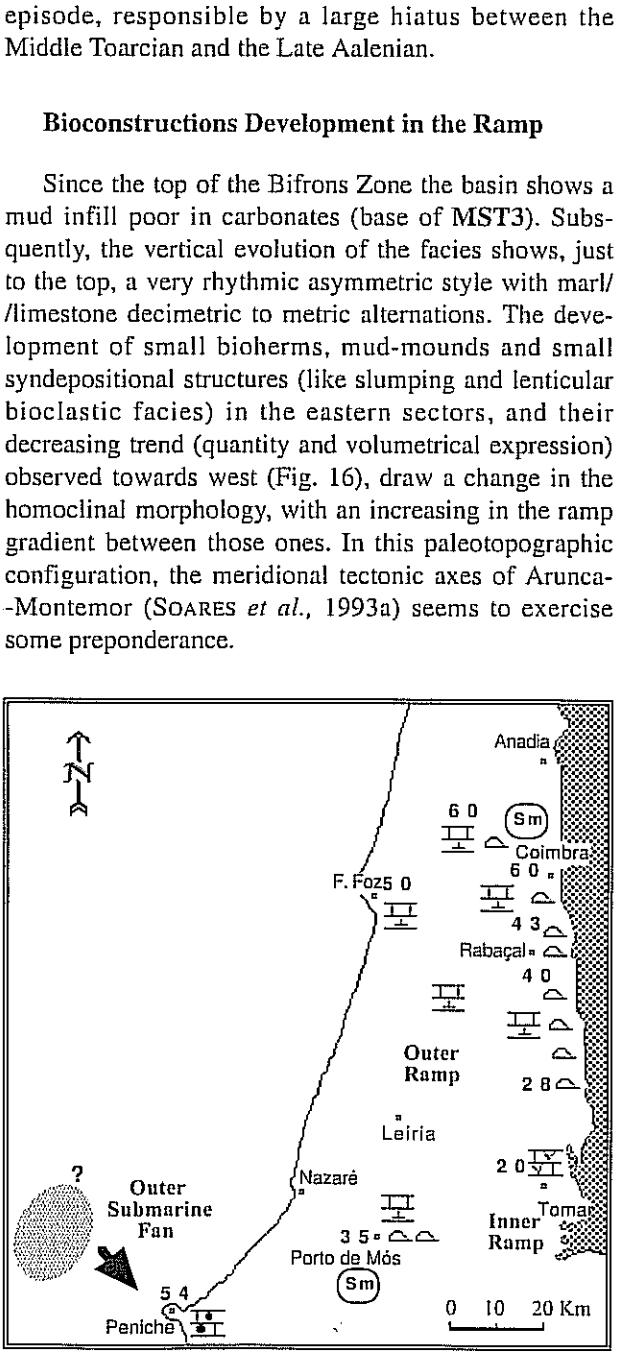

Fig. 16 – Facies and paleogeographic map during **MST3** (**MSTT3** and **MSTP3**) phase (Bifrons-Bonarellii) (see legend *in* Fig. 14).

The regressive trend of this phase, is well recorded at the top of **MSTT3** (Tomar) and **MSTP3** (Peniche). In Tomar the facies are predominantly calcareous, very bioclastic, with typical shallow-water benthic associations (corals, large bivalves, echinids, brachiopods and gastropods). In Peniche the sequence is composed by a resedimented sandy and oolitic limestones to prove, according to WRIGHT & WILSON (1984), the evolution of hemipelagic to outer submarine fan environments (Fig. 16). The resedimentation phenomena, well observed in the microfacies (ooids, lumps) suggests that, above the Berlengas igneous block it has developed a shallow carbonate platform (WRIGHT & WILSON, 1984). This idea is well corroborated by the clay minerals distribution, where it is notorious the absence of chlorite after the base of **MSTP3** (DUARTE, 1997).

The Upper Toarcian to Opalinum Regressive Phase

At the base of the Upper Toarcian it begins to draw a depositional differentiation in the basin that seems to be the prediction of an important carbonate progradational phase. This stacking pattern must have had its culmination during the Upper Bajocian/Lower Bathonian (SOARES *et al.*, 1993a; HENRIQUES *et al.*, 1991) through a dystally steepened ramp creation (AZEREDO, 1988, 1993; WATKINSON, 1989).

The strong argillaceous input at the base of this infilling phase (**MST4A** and **MSTP4A**), corresponding to a deepening which was the result of an accommodation increase, developed a small transgressive system tract, very rich in tiny brachiopods. With the exception of Figueira da Foz section, the fine detrital sediments show just to the top of the megasequence (top of **E2** in SOARES & DUARTE, 1997), an argillaceous association composed almost exclusively by illite (DUARTE, 1997).

With **MST4B**, the sedimentation returns to a calcareous domain, with rhythmic sequential styles (from the elementary to the macrosequential scale). The occurrence of asymmetric mud-mounds only in the East, seems to prove a carbonate ramp with a gentle slope creation. In the west (Figueira da Foz and Cantanhede) standing out, in the outcrops, a hemipelagic deposition, through a very regular marl/limestone rhythmic alternations. The regressive trend of **MST4**, much less obvious in this distal sector, is well preserved in the **MSTP4B** coarser sandy carbonate facies and by their macrofaunal contents, typically of shallow waters characteristics. According to WRIGHT & WILSON (1984), the depositional architecture in Peniche corresponds to an outer to mid submarine fan evolution (Fig. 17).

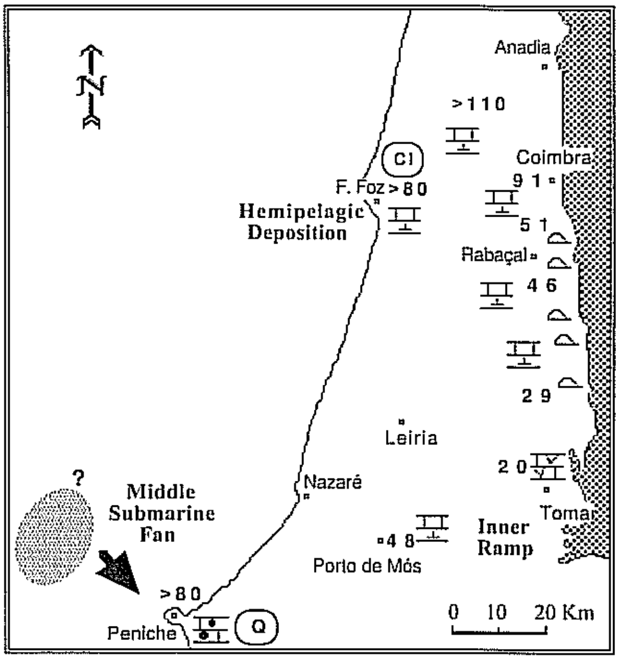

Fig. 17 – Facies and paleogeographic map during MST4 (MSTT4 and MSTP4) phase (Speciosum-Opalinum) (see legend Fig. 14).

UNCONFORMITIES: EUSTASY AND TECTONIC CONTROL

The geographic position of the Lusitanian Basin seems to be a favourable sector to detect the main tethyan and atlantic sedimentary unconformities.

Not being necessarily a direct consequence of eustasy, the equivalence between the unconformities recognized in the basin with others recognized in close basins, allows us to come forward with a global justification of allogenetic nature. It is possible that these abrupt oceanic volume variations may be explained by the oceanic dorsal activity.

DT1 (= DTT1 = DTP1): Intra Polymorphum Unconformity

In the tethyan european and atlantic margins, the Pliensbachian/Toarcian boundary corresponds to an important unconformity responsible by a deepening sedimentary phase (BASSOULLET *et al.*, 1991; BENSHILLI, 1987; CONTINI, 1989; CUBAYNES, 1986; GABILLY *et al.*, 1985; PARKINSON, 1992; PONSOT-JACQUIN, 1992; SADKI, 1992).

Particularly remarkable in the southeast part of the Lusitanian Basin (Tomar-Alvaiázere sector), **DTT1** corresponds to a hardground surface in a bioclastic and dolomitic grainstone. This unconformity tends to disappear in the distal sector of the basin but **DT1** shows therefore a pronounced facies variation. This event is the testimony of a break in the deposition resulting from a transgressive mechanism. The effect of this flooding phase, provokes a decrease in the ramp carbonate production, with consequent deposition of silty-argillaceous sediments. This unconformity is also observed in the west part of the Algarve basin. The calcareous dolomitic facies of the top of Middle Liassic is followed by a fossiliferous series with marl/limestone alternations (*vide* ROCHA, 1976; DUARTE, 1995).

Contrarily to the Exxon eustatic curve (HAQ *et al.*, 1988) that shows inversion in the Spinatum Zone (top of the third-order cycle UAB 4.2), Hallam's curve (HALLAM, 1988) shows a rapid eustatic inversion, with deepening during the early Polymorphum Zone.

DT2 (= DTP2): Polymorphum-Levisoni Unconformity

The basal part of the Levisoni Zone (Falciferum) is known in other points of the Central Europe as an important time of anoxic events, resulting from a widespread deepening phase. This largest paleobathymetric modifications recorded in the atlantic and tethyan regions, is responsible for strong changes in the biological record (BAUDIN, 1989; BASSOULLET & BAUDIN, 1994), also with notorious reflex in the Lusitanian Basin (MOUTERDE & RUGET, 1984).

In spite of the Hallam and Exxon eustatic curves (HALLAM, 1988; HAQ *et al.*, 1988) denoting an expressive sea-level rise between the two Zones of the Lower Toarcian, in fact, the sedimentological features of **MST2A** and **MSTP2A** indicate an inverse direction, with abrupt diminution of the paleobathymetry. Contrarily to the eustatic development admitted by these curves, **DT2** is explained by the regional tectonics. In the east, by reactivation of the main meridian or submeridian faults (includes Coimbra fault, Choisinha and Arunca-Montemor alignments; SOARES *et al.*, 1993a) and some transversal alignments parallel to the Nazaré fault. This scheme may explain the large facies changes observed between **MST1** and **MST2** (macrofacies, biofacies, ichnofacies, clay minerals and geochemistry), and the erosive behaviour of this unconformity detected in the Rabaçal region. In the west, with the uplift of the hercynian Berlengas block, responsible by the gravitic supply of siliciclastic material observed at Peniche. These detrital sediments are very similar to the mineralogy of Berlenga granite.

This tectonic phase, generalized to all the basin, shows in the western part of Algarve, a compressive feature like is shown by TERRINHA & RIBEIRO (1995).

DT3 (= DTT3 = DTP3): Intra Bifrons Unconformity

This boundary is located in the Bifrons Subzone (DUARTE, 1991), and it is correlative with some discontinuities recognized in some european basins (CONTINI, 1989; HANZO *et al.*, 1992; REY & CUBAYNES, 1992). Discernible in all the basin, **DT3** corresponds to a great change in the sedimentary regime, resulting from a flooding phase. The high proportion of terrigenous mud and the positive carbon-isotope shift observed in Rabaçal section (DUARTE, 1997) at the base of **MST3**, may to represent a relative sea-level rise. This event is observed in the Exxon eustatic curve (boundary between the third-order cycles UAB 4.2 and 4.3; HAQ *et al.*, 1988). The same is shown by the Hallam's curve (HALLAM, 1988): to the rapid fall, verified in the lowermost of the Middle Toarcian (Bifrons Zone), follows a progressive increase at the base of the Gradata Zone.

DT4 (= DTP4): Intra Bonarellii Unconformity

With a regressive trend, the top of **MST3** shows in eastern part of the basin, a bioclastic level, with a diversified macrofaunal elements (rhynchonellids, bivalves, crinoids, belemnites), which represents an increase in the depositional hydrodynamics. In the proximal sector of the basin (Tomar), the last levels of **MSTT3**, show a phosphatic bioclastic facies with ahermatypic corals (between horizons 49a and 49b of MOUTERDE *et al.*, 1971); towards west, this bioclastic facies disappear laterally, but in all the basin, **DT4** always shows a strong change in the depositional styles. This unconformity seems to occur in the Bonarellii Zone. ALMERAS (1994) recognize in the Rabaçal region a stratigraphic condensed section including the Fallaciosum and Speciosum Subzones.

Basically, **DT4** corresponds to the boundary between the third-order cycles UAB 4.3 and UAB 4.4 of HAQ *et al.* (1988). In this stratigraphic position, Hallam's curve (HALLAM, 1988), shows an eustatic inversion with a gradual fall just to the Late Opalinum Zone.

DT5: Intra Opalinum Unconformity

In all the sectors, **DT5** shows large sedimentological differentiations. The sequential development of **MF** allows us to conclude that the ramp morphology is very heterogeneous.

In the east (Rabaçal-Alvaiázere-Porto de Mós sectors), **DT5** shows an abrupt facies variation, being the basal part of **MF** composed by a micritic series, much more marly in the Alvaiázere region; the top of **MST4B** corresponds, in these regions, to a bioclastic limestones succession with hardground and burrowed surfaces.

In the west (Cantanhede-Figueira da Foz region), the same type of rhythmic marl/limestone alternations of the late Upper Toarcian are observed during all the Aalenian series. **DT5** is marked by strong condensation in the Opalinum Zone and Haugi and Murchisonae Subzones (HENRIQUES, 1992). This sedimentary break is well recorded in the carbone isotope curves, established to the Rabaçal and Porto de Mós sections (DUARTE, 1997). In fact, a positive incursion is observed in this unconformity, which contradicts the gradual decrease trend materialized in all **MST4**.

Globally, **DT5** is synchronous with the UAB-4 and LZA-1 supercycles boundary (HAQ *et al.*, 1988), located between Opalinum and Murchisonae Zones. Hallam's curve (HALLAM, 1988) shows a slight positive incursion of the sea-level during the Middle Aalenian.

CONCLUSIONS

The Upper Liassic of the Lusitanian Basin has predominantly marly-limestone sedimentation. In the Triassic-Upper Callovian sedimentary cycle, the Toarcian-Lower Aalenian series is organized in two large sequences (**ME1** and **ME2**; DUARTE, 1995), separated by a regional tectonic unconformity. **ME1** and **ME2** show a sequential arrangement that is visible all over the basin. Facies analysis and sequence typology of these units allow us to conclude that sedimentation during the Late Liassic developed in a homoclinal ramp, dipping towards the west and controlled by N-S and NE-SW tectonic trends. On the western side of the basin, in straight dependence with the Berlengas igneous massif, terrigenous deposition and resedimented oolitic limestones are developed (WRIGHT & WILSON, 1984).

The use of the allostratigraphic fundamentals allowed the recognition of the main intra Toarcian unconformities (**DT**). This sequential framework was resumed in four main phases of sequential infilling (**MST**). For the Tomar and Peniche regions an individualized nomenclature was applied, considering the particularity of its facies (**MSTT** and **MSTP** respectively).

MST1 (**ME1**) shows a deepening phase with marly deposition, that follows the progradational phase observed at the top of the Pliensbachian. The unconformity of the base of **MST1** is isochronous all over the basin (Polymorphum Zone). The top is bounded by an unconformity (DT2) which, in some sections, appears as an erosive surface. DT2 marks the strongest variation of the facies recorded along the Upper Liassic, being polarized between the Polymorphum and Levisoni Zones.

ME2 shows an evolution consisting of three depositional sequences (MST2, MST3 and MST4), fundamentally identified by their rhythmic alternation style. They are all bounded by regional unconformities (DT2, DT3, DT4 and DT5) which, except for the base, as a result of a global variation of the sea level owing to their similarity with known eustatic curves.

MST2 shows, at the base, an organization of a silty to fine sandy limestone facies (MST2A) as a result of tempestitic-turbiditic mechanisms as well as a generalized phase of shallowing (DUARTE & SOARES, 1993a, b). Laterally, at Peniche, there can be found the first sandy bodies derived from west (MSTP2A). The series evolves to an alternate marl/limestone series (MST2B), quite rhythmic, initially transgressive, and inverting afterwards to a regressive development.

MST3 corresponds to a regressive mesosequence, highly bioclastic at the top. Its individualization is done as bioconstruction with sponges occur, whose lateral distribution enable us to infer a stronger topographic slope. In the western part, there is a resedimented oolitic facies (MSTP3) that gradually shows a filling from outer to middle submarine fan (WRIGHT & WILSON, 1984).

MST4 materializes two distinctive sedimentation phases: at the base, a marly accumulation (MST4A) follows MST3 bioclastic limestones, as available space in the basin (accommodation) increased. For the top there is a progressive return to a carbonate environment (MST4B). The regressive tendency of this sequence is confirmed and is better interpreted in Tomar and Peniche sectors. The latter has a strong bioclastic and detritic sedimentation, gradually increasing (MSTP4), with a notorious migration towards a proximal submarine fan model (WRIGHT & WOLSON, 1984). The top of MST4 (DT5) precedes a marly-calcareous lutitic phase, well visible in the eastern part of the basin.

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PLATES

PLATE I

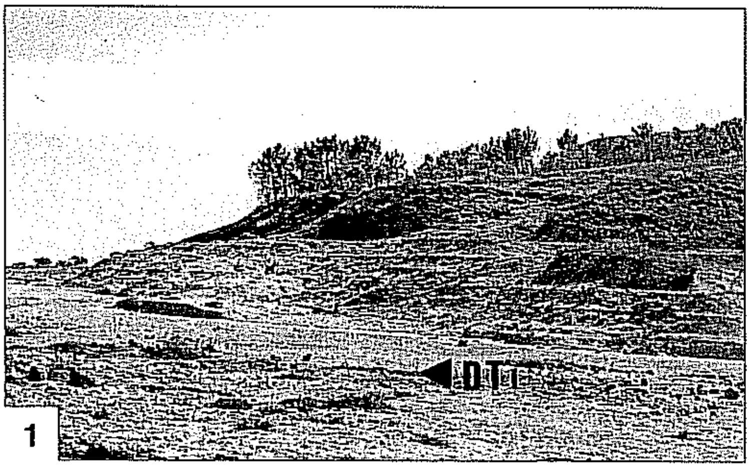
Fig. 1 – Facies variation (**DT1**) between **MD** and **MST1** in the Rabaçal region (251FC section).

Fig. 2 – Marl/limestone decimetric alternations of **MST1** in the Coimbra region (230R section).

Fig. 3 – General view of **MST2A** in the Rabaçal region (251FC section). Note the nodulose aspect of the thin alternations marl/limestone, very typical in all the basin.

Fig. 4 – Microsequential pattern of a limestone bed from **MST2A** (Montemor-o-Velho region): a) sandy limestone with planar cross lamination; b) bioturbated (Chondrites) mudstone.

Fig. 5 – Current-ripples facies at the top of a limestone bed (**MST2A** from the Coimbra region).



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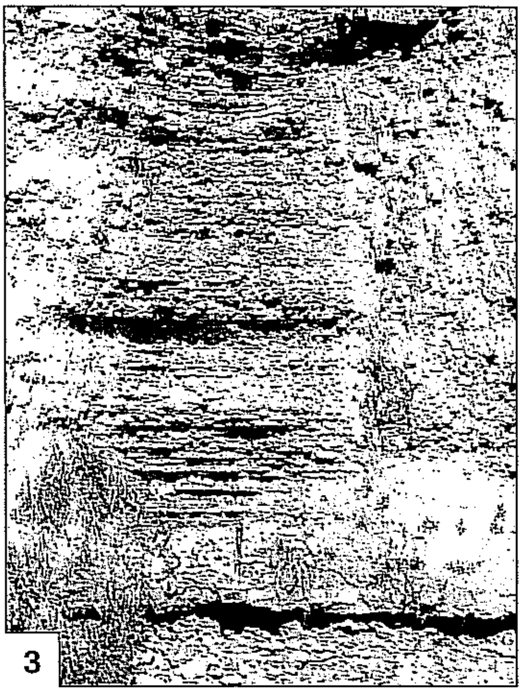

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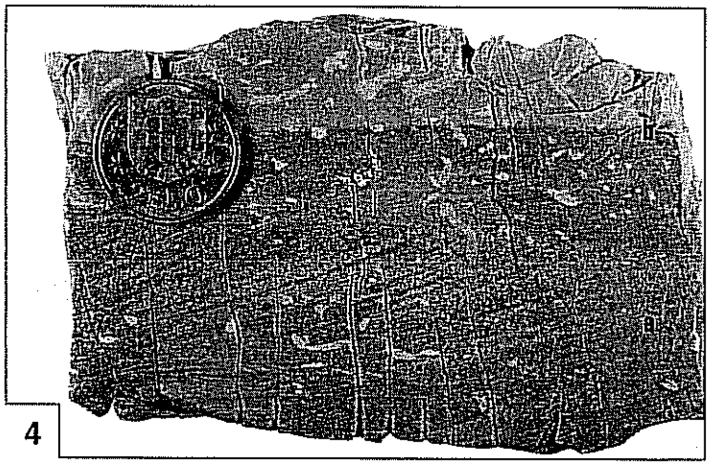

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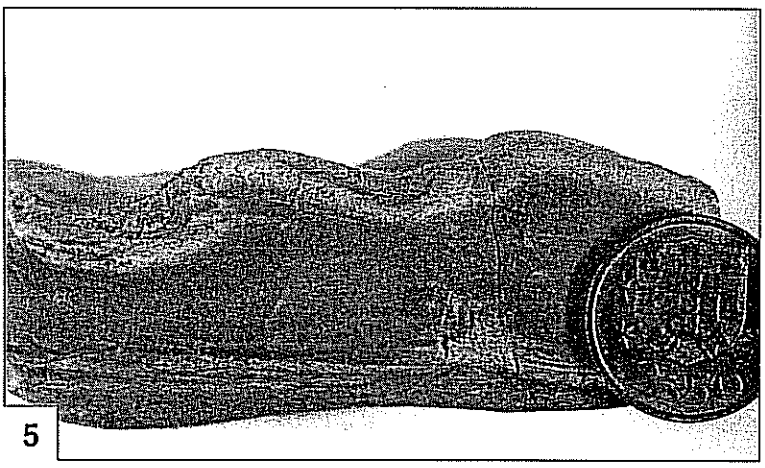

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PLATE II

Fig. 1 – Marl/limestone metric alternations of the base of **MST2B** (Levisoni Zone) in the Rabaçal region (251Z section). This part of the series is very rich in brachiopods.

Fig. 2 – Marl/limestone metric alternations of **MST2B** (Levisoni/Bifrons Zones) in the Coimbra region (219MM section). These levels are very rich in thin-pelagic bivalve shells.

Fig. 3 – Photomicrograph of a biomicrite/wackestone facies with thin-pelagic bivalve shells (**MST2B** from the Montemor-o-Velho region) (amp. 63x).

Fig. 4 – General view of the base of MST3 in the Rabaçal region (251Z section). Note the regular marl/limestone alternations of the series after a strong marly accumulation.

Fig. 5 – Bioherm in the **MST3** series from the Alvaiázere region (287BM section). These bioconstructions show sponges in association with others benthonic organisms.

Fig. 6 – Siliceous sponge spicules in a bioherm macrofacies (**MST3**). Photomicrograph with amp. 32x.

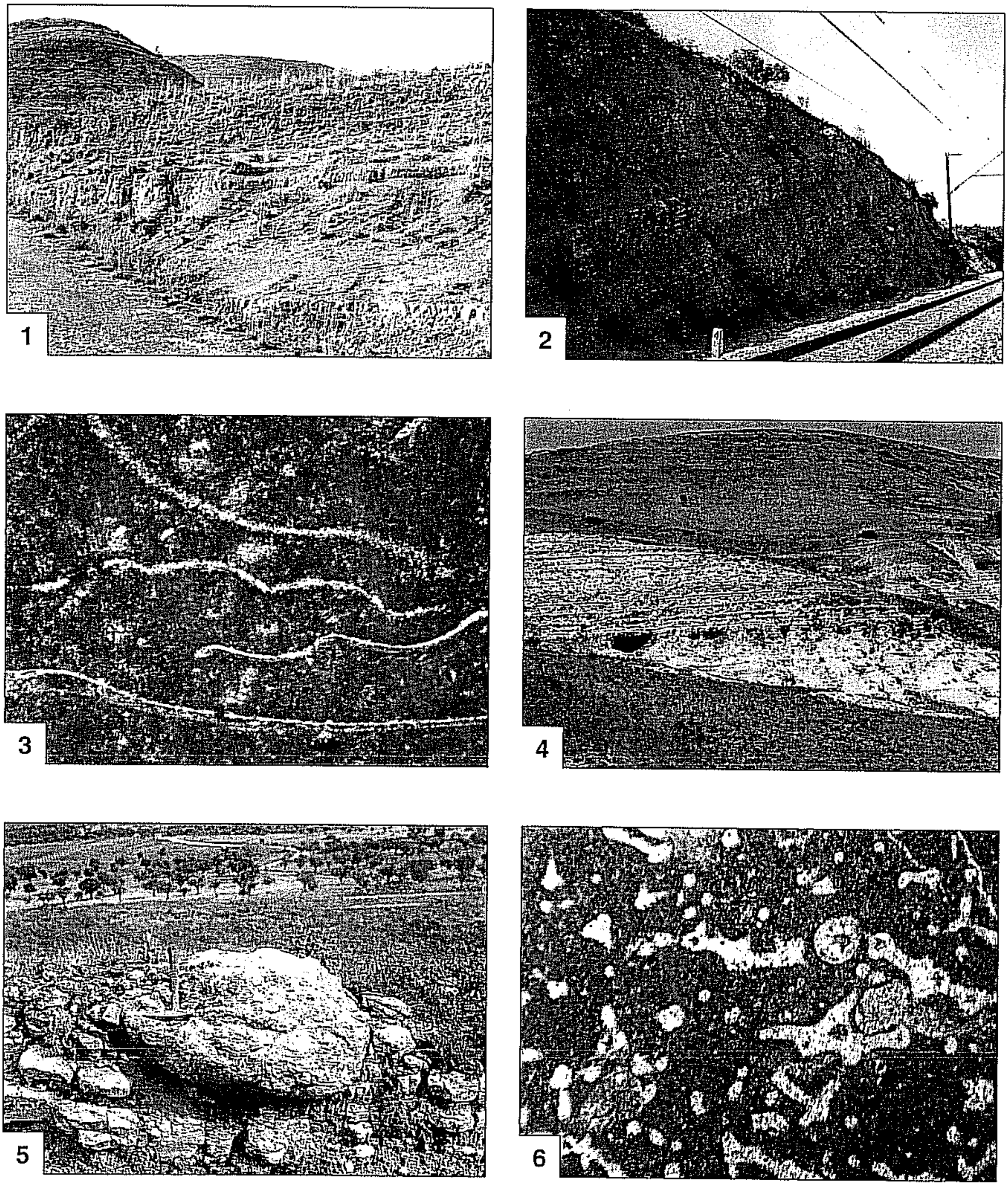
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PLATE III

Fig. 1 – The **MST4A** succession in the Rabaçal region. In all the basin, this unit is characterized by a strong marly accumulation (251Z section).

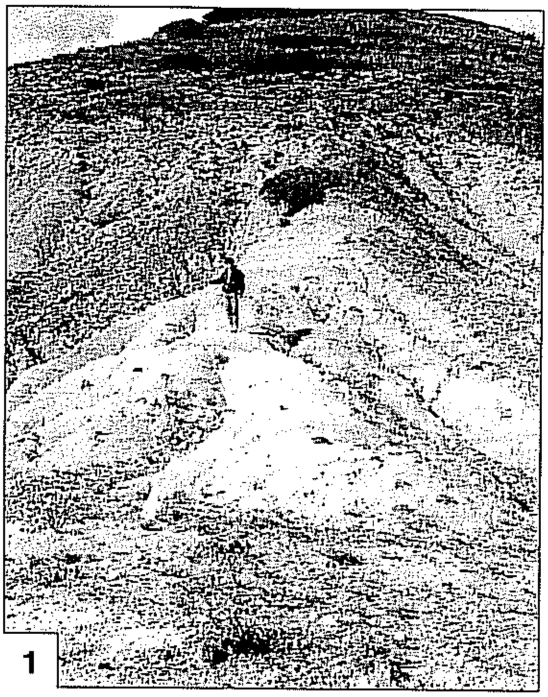
Fig. 2 – Partial view of the macrosequential style of **MST4B** in the Coimbra region (arrows in the macrosequential boundaries) (230B section).

Fig. 3 – Detail of the top of **MST4B** in the Porto de Mós region (308PM2 section).

Fig. 4 – Facies variation (**DT5**) between **MST4B** and **MF** in the Alvaiázere region (287BM section). To the bioclastic limestone facies of the top of **MST4B** follows an important marly accumulation.

Fig. 5 – Unconformity between **MD** and **MSTT1** in the Tomar region (310FQ section). In this sector, the top of **MD** shows a bioclastic and dolomitic facies.

Fig. 6 – Partial view of **MSTT3** with bioclastic limestone facies (biomicrites/wackestone-packstone) (310PR section).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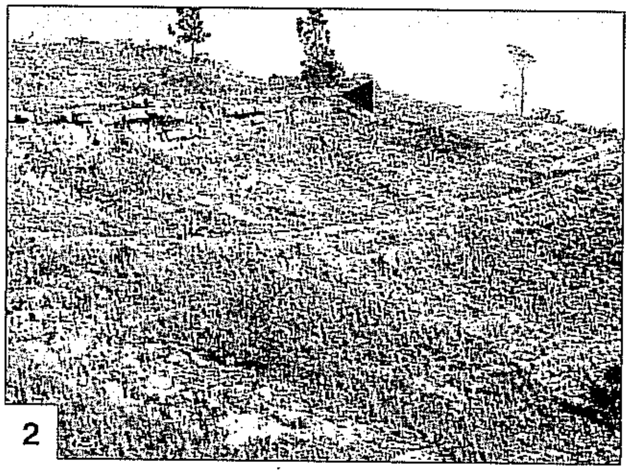
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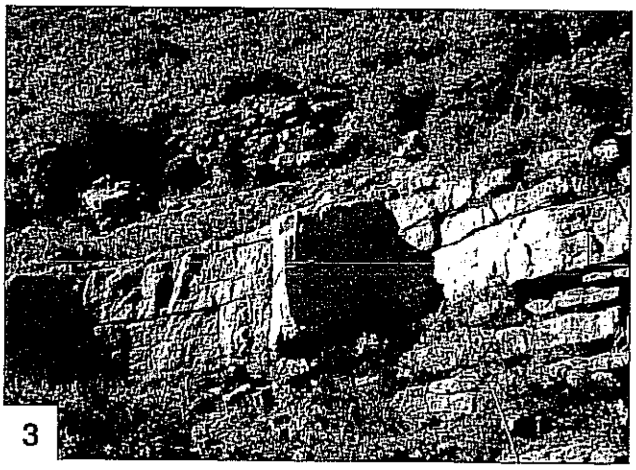
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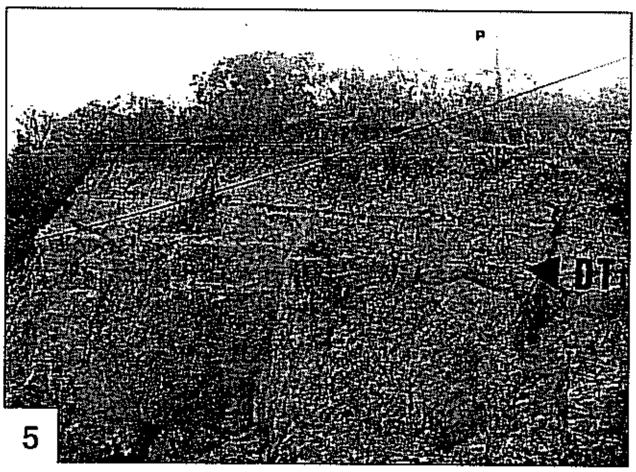

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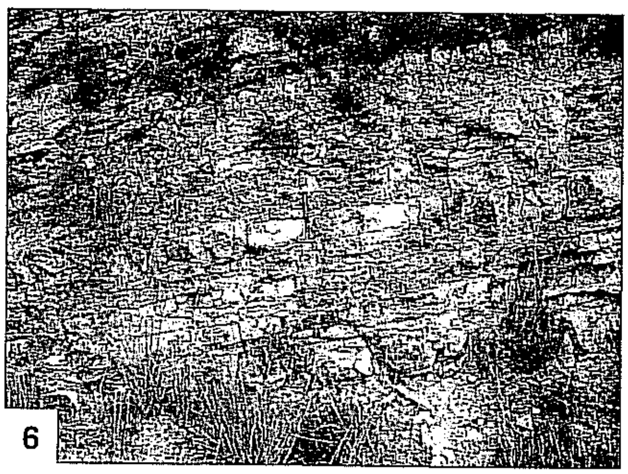
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PLATE IV

Fig. 1 – General view of **MSTP1** (Praia do Abalo, Peniche). Note the strong facies variation between **MD** and **MSTP1** (**DTP1**).

Fig. 2 – Alternations of marls, limestones (wackestones) and lenticular sandy limestone levels (arrows) in the top of **MSTP2A**. Partial view of the base of **MSTP2B** (Praia do Abalo, Peniche).

Fig. 3 – Groove-casts at the base of a sandy limestone level (**MSTP2A**). These sole marks (arrows) show paleocurrents with N80W direction.

Fig. 4 – Partial view of **MSTP3** showing alternations of marls and peloidal oolitic grainstone levels (Baixa do Outeiro, Peniche).

Fig. 5 – Sandy oopelsparite grainstone, typical microfacies of **MSTP3** (amp. 32x).

Fig. 6 – Partial view of **MSTP4**: oolitic sandy limestones with planar cross bedding (Remédios, Peniche).

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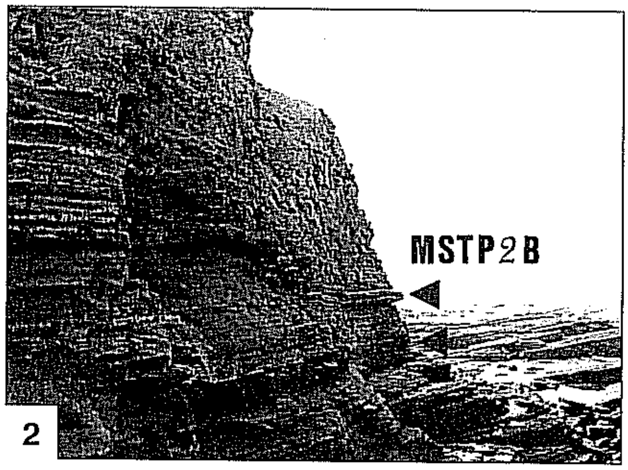

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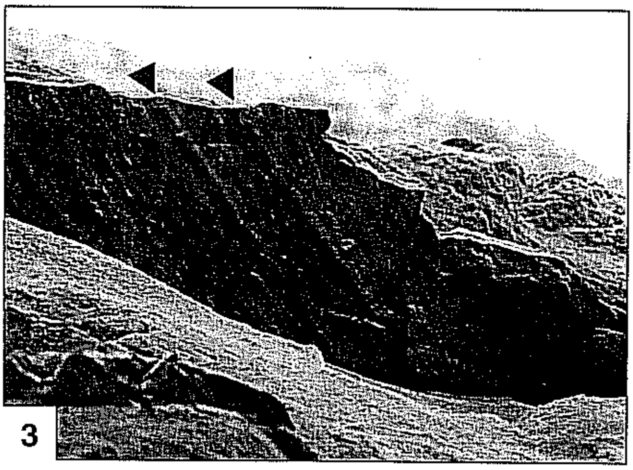

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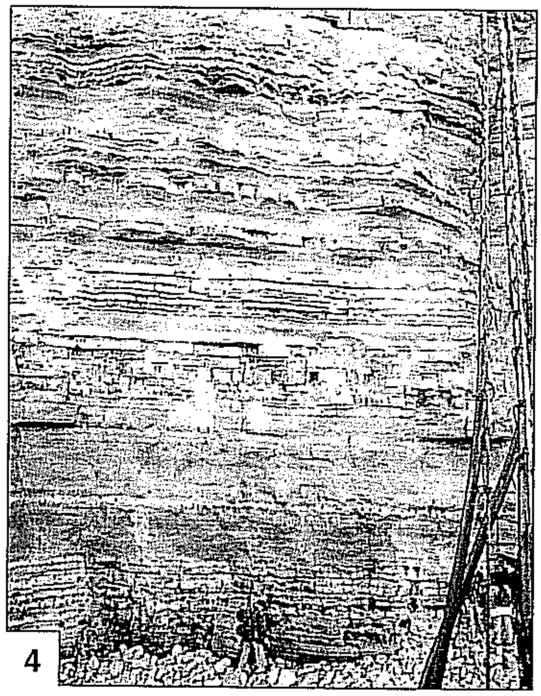

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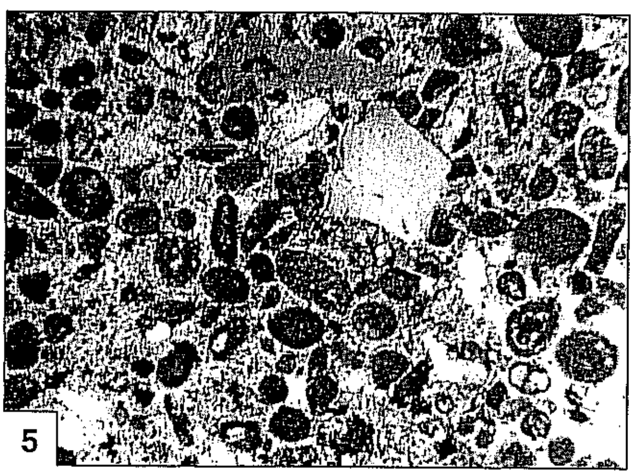

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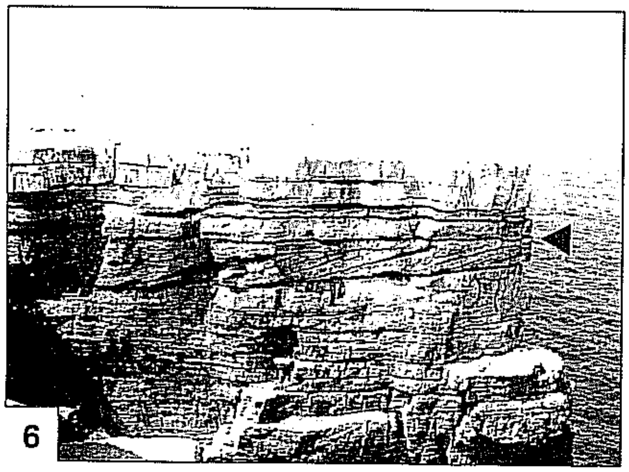

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