

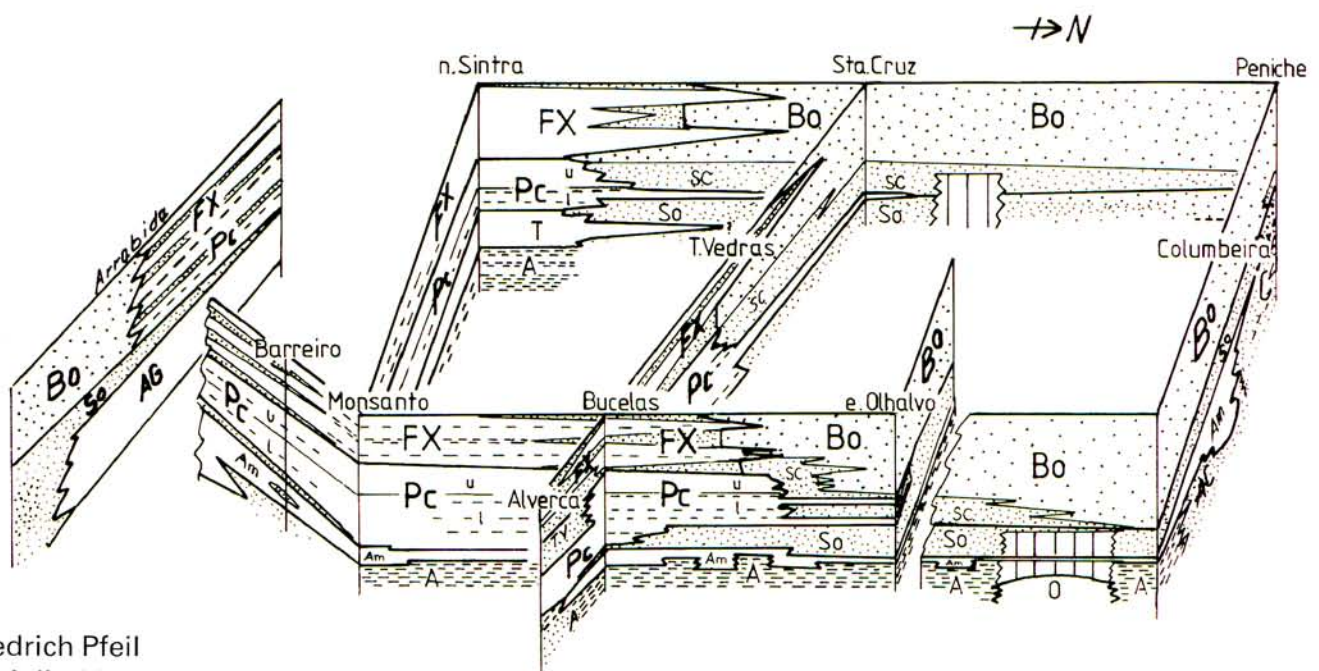
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7

Reinhold R. Leinfelder

Facies, Stratigraphy and Paleogeographic Analysis
of Upper? Kimmeridgian
to Upper Portlandian Sediments
in the Environs of Arruda dos Vinhos,
Estremadura, Portugal



*Olhai que há tanto tempo que, cantando
O vosso Tejo e os vossos Lusitanos,
A fortuna me traz peregrinando,
Novos trabalhos vendo e novos danos:
Agora o mar, agora experimentando
Os perigos Mavórcios inumanos,
Qual cánace, que à morte se condena,
Nũa mão sempre a espada e noutra a pena;*

Canto VII, 79

Os Lusíadas, Luis de Camões

To Raquel

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Facies, Stratigraphy and Paleogeographic Analysis of Upper? Kimmeridgian to Upper Portlandian Sediments in the Environs of Arruda dos Vinhos, Estremadura, Portugal *

by

Reinhold R. LEINFELDER **

SUMMARY

Late Upper Kimmeridgian to final Portlandian sediments in the environs of Arruda dos Vinhos, Portugal, consist of deltaic siliciclastics, the Sobral formation, and lagoonal deposits, the limestone–marl sequence of the »Pteroceriano« formation and the limestone–marl–sandstone sequence of the Freixial formation. The lagoonal sediments grade into coastal and terrestrial clastics in northward and westward direction.

Formal definition according to the ISSC norms is suggestively given for all lithological units and tentatively applied to further regions by basing on published studies in order to give a lithostratigraphic framework for the highly intertonguing sequence of the study area and the entire Lusitanian Basin. This approach is of special importance, since available stratigraphic data are scarce and sometimes even contradictory. The examined sequence lies within the *Virguliana* biozone and the *Lusitania* biozone, based on benthic foraminifers. A further subdivision of the first is possible by the appearance of the alga *Permodiculus* n.sp. which is preliminarily described.

The lack of a refined biostratigraphic classification can be partly balanced by considerations on subsidence and depositional rates, global sea level changes, diachronism, sedimentary processes and depositional models, so that a sketch–like paleogeographic reconstruction can be concluded.

The Upper to late Upper Kimmeridgian Sobral formation consists of three main sediment types: Sandstones exhibiting the brackish water bivalve *Eomiodon securiformis* are attributed to delta front environments, thin oolitic horizons are interpreted as distal/tidal bars, and silty–marly sediments, often with bivalve meadows of *Gervillia sobralensis* or bivalve banks of *Isognomon lusitanicum*, represent prodelta and interdistributary bay deposits. Soft bottom substrata were also inhabited by the specialized regular sea–urchin *Pseudocidaris lusitanicus* and occasionally by adapted corals which are interpreted in respect of functional morphology.

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The delta complex was prograding from west and north. It was biparted in N–S direction by a morphological and structural ridge, possibly caused by uprising salt diapirs. The delta not only outwedges towards south but also towards southeast due to another structural high along the Vila Franca fault system. This resulted in lowered subsidence rates, so that distribution of the eastern part of the delta was mainly determined by the heavily subsiding Arruda depo–center.

The superimposed, uppermost Kimmeridgian to early Lower Portlandian »Pteroceriano« formation is mainly restricted to this Arruda depo–center, only extending further north and west at its base, probably coinciding with the peak in global eustatic sea level highstand.

The formation's lower part is mainly composed of low energetic marls and limestones, among which the nodular *Arcomytilus* limestones deserve special interest, since they indicate occasional very rapid deposition of lime mud followed by morphological adaptations of the bivalve *Arcomytilus morrisi*. Macrofaunal shell coquinas interpreted as storm layers are another important facies type.

Intensive subsidence in the Arruda depo–center caused large thicknesses and pronounced channelling of terrigenous clay, in contrast to the structurally higher block further east where low depositional rates led to oncoid formation and occasional establishment of coral facies. Heavy, though intermittent, subsidence in a wrench block directly bordering the Vila Franca fault system further east resulted in considerable thicknesses in this area. Contemporaneously, marginal marine siliciclastics (Santa Cruz member of the Bombarral formation, upper sandstone group) were deposited further west and north which only occasionally affected the area of »Pteroceriano« facies around its western and northern borders. This indicates the establishment of a clastic trap in the north and the continuing activity of the mentioned morphological elevations, now acting as clastic fences in the west and east.

General shallowing in the upper part of the »Pteroceriano« formation led to a vast establishment of mud–rich coral patch reefs and associated high and low energy facies types. Particularly discussed here are the adaption of corals to fairly high background sedimentation and the systematic position of some algae (*Marinella lugeoni*, *Solenopora cayeuxiformis* n.sp., *Lithocodium* sp.).

This development was restricted to the Arruda depo–center. Perfect sheltering from terrestrial clastics in the west, north and, probably, east (Bombarral formation) indicates once more highly potent clastic fences in form of now emerging elevations. High subsidence rates in the north resulted in trapping coarse clastics, only allowing terrigenous clay to pass which settled down in tranquil water settings between individual patch reefs.

During deposition of the late Lower to final Portlandian Freixial formation, no clastic traps or fences were obvious, so that episodic hinterland uplift and minor sea level fluctuations resulted in rapid spreading and withdrawal of sand facies from and to the west, north and east. More basinwards, typical lagoonal limestones were deposited, dominated by foraminifers during times of slightly elevated salinities or by algae during more normal periods.

The study area silted and sanded up completely towards the Cretaceous boundary.

The late Upper Jurassic Lusitanian Basin displays the typical character of a protoocean marginal basin, characterized by calcareous facies into which clastic wedges were prograding. Yet, basin configuration and symmetry of sediment arrangement differs from other Jurassic marginal basins of the young Northern Atlantic, thus pointing out the control of basin development by local parameters.

ZUSAMMENFASSUNG

Die Sedimente des oberen Oberkimmeridgium und Portlandium in der Umgegend von Arruda dos Vinhos, Portugal, bestehen aus deltaischen Siliziklastika der Sobral Formation, sowie lagunären Ablagerungen der kalkig–mergeligen »Pteroceriano« Formation und der kalkig–mergelig–sandigen Freixial Formation. Westwärts und nordwärts gehen die Lagunensedimente in küstennahe und terrestrische Klastika über.

Die auftretenden lithologischen Serien wurden anregungsweise gemäß den ISSC–Normen formal definiert. Unter Verwendung bestehender Arbeiten wurde diese Gliederung versuchsweise auf das gesamte Lusitanische Becken angewandt. Dadurch konnte eine lithostratigraphische Gliederung der sich stark verzahnenden Serien sowohl im Arbeitsgebiet als auch für den Rest des Lusitanischen Beckens erreicht werden. Ein derartiges methodisches Vorgehen scheint wichtig, da nur sehr spärliche, z. T. sogar widersprüchliche biostratigraphische Daten zur Verfügung stehen. Die untersuchte Abfolge liegt in den auf benthonischen Foraminiferen beruhenden *Virguliana* und *Lusitanica* Biozonen. Erstere ist weiterhin unteilbar durch das Erstauftreten der Alge *Permocalculus* n.sp., von welcher eine vorläufige Beschreibung gegeben wird.

Der Mangel einer feinen biostratigraphischen Gliederung kann teilweise durch Überlegungen über Subsidenz– und Sedimentationsraten, globale Meeresspiegelschwankungen, Diachronie, Sedimentationsprozesse und Ablagerungsmodelle wettgemacht werden, so daß daraus eine skizzenhafte Rekonstruktion der Paläogeographie abgeleitet werden kann.

Die Sobral Formation (Oberes bis oberstes Kimmeridgium) besteht überwiegend aus Deltafrontsandsteinen, welche die Brackwassermuschel *Eomiodon securiformis* führen, aus oolithischen Horizonten, die distalen bzw. tidalen Barren zugeordnet

werden, sowie aus Silten und Mergeln eines flachen Prodelta- und Deltabuchtenbereichs, welche durch Muschelrasen von *Gervillia sobralensis* oder Muschelbänken von *Isognomon lusitanicum* charakterisiert sind. Die Weichböden wurden auch vom spezialisierten regulären Seeigel *Pseudocidaris lusitanicus* und gelegentlich von angepaßten Korallen bewohnt. Diese Formen werden funktionsmorphologisch untersucht.

Das Delta baute sich aus Westen und Norden vor. Durch einen an aufsteigende Salzdiapire gebundenen morphologischen und strukturellen Rücken wurde es in N–S Richtung zweigeteilt. Der Deltakomplex keilt nicht nur nach Süden, sondern auch nach Südosten aufgrund eines weiteren Strukturhochs entlang des Störungssystems von Vila Franca aus. Dieses Strukturhoch drückt sich durch erniedrigte Subsidenzraten aus, so daß die Verteilung des östlichen Deltazweigs hauptsächlich vom schnell absinkenden Arruda Depocenter bestimmt wird.

Die Verbreitung der überlagernden »Pteroceriano« Formation (oberstes Kimmeridgium bis unteres Unterportlandium) ist hauptsächlich auf dieses Arruda Depocenter beschränkt. Nur die basalen Bereiche griffen, möglicherweise im Zusammenhang mit dem globalen Meeresspiegelmehrstand, weiter nach Norden und Westen vor.

Der untere Teil der Formation setzt sich überwiegend aus niedrig energetischen Kalken und Mergeln zusammen. Die knolligen *Arcomylus*-Kalken verdienen dabei besondere Aufmerksamkeit, da sie eine gelegentlich sehr schnelle Sedimentation von Kalkschlamm anzeigen, was von einer morphologischen Adaption der Bivalve *Arcomylus morrisi* gefolgt wird. Schalenzusammenschwemmungen von Makrofossilien sind ein weiterer wichtiger Faziestyp und werden als Sturmablagerungen interpretiert.

Verstärkte Subsidenz im Arruda Depocenter verursachte erhöhte Mächtigkeiten und eine akzentuierte Kanalisierung von terrigenem Ton. Dies steht im Gegensatz zum östlichen, strukturell höherliegenden Block, wo niedrige Sedimentationsraten in Onkoidbildung und gelegentlichem Korallenwachstum resultierten. Weiter im Osten führte intensive, jedoch ruckweise Subsidenz eines Scherblocks in der direkten Nachbarschaft des Störungssystems von Vila Franca zu beträchtlichen Mächtigkeiten. Zeitgleich wurden im Westen und Norden randmarine Siliziklastika abgelagert (Santa Cruz Formationsglied der Bombarral Formation, Obere Sandstein Gruppe), welche jedoch nur selten das Gebiet der »Pteroceriano« Fazies randlich beeinflussten. Dies deutet auf die Einrichtung einer »klastischen Falle« im Norden sowie auf die weiterhin andauernde Aktivität der erwähnten morphologischen Erhebungen im Westen und Osten, welche für klastische Sedimente nun als Schranken fungierten.

Eine generelle Verflachung führte im höheren Teil der »Pteroceriano« Formation zur ausgedehnten Entwicklung von schlammreichen Korallenriffknospen und damit vergesellschafteten hoch- und niederenergetischen Faziestypen. Besonders diskutiert werden Anpassung der Korallen an relativ hohe Hintergrundsedimentation sowie die systematische Stellung einiger Algen aus den vergesellschafteten Sedimenten (*Marinella lugeoni*, *Solenopora cayeuxiformis* n.sp., *Lithocodium* sp.).

Perfekter Schutz vor Verunreinigung durch weiter westlich, nördlich und wahrscheinlich östlich beheimatete terrestrische Klastika deutet wiederum auf höchst effektive Schranken in Form von nun subaerischen Erhebungen. Hohe Subsidenzraten im Norden führten zum Abfangen von grobkörnigen Klastika; Tontrübe konnte jedoch ins Becken gelangen und setzte sich in ruhigen Bereichen zwischen den einzelnen Riffknospen ab.

Für die Ablagerung der Freixial Formation (oberes Unterportlandium bis oberstes Portlandium) sind keine Klastikafallen oder –schränken erkennbar, so daß episodischer Hinterlandaufstieg und kleinere Meeresspiegelfluktuationen zum schnellen Ausbreiten bzw. Rückzug von Sandfazies aus bzw. nach Westen, Norden und Osten führten. Weiter beckenwärts kamen typische Lagunenkalke zur Ablagerung, welche bei leicht erhöhter Salinität von Foraminiferen, bzw. in normalen Zeiten von Algen dominiert wurden.

Zur Kreidegrenze hin verlandete das untersuchte Gebiet vollständig.

Das Lusitanische Becken weist im späten Oberjura die typischen Züge eines protooceanischen Randbeckens auf, was sich im Wettstreit von kalkiger Fazies und vorrückenden Klastika ausdrückt. Beckenkonfiguration und Symmetrie der Sedimentverteilung unterscheiden sich jedoch von anderen jurassischen Randbecken des jungen Nordatlantiks und zeigen somit die Beeinflussung der Beckenentwicklung durch lokale Parameter an.

RESUMO

Os sedimentos do Kimmeridgiano Superior e do Portlandiano nos arredores afastados de Arruda dos Vinhos, Portugal, constituem-se de siliciclásticos deltaicos da formação de Sobral, e de depósitos lagunários da formação »Pteroceriano« (calcários e margas), e da formação de Freixial (calcários, margas e grés). Os depósitos lagunários tornam-se em clásticos litóclásticos e terrestres para o norte e oeste.

Aqui dada sugestivamente é uma definição formal segundo as normas da ISSC para todas as unidades litológicas, que, além disso, é aplicada tentativamente para outras regiões, baseando em trabalhos publicados, de modo a dar um quadro litostratigráfico à sequência altamente interdigitada da área em estudo e da inteira Bacia Lusitânica. Este procedimento é de importância especial, devido ao facto da informação estratigráfica disponível ser pouca e por vezes até contraditória. A se-

quência investigada situa-se entre a biozona *Virguliana* e a biozona *Lusitânica*, que são baseadas em foraminíferos bentónicos. Uma subdivisão da primeira zona é possível devido ao aparecimento da alga *Permocalculus* n.sp., da qual uma descrição preliminar é dada.

A falta de uma classificação bioestratigráfica pormenorizada pode ser parcialmente compensada por considerações em graus de subsidência, espessuras de depósitos, mudanças globais do nível do mar, diacronismo, processos sedimentários e modelos depositários, para que uma reconstrução paleogeográfica, tipo esboço, possa ser concluída.

A formação de Sobral (Kimeridgiano Superior ao Kimeridgiano Superior final) compõe-se de três principais tipos de sedimentos: grés com o lamelibrânquio *Eomiodon securiformis* de água salobre são atribuídos aos ambientes de delta externa; horizontes oolíticos delgados são interpretados como barras distais ou barras de marés; sedimentos limosos—margosos, frequentemente com o lamelibrânquio *Gervillia sobralensis* em quantidades razoáveis ou com bancos do lamelibrânquio *Isognomon lusitanicum*, representam depósitos de tipo prodelta e de baías deltaicas. Substratos macios foram também povoados pelo equinóide regular *Pseudocidaris lusitanicus* e às vezes por corais adaptados, os quais são interpretados em relação à sua função morfológica.

O complexo deltaico avançou do oeste e do norte, ficando dividido em direcção N—S por uma elevação morfológica e estrutural que foi causada possivelmente por diapiros salinos em ascensão. A delta não só adelgaça para o sul mas também para o sudeste devido a outra elevação estrutural ao longo do sistema de falhas de Vila Franca de Xira. Isto deu origem a graus reduzidos de subsidência, de modo que a distribuição para parte oriental da delta foi principalmente determinada pelo depocentro de Arruda que estava descendo vigorosamente.

A formação sobreposta »Pteroceriano« (Kimeridgiano final ao Portlandiano Inferior p.p.) limita-se principalmente a este depocentro. Ela estende-se apenas na sua base mais para o norte e oeste, coincidindo provavelmente com o máximo da subida global do nível do mar. A parte inferior da formação é composta essencialmente por margas e calcários de baixa energia hidráulica. Entre esses, os calcários nodulares com *Arcomytillus* merecem interesse especial, por eles indicarem uma deposição de limo calcário por vezes muito rápida, seguida por adaptações morfológicas do lamelibrânquio *Arcomytillus morrisi*. Coquinas macrofaunísticas são interpretadas como depósitos de tempestades.

Subsidência aumentada no depocentro de Arruda causou espessuras consideráveis e canalização pronunciada de argila terrígena. Isto contrasta com o bloco estruturalmente elevado, situado mais para o oeste, onde graus depositários diminuídos resultaram na formação de oncólitos e no estabelecimento ocasional da fácies corálica. Mais para o este, subsidência intensiva, embora intermitente, de um bloco entalado (»wrench block«) na vizinhança do sistema de falhas de Vila Franca, levou a espessuras consideráveis. Simultaneamente sedimentaram-se siliciclásticos litorais no oeste e no norte (membro de Santa Cruz da formação de Bombarral, grupo de grés superiores), apenas influenciando rara e marginalmente a área do desenvolvimento da fácies »Pteroceriano«. Este facto indica o estabelecimento de uma »armadilha clástica« no norte e a actividade persistente das elevações mencionadas no oeste e no este, actuando agora como »barreiras« contra sedimentos clásticos.

Geralmente ficando pouco profunda na parte superior da formação »Pteroceriano«, a bacia foi ocupada por manchas arrecifais limosas e tipos associados de fácies de alta e baixa energia hidráulica. Particularmente consideradas são as adaptações dos corais a uma sedimentação »de fundo« relativamente elevada, e a posição sistemática de algumas algas de sedimentos associados (*Marinella lugeoni*, *Solenopora cayeuxiformis* n.sp., *Lithocodium* sp.).

Este desenvolvimento foi limitado ao depocentro de Arruda. Uma protecção perfeita contra contaminações por clásticos terrestres depositados mais no oeste, norte e provavelmente, este, indica mais uma vez »barreiras clásticas« altamente efectivas (formação de Bombarral) em forma de elevações agora subaéreas. Altos graus de subsidência no norte resultaram em apanhar grés grosseiros, deixando apenas argila passar para a bacia, depositando-se em áreas tranquilas entre as manchas arrecifais individuais.

Durante a deposição da formação de Freixial (Portlandiano Inferior tardio ao Portlandiano final), nenhuma »armadilha clástica« foram evidentes, de modo que uma subida periódica do retopais e flutuações menores do nível do mar resultaram no progredimento e na retirada da fácies gresosa, do e para o oeste, norte e este. Mais no centro da bacia sedimentaram-se calcários lagunários típicos, dominados por foraminíferos durante tempos de salinidades ligeiramente elevados ou por algas durante tempos normais.

A região investigada estava a colmatar completamente em direcção para o limite Jurássico/Cretácico.

No Jurássico Superior tardio, a Bacia Lusitânica mostra as características típicas de uma bacia marginal proto—oceânica expressada pela competição entre o facies calcário e clásticos em progredimento. A configuração da bacia e a simetria da distribuição dos sedimentos distinguem-se, todavia, das outras bacias marginais Jurássicas do novo Atlântico do Norte, indicando a influência de parâmetros locais no desenvolvimento da bacia.

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1. INTRODUCTION

1.1 Location

This study was worked out in Upper Jurassic beds of the Portuguese province Estremadura (district of Lisbon), precisely in the surroundings of the gentle structural updoming of Arruda dos Vinhos, as well as in the vicinities of the Matacães – Torres Vedras diapir.

The key area is confined by the Cainozoic beds of the Tejo (Tagus) valley in the east (Vila Franca de Xira), by the Cretaceous outcrops forming a hill range from Alverca via Bucelas to Montachique in the South, by the Runa–Matacães salt diapir area in the west and by the elevation of the Montejunto syncline as well as by the Cretaceous clastics around Abrigada in the north.

Additionally, the region further north (Bombarral) and particularly further west (Atlantic borderland) were also taken into consideration (fig.1).

1.2 Survey of Basin Development

The Lusitanian Basin, the depositional area of the sediments treated herein, originated in the course of early North Atlantic rifting, starting with a first transgressive phase from the Upper Triassic/Lower Liassic (terrestrial clastics with basalts) up to the Callovian (Lower and Middle Jurassic platform carbonates) (RAMALHO 1971, MOUTERDE et al. 1972, BALDY et al. 1977).

The second transgressive phase, beginning after a widespread Lower Oxfordian depositional gap, led to a more accentuated basin morphology, due to pronounced rifting. This is probably linked to the main rifting phase between the Iberian Peninsula and the Grand Banks in Kimmeridgian times (R. WILSON 1979). Accelerated subsidence rates and abrupt influx of coarse clastic sediments, interfingering with calcareous deposits, fit well into this picture.

At that time the basin was sheltered in the west, both by salt diapir ridges and uplifted basement rocks (e.g., R. WILSON 1975a, 1979, FÜRSICH & SCHMIDT–KITTLER 1980). With the end of the Jurassic the basin sanded up almost completely. In the course of the Cainozoic, the sea again returned several times (e.g., ANTUNES 1979, BERTHOU & LAUVERJAT 1979, REY 1979).

1.3 Earlier Works

Much has been published on the Upper Jurassic of the Lusitanian Basin so far. Interest goes back up to the last century, where the description of the rich macrofauna was the main objective (e.g., SHARPE 1850, LORIOL 1890, CHOFFAT 1885–88).

Published and unpublished research results of oil companies in the fifties/early sixties (e.g., MEMPEL 1955, OERTEL 1956, CHAUMEAU 1962) as well as biostratigraphic studies (e.g., RUGET–PERRROT 1961) served as basis for establishing the official geological maps (e.g., the maps used in this work: ZBYSZEWSKI 1964, ZBYSZEWSKI & TORRE de ASSUNÇÃO 1965, ZBYSZEWSKI et al. 1955, 1966, CAMARATE FRANCA et al. 1961). Following was a phase of minute stratigraphic studies (RAMALHO 1971, 1981, RAMALHO & REY 1975, MOUTERDE et al. 1972).

The appearance of plate tectonics theory drew new interest on the Recent shelf (e.g., BOILLOT & MUSELLEC 1972, BOILLOT et al. 1975, 1979) and the Lusitanian Basin itself. R. WILSON (1975b) was the first one to ex-

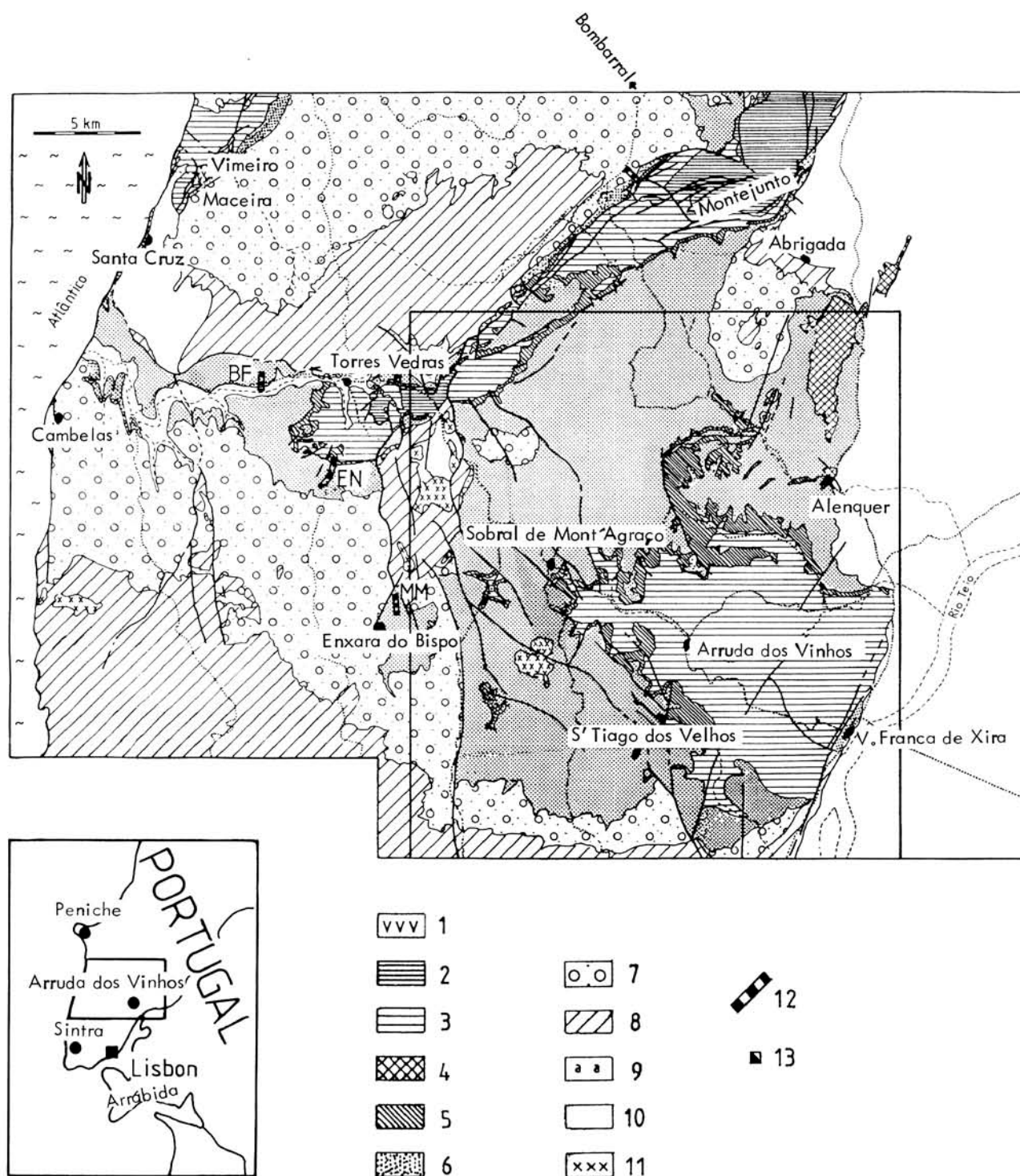
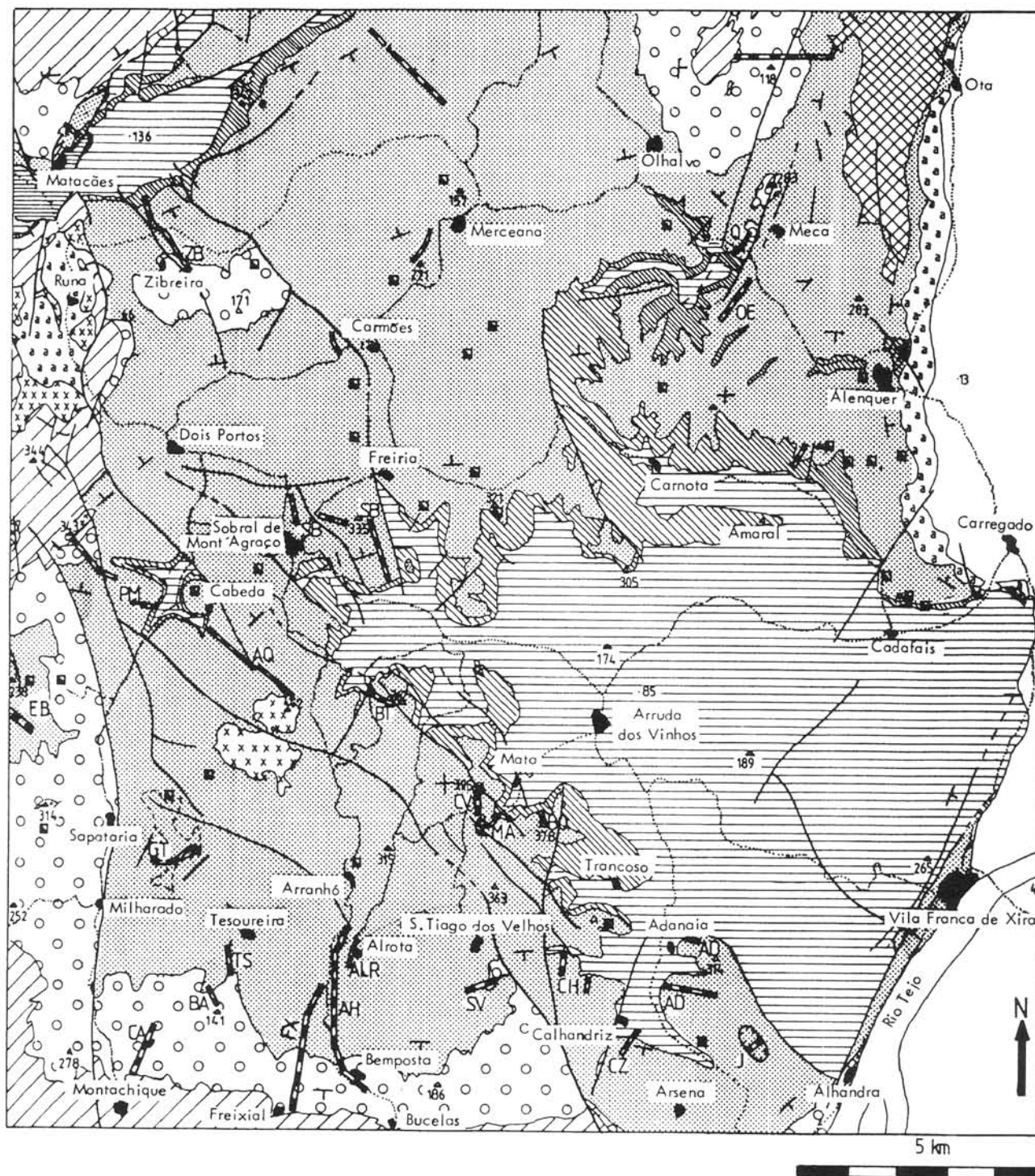


Fig. 1: Study area: geological map and location of lithological sections.

Geology based on official geological maps, with minor changes; age of units also based on RAMALHO (1971) and this study.

Legend: 1) Dagorda beds (Upper Triassic/Lower Liassic); 2) Montejunto beds and Cabaços beds (Upper Oxfordian); 3) Abadia beds (Kimmeridgian p.p.); 4) Ota limestone (Kimmeridgian p.p.); 5) Corálico do Amaral (Upper Kimmeridgian); 6) J4: Sobral unit («Middle»? to upper Kimmeridgian: «Pteroceria-no» unit (uppermost Kimmeridgian to late Lower Portlandian) and clastic equivalents («Santa Cruz unit»); 7) J5: south, Freixial unit (final Lower to uppermost Portlandian); north, «upper sandstones» («Bombarral unit», Portlandian); 8) Cretaceous; 9) Paleogene (right map only); 10) Tertiary/Quaternary; 11) volcanic and subvolcanic rocks; 12) sections; 13) further important outcrops.



Recorded sections: AD Adanaia; AH Arranhó–Bemposta; ALR Alrota; AQ Alqueidão; BF Benfica; BO Boieiro; BT Batalha; CH Chão da Vinha; CV Carvalha; CZ Calhandriz; EB Enxara do Bispo; EN Engenheiro; FX Alcubela–Freixial; GT Gotleis; J Bom Jesus; MA Mata; MM Moinhos do J. Miguel; OE Oerca; PM Patameira; Q Sta. Quitéria; SB Sobral; SV S. Tiago dos Velhos; TS/BA/CA Tesoureira–Casais da Serra; ZB Zibreira.

plain the Upper Jurassic development of the basin in terms of the new theory. This was accompanied by a first brief description of the occurring facies variety (R. WILSON 1975a).

Facies interpretation, combined with stratigraphic considerations, led to generalized paleogeographic sketch maps for the entire Portuguese Jurassic, given by MOUTERDE et al. (1979) and, more detailed, for the Upper Jurassic of the Lusitanian Basin by R. WILSON (1979). The outlined picture, though, was still fairly rough, so that consequently interest was set on detailed examinations on sedimentology, facies and ecology, to illustrate the given framework (e.g., FÜRSICH & SCHMIDT–KITTLER 1980, FÜRSICH 1981, FÜRSICH & WERNER 1984, WERNER 1986, DÖHLER 1984).

1.4 Objective

The elaboration of a detailed paleogeographic picture, however, still causes problems. Only in the southeastern part of the Lusitanian Basin, the paleogeographic development could be clarified (FÜRSICH & SCHMIDT–KITTLER 1980, FELBER et al. 1982, LEINFELDER 1983), whereas elsewhere the rarity or lack of suitable hostrocks for exhibiting biozonal indicators complicates the correlation of individual outcrops.

In the central part of the basin, the paleogeography of Upper Oxfordian beds (calcareous Cabaços and superimposed Montejunto Beds) and Kimmeridgian beds (shaley to sandy Abadia Beds) are under study (R. WILSON, Milton Keynes & coworkers). The superimposed Corálico do Amaral (Upper? Kimmeridgian) was investigated by DÖHLER (1984).

The subject of this study are the overlying so-called Oórito, Sobral, Pteroceriano and Freixial beds, an intercalation of siliciclastics, marls and limestones of presumed Upper? Kimmeridgian to Uppermost Portlandian age.

The main objective was to describe the varying micro- and biofacies types, to point out their temporal and spatial arrangement, and to deduce from this a detailed picture of the varying paleogeographic pattern. Concomitantly, an attempt was submitted to re-define the lithostratigraphic classification of this area.

The chosen region was particularly a matter of interest due to its interfingering of calcareous and siliciclastic sediments, whereas age-equivalent beds further south show entire calcareous, respectively further north, entire siliciclastic development.

In the present study, main interest is set on calcareous facies types, since the poorly exposed marls and siliciclastics can be well compared to the excellently exposed cliffs along the shore, as studied by R. WILSON (1979), FÜRSICH (1981) and WERNER (1986).

2. NATURAL CONDITIONS, METHODS AND DEFINITIONS

2.1 Survey of Stratigraphy

Field work was based on the official geological maps, scale 1:50 000, and their explanations (see 1.3). The lithologic units mostly dealt with here correspond to mapping units J^4 and J^5 in the related maps, assigned respectively as »Kimeridgiano«, »Pteroceriano« or »Complexo Pteroceriano, incluindo as Camadas com *Lima pseudoalternicosta*« (J^4), and Portlandiano« or »Camadas de Freixial« (J^5). The rhombic shaped patch east of Sapataria, assigned as J^{3-4} , was also examined (see Chap. 8).

For a survey, table 1 gives the stratigraphy of the study region, based on CHOFFAT (1901) and CHAUMEAU (1962). For complete treatment of stratigraphy refer to Chap. 5.

CRET.	official maps	CHAUMEAU 1962, based on CHOFFAT 1901		Thickness
PORTLANDIAN	J^5	Freixialien (CHOFFAT)	Freixialien supérieur	0-200 m pers. invest.
			Freixialien inférieur	
	J^4	Pterocérien (CHOFFAT)	Marno-calcaire supérieur	0-250 m pers. invest.
			Calcaire d'Alrota	
			Marnes (à intercalations calcaire)	
KIMMERIDGIAN		Sobral (ROBBINS)	Marno-calcaire inférieur	0-?200 m pers. invest.
	J^d_3	Corallien d'Amaral (CHOFFAT)	Oolithique (miliaire)	0-?20 m pers. invest.
			Calcaire de Trancoso	0-30 m DÖHLER 1984
	J^c_3	Marnes d'Abadia (CHOFFAT)		800 m WILSON 1979

Table 1: Stratigraphic sequence of the Upper Jurassic pp in the surroundings of Arruda dos Vinhos, as given by CHOFFAT (1901) and CHAUMEAU (1962). Age correlations after RAMALHO (1971).

The Sobral, »Pteroceriano« and Freixial units are further treated in this study.

Also compare to fig.7

2.2 Structural Setting.

The main structural elements determining the attitude of beds in the study area are (in part after CHAUMEAU 1962) (cf. to fig. 1):

- The gentle structural updoming of Arruda dos Vinhos
- The monocline of Bucelas
- The synclinorium of Olhalvo
- The anticline of Montejunto, extending to Matacães and further to Enxara do Bispo. Its apex is pierced in the diapiric region of Runa
- The horst–block of Ota
- The anticlinorium of river Sizandro west of Torres Vedras
- The anticline of the Vimeiro–Maceira diapir as the southern prolongation of the Caldas da Rainha diapir
- The synclinorium of Bombarral–Cadaval

The most important fault system borders the Tejo Basin in SSW–NNE direction. This direction is also realized further west. Equally important are also the NW–SE and the N–S directions. Faulting in diapiric areas often has no preferred orientation.

Bedding attitude is generally very flat (0° – 15°), only becoming steep in the anticlines of Montejunto–Maceira and Vimeiro (up to 70° , with local inverse dipping), as well as along the faults of the Tejo valley. Here, antithetic faulting also appears.

Common, often intensively altered, doleritic dykes and basaltic vents are piercing the region. A larger lakkolith of teschenite (ZBYSZEWSKI & TORRE de ASSUNÇÃO 1965) is situated 3 kilometers north of Sobral de Monte Agraço, around Forte de Alqueidão.

Some of these structural elements were already evident during the Upper Jurassic, thus influencing the distribution of sediments (see Chap. 6).

2.3 Geographic Setting

The studied region is characterized by generally only mild topographic undulations. Except for the Montejunto elevation with 664 meters and values between 250 and 400 meters in its southwestern prolongation to Matacães, the highest altitudes appear in the vicinity of the »Corálico« outcrops surrounding the wide but steeply inclined valley of Arruda dos Vinhos, decreasing continuously towards west and northwest.

Numerous small–scaled hills, partly with steeply inclined slopes, accentuate the morphology. Erosion was occasionally hindered by volcanic extrusions (e.g., basaltic hilltops of Carvalha, SW Arruda dos Vinhos, or S. Quitéria, W Olhalvo). The large subvolcanic intrusion north of Sobral de M. Agraço forms an elevation of 442 meters above sea level.

Draining in the southern part is carried out by several brooks running south to the Tejo, elsewhere by rivulets flowing east and also entering the Tejo. West of Matacães draining follows westward direction towards the Atlantic. Most brooks and rivulets carry water only ephemerally.

The entire region is intensively cultivated, with viticulture dominating by far, particularly in the western regions. Cereal growing is restricted to wind–protected areas, such as rivulet valleys. In more elevated parts, agriculture is often abandoned or hills are covered with Eucalyptus forests. Mediterranean thicket is only developed where slopes are northwards directed or too inclined, so that viticulture is made impossible.

The region is densely populated with a series of small towns (e.g., Vila Franca de Xira, Sobral de M. Agraço, Torres Vedras, Alenquer, Olhalvo, see fig. 1) and innumerable villages, hamlets and solitary small farms.

Accessibility is ensured by a very dense network of narrow roads, tracks and pathways.

Outcrop conditions are moderate in general, but vary considerably. Best exposed is the thick—bedded, weath-ering—resistant »Corálico/Oólito« unit which, though, is only of marginal interest here.

Similar good conditions appear on steep inclined slopes, if hard, thick—bedded limestone is the prevailing bed-rock, such as the upper »Pteroceriano« around Alrota, south of Arruda dos Vinhos.

Sequences with common marl intercalations, like the lower »Pteroceriano« or the Sobral unit are only to be seen along recent road cuts or pathways. The marls themselves are deeply weathered and mostly of no use for fau-nal investigations, except when cuts are very fresh.

In the western and northern part of the study area, exposure conditions are normally very poor, due to the do-minance of subcropping clastics. Yet, information could be achieved by inspecting loose fauna and rock rubble from ploughed fields after the harvest in Autumn or from bare vineyards in Spring.

Recent quarrying only takes place in the quarries of »Pedreiras de Bom Jesus« of »Cimentejo« above Alhandra on the river Tejo. Few former quarries of minor extent, e.g., around Arranhó, Tesoureira or Freixial, are some-what improving the outcrop conditions.

The excellently exposed cliffs along the coast were matter of separate studies (e.g., FÜRSICH 1981).

As a whole, outcrop conditions apparently alter considerably from year to year. Thus, fossil sites, cited in earlier works, are often destroyed by infrastructural changes, vegetation overgrowth or erosion. On the other side, most of the fossil sites discovered during this study are not mentioned elsewhere.

Another example are the catastrophic rainfalls and floodings in the district of Lisbon in Autumn 1983, which de-stroyed former outcrops but also created many new ones due to landslides and wash—offs.

2.4 Field Methods

Field methods are determined both by the scope of this study and by the outcrop conditions. For registering on-ly the variety of facies types, individual unlinked outcrops would suffice; for interpreting the paleogeographic evolution, a set of correlated stratigraphic sections is a necessity.

Since the lack of suited biostratigraphic markers and the rapid lateral change of facies types soon became evi-dent during field work, it had to be achieved to take sections of large stratigraphic extent, to elaborate a rather high density of sections, and to correlate the sections preferably already in the field.

Section sampling was hindered by the flat attitude of beds, by faulting and by moderate exposure conditions. Thus, the working out of suited courses for individuals sections and the tracing of certain diagnostic beds to neighboured profiles are rather time—consuming in such cases.

Sections are of the kind to climb up hill slopes, or to follow valley thalwegs and roads or pathways. Exposure gaps are always very frequent and often of major extent. If possible, parallel closeby sections were examined to eliminate the informational loss within gaps.

South and southwest of Arruda dos Vinhos, sections may reach lateral extensions of more than 10 times larger than their corresponding true thicknesses, due to the very flat southward dipping of beds. This flat bedding at-titude not only causes unavoidable summarizing of lateral facies variations in the course of the sections, but al-so considerable difficulties in determining exact true thicknesses and particularly vertical extensions of gaps. In these cases, apparent extensions, azimuths and inclinations along the course of a section were measured and re—evaluated to true thicknesses by geometrical means, using strike and dip readings of neighboured out-crops.

A section without exposure gaps could be recorded only from the quarries of Alhandra (Tejo), although even in this case some steep, recently dynamited walls were not accessible.

In the northern and western part no extensive sections could be worked out, due to both unsatisfying exposure conditions and unsuited bedding attitudes, together with only minor topographic changes. The sections recor-ded from there are somewhat interpretative, since major parts had to be reconstructed by loose rock rubble.

Besides recording sections, interest was also set on examining isolated outcrops and on tracing the extension of calcareous »Pteroceriano« and Freixial development to the north and west.

Field descriptions of sedimentology and biofacies were accompanied by sampling of fauna and rock specimens. Sample density is varying and can be drawn from the lithological section charts (chap. 8).

Field work was performed in Summer 1981 (7 weeks) and Springs of '82 (5 weeks) and '83 (6 weeks). A last look was given in Spring '84 to note the changes due to the vast floodings of Autumn '83.

2.5 Laboratory Methods and Storage of Samples

For microfacial investigations 322 polished hand—specimens, 310 partly large—sized acetate peels and 210 thin—sections (5x5 cm), mostly of calcareous deposits, were manufactured.

While thin—sections are indispensable for determining microfossils, particularly the litiolids and algae, acetate peels have great advantages when samples are inhomogenous in respect of lime content, structural density, colouring, etc.. Thus, their application is very useful particularly for sandy limestones or sandstones with calcareous matrix, sparitic or marly limestones.

Quartz grains, due to their etching resistance, cause characteristic high relief stains in peels, Sparitic cements as well as primary shell structures exhibit very clear crystal boundaries and inner structures. Marly limestones do not require any hardening or impregnating. On top, primary differences in marl content or colouring are preserved in the corresponding peels.

25 of the marl samples were sufficiently fresh to preserve microfossils or imprints and thin shells of soft bottom macrofauna.

Unaffected soft bottom fauna can only be obtained from moist marl samples. Since '82/'83's working periods were preceded by very dry Winters, satisfying results could be achieved by wrapping samples in wet paper and keeping them for several weeks in densely closed plastic bags, adding water from time to time.

All originals of fauna or other samples figured on plates are stored in the »Serviços Geológicos de Portugal«, Rua de Academia das Ciências, Lisbon, under S.G.P., Coleção Leinfelder. Further documentary material is stored in the »Institut für Geowissenschaften, Universität Mainz«.

2.6 Note on Paleoecological Analysis Methods

Analysis of faunal paleocommunities is a rather young paleontological subject. Based on studies of Recent benthic community structures (e.g., TURNEY & PERKINS 1972, ZIEGLER et al. 1974, HILL et al. 1982) and morphological interpretation of Ancient taxa (e.g., STANLEY 1972), the structures of Ancient communities are evaluated. A modern approach in this respect is the trophic nucleus concept, based on quantitative analysis (e.g., RHOADS et al. 1972, WALKER 1972, SCOTT 1976). STANTON, Jr.(1976), however, tested the relation of fossil to original communities in a thorough study, concluding that the »trophic structure of the fossil community is not a good estimate of that of the biocoenosis [and that] the expected correlation of structure with environment is absent. [On the other side,] patterns in the physical environment interpreted from fossil communities coincide with those of the original biocoenosis« (op.cit., p.122). MACDONALD (1976) emphasized that restriction on shelled taxa yields better relationships to original community characteristics. Moreover, qualitative characteristics of shelled fauna, such as environmental setting, distribution and taxonomic composition are most often sufficiently preserved in the fossil assemblage, being able to be re—evaluated by simple qualitative species presence—absence patterns.

A quantitative concept was further developed, mainly by FÜRSICH (e.g., 1976b, 1977), taking also falsification into account due to faunal mixing and condensing (e.g., FÜRSICH 1978) and combining sedimentological with ecologic environmental interpretation (e.g., FÜRSICH 1976a, 1981).

Fully quantitative ecoanalysis is beyond the scope of this study and would be furthermore hindered by the rarity of unweathered, outcropping marls. Together with MACDONALDS (1976), however, it is believed that qualitative or semiquantitative analysis yields sufficient information for paleoenvironmental interpretation, moreover

since comparison with roughly age—equivalent, calibrated associations along the coast (FÜRSICH 1981, FÜRSICH & WERNER 1984, WERNER 1986) is possible.

For pragmatic reasons, associations are named here according to the biomass—dominating hard part species, allowing rapid classification in the field and application to solid rocks as well.

The lack of synecological information is balanced by the occurrence of many autecologically important forms or, in other words, facies fossils. Thus, together with additional sedimentological information of the host sediment and the over— and underlying beds, satisfactory interpretation of paleoenvironments could be achieved.

2.7 Definition of Sedimentological Terms

Determination of bedding thicknesses follows the terminology given in REINECK & SINGH (1975)

very thick	>100 cm
thick	30—100 cm
medium	10—30 cm
thin	1—10 cm
very thin	<1 cm

The term sandstone is only applied here for siliciclastic deposits. Consequently, »silt— or sand—bearing« implies »quartz—silt or quartz—sand bearing«.

The item mudstone is only used for carbonates; siliciclastics of the same grain size are termed clays.

FOLK's (1962) micrite/sparite classification of limestones is only used for generalizing descriptions. In this study it is normally referred to DUNHAM's (1962) classification and its expansion by EMBRY & KLOVAN (1972). The prefix lime(e.g., lime wackestone) is not used; the few occurring dolomites are termed as such.

FLÜGEL's (1982:373f) proposal to use the terms floatstone and rudstone only for, in the latter case sparitic, sediments with clearly allochthonous reef detritus, is not followed. The original paper of EMBRY & KLOVAN (1972:676) defines rudstone as a grain—supported carbonate rock with >10 vol.% particles larger than 2 mm. Furthermore, (cite): »Thus, floatstone is the conglomeratic analogue of wackestone, while rudstone corresponds to packstone and grainstone«. VISSER (1980:239) also follows this definition.

This mere descriptive definition, being only a grain size subdivision of DUNHAM's terms, is preferred here to the interpretative, reef—connected definition of FLÜGEL (1982).

Further definitions required are given in the corresponding chapters.

3. FACIES TYPES AND THEIR CORRELATED ENVIRONMENTS (WITH EMPHASIS ON SPECIAL DEVELOPMENTS)

Despite transitions, sediments can somewhat schematically be classified into, normally environment—correlated, facies types. These will be treated in this chapter, either briefly, when already described elsewhere in the regional literature or sufficiently discussed in general, or in more detail, when of special interest for the purpose of this study.

3.1 Facies Types of the Oórito Unit and the Sobral Unit

The Oórito/Sobral units are composed of fine— to medium—grained clastics with variable carbonate content, ranging from mostly silty marls to siltstones to medium—grained, rarely conglomeratic, sandstones and medium—grained oolites with predominantly quartz—cored ooids. Brownish weathering colours are prevailing.

3.1.1 Oolites

Distribution : Oolites are almost completely substituting the Corálico unit east of Cadafais, along the the Matacães—Montejunto anticline, and partially east of Trancoso and north of Carnota. They overly the Corálico unit in its central area of development around Arruda dos Vinhos (Oórito miliar s.str.). Oolites also occur as frequent intercalations in the Sobral unit, especially in its lower part.

Description (pl. 2/1 – 5) : The rocks exhibit light to dark grey or brownish colouring. Bedding thicknesses range from very thin to thick, normally medium. Large scale cross—bedding, rarely with concave—downward foresets (pl. 2/1) and erosional surfaces as well as *Scolithos*—type burrows may occur.

Prevailing is a sparitic groundmass, particularly in the lower parts of the Oórito unit. Nevertheless, packing of the poorly to well sorted particles is often fairly dense. Good sorting, mostly together with a marly groundmass in the higher levels, causes a typical circumgranular fracturing, what gave rise to the name »Oórito miliar« (millet oolite), used in the local literature.

The main characteristic of these oolites is their high amount of quartz—cored ooids. In the lower part of the Oórito unit, 30—50% of all ooids display quartz—nuclei; in its upper part and in the Sobral unit the value is close to 100%.

Polyooids and multiple ooids (ooids lumps) are also fairly frequent in the lower levels (pl. 2/2).

Cortices are normally thick, depending largely on nucleus size in well sorted ooids, thus demonstrating their mature character. In poorer sorted types, there often exists a wide spectrum of cortex and ooid sizes. The largest ooids appear in the Oórito unit (—1mm Ø).

Both tangential and radial microfabrics occur. Radial fabric is rather common in the lower unit, but also occurs in the upper one. In the latter, an alternating zonation of radial and tangential fabric within one cortex is widespread, often with additional micritic rings.

Ooids are also often completely micritized or recrystallized. Besides ooids, particles consist of microbored or superficially algal—encrusted bioclasts (cortoids sensu FLÜGEL 1982) with prevailing bivalve (esp. oyster) and gastropod (nerineid) clasts which are partly of large size and create a closed fabric where interstitial pores are

filled with ooids. Furthermore, fragments of echinoids (esp. echiniid spines), bryozoans, *Marinella lugeoni* and lignite litter occur. These bioclasts also serve as ooid nuclei.

Lituolids (*Pseudocyclammia* sp., *Freixialina planispiralis*, »*Haplophragmium*« sp., *Nautiloculina oolithica*), other foraminifers (e.g., *Lenticulina* sp.), the bivalve *Eomiodon securiformis* and one finding of a fragmented nautilid conch are to be mentioned among the biomorphs.

Rare oncoids and algal nodules (partly of *Girvanella minuta*), intraclasts and extraclasts appear additionally.

Non-encrusted terrigenous particles are often common, normally consisting of moderately rounded detrital quartz, but feldspar grains, reworked sandstone fragments and mica may occur as well.

During diagenesis staining with iron hydroxides and occasional infiltration of bitumen (pl. 2/3) as well as bioclast fracturing and compactional ooid pitting (pl. 2/5) occurred.

Summarizingly, five microfacies types can be differentiated:

- (1) moderately to well sorted, fine- to medium-grained, oolitic grainstones (pl. 2/5)
- (2) poorly sorted, medium- to coarse-grained, bioclast-bearing oolitic grain/packstones with additional algal nodules and intraclasts (pl. 2/2)
- (3) poorly sorted, oolitic bioclast rudstones (cf. to pl. 2/4)
- (4) poorly to moderately sorted, marly, oolitic packstones with non-encrusted detrital quartz (pl. 2/3)
- (5) oolitic sandstones

Discussion: Much has been published about the genesis and depositional environments of oolites. For a synopsis see, e.g., FLÜGEL (1982) and RICHTER (1983). Yet, the mechanisms of formation are not fully understood. Hence, biochemical versus physicochemical or even merely mechanical origin is still discussed (e.g., PURSER 1980, above authors). Moreover, conditions for forming radially structured cortices are still unclear. Both primary and secondary radial orientation of crystallites seem to exist. While in more ancient studies radially structured Recent ooids were mentioned only from hypersaline quiet-water environments, lately radial fabric is also reported from brackish-lacustrine Pyramid Lake (POPP & WILKINSON 1983). On the other side, the hypersaline Dead Sea surprisingly exhibits tangentially structured ooids (GARBER & FRIEDMAN 1983).

Regular small oncoids composed of heavily calcifying cyanophytes may also resemble radially structured ooids in rare cases (cf. to LEINFELDER 1985).

REIJERS & ten HAVE (1983) consider cortex fabric as a bathymetric indicator for shelf – slope transitions. Radial fabric should reflect tranquil deeper marine slope settings, whereas tangential fabric should be related to agitated shallow shelf environments. This assumption, however, might be only valid for originally aragonitic ooids, since according to MEDWEDEFF & WILKINSON (1983) Recent calcitic ooids always exhibit radial fabric, whereas aragonitic ooids may have tangentially or radially oriented cortical crystals.

WILKINSON & LANDIN (1978) explain the predominance of radial fabric in Paleozoic and Mesozoic ooids with all ooids being primarily calcitic at that time, possibly due to different chemical composition of waters.

Beyond discussion, however, oolite formation demands relatively stable environmental conditions over a longer period (growth rate of Recent ooids ranges from 100–1000 years, FLÜGEL 1982:156) and bidirectional currents to remain in place of formation during the time of growth (PURSER 1980:27).

Concentric tangential fabric of cortices seems to be related to agitated bottoms, whereas early diagenetic, organism-induced micritization of ooids or parts of the cortex apparently happens, where bottoms are stabilized, say, by seaweeds (cf. to HARRIS 1983). Cerebroid structures seem also to be due to bacterial alteration of the ooid's shape (KAHLE 1974).

Irregular and clotted ooids as well as primary radial fabric of cortices, following REIJERS & ten HAVE (1983), may be restricted to only weakly agitated environments, whereby, however, no bathymetric or salinity values can be drawn from.

Consequently, the well sorted, cross-bedded oolitic grainstones with low amount of quartz-nuclei refer to very shallow (2–4 m), active, mobile ooid bars. Concave-downward crossstratification is one main feature of

parabolic dunes (REINECK & SINGH 1975:202). Hence, oolites exhibiting this feature may have undergone local aeolian reworking. Such eolianites or limestone dunes are easily cemented, thus having a high potential to remain preserved, even when flooded subsequently (GOLDSMITH 1978).

In stabilized or bar-sheltered areas, radially structured ooids could develop, micritization took place and cementation was fast, causing clotting of ooids resulting in ooid lump formation.

The oolites substituting parts of the Corálico unit or belonging to the Oólitico unit are to be referred to such zones, where tidal or wind-induced mixing of neighboured areas was a common fact, as can be seen by the admixing of lagoonal bioclastic cortoids, foraminifers, red algae, oncoids and earlier cemented oolite lithoclasts. By the occurrence of echinids, red algae and a fragmental nautilid rather normal salinity values are likely. Early cementation, solution and fracturing features indicate early subaerial exposure.

On the other side, the thin intercalations of mostly marly, very sandy oolites within the Sobral clastic sequence evoke a somewhat different origin: Terrigenous influence is evident by the large amount of detrital quartz, by lignite litter, by the input of clay minerals and by the general geological setting. *Eomiodon securiformis*, found within these oolite beds, is a typical brackish water bivalve (FÜRSICH 1981). Remains of red algae, however, indicate neighboured, more normal marine sediments.

The smaller size of ooids and the high amount of superficially coated or uncoated quartz grains evokes less stable environmental conditions. The common micritic layers also point at longer periods of cortical non-accretion. It is generally accepted that already a small supply of fine-grained siliciclastics suppresses carbonate production severely (e.g., WALKER et al. 1983). Hence, ooid growth was certainly intermittent, stopping whenever terrigenous clay was put into the environment.

Interpretation of these oolites has to be seen in relation to the interpretation of the embedding clastics, representing a delta complex (chap. 3.1.2). Ooids were formed in distal bars, where delta sands were reworked in the transition zone between seaward flowing freshwater jet and landward or oblique, wind- or tide-induced coastal flow, or in tidal bars situated more towards the delta plain in estuarine-like distributary channels (cf. to chap. 6.2). The short-termed oolite formation ended with a mixing-up of surrounding prodelta or interdistributary bay marls, or a grading into non-oolitic delta sands.

Since overburdening of sediments within a delta complex is rather rapid, and compaction may often be accelerated by high marl contents within the sequence, deltaic oolites may often exhibit distinct compactional features, especially pitting of ooids.

3.1.2 Brown Siltstones and Sandstones partly with *Eomiodon securiformis*

Distribution: Sandstones already occur as minor intercalations in the Oólitico unit; in the Sobral unit they play the dominant role together with associated marls. The best outcrops occur north of Sobral de Monte Agraço.

Description (pl. 2/6 – 8, pl. 3): Most obvious is the siliciclastics' ocre-brownish weathering colour due to iron hydroxide staining of the groundmass. Fresh rocks are dark grey. In the north, conglomeratic sandstones, sandstones and siltstones may occasionally exhibit reddish colour, the latter also caliche nodules.

Another important feature is their »dirty« character, that is, general poor sorting, marly matrix with a very high amount of mica and a high content of lignite litter. Mica and lignite are particularly enriched on bedding or strata planes. Especially siltstones are always very »dirty«, whereas fine- and medium-grained sandstones may rarely be well sorted.

Bedding thicknesses vary largely, with the thickest beds being exposed best. Thick to very thick-bedded »dirty« sandstones are often structureless or indistinctly evenly stratified, though both large and small scale cross-stratification is also common. Being also bi- or multidirectional (pl. 3/2), a simple southward dipping of beds seems nevertheless to prevail, indicating dominantly southward water flow. Cross-bedding strata planes are even, tangential or rarely sigmoid. Though normally steeply inclined, very low angle dipping also occurs in clean, fine-grained sands, which also often exhibit horizontal lamination (pl. 3/3). Further features are trough-cross bedding, erosional channel downcuts (also dominantly with N-S axis) (pl. 3/1), climbing ripples (pl. 2/8) and small-scaled wave ripples on bedding surfaces.

The components of sandstones consist almost exclusively of detrital quartz which is normally only subrounded. Feldspar grains are very rare. Occasionally, sandstones contain pebbles measuring up to 5 cm in diameter. They consist of reworked, poorly to moderately rounded caliche deposits, calichefied lignitic mudstones and very sandy micrites (pl. 2/6). Mud pebbles, composed of clay, occur both in conglomeratic and non-conglomeratic facies.

Several sandstones bear ooids, bioclasts (preferably of oysters), gastropods, ostracods and rare litiolids. Rarely, coarse skeletal fragments may be very densely packed so as to form sandy rudstones.

In the north, an ammonite fragment was found at the base of the Sobral unit (cf. to chap. 5.1.1).

The most common faunal element is *Eomiodon securiformis*, occurring partly in life position and partly enriched in clusters, yet always being double-valved.

Lignite litter can be very large; west of Alenquer a conifer trunk was found measuring 1 m in length (kind pers. comm. K. Orschied, Mainz).

The packing of particles is generally very dense with common long-grain contacts, if grains are not isometric. The matrix is often marly, though sparitic groundmass is not uncommon.

Sandstones with micritic groundmass, with transitions to sandy micrites, are also locally occurring.

D i s c u s s i o n : The fluvio-marine character of the Sobral clastics is pointed out by various proofs: Marginal marine influence is demonstrated by faunal remains, especially by the brackish water bivalve *Eomiodon securiformis*. Caliche nodules within siltstones and red coloured, coarse-grained sandstones, on the other hand, represent fluvial environments. The dirty character of the clastics, their sedimentary structures, the intercalated marls bearing brackish-water fauna (chap. 3.1.3), the spatial arrangement of facies types (cf. to chap. 6.2), and the lateral interfingering with marine deposits can only be explained by a deltaic depositional environment for the Sobral clastics, an interpretation already given by CHAUMEAU (1962).

R. WILSON (1979) and FÜRSICH (1981) described a very similar deltaic sequence of about the same stratigraphic level (cf. to chap. 5.2.2.4) along the coast of Santa Cruz.

Since, unfortunately, no major outcrops are existing in the Sobral delta clastics, environmental interpretation of the sediments is, to some extent, hypothetic and dependant on facies sequences. Thus, siltstones occur in prodelta, delta front, interdistributary bays and flats, or even in the delta floodplain. Most diagnostic are dirty clastics with *Eomiodon securiformis*, representing delta front sands, laid down under oligo- to mesohaline conditions (FÜRSICH 1981). Cross-stratification is apparently often destroyed by bioturbation. On the other side, thick-bedded channel-fill deposits often exhibit pronounced cross-bedding, although it may lack, if sediments were deposited under turbulent conditions.

Clean, well sorted sands can be attributed to distal and tidal bars, or to beach ridges, particularly when exhibiting low angle cross-bedding. Small-scale and climbing ripple lamination tend to be very common in subaerial levees. These may be cut by crevasse splays which in this case often were reworking floodplain deposits with caliche development, resulting in conglomeratic sandstones with limestone pebbles. The same facies, with additional reworked ooids and cortoids may also occur as channel lag deposits of submarine distributary channels.

(For environmental interpretation cf. to, e.g., DONALDSON 1970 et al., ELLIOT 1978, WRIGHT 1978, MOUSAVI-HARAMI & BRENNER 1984; see also chap. 6.2)

3.1.3 Marls, Containing Oyster and Coral Patch Reefs, *Isognomon* Clusters and *Gervillia* Meadows

D i s t r i b u t i o n : Marls possibly represent about half of the Sobral unit, although they are rarely outcropping. While *Isognomon* clusters may occur in any part of the Sobral sequence, the *Gervillia* marls are more confined to its uppermost part. Oyster patch reefs are also widely distributed, but tend to occur particularly in the transition level to the underlying Oólitó unit.

In the Oolito unit marls play only a negligible role.

Description (pl. 3/4, pl. 15): Marls are mostly dark grey to black. They may turn to reddish brown, if containing a larger amount of silt fraction. Generally being very micaceous and lignitic, with enrichments on bedding planes, both kind of particles may also lack totally, particularly in black varieties. Silty marls may contain ooids and sand-sized detrital quartz grains. Bioturbation is partly intensive with distinct burrows of *Planolites*, small *Thalassinoides* and *Ophiomorpha*. The latter burrow is mantled with ooids.

Macrofauna in the Sobral marls is generally rare, but if occurring, low diverse and individual-rich. Small imprints of bivalves and, more rarely gastropods are more frequent, also displaying low diversity patterns.

The following associations can be found:

(a) *Praeexogyra pustulosa* – *Nanogyra nana* association

This association is already known from other parts of the Portuguese Upper Jurassic (FÜRSICH 1981, FÜRSICH & WERNER 1984). *P. pustulosa* forms the framework of oyster patch reefs; the frequency of additional *N. nana* is variable. Further faunal constituents are *Placunopsis suprajurensis* (also rarely forming monospecific horizons), *Plicatula* sp. and serpulids. Growth always starts on secondary hardgrounds, most commonly on shells of *Isognomon lusitanicum*. The scale of such overgrowths ranges from thin covers of only one oyster generation up to several meters large and 50 cm high patch reefs. Normally, however, only small patches are constructed.

Worth mentioning is a 1.5 m thick coquina of *Arcomylus morrisoni* shells in marly matrix west of Boieiro hill-top. The ratio of single to double-valved specimens is 2:1. Primary fraction rate was low, Recent weathering, however, caused intensive brittling, what can be distinguished by in-situ orientation of related clasts. Both types of *Arcomylus* shapes are frequent (cf. to chap. 4.1), size of specimens is up to 15 cm. *Eomiodon securiformis* also occurs rarely. The valves are normally heavily encrusted by serpulids, bryozoans, *Plicatula* sp. and, above all, by oysters. Overgrowth is located mostly on outer, partly on inner, and rarely both on outer and inner shell surfaces. Oyster patch reefs arising from this overgrowth are embedded in the coquina, normally forming only small nodules (diameter 10–30 cm). In the base part, however, a laterally persistent, 40 cm thick, oyster bank is intercalated.

(b) Coral cluster and coral patch reef association

Oyster reefs may contain isolated corals, e.g., in the Mata section (see chap. 8): The solitary coral *Axosmilia* is dominating by far (*A. crassa*, *A. carrapateirensis*, *A. cf. corallina*); Furthermore, the branching coral *Actinastrea crasso-ramosa*, *Praeexogyra pustulosa*, single valves of giant *Protocardia* sp. A (middle to upper part of section) and spines of *Pseudocidaris lusitanicus* appear. Overgrowth by serpulids, bryozoans and especially cyanophytes and *Marinella lugeoni* results in formation of macroids and oncoids. They are partly concentrated to form a marly oncolite which is outwedging over a short distance.

Corals, associated with oyster patch reefs and *Gervillia* marls (see below) are astonishingly frequent in the eastern part of the study area. Sets of several *Axosmilia* specimens (often close to the species *discoidea*) are most common. *Ovalastrea cf. lobata* also appears in monospecific clusters. Around Adanaia exist more extensive coral meadows up to 30 cm thick which are dominated by the branching form »*Calamophyllia flabellum*«, with further *Axosmilia cf. carrapateirensis*, *O. cf. lobata* and oysters occurring. A three meter thick coral patch reef between Adanaia and Alverca belongs most likely also to this level. »*Calamophyllia flabellum*«, often in-situ, dominates, but additionally ?*Thecosmilia trichotoma*, *Convexastrea stellata*, *A. carrapateirensis* and the massive forms *Thamnasteria pseudarachnoides*, *Cyathophora cesaredensis*, *Stylina (Heliocoena) choffati* and *Microsolenia agariciformis*, oysters and serpulids are also occurring.

(c) *Isognomon lusitanicum* association

Shell beds of disarticulated specimens or, more common, banks of mainly double-valved *I. lusitanicum* are rather widespread in the Sobral unit, particularly in its lower part. Double-valved specimens are commonly preserved in life position. This association is sufficiently described in FÜRSICH (1981). In the Sobral unit, the low diverse variety of the association occurs, hardly containing additional elements, except for common overgrowth of oysters of the *P. pustulosa* – *N. nana* association. Substratum and matrix is normally a marly silt.

In contrast to the laterally persistent banks at the coast (op.cit.), the present *Isognomon* banks tend to out-wedge rather rapidly, sometimes already after a few meters. Clusters of double-valved specimens also appear in small lentil-shaped patches.

(d) *Gervillia sobralensis* association

One of the most characteristic facies types of the Sobral sequence are marls with *G. sobralensis* (pl. 15/4).

The grey marls are hardly contaminated by silt or sand; lignite content is variable, often low.

G. sobralensis appears most commonly double-valved, embedded with the long axis in horizontal position, often parallel to the next specimen lying several centimeters aside. Frequently, only one of these shell layers is developed.

Less common are disarticulated shells which are mostly intact (unless fragmented by Recent weathering). Single valves are more densely concentrated than double-valved specimens.

Shells are sometimes encrusted by *Nanogyra nana*, *Placunopsis suprajurensis* or by serpulids and bryozoans. Byssal attachment knots of *Anomia* sp. are common. Rarely, pentagonal scratch marks of *Gnathichnus pentax* (pl. 15/3) as well as attached ostracod shells are also occurring.

Another characteristic form is the gastropod *Nerinea turbinata* (pl. 15/1) which, however, is not appearing in all outcrops. Further macrofaunal elements, e.g., *Pteroperna* sp., spines of *Pseudocidaris lusitanicus* and corals are rather rare. Because of the weathered condition of the host sediment, soft-bottom or micro-fauna could be only discriminated in one sample: *Corbulomima* sp., *Isocyprina* sp., *Protocardia* sp., *Mesosacella* sp. and *Jurassicorbula edwardi* point out similarities to both of FÜRSICH's (1981) *Mesosacella dammariensis* – *Corbulomima suprajurensis* and *Jurassicorbula edwardi* associations.

Most often, the marls with *G. sobralensis* only could be traced by shell debris ploughed up from subcrops.

(e) Small-sized soft bottom association

Apart from the above described intercalations of faunal shell beds, banks or patch reefs, the Sobral marls exhibit very few or no further faunal elements.

Most widespread is the very low diverse *Eomiodon securiformis* association (cf. to FÜRSICH 1981) with specimens averaging only 5 mm in size. A cerithiid gastropod as well as unornamented ostracods and crab remains may also occur. Several samples show transitions to the *J. edwardi* or to the *M. dammariensis* – *C. suprajurensis* associations of FÜRSICH (1981), exhibiting forms already mentioned from the *Gervillia* marls.

Discussion: By their position within delta clastics, by their high content of lignite litter and by their faunal characteristics, the Sobral marls clearly fit to the fluvio-marine interpretation of the entire sequence.

Reddish brown silty marls often grade into silts with caliche nodules, thus pointing out their depositional environment as flood plains or abandoned fluvial channels.

Both the *P. pustulosa* – *N. nana* and the *I. lusitanicum* associations are attributed by FÜRSICH (1981) to brackish, precisely brachy- to mesohaline, protected inlet bays and lagoons. This interpretation is followed here. The *I. lusitanicum* association also seems to have populated abandoned submarine channels, forming lentil-shaped clusters. In contrast to the protected quiet water environments of the *Isognomon* banks which were only rarely affected by storms, oyster patch reefs required somewhat higher energy conditions combined with low sedimentation rates in order to create the settling substratum, here always in form of secondary hard-grounds such as storm shell layers, and to prevent further deposition of sediments during the growth of the patch reefs. A good example are the patch reefs within the *Arcomytilus coquina* at Boieiro hill: Apparently several times, *Arcomytilus* valves were shoaled together by storms from very closeby areas, evidenced by the high amount of double-valved shells.

Moreover, the oyster patch reefs were very tolerant in regard to salinity conditions: Patch reefs, built almost exclusively of *P. pustulosa* and *N. nana* and situated within non-fossiliferous marls or occurring together with the *Eomiodon securiformis* association, surely grew in environments with drastically lowered salinity values. Oc-

currence of corals, on the other side, point out fairly improved salinity conditions at certain times or certain regions. However, these corals which also occur in oyster reefs are most probably no pure stenohaline forms, since coral diversity is very low. Further restrictions for coral growth were the soft substratum, necessitating flat resting growth forms, such as *Axosmilia discoidea* and *Ovalastrea lobata* (cf. to chap. 3.2.5), and continuous though lowered deposition of fine-grained sediments, demanding branching fast growing forms as the highly adapted »*Calamophyllia*« which is known from similar environments elsewhere (e.g., WERNER 1986). Associations of up to eight coral species announce conditions more favourable for coral growth.

Heavy local incrustations by algae evidence longer periods of non-deposition.

The euryhaline *Arcomytilus morrissi* which is only occurring in paraautochthonous coquinas (see above) apparently requires somewhat stable conditions within the brachyhaline regime for maximum growth and frequent occurrence (cf. to chap. 4.1). Consequently, both coral patches and *Arcomytilus* clusters are attributed to intertributary bays and lagoons, with the first assemblage representing euhaline to upper brachyhaline and the latter lower brachyhaline conditions.

The *Gervillia sobralensis* association clearly represents the most stable environments within the Sobral delta sequence: both its lateral persistence and the accompanying fauna, indicating only moderately lowered salinity, point to a shallow prodelta environment, also possibly extending into broader intertributary lagoonal bays.

G. sobralensis was forming extensive, though loosely populated meadows below normal wave base. The soft substratum only could be inhabited by infauna or by adapted epifaunal forms such as flat shaped corals or the regular echinid *Pseudocidaris lusitanicus* (cf. to chap. 4.2). *P. lusitanicus* apparently was grazing algal covers on shells of *G. sobralensis*, creating characteristic *Gnathichnus pentax* scratch marks (cf. to BROMLEY 1975, see also FÜRSICH 1981).

Intensive algal growth also served as food for the grazing gastropod *Nerinea turbinata*, resulted in sticking ostracods at the *Gervillia* shells and provided clear water by trapping sediment particles, so that suspension feeding forms could establish.

Further encrusting of *Gervillia* shells by bryozoans, serpulids, *N. nana* and *P. suprajurensis* occurred both during life time and post-mortem.

The elongated shape of *G. sobralensis* and occasional oriented overgrowth by *N. nana* on its posterior end makes a semiinfaunal life habit of this form likely, being stuck in the sediment like Recent *Pinna*, what is also guessed by STANLEY (1972) for the entire genus *Gervillia*. However, the sabre-shaped shell and the flat cross-section of *G. sobralensis* would, according to SEILACHER (1984), rather point to a pendant epibyssate attachment. If following this interpretation, seaweeds could have served as a fixing substratum. If assuming a semi-infaunal life habit, shells were either laid flat by burrowing organisms, especially crabs, or were concentrated by storms, showing only minor effects in these depths, such as winnowing of the fine sediment fraction and small scale transport of entire shells.

Marls without distinct macrofauna can be attributed to corresponding environments according to their soft-bottom fauna. Thus, similarities to FÜRSICH's (1981) *Mesosacella dammariensis* – *Corbulomima suprajurensis* or *Jurassicorbula edwardi* associations refer to prodelta and open lagoonal environments, whereas the tiny monospecific fauna of the *Eomiodon securiformis* association points to more restricted tidal inlet bays.

3.2 Facies Types and Environments of the »Pteroceriano« Unit

The term »Pteroceriano« is used here only to define a facies-related lithostratigraphic unit (cf. to chap. 5.2.2.3), composed of limestones and marls with variable content of carbonate.

Roughly, a lower, predominantly marly, micritic part can be distinguished from an upper one, developed only in the south, exhibiting local coral bank development and high energy sediments.

3.2.1 Marly, Mostly Nodular, Low–Diverse *Arcomytilus* Limestones

Distribution: Particularly in marly sequences of the lower part of the »Pteroceriano« unit; prevailing facies type in this level.

Description (pl. 4/1 – 4, pl. 5/1, 2): All varieties of this facies types exhibit grey, mostly dark grey colouring. Brown impregnation caused by iron hydroxides is rather rare.

Macroscopically, four subtypes can be distinguished:

- (a) thick-bedded, marly mudstones with whole-body fossils, often transitional with marls (pl. 4/1)
- (b) medium-bedded, nodular mudstones/bioclastic floatstones with high fragmentation rate of fauna
- (c) thin horizons of nodular mud/floatstones within marly sequences (pl. 4/2)
- (d) very sandy, nodular mud/wackestones.

Common characteristics are intensive bioturbation causing nodular fabric (except for (a)) and a low diversity fauna and flora.

The following forms which are best preserved in type (a), are occurring (dominant forms indicated with ++; forms only dominating at times with +):

++ *Arcomytilus morrisi* (clusters), ++ *Protocardia intexta*, + giant *Protocardia* sp. A, + *Protocardia* sp., *Antiquicyprina* sp. (r)¹, ++ *Myopholas multicostata*, *Mactromya concentrica*, *Jurassicorbula edwardi*, *Camptonectes* cf. *auritus*, *Trichites* sp. (r), + *Nanogyra nana*, *Placunopsis suprajurensis*, *Praeexogyra pustulosa*, heterodonts indet.; + gastropods, rarely nerineids, *Ampullina* sp.; *Pseudocidaris lusitanicus* (r, spines), cidaroid indet.; ++ *Thalassinoides suevica*, ++ *Thalassinoides* sp., ++ *Rhizocorallium irregulare*; ++ *Everticyclammina virguliana*, + *Pseudocyclammina* gr. *parvula*–*muluchensis*, *Rectocyclammina* sp., »*Haplophragmium*« sp., *Freixialina planispiralis*, ?*Feurtillia frequens*, *Glomospira* sp.; serpulids, ostracods, bryozoans (r), cyanophytes, *Marinella lugeoni* (r), dasycladaceans (r, e.g., *Cylindroporella* cf. *arabica*), algal spores; lignite litter (r) and the coprolith *Favreina* cf. *salevensis*.

Most characteristic are the bivalves *Arcomytilus morrisi*, often occurring in clusters (cf. to chap. 4.1), *Protocardia* and partly *M. multicostata* as well as the litiolid foraminifer *E. virguliana*.

Degree of bioturbation, mostly by *Thalassinoides* and *Rhizocorallium* varies largely. Type (a) normally shows either no signs of bioturbation or well preserved burrows only on bedding surfaces, with very irregular *Rhizocorallium* prevailing (pl. 4/3, 4). Type (c) consists exclusively of calcareous burrow fillings of the above mentioned ichnotaxa, embedded in marl (pl. 4/2). Type (b) is intensively burrowed which together with diagenetic overprinting results in a very nodular structure without individual burrows being distinct anymore. Very sandy nodular limestones (type (e)) are restricted to the north and east of the »Pteroceriano« development.

Mudstones contain only very scattered biomorphs and bioclasts which are, though, often enriched in clusters. Mollusk shells within wacke- and floatstones are distributed very inhomogenously, show a wide range in size and are normally fragmented. At times, bioclasts are microbored or thinly coated by algal films (cortoids). Very often, oyster cortoids show red colouring. Bioclastic pack/rudstone areas with imbricated layering of shells normally occur as centimeter-thick horizontal, vertical and oblique strings (pl. 5/1). Rarely, nodular limestones occur, consisting entirely of bioclastic, micritic pack/rudstone fabric.

All particles are embedded in a micritic, often inhomogenous matrix. Inhomogeneity is due to varying colouring (bitumen), varying marl content or, most often, due to partial recrystallization to microspar. Moreover, clotted micrite, presumably caused by fused soft pellets, or pelletal packstone also often forms respectively the matrix and the pseudomatrix.

Diagenetic alteration is widespread. Microsparitization often starts from the common early diagenetic dessication and compaction cracks (pl. 5/2). Total recrystallization, at times, also led to complete alteration to neospar.

Footnote¹: Frequency abbreviations used here and in the forthcoming chapters: r rare, o occurs, c common, a abundant.

Apart from some marly samples, where primary shell structures are partially preserved, aragonitic shells are always recrystallized, partly after early solution. Biomolds collapsed partially, if the host sediment was not completely hardened at the time of leaching.

Discussion: The origin of shallow marine nodular limestones due to *Thalassinoides* burrowing and subsequent early cementation and compaction is thoroughly explained by FÜRSICH (1973a).

(FÜRSICH (1973b) pointed out that the name *Spongiomorpha* has priority. This revision, however, was not regarded in literature so that the author himself turned back to the well established term *Thalassinoides* (e.g., FÜRSICH 1981))

In Portugal, nodular limestones were already described from the Upper Jurassic south of Lisbon by FÜRSICH & SCHMIDT–KITTLER (1980) who also mentioned the partial faunal dominance of the deposit feeding organism producing *Rhizocorallium irregulare* burrows. This is also valid for the here treated nodular limestones.

Generally, burrows are only poorly preserved, mostly due to intensive diagenetic accretion, although at times *Rhizocorallium* exhibits scratch marks and spreiten, originating from the burrow producing decapod crustacean.

Preconditions for intensive horizontal burrowing and its preservation are slow depositional rate and lack of high energy events. Moreover, distinct burrow boundaries and scratch marks indicate a partially rather high degree of consolidation of the substratum at the time of burrowing (FÜRSICH 1975).

Such a semifirm to firm ground could only be inhabited by shallow burrowing, suspension feeding bivalves, such as *Protocardia*, *Mactromya*, *Jurassicorbula* and epibyssate forms like *Camptonectes* or the highly adapted, clustering semiinfaunal to epifaunal *Arcomytilus morrisoni* (cf. to chap. 4.1). *Nanogyra nana* and *Placunopsis supajurensis* were not only overgrowing epifaunal shells but also the infaunal giant *Protocardia* sp. A, brought up to the sea floor by burrowing activity or by winnowing (pl. 15/7). Winnowing of soft sediment apparently also uncovered already cemented *Thalassinoides* burrows which *N. nana* settled on. The oyster's occurring only on the upper side of the burrows makes a diagenetic imprinting of *N. nana* due to compaction unlikely (pl. 16/5).

The local common appearance of the deep burrowing bivalve *Myopholas multicostata* points to lower primary consolidation of the corresponding beds.

Burrowing in the nodular limestones took place during all degrees of consolidation. Most common is a mottled, inhomogenous structure or a clotted pelletal fabric, originating from very early bioturbation. Distinct burrowing traces, yet without clear boundaries to the surrounding sediment, are outlined by enrichments of imbricated bioclasts and represent a later stage of burrowing. Clear differences between the burrow–filling sediment and the host rock point to biogenic activity in semifirm beds. At last, burrows filled with sparitic sediment correspond to late activity in fairly consolidated deposits. This, however, is a rather rare feature in the *Arcomytilus* nodular limestones.

Bioturbation also affected marls underlying nodular limestones, partly resulting in distinct, early cemented, calcareous burrows, predominantly of deposit feeding *Rhizocorallium irregulare*.

Taking all informations into account, a protected shallow water depositional environment is evident for the *Arcomytilus* limestones. No signs of faunal high energy reworking occur throughout all varieties. Bioclast formation is thus only due to burrowing. Bioclast enrichment resulted from winnowing during stages of somewhat elevated energy or from relative concentration due to lowered sedimentation. Low depositional rates are as well proved by the intensive burrowing, by oyster encrusting of shells forming also small patch reefs, and by occasional microborings on epifaunal shells.

On the other hand, however, the normally low faunal density and the general prevalence of non–microbored bioclasts suggest accelerated rather than slow deposition.

Sedimentation was apparently intermittent. Clouds of carbonate muds, most probably derived from neighbored carbonate bank areas during storms, were deposited fairly rapidly, burying the epifauna. A rather long phase of slow or non–deposition accompanied by gentle water circulation followed subsequently. During this interval burrowing by sediment dwellers and deposit feeders, hardening of the substratum, settlement of epifauna and cortoid formation could take place until the next depositional event happened.

In the base part of the »Pteroceriano« unit, depositional rates were continuously higher in some areas, causing formation of non–nodular, thick mudstones with very low faunal densities and a partial dominance of deep burrowing *Myopholas multicostata*.

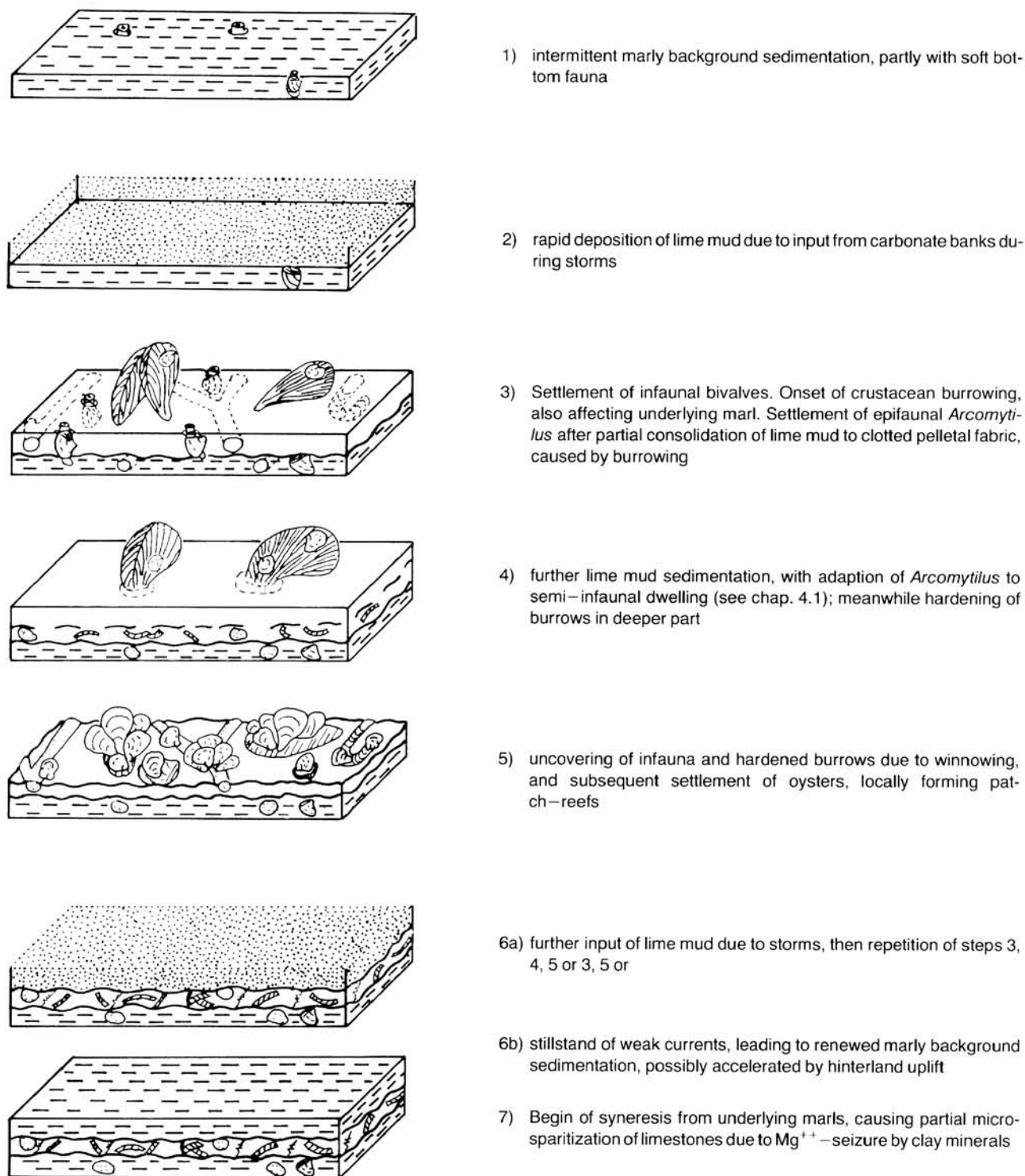


Fig. 2: Genesis of nodular shallow water limestones in the »Pteroceriano« unit (partly after FÜRSICH 1973a)

The faunal diversity is constantly low, with adapted, euryhaline forms prevailing. The composition shows certain similarities to the *Jurassicorbula edwardi* association of FÜRSICH (1981), though the relative frequencies are quite different and deep burrowers are not occurring, except for *M. multicostata* (see above). Most of the forms are also appearing in FÜRSICH's (1981) delta abandonment facies of sediments at the coast of Santa Cruz, although there the diversity is higher, what, however, according to the same author, could be an effect of faunal condensation.

The lituolid *Everticyclammina virguliana*, dominating the foraminiferal assemblage, is known for its ecological tolerance, thus occurring up to intertidal environments (e.g., PÉLISSIE & PEYBERNÈS 1983).

Hence, lower to middle brachyhaline conditions apparently prevailed. Horizons with rare coralline algae (*Marinella lugeoni*, cf. to chap. 4.3), dasycladaceans, *Trichites* and *Pseudocidaris* probably represent stages of somewhat improved salinity conditions (cf. to chap. 3.2.2), whereas varieties with considerable amount of detrital quartz and lignite litter might represent fairly brackish settings. Intermittent deposition also had restricting effects on the fauna.

Although the clustering bivalve *Arcomytilus morrissi* is a close relative of the Recent intertidal *Mytilus edulis*, the Ancient form clearly inhabited subtidal areas. *Rhizocorallium* indicates a position below fair weather wave base (see above) and is restricted to stable substrata (FÜRSICH 1975). Such a bathymetric situation also becomes evident by the lack of high energy grainstones. Pelletal packstones represent most probably faecal remains.

The common microfractures and compactional cracks need not necessarily originate from early diagenetic emerging. They might be caused by early syneresis due to the high water content of the intercalated marls and the consistence of the plastic calcareous muds. On the other hand, a too mighty water column would prevent preservation of these cracks.

Early cementation of burrows also requires shallow depths.

Besides in freshwater settings, early microsparitization may as well occur in the marine phreatic zone. Precondition is a removal of the crystal growth poisoning Mg^{2+} content within the primary lime mud. This can be managed by mixing up with meteoric waters due to occasional heavy rainfalls or fluvial input, or seizure of Mg^{2+} ions by the clay minerals of the interbedded marls (cf. to FOLK 1974:49). The latter case is often realized here, as can be seen by the distribution of microspar along syneresis cracks.

Early solution phenomenon, though more common in meteoric diagenetic environments, may also occur in a mixed marine–brackish phreatic zone (LONGMAN 1980).

Summarizingly, maximum values of about 25 m should not have been superceeded for the formation of the *Arcomytilus* limestones. Their depositional history is sketched in fig.2.

3.2.2 *Trichites* Limestones

Distribution : Lower part of the »Pteroceriano« unit, particularly in the east.

Description (pl. 4/5, pl. 16/6) : *Trichites* limestones are light cream coloured and thick-bedded in the typical case. They may exhibit a rather nodular structure, though more commonly bioturbation by *Thalassinoides* and, less important *Rhizocorallium irregulare* only affected the lower surfaces of beds.

Many intact faunal elements as well as bioclasts are floating in the micritic matrix. Very rarely, a large amount of detrital quartz occurs (Sta. Quitéria section, see chap. 8).

Since *Trichites* limestones develop from *Arcomytilus* limestones, almost all forms of the *Arcomytilus morrissi* association can be found, particularly *A. morrissi* and *Protocardia* ssp.. Most typical, however, is the large pinnacean bivalve *Trichites* aff. *saussurei* which sometimes occurs in life position (cf. to FÜRSICH 1980; see pl. 16/6). Occasionally forming small clusters on the bedding planes, its shells serve as secondary hardgrounds for intensive boring activity of *Lithophaga* sp. and attachment of *Nanogyra nana*, giving even rise to the development of small oyster patch reefs. *N. nana* is also incorporated in the micritic sediment by burrowing. *Coelastarte discus* and spines of *Pseudocidaris lusitanicus* are very widespread. Calcisponge and coral debris and also small in-situ coral heads occur at times. Furthermore, *Marinella lugeoni* is typical for this facies type, occurring both in fragments and subspherical nodules up to 5 cm in diameter (pl. 4/5). *M. lugeoni* can even dominate the biomass, thus forming an algal nodule micritic rudstone (cf. to chap. 3.2.9). Bioclasts are most commonly microbored (cortoids). Initial or, rarely, advanced oncoïd formation also took place. Thicker shells may be affected by boring sponges. Microanalysis reveals the litiolids *Pseudocyclammia* gr. *parvula*–*muluchensis*, *Everticyclammina virguliana*, »*Haplophragmium*« sp., dasycladacean debris (r–o), »cayeuxiids«, bryozoans, ostracods (r) and serpulids.

Syneresis cracks and other early vadose features may be common as in the *Arcomytilus* limestones.

Discussion : Apparently rather stable environmental conditions gave rise to this facies type. Thick bedding is not due to rapid deposition, since the fauna, dominated largely by suspension feeders, occurs through-

out the entire bed, proving rather low depositional rates with possible times of nondeposition where encrusting forms could settle. This is also evidenced by the formation of cortoids, superficial oncoids and the growth of coralline algal nodules which additionally required slightly elevated energy conditions (cf. to chap. 3.2.9).

The semi-infaunal *Trichites* requires a relatively soft substratum (FÜRSICH 1980) which, however, was firm enough for the adapted sea urchin *Pseudocidaris lusitanicus* to cross (cf. to chap. 4.2).

Degree of burrowing is much lower than in the *Arcomytilus* limestones which is probably due to a better oxygenated sediment not being suited for deposit feeders like *Rhizocorallium irregulare*. Better oxygenation is caused by the generally higher energy level, by algal growth and by slow but fairly continuous sedimentation compared to the intermittent rapid deposition of the *Arcomytilus* limestones.

The occurrence of corals, echinids, dasycladaceans and coralline algae indicates fairly normal salinities.

Water depth was rather shallow so that small oyster patch reefs and coral heads could flourish. Weak water currents prevented deposition of terrigenous mud.

Consequently, the *Trichites* limestones represent local, shallow water carbonate banks under rather fully marine conditions.

A *Trichites* aff. *saussurei* association is also mentioned from the Portlandian of Cabo Espichel, south of Lisbon, by FÜRSICH & SCHMIDT-KITTLER (1980) and from the Upper Kimmeridgian/Lower Portlandian of Peniche by WERNER (1986) who come to similar conclusions.

The occurrence of common *Trichites* fragments within a limestone bed with considerable amount of coarse detrital quartz in the north is certainly caused by outwinnowing of lime mud and admixing of clastics during a storm.

3.2.3 Marls with Scattered Bivalve Fauna

Though major parts of the »Pteroceriano« unit are apparently composed of marls, these crop out only occasionally. Particularly rare are fresh samples. Because of this and especially because of already existing minute examinations on marly sequences of the same (FÜRSICH 1981) or slightly lower level (WERNER 1986) along the Atlantic coast, description is only brief here and the reader is also referred to the cited works.

Distribution: Throughout the entire »Pteroceriano« unit, particularly in its lower part; normally in association with marly or nodular limestones. Thicknesses ranging from cm-thick intercalations to m-thick beds.

Description: The marls exhibit mainly a dark to light grey colour, though reddish brown horizons are not uncommon. Carbonate and silt content is variable, the latter normally very low. Lignite litter and mica are current though minor constituents. Framboidal pyrite may be frequent in some samples. Rarely, authigenous quartz crystals occur.

Bioturbation frequently led to mottled marls, occasionally with preserved vertical burrows. Horizontal burrows are represented by thin horizons of nodular mudstones, composed exclusively of diagenetically altered *Thalassinoides* and *Rhizocorallium* traces (cf. to chap. 3.2.1). In the lower part of the unit, however, marls are often well laminated.

The microfauna consists mainly of litioloid foraminifers among which *Everticyclammina virguliana* is dominating. Ostracods may also be frequent or dominant in some samples. *Cytherella suprajurassica*, *Asciocythere* sp., *Cytheropteron* sp., aff. *Theriosynoecum* sp. could be identified.

The benthic macrofauna is mainly composed of bivalves. Most outstanding is the macroscopic dominance of *Myophorella lusitanica* in many samples. Often, the bivalve is preserved with both shells in life position, though univalved enrichments also occur frequently. Samples with double-valved specimens exhibit additional imprints of tiny bivalves such as *Corbulomima suprajurensis* (c), *Mesosaccella dammariensis* (c), *Isocyprina* sp. (c), *Nicaniella* sp. (c), *Protocardia* sp., *Pteroperna pygmaea*, small *Arcomytilus morrisi*, cerithiid gastropods (r), etc., and are thus comparable to the *M. dammariensis* – *C. suprajurensis* association of FÜRSICH (1981) or the *C. suprajurensis* – *M. dammariensis* association of WERNER (1984). Another common association is a co-occurrence of *Jurassicorbula edwardi* (dominant) with *Myopholas multicostata*, *Protocardia* sp., *Nicaniella*

sp., *Placunopsis suprajurensis* and others, resembling the *J. edwardi* association of the above authors. An assemblage with very tiny imprints of ?*Eomiodon* sp. and ?*Neomiodon* sp. is also already described by WERNER (1986).

In bare fields, further macrofaunal forms, most probably derived from subcropping marls, could additionally be collected. They correspond to taxa which also form shell coquinas, as treated in the following chapter.

Discussion: Marls commonly lack environment—diagnostic sedimentological features, apart from an eventual fine lamination which would indicate fairly anaerobic conditions so that not even bioturbation could take place.

This is rarely the case in the present marls. Local slight anaerobic conditions could, however, be documented by marls with framboidal pyrite. Normally, a fairly high amount of infaunal tiny bivalves in non—weathered samples permits to exclude overall non—oxygenated sediments.

When comparing the »Pteroceriano« soft bottom fauna to quantitatively evaluated associations (FÜRSICH 1981, FÜRSICH & WERNER 1984, WERNER 1986), the present marls should represent salinities ranging mainly from the upper mesohaline to the lower euhaline regime, thus pointing out brackish to open lagoonal environments.

In weathered outcrops, where tiny bivalve imprints are not preserved anymore, it seems possible to consider findings of *Myophorella lusitanica* as approximately indicative for somewhat better salinity conditions, since FÜRSICH (1981) recognizes the form only in the *M. dammariensis* — *C. suprajurensis* association.

Common findings of *Jurassicorbula edwardi* may then analogously point to the *J. edwardi* association, where the form dominates by far (cf. to FÜRSICH 1981) and might thus be representative for lowered salinity conditions.

The frequent litiolid *Everticyclammina virguliana* as well as the ostracods also mainly indicate unstable, often lowered salinities (cf. also to WERNER 1986).

The rarely occurring authigenous idiomorphic quartz, diagnostic for hypersaline pore waters, eventually indicates early breakthrough and leaching of Upper Triassic salts (for discussion see WERNER 1986; cf. also to chap. 6.5.1).

3.2.4 Marly—Silty *Isognomon* Banks, Shell Beds and Coquinas

Distribution: Intercalations in the central area of »Pteroceriano« development; dominant representative of »Pteroceriano« facies in its marginal (northern and western) zone.

Description (pl. 15/8): The uniform, grey marly—micritic lower part of the »Pteroceriano« unit exhibits several intercalations of faunal enrichments which commonly are embedded in an ocre—coloured, silty—marly groundmass. Some of these beds can be traced over several kilometers, thus being an important tool for correlating neighboured sections, whereas others apparently disappear after several meters.

Three types of faunal concentrations can be distinguished:

- (a) banks of *Isognomon lusitanicum* in life position
- (b) shell beds of univalved *I. lusitanicum* with additional forms
- (c) coquinas of »Pteroceriano« fauna with a high amount of double—valved specimens.

The *I. lusitanicum* banks of the »Pteroceriano« unit normally resemble very much those of the underlying Sobral unit, i.e., they are characterized by the same low diversity association, mainly formed by *I. lusitanicum* itself and by an additional overgrowth of *Praeexogyra pustulosa*, *Nanogyra nana* and *Placunopsis suprajurensis*. Only locally, further species such as *Isognomon flambarti*, *Coeastarte discus* or *Arcomytilus morrisi* occur.

The beds normally consist of only one set of double—valved *I. lusitanicum* in life position, closely reclining at each other. The top of such layers may grade into a horizon of disintegrated shells.

In thin *I. lusitanicum* shell beds, composed of single-valved specimens, further elements as *Eomiodon securiformis*, *Myopholas multicostata*, *Pteroperna* aff. *credneriana*, *Axosmilia* cf. *discoidea*, *Pseudocidaris lusitanicus* (spines) may be admixed. *P.* aff. *credneriana* also dominates some shell beds.

Very characteristic and laterally fairly persistent are 30–40 cm thick macrofaunal coquinas with an astonishingly high percentage of double-valved bivalves (up to 80%). Shell debris is added in varying quantities. The faunal elements are normally embedded in a silty-marly groundmass.

Almost all representatives of »Pteroceriano« fauna (except for the entire coral variety, s. below) can be found in these coquinas, although the spectrum normally consists of less than ten species.

Most typical are the following forms: *Unicardium crassum*, *Antiquicyprina* sp., *Isognomon lusitanicum*, *Gervillia sobralensis* or *Gervillia aviculoides*, *Coelastarte discus*, *Trichites* sp. (fragments), *Arcomytilus morrissi*, *Præexogyra pustulosa*, *Nanogyra nana* (of both normally only right valves, *Ampullina* sp. and large lignite litter (up to 10 cm long).

Additionally may occur: *Myopholas multicostata*, *Pteroperna* sp., *Isognomon flambarti*, *Pseudocidaris lusitanicus* (spines), the corals *Axosmilia* sp. and *Ovalastrea* cf. *lobata* and fragments of *Marinella lugeoni*.

One single bivalve species may occur both double- and single-valved in the same sample. Packing of shells is very close. Shell debris may stick in upright position between entire valves but is sometimes concentrated on top of the coquinas. Elongated shells apparently do not exhibit preferred orientation.

Discussion: *Isognomon* banks characterize environments which are already mentioned in chap. 3.1.3. In comparison with those of the Sobral unit, some banks of the »Pteroceriano« unit should represent somewhat more stable conditions, so that less tolerant forms like *I. flambarti* (cf. to FÜRSICH 1981) or *C. discus* could appear.

Shell beds of disarticulated but mostly intact *I. lusitanicum* were created during short-termed high energy events, most probably gentle storms which caused outwinnowing of the host sediment and admixing of further faunal elements from surrounding environments. Disintegration of shells took place due to current energy, predators or simply ligament decay. The two latter possibilities would claim a certain period of non-deposition.

Thus, the *Isognomon* banks characterize very shallow, marginal marine lagoonal environments within the »Pteroceriano« unit. The vicinity to the coast is responsible for the slightly brackish conditions, the supply of clay and silt, and occasional mild reworking of these banks.

Almost monotypic shell beds of *P.* aff. *credneriana* signalize a dense settlement of this form similar to the *Isognomon* banks in neighboured environments with slightly improved conditions. The epibyssate *P. credneriana* was most probably directly lying on the sea floor (twisted recliners of SEILACHER 1984).

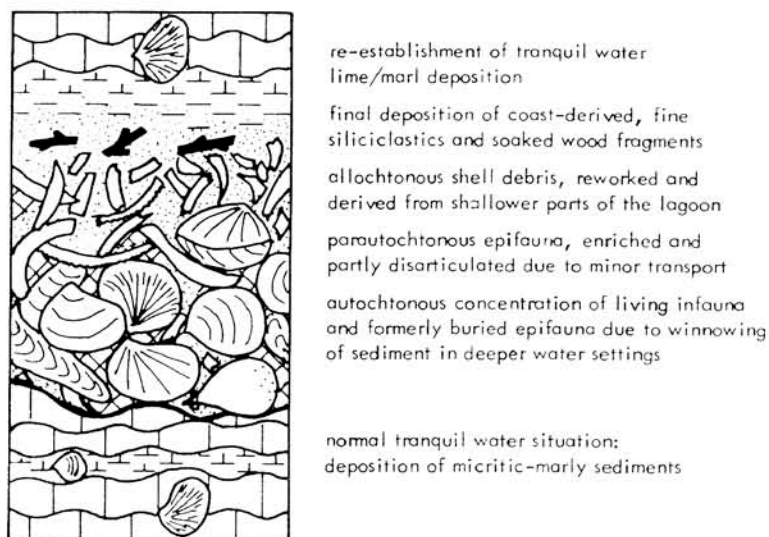


Fig. 3: Idealized sequence of storm layer from deeper settings within the »Pteroceriano« depositional environment.

Laterally persistent macrofaunal coquinas certainly originated due to heavy off-land storms which affected larger parts of the depositional area in the following steps (see fig.3):

- input of suspended terrigenous fine clastics and wood fragments from coastal areas and hinterland
- faunal reworking in shallower parts of the basin
- intensive winnowing of sediments in deeper parts of the basin, thus digging out and concentrating of burrowing or buried double-valved fauna
- subordinate transport and mixing of fauna at maximum of storm
- deposition of reworked shell debris, derived from shallower environments, with decreasing of water energy
- deposition of water-soaked wood fragments, silt and clay with further decreasing of water energy
- renewed establishing of lime mud sedimentation.

These processes would lead to a theoretic sequence of a base sheet of double-valved bivalves, a layer composed of bioclasts and a top layer composed of lignite bearing silt. This, however, is not always realized completely, since silt also penetrated the interstitial pores of lower layers and subsequent bioturbation caused partial mixing, also destroying an eventual preferred orientation of elongated shells.

Lateral gradations from coquinas with predominantly double-valved bivalves to shell beds composed of single-valved, mostly fragmented specimens represent a change from lower to higher water energy and thus correspond most probably to respectively deeper and shallower parts of the storm-affected basin.

3.2.5 Coral Banks and Coral Patch Reefs

Distribution: Coral facies is astonishingly widespread in the »Pteroceriano« unit. Some sites are known since Koby (1904/05) and GEYER (1955), while others are new. Coral facies is much more common in the upper part of the unit where the patch reefs around Alrota are particularly worth mentioning.

Description (pl. 5/3, 4, pl. 13): Corals form up to 5 m thick banks which, however, do not show distinct primary morphologic relief. They are normally outwedging over a few tens or hundreds of meters, interfingering with other facies types.

Corals appear in isolated in-situ or tumbled colonies or heads (up to 50 cm Ø) which are either embedded in lime mud (coral floatstone) or marl, or form connected meadows and knolls (coral boundstone).

The term boundstone is used here in a broad sense, i.e., a considerable amount of colonial organisms are connected to each other, though floatstone areas may still appear as well.

Sampling of corals was almost exclusively restricted to coral marls, though some taxa of lime boundstones could be identified as well.

Normally, corals could only be collected in recently ploughed bare fields where they are derived from subcropping marls. The original associations, however, are difficult to find out, since mixing of different levels may have taken place. Only in a few cases, unweathered marly coral patch reefs are outcropping (see below).

Coral Marls

The following taxa could be identified² from coral marls:

Solitary corals: *Axosmilia crassa*, *A. caudata*, *A. carrapateirensis*, *A. cf. cuneata*, *A. cf. corallina*, ?*A. (Blastosmilia) sp.*, *Montlivaltia obconica*.

Footnote²: The author is aware of the need to revise the taxonomy of Portuguese Upper Jurassic corals (see also WERNER 1986). To facilitate such future work, ancient invalid generic names are also given in case they are largely summarized to single genera by later authors (mainly GEYER 1955, WELLS 1956).

Phaceloid corals: ?»*Calamophyllia*« *crassa*, »C.« (*Calamoseris*) *flabellum*, ?»C.« (*Calamoseris*) *variabilis*.

Dendroid corals: ?*Dermosmilia capitata*, *Dermosmilia*? sp., *Ovalastrea* cf. *lobata*, *O. gemmata*, *O. cf. plicata*, *Ovalastrea* sp..

Dendroid – phaceloid plocoid corals: *Stylina* (*Convexastrea*) *sexradiata*, *S. (Convexastrea) stellata*, *S. (Convexastrea) lobata*.

Massive plocoid corals: *Stylina girodi*, *S. tubulosa*, ?*S. delabechii*, *S. aff. deluci*, *S. (Heliocoenia) choffati*.

Dendroid cerioid corals: *Actinastrea crasso–ramosa*, *A. ramulifera*.

Massive cerioid corals: *Amphiastrea piriformis*, *A. gregoryi*, *Cyathophora bourgueti*, *C. cesaredensis*, *Actinastrea trochiformis*.

Thamnastroid corals: *Microphyllia davidsoni*, *Thamnasteria pseudarachnoides*, *T. lobata*, *T. gracilis*, *Microsolena agariciformis*.

Meandroid corals: *Comoseris meandrinoides*, *Meandrophyllia* (*Latimeandrea*) *helvellidoes*, *M. (Meandrea) bonanomii*, *Polyphylloseris* (*Crateroseris*) *bellis*.

Despite the large general variety of 40 species, diversity in individual samples is mostly low to very low. The rare coral marl outcrops show very low diversity, with one species of phaceloid or dendroid corals largely prevailing. Most common are associations dominated by »*Calamophyllia*« *flabellum*. Dominance of *Stylina* (*Convexastrea*) *sexradiata*, *Actinastrea crasso–ramosa* or *A. ramulifera* is also widespread. These corals may be still in life position (pl. 13/1). Additional common elements are the corals *Amphiastrea piriformis*, *Axosmilia* ssp., echinid spines (*Pseudocidaritis lusitanicus* and other cidaroids), and coral–encrusting forms as calcisponges, bryozoans, sepulids, *Praeexogyra pustulosa*, *Nanogyra nana* and *Anomia* sp.. Particularly the oysters may appear in astonishingly high number.

Isolated microfauna could not be obtained.

Coral Lime Boundstone

Marly coral thickets may develop from or grade into light grey to light brown, thick to very thick–bedded calcareous coral patch reefs. This is normally accompanied by a change in the coral fauna to a dominance of massive coral heads among which *Amphiastrea piriformis* often prevails by far. Different species of *Stylina* as well as the branching forms »*Calamophyllia*« and *Dermosmilia* are also common. Few samples show a high variety of nodular, branching and solitary corals (see below).

Three microfacies types can be differentiated, coral float/ boundstones, coral bafflestones and coral frame/ bindstones.

(a) Coral float/boundstones

In this type, coral debris and small coral colonies are floating in a bioclastic micritic groundmass. Corals are normally of the branching type, forming small, mostly tumbled clusters which may join together to larger patches. Massive corals form bigger knolls by superposition of individual heads.

Corals are at times matter of encrustation by bryozoans, serpulids and oysters. *Lithophaga* borings are particularly common in massive heads.

The groundmass exhibits microbored bioclasts of corals, echinids, mollusks, *Marinella lugeoni*, rare dasy-cladaceans and foraminifers (see below). Signs of bioturbation are also common.

(b) Coral bafflestone (pl. 5/3)

This is a widespread type of coral limestone. Branching phaceloid or dendroid corals (mainly »*Calamophyllia*«, *Dermosmilia*; also *Actinastrea*) form thickets and coppices which are largely in growth position. Additional corals may occur. Encrusting of corals by other organisms plays a minor role.

The trapped sediment is a bioclastic, often altered micrite (wacke/packstone).

Angular, non-encrusted or non-microbored, recrystallized bioclasts most probably represent coral debris.

(c) Coral frame/bindstone (pl. 5/4)

This facies type resembles best a typical »reef« limestone and forms the thickest beds in the study area (up to 5 m). They may outwedge over a short distance. Various types of corals, at times dominated by the massive *Amphiastrea piriformis*, are often encrusted and connected by different sessile organisms like cyanophytes, *Cayeuxia kurdistanensis*, *Marinella lugeoni* (encrusting form), *Lithocodium* sp., *Bacinella irregularis*, *Solenopora cayeuxiformis* n.sp., *Solenopora* sp., sessile foraminifers (nubeculariids), calcisponges, bryozoans and oysters. The boring bivalve *Lithophaga* attacked the corals often in subsequent generations.

Calcisponges may dominate in some samples so as to form frame/bindstones (pl. 5/6, 9).

Most of the occurring calcisponges are representatives of the stromatoporoids, which were formerly attributed to hydrozoans (e.g., LECOMPTE 1956, MILAN 1969) or, in part, to tabulate corals (e.g., FENNINGER & HÖTZL 1965). Later, their attribution to the calcisponges (STEARN 1972, 1975), was widely accepted (e.g., WENDT 1976, HARTMAN et al. 1980, FLÜGEL 1982). Some authors, however, only attributed the chaetetids to the sclerosponges (DIECI et al. 1977, KAZMIERCZAK 1979), whereas the rest of the stromatoporoids was interpreted as cyanophytes (KAZMIERCZAK 1981).

In the present material, stromatoporoids often exhibit the characteristic fibrous clinogonal or orthogonal microstructures (pl. 16/8).

Algae and fixed foraminifers may also form individual nodules (cf. to chap. 3.2.9) or, rarely, bind parts of the bioclastic sediment between the corals. Further organic particles of the, partly sparitic, pack/rudstone interstices are corroid debris of corals, echinids, brachiopods and mollusks, rare fragments of dasycladaceans and *Permocalculus* n.sp., and the foraminifers »*Haplophragmium*« sp. (c), *Pseudocyclammina* gr. *parvula*–*muluchensis*, *Everticyclammina virguliana*, *Nautiloculina oolithica*, verneuilinids, miliolids (r), *Glomospira* sp. (r) and *Lenticulina* sp. (r).

Non-skeletal elements are intraclasts, peloids and clotted aggregates (lumps).

At times, a very thick, isopachous, fibrous needle cement A overgrew the corals (pl. 5/4).

Both groundmass and components were subject of iron hydroxide staining and intensive recrystallization.

D i s c u s s i o n : Despite the abundance of corals and despite the associated coralgall, debris, oolite and lagoonal facies (see subsequent chapters), no mature reefs developed in the study area. This is evident by the lack of primary relief forming and, above all, by the kind of interfingering of the individual facies types. For a complete interpretation of this coral patch environment, the associated sediments and their spatial arrangement must be taken into consideration (cf. to chap. 6.3.2).

The following informations, though, can be obtained by analysing the individual coral banks:

Most of the banks are built of very few coral species, mainly dominated by only one or a few branching corals. The basic environmental restriction for coral growth was a fairly high depositional rate, selecting the branched, fast growing forms. Recent colonies of branched stone corals can grow up by 26 cm/yr., with averages of 2 to 4 cm/yr., whereas massive corals grow at less than 3 cm/yr. (MILLIMAN 1974:95).

All Recent scleractinian corals are, to some extent, capable of removing silt-sized sediment particles by ciliary action and most of them even manage to get rid of coarser particles by stomodal distension due to the uptake of water (HUBBARD & POCKOCK 1972). The most effective sediment rejectors are characterized by a large number of ornamented septae, by a high calical relief and by V-shaped broad calical floors (op.cit.).

Thus, »*Calamophyllia*« with its few, loosely arranged branches and only one top-standing, septae-rich polypid per corallite was apparently best adapted for higher rates of background sedimentation. This form was most likely the fastest grower, being able to keep pace with accelerated sedimentation. Infilling of sediment between corallites and thus their stabilization might have been even a precondition for the pronounced upward growth of the fragile colonies.

Ramose, digitiform plocoid and cerioid forms like *Actinastrea* and *Stylina* (*Convexastrea*) could also store plen-

ty of sediment between their branches (pl. 13/1), although their growth rate must have been considerably lower than that of the simple, tube-like »*Calamophyllia*« corallites. Sediment rejection in this case was probably simplified by a connected stomodeum.

Most of the other corals also seem to have been adapted to somewhat elevated background deposition (see fig. 4). Thamnastroid forms with flat calices and few septae (pl. 13/3) are the least efficient removers, while plocoid forms with elevated calices manage more easily to transport particles around the polypids (pl. 13/9), particularly when deep V-shaped calical floors provide most efficient attachment of the muscle tissue (pl. 13/2). Meandroid forms with broad valleys (pl. 13/8) are the fastest in moving off sediment. Their high number of septae corresponds to an original high number of tentacles, aiding in the transport (cf. to HUBBARD & POCOCK 1972, HUBBARD 1973).

The different species of the solitary coral *Axosmilia* were most certainly efficient sediment removers. This is evidenced by a fairly high number of partially thickened septae and by the pronounced V-shape of calical floors (if preserved, pl. 13/10), so that strong tentacles could be fastened. Trochoid and cylindrical forms grew in upright position; curved exemplars evidence a renewed upright growth attempt after collapse (pl. 13/12).

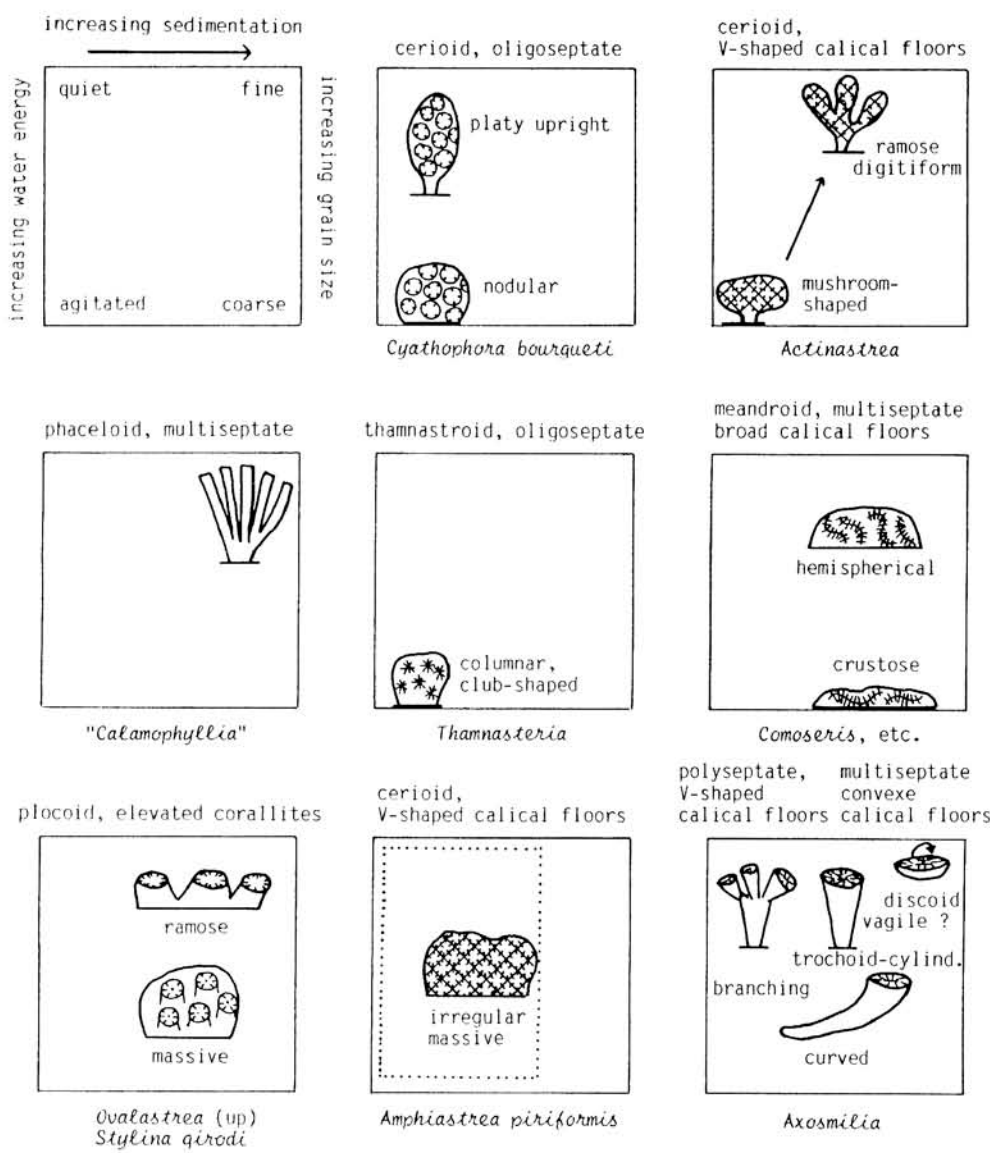


Fig. 4: Environmental diagrams of characteristic »Pteroceriano« corals, based on sedimentological interpretation and on functional morphology of corals (growth form, calical shape, number of septae; see text). Besides high background deposition and low water energy, branched growth is also favoured by inconstant food supply and by unequal illumination what is not considered in the diagrams.

During times of low deposition, when need for pronounced upward growth was lowered, branching by extra-tentacular budding also happened (pl. 13/11). Discoid forms, which also inhabited very unstable environments (cf. to chap. 3.1.3) show the highest number of septae. This might be a response to the change from a deep to a flat convex calice to gain more light in muddy water. Possibly, the discoid form can be compared to modern vagile corals like *Diaseris distorta* which can crawl, turn back in case of being overturned and even free itself when buried (HUBBARD & POCOCK 1972).

The massive cerioid *Amphiastrea piriformis* (pl. 13/7), however, is rather poorly adapted to remove sediment particles, yet it occurs most widespread, both in matrix – rich bafflestones and in higher energetic framestones. The form must have been very tolerant, particularly in respect of salinity (FÜRSICH 1981), so that it is sometimes the only coral representative of a pioneer framestone patch reef.

Background sedimentation and water energy were certainly the most important factors for triggering certain growth forms in the »Pteroceriano« depositional environment. There may be, however, other environmental circumstances as well which favour certain types. Thus, branched growth of corals is also favoured by inconstant food supply and unequal illumination (HUBBARD & POCOCK 1972).

Most likely, marly background sedimentation was intermittent, since constant fall of terrigenous clay particles would have hindered light penetration and thus rapid precipitation of skeletal aragonite which is connected to the consumption of $\text{CO}_2/\text{HCO}_3^-$ by symbiontic zooxanthellae (e.g., MILLIMAN 1974:90).

Accompanying organisms (oysters, algae) and particularly the associated sediments (oolites, oncolites, cortoid biomicrites) indicate coral growth in fairly shallow water.

Water energy was low to moderate in muddy bafflestone coral banks (both with lime mud and terrigenous mud), although marl once being deposited does not get reworked easily because of its adhesive forces, even during periods of elevated energy.

The general variety of 40 different species is well comparable, e.g., with the Recent 59 shallow water species in the western Atlantic (HUBBARD & POCOCK 1972). Consequently, an overall lowered or elevated salinity within the depositional area can be excluded. Possible reasons for the generally low diverse individual associations which always include fairly stenohaline elements (echinids, dasycladaceans) are thus lowered water energy and related elevated, partly terrigenous background sedimentation. This caused lack of light, food, oxygen, carbonate availability and even burial of coral banks.

Summarizingly, six coral associations can be discriminated:

- »*Calamophyllia*« marly banks and lime bafflestones. Additional elements rare, e.g., attached oysters and *Axosmilia* sp.:

Low water turbidity, high persistent background deposition (terrigenous or calcareous muds), possibly lowered salinity.

- Branched coral patch reefs (marly, pl. 13/1, or lime bafflestone), dominated by *Actinastrea* or *Stylina* (*Convexastrea*). Additional elements »*Calamophyllia*«, *Amphiastrea piriformis*, calcisponges, oysters, serpulids, bivalve borers, *Pseudocidaridius lusitanicus*, occasionally dasycladaceans, *Marinella lugeoni*, lituolids:

Low water turbidity, intermittent background sedimentation.

- Marly coral banks with meandroid corals and *Axosmilia* (not outcropping; reconstructed by pick-up sampling). Dominated by large massive meandroid coral heads, with common *Axosmilia*. Further elements frequent:

Elevated water turbidity, firm marl bottom due to adhesion. Periodic deposition of coarser particles.

- High diverse marly coral head patch reefs (not outcropping; reconstructed by pick-up sampling).

Composed of up to 20 different coral species, dominated by coral heads, though branched and solitary corals may appear as well. Many further components, particularly nodules of *Marinella lugeoni* and echinid spines:

Fairly mature coral bank with stable environmental conditions, moderate to elevated water turbidity, with many micro-environments. Minor background deposition.

– *Amphiastrea piriformis* lime framestone.

Composed of only one coral species with low diverse additional elements (serpulids, bryozoans, oysters, cyanophytes, lituolids). Mostly lithoclastic packstone between coral heads:

Medium water turbidity, possibly reduced salinity.

– High diverse lime frame/bindstone.

Very different colonial corals, normally densely encrusted by calcisponges, bryozoans, sessile foraminifers, cyanophytes, red algae, attacked by borers.

Bioclastic, partly sparitic interstitial filling with abundant coral fragments, algae, echinid spines, etc.. Partly thick crusts of fibrous cement A:

High energy conditions, no background sedimentation, reefoid facies.

3.2.6 Reefoid Micritic Debris Facies

Distribution: Associated with coral bank facies (see foregoing chapter).

Description: The grey to brown, iron hydroxide–stained, medium to very thick–bedded limestones consist of various bioclasts which form a closed fabric, embedded in a micritic matrix. Bioclasts do not exhibit preferred orientation. Sparitic areas, mostly filling sheltered pores, are very common. Often, a faint clotted peloid structure points out the original pelletal composition of the the now micritic groundmass.

Components are normally fairly large in size, angular or only poorly rounded and poorly sorted, so that micritic rudstones are largely prevailing. Better sorted, densely packed packstones are only occasionally occurring.

Apart from rare ooids, all further particles are of organic origin, consisting either of microfossils or macrofaunal bioclasts.

Bioclast composition allows a further facies subdivision into three subtypes which may be transitional to each other:

(a) Coral debris facies (pl. 5/8)

(b) Coralgall debris facies (pl. 5/7)

(c) Mixed bioclast facies (pl. 5/5)

The coral debris facies is largely dominated by coral fragments of variable sizes, often with common, several cm–large, only partially fragmented remains.

In the coralgall debris facies clasts of predominantly red algae or other questionable algae, such as *Marinella lugeoni*, *Solenopora cayeuxiformis* n.sp. and *Lithocodium* sp., as well as common calcisponge fragments are admixed. Thus, this subtype shows clear transitions to rhodolithic facies (cf. to chap. 3.2.9).

Besides coral, calcisponge and red algal fragments, the mixed bioclast facies contains frequent echinoid fragments (among these, entire spines of *Pseudocidaris lusitanicus*, crinoid ossicles), clasts and entire shells of terebratulid brachiopods and common bivalve fragments, particularly of oysters.

Oysters may occur in any subtype, as well as ostracods, bryozoans, serpulids, crustacean fragments, sponge spiculae (partly common), dasycladacean debris, *Permocalculus* n.sp. and, above all, the foraminifers *Everticyclammina virguliana*, *Pseudocyclammina* gr. *parvula*–*muluchensis*, »*Haplophragmium*« sp., *Reophax* sp., *Nautiloculina oolithica*, verneuiliids and nubeculariids.

Macrofaunal bioclasts are normally covered with a thin film of spongiostromate cyanophytes or are microbored by algae and fungi (cortoid formation). Borings of sponges, serpulids and *Lithophaga* are also common.

Diagenetic alterations are widespread. Most current is microsparitization which can hold on up to the formation

of neospar. Some samples exhibit early diagenetic cracks and associated solutional spar-filled vugs. Dolomitization along these cracks and strobilobedding is also a common feature.

Discussion : The high amount of coral clasts clearly relates these debris facies to zones nearby areas with active coral growth. Poor sorting, size and angular shape of the bioclasts, as well as the bioclastic matrix evidence an only one-time, short-distance transport of components without subsequent reworking. This suggests abrasion of corals from active coral patches during times of higher water energy, i.e., lowered wave base and transport to surrounding, slightly deeper zones, where the accumulating components were embedded in lime mud. Boring normally affected the particles prior to their transport, as can be seen by unaffected fracture boundaries or fractures which cut borings.

Composition of components seems to be mostly dependent upon the composition of the affected coral patch reefs. Thus, a low diverse bank association of sediment baffling corals with only few additional elements led to an analogously low diverse debris association. On the other hand, corallgal debris facies should be linked to higher diverse coral framestones. The additional microfaunal elements, particularly the coarse agglutinating lituolids, are also constituents of coral bank facies and thus clearly derived from there.

It should be mentioned that there hardly exist differences between the reefoid debris facies treated here and the filling sediment between individual coral colonies within a coral patch reef or bank, when only examining thin-sections. Thus, additional field information is inevitable for correct distinction between these sediment types.

The mixed debris facies also displays non-reefoid elements such as terebratulids and crinoids, both of which possibly derived from somewhat deeper settings. Further components, like dasycladaceans, clasts of gastropods and bivalves, and ooids also seem to be admixed from different environmental zones.

This fact, together with the very thick bedding, levels with cross-stratification, indistinct fining upwards starting with sparitic base, and chaotic orientation of components suggests a genesis of this subtype due to heavy storms. Material was gathered not only from coral bank areas but also from adjacent lagoonal environments.

Early diagenetic solution features may correspond to such storm-created thick debris swells which top parts surpassed the normal tranquil water sea level and thus underwent syndimentary subaerial exposure.

3.2.7 Oolites and Oolitic Limestones

Distribution : Oolitic facies is of minor distribution in the »Pteroceriano« unit. It is restricted to some horizons of the coral limestones around Alrota, Tesoureira and S'Tiago dos Velhos.

Description (pl. 6/1 – 5) : Three subtypes of oolitic facies may be distinguished:

- (a) moderately to well sorted oolitic grainstones.
- (b) oolitic bioclastic packstones (grainstones) with scattered intraclasts and oncoids (pl. 6/3,4).
- (c) cortoid grain/packstones with ooids (pl. 6/5).

Beds of »Pteroceriano« oolites are medium to very thick. They exhibit predominantly brownish colours. Very thick beds of oolitic bioclastic pack/grainstones may display low angle cross-stratification with commonly outwelling undular sets. The sets are separated by thin marl laminae (pl. 6/1). These beds are grading laterally within few tens of meters into marly bioclastic oncolite facies (pl. 6/5; see also fig. 5) which is often bioturbated (pl. 6/2).

Ooids are of small size (mean diameter 0.25–0.4 mm), only exhibiting cortices thinner than their nuclei. In the better sorted oolitic grainstones, tangential cortex fabric is prevailing, while otherwise radial structure is common. Polyoids (i.e., several ooids serving as nucleus for a new ooid), multiple ooids (i.e., several ooids growing together) and irregularly shaped ooids may also occur, particularly in the bioclastic subtype. Normally, however, cortices tend to smoothen an irregular form of nuclei.

Nuclei consist preferably of bioclasts, though detrital quartz also serves rather often for this purpose. Ooids with multiple nuclei are as well not uncommon. Mollusk and echinoid debris is prevailing among the bioclastic cores, though clasts of brachiopods, *Marinella lugeoni* and dasycladaceans occur as well.

Occurring bioclasts are mostly microbored or superficially encrusted by algae. Their size is up to 1 cm, normally being much smaller. Most current among them are bivalves (in part oysters); additionally occurring are gastropods, brachiopods, echinoids, corals, calcisponges, *M. lugeoni*, *Terquemella* sp., *Lenticulina* sp., verneuilinids, etc..

Faunal remains have very different degrees of preservation. While bivalves may be completely unaffected, at times occurring even double-valved, gastropods are often reworked up to their columella. Generally, bioclasts are strongly fragmented and rounded or even reworked from intraclasts and oncoids.

Cortoid grain/packstones with ooids (subtype (c)) are also mentioned in this chapter, since their bioclast composition corresponds completely to the content of bioclast and ooid nuclei of the first two types. Apparently, the micritic envelopes of the small-sized bioclasts are not only due to microbial microborings but also to initial ooidic encrustation. This can be seen by transitions from cortoids to superficial ooids. However, a subsequent attack of ooids by microborers might also account for the same structures in some cases.

Several mm-large intraclasts and oncoids are further constituents of the oolites. The subangular intraclasts exhibit either bioclastic oolitic packstone facies quite similar to the host rock, or pelmicritic facies containing scattered bioclasts. Oncoids are common in some samples, though they normally exhibit only very thin irregular envelopes. Large ovoid concentric spongiostromate oncoids with bryozoans, serpulids and *Lithophaga* borings occur at times.

In oolitic bioclastic packstones the bivalve bioclasts often form strings of a convex-upward closed fabric where ooids fill the interstitial pores.

The groundmass of all types is predominantly sparitic. Altered micrite, now occurring as brown microspar, forms geopetal fillings of interstitial spaces in packstone varieties. In a few cases the entire matrix is composed of microspar. An early diagenetic phenomenon and probably a vadose effect is the occasional irregular cracking of components and the detachment of ooid cortices. Later diagenesis caused overprinting in a varying degree. Besides the altering of micrite, sparitic fillings are also often recrystallized. Nevertheless, a relictic fibrous cement A can often be detected. Primary aragonitic mollusk cortoids are normally preserved as ghost structures (pl. 6/3). Even ooids may be strongly recrystallized, so that they lose distinct boundaries to the groundmass. Most likely, an original good sorting is sometimes pretended by the loss of small components due to complete recrystallization.

D i s c u s s i o n : Conditions for oolite formation are already discussed in chap. 3.1.1, yet environmental settings of oolites in the »Pteroceriano« unit seem to have differed considerably. In comparison with the oolites of the Oólitó and Sobral units, the »Pteroceriano« oolites are rather immature. The most stable settings for oolite growth seem to be represented by the better sorted oolitic grainstones, although rather thin ooid cortices suggest a short-termed realization of favourable conditions.

Interpretation of the occurring radial ooid fabric is fairly difficult. For the Sobral oolites with radial ooids a slightly deeper setting such as distal delta bars was likely, whereas for the occurrences within the »Pteroceriano« oolites no direct sedimentological data support such an interpretation. In this case, chemical composition of the sea water (particularly absence of Mg) may have favoured calcite precipitation (MILLIMAN 1974:14) and thus radially structured ooids (MEDWEDEFF & WILKINSON 1983). Irregular ooid shapes are caused by fairly low water agitation.

The high rate of admixed cortoids suggests ooid formation close to very shallow lagoonal environments. The occurrence of corals, calcisponges, brachiopods, *M. lugeoni* and dasycladaceans points to the vicinity of reef-ooid and interreefal environments what also becomes evident by the common association of oolites with coral bank facies.

Different degree of fragmentation and input of terrigenous quartz, on the other hand, indicate a rather wide source region for the derivation of particles.

The oolitic bioclastic pack/grainstone complex downhill Alrota (see Alrota sections, chap. 8; pl. 6/1) shows all signs of a lateral accretion deposit. Typical are low angle crossstratification, rapid outwedging of individual laminae sets and marly films between the latter (e.f., MOWBRAY 1983).

Probable is a laterally migrating submarine axial tidal channel where oolites formed eventually in a small ebbtidal delta lying at the channel's mouth due to the interference of ebb-flow and landward wave action. During

spring tide or storm periods ooids and cortoids were transported into the channel and subsequently deposited, whereas during neap tides a thin marly film settled down.

Such a model also explains the incomplete wash-out of micritic interstitial sediment, the variable ooid content of the individual layers and the gradual transitions to marly oncolitic bioclastic deposits. Infaunal bivalves, partly still double-valved, were admixed to the sediment due to lateral migration and erosion of the channel (see fig. 5).

It is assumed that all occurring cortoid oolitic pack/grainstones are related to similar axial channels within shallow lagoonal environments. The better sorted oolitic grainstones represent bar systems within this lagoon. These bars also acted as dynamic filters for sporadic coarser grained terrigenous input due to seaward storms or seasonally intensified riverine charge.

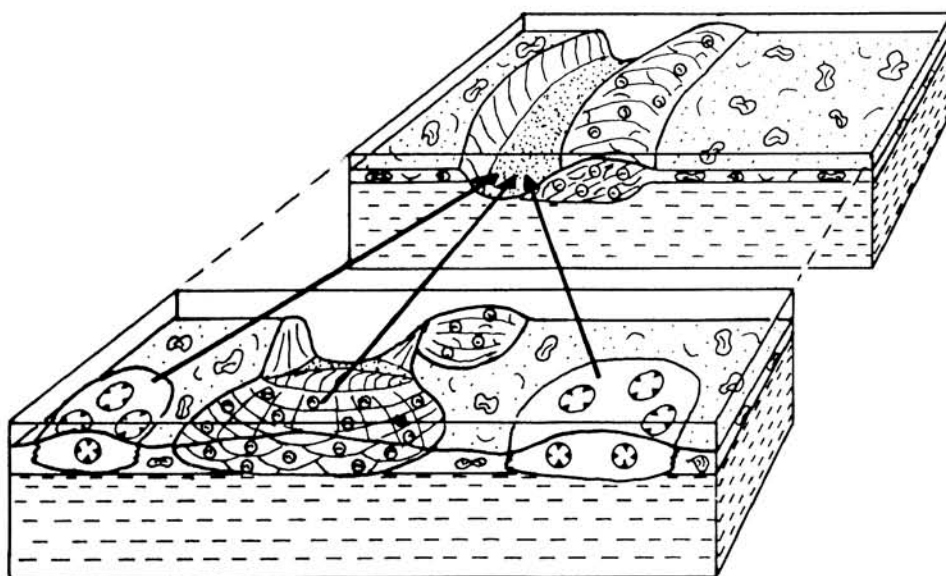


Fig. 5: Depositional model of »Pteroceriano« oolites exhibiting low angle cross-stratification.

Ooids possibly formed in an ebb-tidal delta and, together with fragmented corals, were swept into the tidal channel during spring tides or storms (arrows). Bivalves and oncooids were admixed by lateral migration of the channel, resulting in a lateral accretion deposit.

3.2.8 Open Lagoonal Micritic Cortoid Limestones

Distribution: In areas and levels with coral patch reef development.

Description: Under this category, a large variety of subtypes is summarized. Common characteristic is their micritic matrix and the high content of normally microbored bioclasts and microfossils, among which the overall occurrence of corals, echinids and dasycladaceans is most important. These sediments are thus mostly associated with coral bank and reefoid debris facies. Bedding is medium to thick, often slightly nodular. The rocks exhibit a light grey to brownish colour.

The following subtypes may be differentiated though transitions are frequent:

- (a) cortoid pelletal packstones
- (b) foraminiferal packstones (pl. 6/7)
- (c) cortoid wackestones with distinct burrows

- (d) cortoid wackestones, dominated by dasycladacean debris
- (e) coral floatstones with small coral colonies
- (f) nerineid floatstones.

The below listed particles may, with varying quantities, occur in any subtype:

Bioclasts and microfossils: corals, calcisponges, sponge spiculae, echinoids, echinid spines, bivalves, gastropods (p.p. nerineids), brachiopods, serpulids, bryozoans, ostracods, *Permocalculus* n.sp., *Campbelliella striata*, dasycladaceans indet., *Marinella lugeoni*, *Solenopora cayeuxiformis* n.sp., *Solenopora* sp., *Lithocodium* sp., *Cayeuxia* sp., *Pseudocyclammina* gr. *parvula*–*muluchensis*, *Pseudocyclammina* sp., *Rectocyclammina* sp., *Everticyclammina virguliana*, »*Haplophragmium*« sp., verneuulinids, *Glomospira* sp., *Lenticulina* sp..

Biomorphs: corals, gastropods, bivalves, brachiopods (r).

Besides being commonly microbored, bioclasts may also appear superficially encrusted by cyanophytes.

Intraclasts of various sizes are as well a frequent rock–constituent.

In gastropod shells which were not filled up by sediment, a diagenetically overprinted, brownish, fibrous needle cement A is preserved at times.

Discussion : Despite their varying individual characteristics, all the listed subtypes clearly represent a fairly open marine, lagoonal environment. Intensive cortoid formation suggests very shallow, warm water conditions. Common coral clasts and small in–situ coral colonies as well as the overall occurring though transported dasycladaceans, rare brachiopod findings and common echinid debris imply highly euhaline conditions at least for certain periods. Lagoon–typical pelletal fabric was most likely much more widespread originally, yet later compaction led to a micritic matrix.

The homogenous distribution of components is probably due to complete bioturbation in the soft substratum. Burrowing, leaving distinct traces and leading to a later nodular development of beds, took place during advanced stages of sediment consolidation.

While dasycladaceans only dominate in some beds, benthic lituolid and verneuulinid foraminifers are very common, sometimes even concentrated to foraminiferal packstones by winnowing.

Higher quantities of nerineids only occur in few beds, representing higher energy environments possibly on topographic highs.

3.2.9 Cyanophyte Oncolites and Red Algal Limestones

Distribution : Occasional horizons throughout the entire »Pteroceriano« unit, particularly in the coral limestones around Alrota, Tesoureira and S'Tiago dos Velhos, also along the Tejo valley.

Description (pl. 7; see also pl. 10 – 12) : »Pteroceriano« oncolites can be divided into three subtypes:

- (a) oncolitic floatstones with spongiostromate oncoids (pl. 7/2)
- (b) oncolitic rudstone with spongioporostromate oncoids with *Girvanella minuta* and nuclei mainly of *Marinella lugeoni* (pl. 7/3, 4)
- (c) algal rud/floatstones with large red algal nodules and their fragments (pl. 7/5, 6).

Brownish oncolitic floatstones may develop laterally from oolite beds (cf. to chap. 3.2.7), mainly by decreasing ooid quantity. They also occur rarely within mudstone sequences.

The mostly thin and often highly irregular oncoïd cortices display a completely micritic structure. An original tangential fabric is, however, indicated by zonal iron hydroxide impregnation and by intergrowths of bryozoans (= Mikroproblematikum 4 of WERNER 1986; pl. 7/2). Serpulids are also incorporated in the cortices or are attached on the outer surface of oncoids. Oncoïd nuclei are composed of bioclasts, most commonly of oysters.

Bioclasts may float non-encrusted in the micritic, often slightly recrystallized matrix. All components are inhomogeneously distributed in the groundmass.

Early diagenetic solution of oncoid nuclei as well as circumgranular, intragranular and matrix cracks are common features. This, together with the iron hydroxide staining, the lateral persistence and the rarity of beds makes this subtype an useful marker for correlations within mudstone sequences (cf. to chap. 5.2.1).

Widely distributed are oncolites with a high amount of the coralline red alga *Marinella lugeoni* (cf. to chap. 4.3) which causes typical porcellaneous white spots in hands—specimens. The brownish to rarely dark grey, partly marly beds are thick to very thick—bedded and show occasionally downcutting surfaces or even thin out rapidly. Similar oncolites also occur in the Corálico do Amaral (DÖHLER 1984) and the Consolação beds at Peniche (WERNER 1986), so that only a brief description and interpretation is given here:

Oncoids and further components form a matrix—rich, poorly sorted, closed fabric with occasional wacke/float-stone areas. The matrix consists of an altered micrite (microspar or neospar).

Oncoid sizes vary from 1 to 50 mm, most commonly ranging between 4 to 10 mm. The largest oncoids occur in a marly matrix. In some cases, oncoid size increases upwards within one bed, with an occasional renewed decrease towards the top.

Oncoids are roughly ovoid in shape, though their outline is commonly wavy and may show irregular protrusions. Thickness of cortices in relation to the nucleus diameter is highly variable, ranging from superficial encrustings to nucleus—lacking oncoids. Most characteristic are thick, well developed envelopes.

Cortices may be densely laminated, spongy or, alternately, both. Generally, they are composed of spongostromate or porostromate cyanophytes, the latter mainly represented by well preserved *Girvanella minuta* which most often occurs on the outer surface of oncoids. Besides the cyanophytes, a large variety of other organisms contributes to the formation of envelopes, amongst which are to be mentioned *M. lugeoni*, *Lithocodium* sp., *Bacinella irregularis*, serpulids, sessile foraminifers, bryozoans (Mikroproblematikum 4 of WERNER 1986), boring Mikroproblematikum 10 of WERNER, Mikroproblematikum 9 of WERNER, attached oysters and occasionally incorporated bioclasts (pl. 7/1). *M. lugeoni* forms hemispherical small domes which are again overgrown by cyanophytes. Such a mutual sequence may be repeated several times.

The nuclei of oncoids consist mostly of fragmented, spherical or branching forms of *M. lugeoni*. Fragments of gastropods (particularly *Nerinea* sp.), bivalves and echinids (in declining frequency) also account for nuclei.

Commonly, the oncoids are intensively affected by borings of lithophagous bivalves which normally penetrate up to the oncoid cores. Often, empty boreholes were subsequently populated by serpulids. Small oncoids are frequently composed of very regular smooth concentric dense films, resembling closely an ooid structure.

Further components are non-encrusted fragments of *M. lugeoni* (c), non-encrusted bivalve clasts, double-valved bivalves (r), entire cidaroid spines (pl. 7/4), *Permocalculus* n.sp., lituolids (*Pseudocyclamina* sp., *Everticyclammina virguliana*, common »*Haplophragmium*« sp., *Freixialina planispiralis*, *Nautiloculina oolithica*), other foraminifers (*Glomospira* sp., *Lenticulina* sp., *Conicospirillina basilensis*, verneulinids and valvulinids).

Less common, yet an outstanding characteristic subtype are algal rudstones composed of large algal nodules. Clearly developing laterally from the above mentioned type, they are dominated by *M. lugeoni*, occurring both as fragments and large entire subspherical or columnar—branching thalli. Coating by cyanophytes is of minor importance; further heavy encrustings are mainly performed by different species of the probable algae *Lithocodium* sp. and *Bacinella irregularis* (cf. to chap. 4.6). Additionally occur up to 4 cm large nodules of *Solenopora cayeuxiformis* n.sp. (cf. to chap. 4.5) which are as well encrusted by the mentioned sessile forms. Cayeuxian algae may also occur (but see chap. 4.5). Calcsponges, rare corals and common echinid fragments besides intraclasts and peloids are further elements. The microfauna and —flora is identical to above.

The predominantly microsparitic matrix may exhibit large spar areas which in this case may be both of primary and neomorphic origin.

Discussion: Most important for environmental interpretation in the present example is the transition from oncolites to rhodolith beds. All transitional steps are represented, i.e.,

- (a) mere red algal limestones,
- (b) beds with nodules composed of intergrowing red and blue—green algae,

- (c) oncolites containing *Marinella*—cored oncoids,
- (d) floatstones with poorly developed, mollusk—cored cyanophyte oncoids only.

This gradational line clearly corresponds to the different degree of mixing of three subenvironments, where

- large irregular nodules of encrusting algae(?)
- *Marinella lugeoni* nodules
- cyanophyte oncoids (cyanoids sensu RIDING 1983) were forming.

Although *M. lugeoni* is most widespread, its original environment of formation is poorly documented. The alga normally occurs as fragments. Yet, the prevailing growth habits, laminar, columnar, densely digitiform, are clearly distinguishable. *M. lugeoni* formed both free rhodoliths and attached thalli. Beds solely composed of densely packed small rhodoliths or their fragments are clearly par—autochthonous and document the form's fairly high energy demand.

Nowadays, rhodoliths of coralline algae occur preferably in fore reefs, reef intertidal flats and channels, and back reefs. They occur down to 90 m of water depth, though deep water settings are of minor importance and inhabited by adapted taxa only (BOSENCE 1983). Laminar and densely branching forms like *M. lugeoni* correspond to high energy settings (cf. to op. cit.).

Recent coralline algae grow under fully marine salinity conditions, although some forms may tolerate a certain freshwater influx (FLÜGEL 1982:472). The early coralline alga *M. lugeoni* is often associated with echinid, coral and calcisponge debris as well as with dasycladaceans, so that fairly normal salinities might be indicated. WERNER (Munich, kind pers. commun.), however, reckons a high tolerance of *M. lugeoni* due to findings in deltaic sediments (cf. also to WERNER 1986). Apparently, growth of *M. lugeoni* started in different environments whenever high hydraulic conditions, low sedimentation rates and salinities not too far from normal established. Possibly most widespread in the present case was rhodolith formation around, between and on top of small coral patch reefs. *Lithocodium* sp. and *Bacinella irregularis* are very closely related to such reefoid structures, encrusting reefal debris and the proper red algae *Solenopora* and *Marinella*.

The light porous fragments of *Marinella* were continuously swept into zones with cyanoid formation what is documented by the variable degree of encrustation of the alga by cyanophytes. Rarely, the environmental conditions for oncoid development improved, so that *Marinella* also participated in cortex formation.

Cyanophyte oncoids form in a variety of different environments, yet commonly requiring slow sedimentation rate and rather shallow water settings with tranquil, though intermittently elevated energy conditions (for survey see FLÜGEL 1982, PERYT 1983, CATALOV 1983). JONES & WILKINSON (1978) and MONTY & MAS (1981) pointed out that oncoids may also develop concentric laminae by in—situ growth on all sides in continuously non—agitated water.

However, the high amount of angular intraclasts and peloids, the occasional input of ooids, co—occurrence of mature and superficial oncoids within one bed clearly indicate occasional higher water energy in a generally tranquil environment with low micritic or marly background deposition. Very regular, ovoid, concentric oncoids also grew under continuous overturning.

The fact that the largest oncoids often occur in the middle of a thick bed in marly matrix is difficult to explain. Most probably, sedimentation of terrigenous clay minerals was, though very low, yet continuous over the entire bed. Additional deposition of calcareous mud, however, may have stopped. Thus, these marly horizons within thick limestone beds represent the lowest rate of background deposition and hence the optimum conditions for oncoid formation.

Heavy attack of oncoids by boring lithophagous bivalves and common attachment of serpulids and oysters also point to fairly shallow water conditions. These organisms have their maximum distribution in very shallow subtidal to intertidal, partially reefal environments (e.g., TASCH 1980).

Apparently, wide areas of the »Pteroceriano« lagoon underwent cyanophyte oncoid formation during longer times of considerably lowered background deposition. In regions with constantly slightly elevated water currents, background deposition was also hindered and thus oncoids could develop largely. During minor storm events or spring tide current, particles from adjacent facies zones, such as rhodolith fragments, ooids and bioclasts were frequently admixed and oncoids eventually underwent an occasional transport.

Floatstones with superficial, iron hydroxide–stained cyanophyte/serpulid oncolids represent initial stages of oncolid formation during depositional stillstand. The, in this case, patchy distribution of oncolids suggests their later incorporation to the underlying mudstone due to bioturbation.

3.2.10 Sandy Cyanophyte Oncolites: The Alenquer Oncolite

Around Alenquer one or two horizons of a peculiar, often reddish, quartz–bearing oncolite occur. This facies type deserves special interest because of the variety of preserved algal microstructures within the oncolids.

The Alenquer Oncolite is already treated in LEINFELDER (1985).³ The summary is as follows:

»Terrigenous red siliciclastics of Upper Kimmeridgian(?) to Portlandian age around Alenquer, Portugal, comprise a narrow level of oncolid–bearing limestones. Oncoid cortices are composed of cyanophytes which appear in different calcification morphotypes according to changing physicochemical parameters. Recent examples reveal that in most cases each calcification morphotype is related to one single species or one defined association. Hence, the characteristic calcification patterns are mostly biologically rather than abiogenetically controlled. Oncoid shapes, sizes and arrangement, on the other hand, are mainly determined by the hydraulic parameter within the depositional environment.

Accompanying biota as well as sedimentological and diagenetic characteristics suggest a combination of paralic, lacustrine, marsh and fluvial environments with salinities ranging from hypersaline to freshwater conditions. This variety of subenvironments was created by a rapid but short–lived transgression into a graben – or half–graben – like subsiding depression along the active fault system of Vila Franca de Xira.«

3.3 Facies Types and Environments of the Freixial Unit

The Freixial unit, developed in the south of the study area and extending westwards up to the coast, shows likewise similar and very different facies development compared to the underlying »Pteroceriano« unit. It is composed of micritic, rarely sparitic limestones, marls and both marine and terrestrial siliciclastics. Obvious is the stop of reefoid corallgal deposits. Unlike in the »Pteroceriano« unit, most facies types have a wide, continuous distribution. The dominance of the siliciclastics is increasing towards west and north, grading into the upper sandstone mega–unit in the latter case (cf. to chap. 5.2.2.3).

3.3.1 Low Diverse Nodular Limestones

D i s t r i b u t i o n : Sporadically throughout the entire Freixial unit.

D e s c r i p t i o n (p l . 8 / 1) : This facies type resembles the nodular *Arcomytilus* limestones of the »Pteroceriano« unit, although the latter display a more pronounced nodular appearance.

The grey, thin to medium nodular beds often show thin marly intercalations. Scattered components are irregularly distributed within the micritic matrix, thus exhibiting most commonly a mudstone fabric. The micrite shows occasionally a relic clotted peloid fabric. Peloids which may be strongly stained by iron hydroxide also occur within the common burrowing structures (pl. 8/1). Silt–sized quartz debris is frequent in some samples.

Further particles are entirely biogenic: most common are clasts of bivalves and gastropods. Thick–shelled ostracods and the lituolid *Everticyclammina virguliana* are characteristic. Further foraminifers and algae (cf. to chap. 3.3.2, 3.3.3) occur sporadically.

Footnote ³: Please note printing error on plate 30 in LEINFELDER (1985): fig 6d shows a *Dichothrix* Morphotype, not a *Schizothrix* Morphotype!

Macrofauna is very indistinct, consisting exclusively of poorly preserved, double-valved steinkerns of heterodont bivalves, in part attributable to shallow burrowing *Protocardia*, deep burrowing ?*Ceratomya*, and of very rare ampullinid gastropods.

Early irregular desiccation cracks are common in some beds. Often, the matrix is altered to microspar. Important is an occasional partial to complete early dolomitization of the beds.

Discussion : For discussion on formation of nodular limestones the reader is referred to chap. 3.2.1. Diagenetic overprint of the sediment is, however, more complete in the Freixial unit, so that distinct horizontal burrows can be detected only rarely.

The almost total lack of epibenthic macrofauna indicates a soft substratum which most probably was characterized by a dense mud suspension along the substratum/water interface. Attack of bioclasts by boring microbes also was herewith prohibited. The rarity of organisms is moreover due to apparently elevated salinities what occasionally led to early diagenetic dolomitization.

Hence the facies type treated here shows all signs of a sediment, deposited in a restricted, occasionally hypersaline, lagoonal environment.

3.3.2 *Anchispirocyclina* – *Quinqueloculina* Micritic Limestones

Distribution : Upper part of the Freixial unit (one level).

Description (pl. 8/2, 3) : The here treated foraminiferal limestones are easily detectable in the field and thus a characteristic key facies type and stratigraphic guiding level.

The medium-bedded, light grey, micritic limestones are slightly nodular, which again is most likely due to bioturbation. Burrowing is furthermore well visible by the inhomogenous distribution of the almost entirely biogenic particles, so that mud/wackestone, packstone and micritic rudstone fabric often co-occurs within one bed or even one rock sample.

Most characteristic is the high frequency of the lituolid foraminifer *Anchispirocyclina lusitanica* which grows up to 12 mm and thus is well visible already under the magnifying glass. This is also true for the common, in part very large (1.5 mm), miliolid foraminifers from the *Quinqueloculina* group which appear as white dots in reflected light (pl. 8/3). Further microfauna and flora is common as well: among the foraminifers occur (in declining frequency): *Everticyclammina virguliana*, *Rectocyclammina* sp., *Nautiloculina oolithica*, verneulinids and valvulinids, *Lenticulina* sp., nubeculariids and *Glomospira* sp.. Most common among the algae are fragments of the gymnocodiacean? *Permocalculus* n.sp. and the dasycladaceans *Macroporella espichelensis* and *Cylindroporella* cf. *arabica*. Further dasycladacean fragments (*Salpingoporella annulata*, ?*Campbelliella striata* and others) are rather rare. Ostracods which are rarely disarticulated are another important microfaunal constituent.

Macrofauna is mostly represented by partly intensively microbored bioclasts, consisting of varying amount of oysters, other bivalves and gastropods. Nerineids and *Protocardia*-like bivalves seldomly occur unfragmented.

Lignite litter and detrital quartz appear sporadically.

Even pack- and rudstone varieties are normally rich in micritic matrix which, however, is sometimes altered to microspar and neospar. Some interstices and gravitational solution vugs are though filled with primary spar.

Discussion : The high amount and variety of microfossils allows to give satisfactory environmental interpretation of this facies type.

The sudden appearance of the agglutinating lituolid *Anchispirocyclina lusitanica* is due to its stratigraphic onset (cf. to chap. 5.1.2). The form is apparently fairly tolerant in respect of salinity fluctuations, as it is evident by its wide distribution also in Purbeck and Wealden facies (e.g., RAMALHO 1971, ROCHA & MARQUES 1979, GARCIA–HERNANDEZ & LOPEZ–GARRIDO 1979).

Miliolids are the other dominant element in the facies type. They clearly are restricted to very nearshore subtropical environments with normal to hypersaline water, like for instance, the modern Abu Dhabi Lagoon of the

Persian Gulf, where they often graze on algae and bacteria growing on seaweed and seagrass (MURRAY 1970). There the porcellaneous forms account for the total amount of foraminifers in a belt adjacent to the coast, whereas a belt further seawards shows a mixed assemblage of both porcellaneous and agglutinating foraminifers (HUGHES CLARKE & KEIJ 1973; HAYNES 1981:161, also for further references).

This model is perfectly applicable to the limestones discussed here. Some samples display an almost exclusive dominance of large *Quinqueloculina*, so that they are attributed to a nearshore, low energy belt with a very low degree of water circulation. Although miliolids may also be the dominating element in brackish water (ROSE & LIDZ 1977), the very low contamination with terrigenous material and the rare occurrence of associated dolomites (cf. to chap. 3.3.1) rather point out to a hypersaline environment in the present case.

The mixed assemblage of miliolids and litiolids, together with ostracods, is referred to a marginal marine zone adjacent to the miliolid belt. The as well common litiolid *Everticyclammina virguliana* is also known for tolerating unfavourable environments (e.g., PÉLISSIE & PEYBERNÈS 1983). Macrofauna consists of euryhaline elements only. The fairly stenohaline dasycladaceans and cortoids, on the other hand, are highly fragmented and thus certainly derived from a neighboured zone during times of elevated hydraulic conditions. An exception is *Macroporella espichelensis* which is a characteristic, mostly well preserved, common constituent. The Lower Cretaceous *M. embergeri* is meant to be highly tolerant in respect of fluctuating salinities (CONRAD 1977), what should be analogously assumed for its Upper Jurassic relative.

In contrast to the pure miliolid zone, salinity of the mixed assemblage was closer to normal values but underwent common (periodic?) fluctuations. Besides the typical shallow water foraminifers, the very shallow character of the sea is also indicated by solution features which attacked the sediment during early diagenesis in the vadose zone.

3.3.3 *Permocalculus* – Dasycladacean Micritic Limestones

Distribution : Freixial unit, particularly upper part.

Description (pl. 9/3 – 9) : The light grey to brownish, medium-bedded limestones exhibit generally, though not throughout, a pronounced nodular structure.

Most typical are matrix-rich skeletal packstones composed of the very frequent, fragmented gymnocodiacean red? alga *Permocalculus* n.sp. (cf. to chap. 4.5).

Sorting of fragments, though normally poor, may improve in some beds.

Further organic elements are bioclasts of bivalves and gastropods (also nerineids) and rare echinid spines. Occasionally they are microbored. Obvious is a fairly high amount of sponge spiculae. In some samples, content of admixed silt and fine sand-sized, well sorted, detrital quartz as well as of micritic, intensively iron hydroxide-stained lithoclasts and quartz-cored ooids is fairly high.

Another variation is the transition to dasycladacean-dominated types, characterized besides *Permocalculus* n.sp. and bioclasts by a high amount of heavily fragmented dasycladacean debris (pl. 9/2). The following forms are rather likely to account for the fragments: *Macroporella espichelensis*, *Cylindroporella* cf. *arabica*, *Heteroporella* aff. *lemmensis*, *Salpingoporella annulata*, *Clypeina jurassica*, ?*Actinoporella podolithica*, ?*Likaniella bartheli*, *Campbelliella striata*, *Terquemella*(?) sp.. Occasionally, calcispheres are abundant, most probably representing dasycladacean spores. The fabric comprises wacke-, pack- and floatstones.

In all subtypes one may additionally find serpulids, bryozoans, »cayeuxiid« algae, charophyte gyrogonites (rare) and the foraminifers *Anchispirocyclina lusitanica*, *A.* cf. *maynci*, *Everticyclammina virguliana*, *Rectocyclammina* sp., *Freixialina planispiralis*, *Quinqueloculina* sp., *Lenticulina* sp., verneulinids and valvulinids.

Diagenetic alterations are common. As in the foregoing facies types, micro- and neosparitization occur frequently. Bioclasts are often leached in an early diagenetic stage, so that solutional molds disappeared frequently during subsequent compaction. Early cracks, arising from component boundaries are also common.

Discussion : Both by its position within the sequence and by the associated sediments the relations to the above treated facies types are evident. The nearshore, hypersaline, low diverse nodular limestones and the ad-

jacent marginal shallow marine *Anchispirocyclina* – *Quinqueloculina* limestones may be followed by the interior zone of a shallow lagoon which is represented by the algal limestones treated here. Eventually dasycladacean meadows also developed instead of the foraminiferal belt during times of improved salinity conditions (cf. to chap. 6.4).

Similar dasycladacean assemblages, in part also with *Permocalculus*, are well known from the uppermost Jurassic to the Lower Cretaceous of Switzerland (e.g., CONRAD 1977), France (e.g., BOUROLLEC & DELOFFRE 1968), Spain (e.g., CANÉROT 1979) and Portugal (e.g., RAMALHO 1971, REY 1979).

CONRAD (1977), in an example from the Upper Berriasian–Lower Valanginian interval, differentiated a coastal belt with charophytes and *Macroporella* from a very shallow, further seawards situated, seagrass–dasycladacean packstone–wackestone belt with slightly elevated salinities, as evidenced by the lack of »true« stenohaline organisms. This model is also applicable here. An adjacent belt further offshore, consisting of a dasycladacean – encrusting algae assemblage is not preserved or not outcropping in the present case, although rare nodules of cayeuxiid algae point to its development. A bordering, seaward lying, oolite shoal is also indicated by the common input of ooids (cf. also to chap. 6.4).

The very shallow character of this part of the lagoon is furthermore indicated by the common solution features and by the high fragmentation rate of bioclasts, whereby an occasional good sorting suggests episodic fragmentation by high energy events rather than bioclast formation solely due to burrowing. Input of well sorted detrital quartz may also be referred to such events.

The common sponge spiculae in *Permocalculus*–dominated samples might indicate a slightly deeper depositional setting within the shallow lagoon for this variety. An occasional fairly high content of terrigenous silt is not contradictory to this, since these morphological depressions may act as traps for fine clastics.

3.3.4 Skeletal and Non–Skeletal Grainstones and Rudstones

Distribution: Lower part of the Freixial unit.

Description and Discussion: Several sparitic facies types which only occur very scattered in the Freixial unit are briefly summarized in this chapter:

(a) Oolites

Allochthonous ooids occur widespread in different facies types of the Freixial unit. The corresponding ooid bars or shoals, however, are very poorly preserved. Thin sheets of well sorted oolitic grainstones occur only occasionally. Ooids are mostly quartz–cored, strongly altered and heavily stained by iron hydroxides which is eventually related to subaerial postdepositional exposure. This also explains the lack of preserved ooid bar systems which apparently were eroded intraformationally.

(b) Intraclastic grainstones

These beds of grainstones composed of sand–sized, excellently sorted and rounded intraclasts occur somewhat more often. Intraclasts are again stained by iron hydroxides. They are either micritic or composed of early cemented ooid and peloid facies. The reworked ooids occasionally exhibit radial fabric. Commonly admixed are *Permocalculus* fragments and well rounded litiolids of the same diameter as the intraclasts.

The character of grains and their good rounding and sorting suggest long–time reworking in a high energetic shoal system. The intraclasts were initially eroded from different, dried–up parts of the lagoon during storm events.

During later transgressions sediments of such shoals were shifted to form thin sheets covering large areas of the renewed flooded lagoon.

(c) ?*Everticyclammina* – intraclastic grainstones (pl. 9/1)

At times, up to 50% of the intraclasts may be substituted by up to 3 mm large forms of an unidentified litiolid species (aff. *Everticyclammina*). The early planispiral stage of the litiolid foraminifer is only poorly devel-

oped. Size of foraminifers is larger than of well sorted and rounded intraclasts. This, together with the good preservation, suggests that the foraminifers are autochthonous elements. Most probably the high energetic sediment was stabilized by seagrass, so that the elongated to conical foraminifer could semi-infaunally dwell in grain interstices.

(d) Bivalve clast rudstone

The above mentioned types may be associated with sparitic coquinas composed of bivalves shells, particularly oysters, rare gastropods and their fragments. The rather good sorting and the chaotic or overpacked position of bioclasts suggest deposition during storms.

All types are affected by vadose diagenesis due to early exposure. Bivalve clasts are often only preserved by their cortoid envelopes (ghost structures). Interstitial vadose silt occurs commonly in all samples.

3.3.5 Marls

D i s t r i b u t i o n : Throughout the entire Freixial unit.

D e s c r i p t i o n : Though major parts of the Freixial unit are presumably represented by fine-grained siliciclastics and marls, they are very rarely outcropping and fresh samples are a rarity. The sections of the Freixial unit, reported by RAMALHO (1971) along Casais da Serra and Alverca are meanwhile completely overgrown by vegetation. The reader is therefore also referred to the cited author for further information, particularly on the microfauna/flora.

Outcropping marls are greenish-grey or brown, the latter type occasionally bearing considerable amounts of silt. Silt-lacking marls are underlying micritic calcareous levels or are intercalated between limestone beds. Maximum thickness of the detected marl horizons is more than one meter; mostly, however, cm to dm-thick horizons prevail. Unlike in the »Pteroceriano« unit, marls are almost free of mica and contain only minor amounts of fine lignite litter.

Common to abundant in some levels are small, often fragmented *Nanogyra*-like oysters. The rest of the macrofauna is only poorly preserved, consisting of imprints of *Inoperna*, *Nicaniella* and other tiny heterodont unornamented forms. Occasionally echinid spines occur. A mandible of a decapod crab, *Magila* cf. *latimana* (determination kindly controlled by R. FÖRSTER, Munich), was also detected.

Microfossils, if any, consist of *Permocalculus* fragments, *Anchispirocyclina lusitanica*, *Everticyclammina virguliana*, *Rectocyclammina* sp. and the common ostracods *Cytherella* gr. *suprajurassica*, *Paracypris* sp.1, *Schulteridea* sp.1 and *Protocythere* sp.1 (sensu RAMALHO 1971).

D i s c u s s i o n : The dominance of ostracods in the sequence points to salinity conditions away from normal. The low mica and lignite content could suggest elevated rather than lowered salinity. No deep burrowing infauna was found, so that marls were possibly firm already during their deposition what may indicate fairly low sedimentation rates.

Roughly, the marls are related to similar environments than the low diverse micritic nodular limestones (cf. to chap. 3.3.1). They represent periods of slightly elevated clay input what simultaneously inhibited carbonate precipitation.

3.3.6 Very Sandy, Bioclastic Limestones and Fossiliferous Sandstones

D i s t r i b u t i o n : Entire Freixial unit.

D e s c r i p t i o n (pl. 9/4) : In the Freixial unit three varieties of both quartz and skeletal grain-bearing rocks, forming thin horizons, may be differentiated:

- (a) Low diverse, grey, bioclastic floatstones containing oyster clasts and *Anchispirocyclina* sp. besides *Freixialina planispiralis* and rare *Permocalculus* n.sp., may bear high amounts of detrital quartz. The well sorted but angular fine to medium-sized quartz grains are inhomogenously distributed within the matrix. These rocks are normally overlain by sandstones.
- (b) Bioclastic oolitic sandstones are mainly characterized by a moderately to well sorted, fine to medium-grained quartz sand fraction, occasionally common quartz-cored and superficial ooids, and larger cortoids consisting of bivalves (particularly oysters), gastropods (r), echinids, serpulids, ostracods (thick-shelled and often double-valved) and litiolids. Bioclasts are heavily corroded and mostly stained by iron hydroxides. Glauconite grains, calcareous lithoclasts, lignite and mica occur as well. The groundmass may be either sparitic or marly. One horizon contains large macrofauna, consisting exclusively of common, mostly double-valved *Trigonia freixialensis* (pl. 16/9).
- (c) In well sorted lithoclastic sandstones with a fairly large amount of glauconite, skeletal grains are rare and strongly altered. They consist of oyster and serpulid fragments, ostracods (double-valved) and *Anchispirocyclina* sp.. Lignite litter and mica are more common than above. The frequent calcareous lithoclasts are fairly well rounded, strongly impregnated by iron hydroxides and lie mostly within the size range of quartz grains. The groundmass may be again sparitic or marly.

Many brownish, moderately sorted, mica-rich, coarse-grained sandstones and fine quartz conglomerates lack almost any other components. Very rare oyster fragments, however, also group this type under marginal marine sandstones.

Discussion : The here treated thin sheets of marine siliciclastics do not have any direct analogue in the »Pteroceriano« unit. Complete interpretation must be seen in context with the whole sequence (cf. to chap. 6.4), so that only some basic remarks are given here.

The inhomogenous distribution of quartz in the bioclastic floatstones and their direct superposition by sandstones indicate a rapid, event-caused deposition of siliciclastics over unconsolidated lime mud, causing mixing of both sediment types which was most probably supported by subsequent bioturbation.

The bioclastic oolitic sandstones are comparable to parts of the Sobral unit (cf. to chap. 3.2). *Trigonia freixialensis* substituted *Eomiodon securiformis*, though litiolids and rare fragments of echinid spines may prove less brackish salinity values in the present case. However, the corroded stage of lithoclasts and most of the bioclasts makes a reworking from the underlying beds for most of them likely. Only the well preserved, thick-shelled ostracods and possibly some litiolids apparently inhabited the sandy substratum during times of lower water energy.

The fairly high amount of glauconite in lithoclastic sandstones proves longer periods of very low or negative sedimentation rate, where glauconite grew possibly under slightly reducing conditions by the action of sulphate bacteria (DEER et al. 1966:207).

3.3.7 Terrestrial Siliciclastics

Distribution : At base, in middle part and on top of the Freixial unit.

Description and Discussion : Intensively red coloured siliciclastics play a dominant role in the Freixial unit, although they are only poorly outcropping and intensively weathered.

Grain size ranges from clays up to very coarse conglomerates with maximum gravel diameters of 4 cm. Components consist almost exclusively of quartz. Mica is rather rare; feldspar is not uncommon in coarse-grained varieties. A clay matrix is the cause for the rock's weathered and unexposed condition. While rounding is moderate to good, sorting is always poor.

Caliche nodules and nodular horizons are very common in siltstones. They are composed of silt-bearing mudstone with lavender, red and whitish speckled colouring and spar-filled pedogenetic cracks (pl. 8/5).

Sediment structures could be only detected rarely: occasional small—scale cross—bedding as well as trough cross—bedding may occur in sandstones. Generally, however, the beds are even, without distinct structures, and do not grade into each other.

Thus, sedimentation was most likely accomplished by a braided river system, depositing episodically or periodically large sheets of coarse—grained sediments, whereas caliche formation took place in fine—grained flood plain deposits after their drying—up.

3.4. Facies Types and Environments in Areas with Complete Clastic Development

In areas with complete clastic development, there do not occur other main facies types and related environments than already known from other units: They comprise marginally marine siliciclastics, often with common intercalations of lime conglomerates (cf. to chap. 3.1.2), *Isognomon* silts (which can be well compared to *Isognomon* marls described in chap. 3.1.3), marls and silty marls with restricted marine, tiny soft bottom fauna (cf. to FÜRSICH 1981 and chap. 3.2.3), and most important, reddish terrestrial, fine to very coarse—grained siliciclastics (cf. to chap. 3.3.7). Caliche intercalations may reach a thickness of up to two meters (around Zibreira), gravel size of conglomerates up to 12 centimeters. Gravels are not exclusively composed of milky quartz, but also include quartzitic and other metamorphic pebbles as well as large feldspars in quantities up to 20 vol.%.

4. REMARKS ON SELECTED ORGANISMS

4.1 Ecological Adaptions of the Mytilid Bivalve *Arcomytilus morrisi* (SHARPE)

Arcomytilus morrisi is the most widespread faunal form of the »Pteroceriano« unit, characterizing particularly its lower part. Being the dominant element in the *Arcomytilus* limestones (cf. to chap. 3.2.1), the mussel also appears in other facies types, such as the *Trichites* limestones or marls of the Sobral and »Pteroceriano« units.

The very euryhaline character of the species becomes evident by the accompanying fauna which normally is of low diversity, and by sedimentological interpretation of the hostrocks. Maximum size is reached in oligospecific associations, where intensive overgrowth of the oysters *Praeexogyra pustulosa* and *Nanogyra nana* took place already during life time (cf. to chap. 3.1.3, pl. 14/1, 5).

The most typical occurrence is in autochthonous small clusters on bedding planes (see FÜRSICH 1980: fig. 7), though isolated specimens occur as well. All specimens are almost exclusively double-valved. Consequently, FÜRSICH (1980) interprets its life habits as identical to the modern epibyssate *Mytilus edulis*. SEILACHER (1984) also attributes the genus *Arcomytilus* to the epibyssate forms (»edgewise recliner«), but reckons a derivation from an endobyssate ancestor.

While the suspension filtering byssate character is beyond doubt (see byssal notch in pl. 14/4), remarks have to be made concerning the form's life position:

The length of *A. morrisi* ranges from one centimeter (in marls) up to 11 centimeters, with most common values of seven centimeters. Shell shape varies largely from elongate, slightly wedge-shaped to roughly triangular with a largely broadened posterior part and a curved, somewhat twisted anterior region. The spacing of radial, slightly crenulate, often bifurcating, faint ribs (pl. 14/3) is correlated to shell shape, showing a maximum distance of 0.6 to 0.8 mm of individual ribs in the elongated forms, whereas maximum values of 1.6 to 2.0 mm are restricted to the latter variety. All transitions in shell shape occur; broad rib spacing, however, is limited to the posteriorly very broadened forms. Transverse section of the shell in the posterior part gives a non-isosceles triangle with an accentuated ventral flattening. This asymmetry is certainly not due to diagenetic compaction, since it also occurs in well preserved specimens with shells not being affected by any fracturing. This sort of shape clearly indicates that the back part of the shell was lying on the ground (see also STANLEY 1972, SEILACHER 1984), whereas the anterior part was more or less buried, according to its inclination. The variety of shell shape shows the form's high adaptional ability to changing environmental conditions.

It is assumed here that the byssate form originally settled on semifirm ground, attaching itself to shell fragments or similar anchors. Flat ventral side and clustering with some other individuals helped in stabilizing. Due to the slight oblique orientation of the ventral part, sets of two neighboured individuals could support each other, whereby the function of the faint ribs possibly was to raise friction and thus stability between the touching valves (fig. 6; pl. 14/6).

Most likely, *Arcomytilus morrisi* was moreover able to keep pace with a sudden accelerated rate of deposition. Intermittent sedimentation in *Arcomytilus*—bearing hostrocks is implied by sedimentological and paleontological data (cf. to chap. 3.2.1).

Probably, the mussel turned itself into semi-infaunal oblique position during or after accelerated deposition to maintain filtering ability. After the stop of sedimentation, a stable—lying shape was achieved as fast as possible by accreting a posterior part with a typical, stable, ventral flattening (pl. 14/5, 7). The wider spacing of ribs is most likely due to an accelerated allometric growth rate of the shell, in the course of which increase of total size was more important than a material—requiring dense ribbing.

Growth forms of *Arcomytilus morrisi* are sketched in fig. 6.

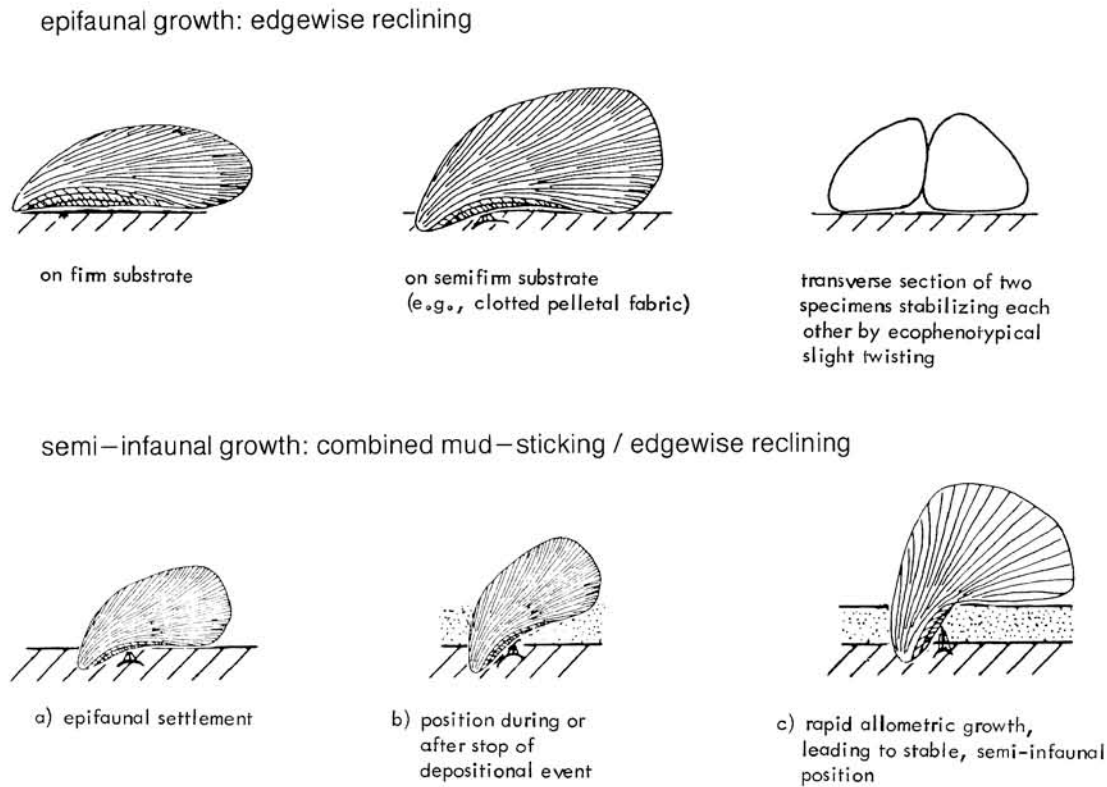


Fig. 6: Life habit of *Arcomytilus morrisi*

4.2 Life Habit of the Sea-Urchin *Pseudocidaris lusitanicus* LORIO

A very common faunal constituent in the »Pteroceriano« unit and even in the Sobral unit are the club-shaped spines of the regular sea-urchin *Pseudocidaris lusitanicus* (pl. 15/2). They may appear in almost the entire variety of facies types, from marl to micritic and sparitic limestones to storm coquinas. They occur frequently both in marly and lime coral facies, but are not less common in *Trichites* limestones and even occur in nodular *Arcomytilus* limestones and in oyster patch reefs. Occasionally, hundreds of spines are swept together to marly coquinas.

The wide range of occurrence clearly points out the not complete stenohaline character of this sea-urchin (cf. also to FÜRSICH 1981).

Club-shaped spines are functionally either interpreted as stabilizing instruments in high energy environments (e.g., CLARKSON 1979:200) or as a defensive armoury, making the sea-urchin too awkward to handle even for fish specialized in snapping aside acicular spines (SMITH 1984:97).

This interpretation may be partially valid for *P. lusitanicus*. Somehow contradictory, however, is the form's main occurrence in quiet water environments. Even in coral boundstones it prefers mud-rich types (compare with occurrences as listed in the section charts, chap. 8).

Consequently, the club-shaped spines may have also had the advantage to prevent sinking into a soft substratum and to enable movement on these soft grounds by their »snow-shoe« like shape.

The almost complete restriction of regular echinids to rocky and stable sand substrata seems to be due to the incapacity to manage movement by use of acicular spines and tube feet on muddy floors, rather than by the location of »gills« on the lower side which would be affected by pollution on muddy substrata, as one might think. Buccal slits of sea-urchins are not

related to the development of gills around the oral region but rather represent pass-ways of expansion sacks compensating protrusive-retrusive movements of the tooth lantern and thus have little to do with the gas exchange (SMITH 1984:72).

On the other hand, the highly porous, light-weight spines had also a high potential to be transported over large distances after the sea-urchins death, particularly since decaying stereom-filling organic stoma possibly resulted in gas production and thus buoyancy. Not considering this aspect leads to a too eurytopic interpretation of the form. Though, making transport processes solely responsible for the wide distribution of *P. lusitanicus* spines is also a wrong point of view: Scratch marks (*Gnathichnus pentax*, pl. 15/3) on bivalves inhabiting soft-bottom substratum (cf. to chap. 3.1.3) are in the present case most likely caused by *P. lusitanicus* (FÜRSICH 1981) and thus evidence a primary occurrence of the form on muddy floors.

Thus, the sea-urchin *P. lusitanicus*, though not completely adapted to soft substrata, was probably enabled to cross semi-firm grounds (e.g., nodular limestones, cf. to chap. 3.2.1) or bottoms with a high density of secondary hardground patches, i.e. bivalve shells (*Trichites* limestones, chap. 3.2.2, eventually in order to search food or possibly only to find another preferred rocky host substratum, e.g., within patch reefs.

This spine adaption rendered it possible for *P. lusitanicus* to rapidly spread over almost all the different facies areas in the entire lagoon, at times where salinity was close to normal.

4.3 *Marinella lugeoni* PFENDER – an Early Corallinacean Red Alga

Marinella lugeoni is a common element in sediments of the Sobral unit and particularly of the »Pteroceriano« unit (cf. esp. to chap. 3.2.9), occurring as subspherical algal nodules up to six centimeter in diameter (pl. 10/1) or, more common as fragments. Thalli may occasionally also encrust skeletal hard parts (corals, mollusks).

M. lugeoni is currently cited, mainly from Upper Jurassic and Cretaceous rocks all over the world (e.g., JOHNSON 1961a, 1964, BOUROULLEC & DELOFFRE 1968, RAMALHO 1971, REY 1972, PERSON & REMANE 1973, MISIK & SYKORY 1982).

Systematic position of *M. lugeoni* is unclear since a long time. PFENDER's (1939) original cyanophyte interpretation was followed by MASSE (1979) and is probably based on the smallness and somewhat undular growth of filaments and their occasional branching (pl. 10/4). This, nevertheless, is not evident, since the oscillatorian cyanophytes whose filament diameters would lie in the range of *M. lugeoni* exhibit a completely different, inhomogenous califying pattern (cf. to LEINFELDER 1985).

Most authors grouped *M. lugeoni* under the codiacean green algae, an also not convincing interpretation, since no Recent and fossil examples exist to justify such a comparison. (Cayeuxian algae which may look somewhat similar to *M. lugeoni* are now attributed to the cyanophytes, e.g., HUDSON 1970, WRAY 1977, TAPPAN 1980.)

Already several times a red algal character was, in part apparently independently, reckoned by several authors: PFENDER (1939) already discussed an eventual corallinacean character, though finally preferring the attribution to another algal group (see above). SRIVASTAVA (1973) guessed a possible red algal origin, though only GOLONKA (1970) and especially IMAITSUMU (1965), by discovering possible conceptacles and vague horizontal walls, gave satisfying reasons for an attribution to the corallinacean red algae.

The present material enables occasional discrimination of conceptacles and vague cross-partitions (pl. 10/2–5) as well as an outer layer of enlarged cells, interpreted as epithallial cells of coralline algae (cf. to JOHANSEN 1981). Chemical wet analysis of one sample revealed a magnesium content of 1.00 vol.%, being well comparable to the 1.74–5.00 vol.% of Recent *Lithothamnium* (MILLIMAN 1974:tab. 15), when taking diagenetic Mg-depletion into account and comparing to the very low magnesium contents of chlorophytes (e.g., *Halimeda*, average < 0.1 vol.% Mg, MILLIMAN 1974:tab. 18).

The thallus is not differentiated into hypothallus and a cortical or outer perithallus, though regular variations in filament diameter and growth direction may be interpreted as a beginning differentiation in this aspect. This lack of true thallial differentiation suggests still close relationship to the solenoporacean algae, or in other words, points out the phylogenetic position of *M. lugeoni* as a very early form of »lithothamnoid« corallinacean algae which are eventually derived from the genus *Solenopora* in the course of the Jurassic (POIGNANT 1977).

A complete description of *M. lugeoni* and discussion on its ecological behaviour and on its systematic and phylogenetic position is in preparation (LEINFELDER & WERNER in prep.).

4.4 »Cayeuxiid« Algae: *Solenopora cayeuxiformis* n.sp.

Solenopora DYBOWSKI, 1877

Solenopora cayeuxiformis n.sp.

Derivatio nominis: The species name is expressing the close morphologic similarities to the genus *Cayeuxia* FROLLO, 1938.

Holotype: Section S'Tiago dos Velhos, at m 17.5 (cf. to chap. 8), district of Lisbon, Portugal, thin—section SV 4, plate 11/1,2.

Type level: »Pteroceriano« unit, upper part, late Lower Portlandian, Upper Jurassic.

Paratypes: S'Tiago dos Velhos, thin—sections SV26/26a, plate 11/5—8; Freixial, thin—section FX I, plate 11/4.

Diagnosis: A new species of *Solenopora* DYBOWSKI with large, slightly undulate tubes exhibiting dominantly round cross—sections and occasional branching.

Description: Tufty, nodular colonies, often spherical in section (pl. 11/7). Composed of, occasionally slightly undulate (pl. 11/4), parallel filaments which are rather closely packed and diverge distally (pl. 11/2, 5). Diameter is constant, with a circular, rarely polygonal cross—section. Side walls of filaments are thick compared to the normally thin, irregularly spaced cross—partitions (pl. 11/1). High angle branching of filaments occurs, whereby parallel growth is quickly achieved after the branching point (pl. 11/1).

Growth habit of the colony is either encrusting, with tubes growing perpendicular to the substratum, or nodule—like, radiating from the center to all directions (pl. 11/4). Growth zones are developed only seldom and vaguely (pl. 11/7).

Measurements:

colonies:	Ø 1–20 mm
cells:	Ø 30–75 µm, most often 55–58 µm length 70–185 µm and more, often 70–140 µm
thickness of walls:	10–35 µm, mostly 12–15 µm
thickness of cross—partitions:	8–15 µm (–30 µm)

Stratigraphic distribution: Found in the Lower? to Upper Kimmeridgian/Portlandian (»Pteroceriano« unit, Freixial unit and the Ota Limestone, Kimmeridgian p.p., for age discussion of the latter see LEINFELDER & RAMALHO in prep.).

Associations: In encrusted red algal nodule facies with corals, bioclasts, *Lithocodium* sp., *Bacinella irregularis*, *Marinella lugeoni*, etc. (cf. to chap. 3.2.9) or as smaller clasts in oolitic bioclastic packstone facies with common litooids.

Discussion: Growth form, arrangement and branching type of filaments show great similarities to the cyanophyte genus *Cayeuxia* FROLLO. Diameter of tubes lies within the range of the species *Cayeuxia pia* FROLLO (75 µm, FROLLO 1938; 60–70 µm, BOUROULLEC & DELOFFRE 1970; 50–90 µm, RAMALHO 1971) or *C. lemaitrae* DRAGASTAN (50–80 µm, normally 60 µm, SCHÄFER & SENOWBARI–DARYAN 1983). Distinction from these taxa is only possible by the often only relic—like preserved cross—partitions, attributing the form most likely to the rhodophyte group Solenoporaceae.

As also known from some »cayeuxiid« algae, the present form may exhibit a connection of neighboured tube lumina and also marginal large sparitic voids (see esp. pl. 11/6). This, however, should not be overemphasized in order to recognize eventual reproductive organs but is rather due to diagenetic alteration (see also SCHÄFER & SENOWBARI–DARYAN 1983:105). Calcified reproductive organs are usually absent in the Solenoporaceae, only occurring in the final evolutionary stages during the Tertiary (WRAY 1977:46).

According to the redefinitions of JOHNSON (1961b) and WRAY (1977), the form should most likely be attributed to the genus *Solenopora* DYBOWSKI, 1877, since the possible genus *Pseudochaetetes* HAUG, 1883, should be abolished (PFENDER 1930:162, WRAY 1977:47).

The genus *Pycnoporidium* YABE & TOYAMA, also included to the Solenoporaceae by many authors (e.g., JOHNSON 1964, IMAITSUMU 1965) differs by its highly flexuous tubes and its pronounced prostrate growth.

The dimensions of filaments approach the upper limits of cell variability of the species »*Pseudochaetetes*« *champagnensis* PETERHANS with tube diameters of 25–50 μm and cell lengths of 40–150 μm and more (PETERHANS 1929:9), and *Solenopora jurassica* NICHOLSON with its different varieties (cf. to BOUROULLEC & DELOFFRE 1970: fig. 3), particularly the subspecies *S. jurassica* var. *lanquinei* PFENDER, with cell dimensions of 70–120 (length) \times 40–70 μm (diameter), often 100 \times 50 μm (PFENDER 1930:154). Both species, however, exhibit a much more regular dense fabric with non–flabellate filaments which are always polygonal in cross–section, thus not displaying the »cayeuxiid« appearance.

Solenopora styriaca FLÜGEL from the Rhaetian exhibits very similar tube diameters but differs by its regular thickenings of cell walls (FLÜGEL 1960).

Solenopora magna GOLONKA is fairly comparable in respect of filament habitus and arrangement, but displays still larger tube diameters (GOLONKA 1970).

R e m a r k s : *Cayeuxia* FROLLO, formerly meant to be a member of the green algal group Codiaceae (e.g., JOHNSON 1961b, BOUROULLEC & DELOFFRE 1968, RAMALHO 1971), is now attributed to the cyanophytes because of close similarities to Recent taxa such as *Scytonema* and related form (HUDSON 1970, WRAY 1977; see also LEIKFELDER 1985). To the present author's opinion, many of the cited occurrences of *Cayeuxia piae* might represent *Solenopora cayeuxiformis* n.sp. with non–preserved cross–partitions. *Cayeuxia*–like growth form and tube branching is already known from another, not identified species of *Solenopora* with smaller tubes (SRIVASTAVA 1973). On the other hand, many forms attributed to *C. piae* may truly correspond to an Ancient cyanophyte species. Thus, systematic interpretation of *Cayeuxia*–like forms must be accomplished carefully, with emphasis to detect eventual poorly preserved cross–partitions which in these cases would attribute the objects to forms around *Solenopora cayeuxiformis* n.sp.. (Examples for such a re–interpretation might be some figures of *Cayeuxia piae* in the literature, e.g., in RAMALHO 1971: pl. 27, fig. 3, upper right part.) In doubtful cases the designation »cayeuxiid« algae may be helpful.

It also should be mentioned here that according to unpublished results of C. BROOK (Cardiff), the solenoporacean algae are not a natural group, with the type species of the genus *Solenopora*, *S. compacta* appearing to be a tabulate or a chaetetid sponge. (Reports of Meetings, Palaeontol. Assoc. Circular 117: p. 3, Summer 1984.) Another example is *S. texana* which is interpreted by BABCOCK (1979) as the outer tissue of a bryozoan.

According to BECKMANN & BECKMANN (1966), the entire group of solenoporaceans could also belong to the hydrozoans.

4.5 The Gymnocodiacean? Alga *Permocalculus* n.sp.

Occurring in the upper part of the »Pteroceriano« unit and frequently becoming the dominant organism in the Freixial unit, is an alga which can easily be grouped under the genus *Permocalculus*. According to ELLIOT (1956b, 1961), organization of the form resembles closely the Recent gymnocodiacean red alga *Galaxaura*, although to the present author's opinion chlorophytes show somewhat similar structures as well (cf. also to SCHÄFER & SENOWBARI–DARYAN 1983).

The occurring species, however, exhibits such a large variety of diagnostic features that it is hardly attributable to an already known species.

Thalli are occasionally well preserved in larger fragments, showing a digitate to bulby form with occasional waxing–and–waning structure (pl. 9/3, 6, 8, 9). Pores are perpendicular to the wall in the outer cortex but may bend down and join with others in the inner cortex which, however, is rarely preserved.

The measurements are as follows:

max. length of thallus:	7.6 mm
diameter of thalli:	0.4 – 2.4 mm
largest variability of thallus	
diameter within one specimen:	0.4 – 1.4 mm
(exceptionally:	1.0 – 3.5 mm)

thickness of wall:	type a)	0.050 – 0.080 mm
	type b)	0.120 – 0.175 – 0.210 mm
diameter of pores (occasional hexagonal cross-section, pl. 9/9):	narrow type	0.010 – 0.015 mm
	normal type	0.015 – 0.025 – 0.030 mm
	large type	0.010 – 0.055 mm
	(pores widening exteriorly, asexual form pl. 9/5)	
diameter of sporangia (pl. 9/7):		0.052 – 0.070 mm

The most common pore diameters suggest a comparison to *Permocalculus inopinatus* ELLIOT which also occasionally shows widening pores, though the rate of pore diameters is much narrower in this species.

P. ampullacea ELLIOT is well comparable by its bulby thallus as well as by the occurrence of asexual and sporangia-bearing specimens, although the mean diameter of pores with 0.012 mm is much less than in our form where the prevailing diameter is 0.025 mm.

RAMALHO (1971) mentions *Permocalculus* sp. from the same stratigraphic level whose measurements lie within the range of the present species. RAMALHO also avoided to attribute the species to an already known one.

A complete diagnosis of the new *Permocalculus* species which apparently is of considerable regional stratigraphic value will be given elsewhere (in prep.).

4.6 The Incertae Sedis *Lithocodium/Bacinella*

In reefoid facies and particularly in the red algal nodule facies, organisms are frequent which may be attributed to the genus *Lithocodium*. *Bacinella irregularis*, though of minor importance is also co-occurring. They both are typically associated with the red algae *Marinella lugeoni* and *Solenopora cayeuxiformis* n.sp. (pl. 7/6).

Most authors put both forms to the codiacean green algae (e.g., ELLIOT 1956a, PRATURLON 1964, BOU-ROULLEC & DELOFFRE 1968, 1970, RAMALHO 1971), although there do not exist very distinct criterions to support such a designation. Consequently, other authors attribute the forms only with restrictions to this group (e.g., FLÜGEL 1979, SENOWBARI–DARYAN & SCHÄFER 1979). Later, SCHÄFER & SENOWBARI–DARYAN (1983) favoured an interpretation as filamentous cyanophyte for *B. irregularis*, while leaving *Lithocodium* in the codiacean group.

Some authors avoid any systematic attribution (e.g., CANEROT 1979) or even place the forms outside the algae: TURNSEK & BUSER (1966) reckon an eventual hydrozoan origin for *B. irregularis*, a possibility which also BECKMANN & BECKMANN (1966) think worth mentioning. Affinities of the form to stromatoporoids are noted by MASSE & POIGNANT (1970). SEGONZAC & MARIN (1972) bring a possible lichen origin into discussion.

In the present material, recrystallization processes in *Solenopora cayeuxiformis* n.sp. may at times also lead to an astonishingly similar structure easy to be confused with *B. irregularis* (pl. 11/6).

Considering the specific form or at least the good preservational stage of the *Lithocodium* species at hand (pl. 12/1–3), composed of narrow packed tubes with occasional cross-partitions (also mentioned by RAMALHO 1971), a hydrozoan or spongian (stromatoporoid) origin is also not beyond any possibility. The interior, irregular ovoid to tube-like horizontal voids, occasionally also occurring in superimposed sets, could then represent a water channel system comparable to astrorhizae or hydrorhizae.

The common general co-occurrence of both *Lithocodium* and *Bacinella* led also to the conclusion that both forms represent one single organism (ELLIOT 1963), interpreted either as different ecological varieties (BOU-ROULLEC & DELOFFRE 1968, followed by RAMALHO 1971) or as differently differentiated parts of one thallus in which *Bacinella* would represent the youth stage and *Lithocodium* the cortical layer (SEGONZAC & MARIN 1972).

Under this point of view one could also assume an ancestral coralline red algal origin: Many published figures of *B. irregularis* do not fundamentally differ from the hypothallus of forms like, e.g., *Archaeolithophyllum* (cf. to WRAY 1977: fig. 72). This is also noted by SCHÄFER & SENOWBARI–DARYAN (1983). The present *Lithoco-*

dium species, with its fairly regular structure and ovoid to tube-like »sporangia« could then eventually be considered as the perithallial cortex.

SADATI (1981) and SCHÄFER & SENOWBARI-DARYAN (1983), however, do not see any systematic relationship between both genera.

While the genus *Bacinella* comprises four fairly well defined species (*B. irregularis* RADOICIC, 1959; *B. ordinata* PANTIC, 1972; *B. ?sterni* RADOICIC, 1972; *B. bicellularis* SADATI, 1981), the species discrimination of the genus *Lithocodium* is not at all satisfying:

Difference between *L. aggregatum* ELLIOT, 1956a and *L. japonicum* ENDO, according to ENDO (1961) should be represented by well marked »sporangia« in the latter species, what, when regarding the present material, seems only to be a preservational difference. The poorly defined *L. japonicum* ENDO and *L. morikawai* ENDO should differ by the presence of tertiary filaments in the latter form (op. cit.) which, however, are also reported from *L. aggregatum* by RAMALHO (1971).

According to BOUROULLEC & DELOFFRE (1968), both *L. japonicum* and *L. morikawai* differ from *L. aggregatum* by their larger filaments. Though, evaluating the original figures of *L. aggregatum* in ELLIOT (1959) and considering the form's measurements given by RAMALHO (1971), no difference in filament diameters compared to the other species are obvious. On top, the structure of densely packed tubes in many of the present specimens (pl. 12/3) coincides with the definition of the genus *Pseudolithocodium* MISIK, 1979. Gradations to forms with more isolated tubes may, however, also indicate a wide primary morphological variety or secondary structural differences due to preservational effects.

Hence, the mentioned taxa urgently need taxonomic revision (in prep., by using additional rich material from other sites of Portugal). For the time being the forms are assigned here as *Lithocodium* sp. and *Bacinella irregularis*.

5. STRATIGRAPHY

5.1 Biostratigraphy

5.1.1 Ammonite Orthostratigraphy

Stratigraphic classification of the late Upper Jurassic in the Lusitanian Basin since ever caused problems, particularly because of the lack or rarity of ammonites. The Upper Jurassic of the Serra da Arrábida, south of Lisbon, for instance, was re-classified various times (for a survey see LEINFELDER 1983: fig. 2). The Upper Jurassic of the central Lusitanian Basin which is of interest here, was originally classified by CHOFFAT (1901) into the stratigraphic units Lusitanian and Neojurassic, the latter with a subdivision into the *Lima*–*pseudoalternicosta* beds, Pterocérien and Freixialien. A clear definition for the Lusitanian, based on ammonites, was, however, only given by RUGET–PERROT (1961: tab. 5), implying the unit's upper boundary to be situated in the upper *Pseudomutabilis* zone what corresponds to the base of the Upper Kimmeridgian in the mesogean French stratigraphic classification (ENAY et al. 1980: 10). The »Pteroceriano« at Cabo Espichel, south of Lisbon, starts with the *Lithographicum* zone and thus with the lowermost Portlandian (MOUTERDE et al. 1972: 96).

Kimmeridgian and Portlandian, the first without the establishing of a »middle« Kimmeridgian, are used here in the French sense, since the British definition (ARKELL 1956) is neither accepted outside Britain (for discussion see HÖLDER 1964: 149), nor always used even inside the United Kingdom in its original sense (see GERASIMOV et al. 1975: pl. 1). Moreover, the Portlandian sensu Gallico corresponds exactly to the boreal Volgian and mediterranean Tithonian stage (op.cit.).

Since no holostratotypes exist for all these equivalent stages (cf. to HÖLDER 1964, GERASIMOV et al. 1975), the term Portlandian is maintained here, both because of its original biozonal definition as given by d'ORBIGNY 1849 prior to the establishing of the Tithonian by OPPEL (1865) and the Volgian by NIKITIN (1881–84) (fide GERASIMOV et al. 1971), and because of its almost exclusive application throughout Western Europe.

In the region under study, stratigraphic knowledge is still low due to an almost total lack of ammonites. Moreover, the data available are confusing. DÖHLER (1984) mentions *Orthosphinctes praenuntius*, *O. vandellii* and *Aspidoceras* cf. *longispinum* from the Abadia marls around Arruda dos Vinhos which indicate the upper part of the *Tenuilobatum* zone and the lower part of the *Pseudomutabilis* zone (SCHAIRER, Munich, in DÖHLER 1984). This would imply that the Sobral, »Pteroceriano« and Freixial units are situated somewhere between the Upper Kimmeridgian and the Cretaceous.

However, a fragmental ammonite, picked up from bare fields by K. ORSCHIED (Mainz, kind pers. commun.) in the lower part of the Sobral unit between Olhalvo and Alenquer (400 m SW of trigonometric altitude Oerca), belongs to the group of Orthosphinctidae (R. ROCHA & B. MARQUES, Lisbon, kind pers. commun.) and thus is possibly equivalent to the ammonites of the upper Abadia marls around Arruda dos Vinhos or even to lower levels.

This would indicate a rather diachronous lower boundary of the Sobral unit.

A further finding is still more puzzling: From old collections of the »Serviços Geológicos de Portugal«, an ammonite was newly identified as *Subdiscosphinctes* cf. *aeneas* and attributed to the middle Oxfordian *Plicatilis*/*Transversarium* zones (B. MARQUES & R. RAMALHO, Lisbon, kind pers. commun.). Finding site, according to the original label, should be Casal do Folgar which is situated north of Calhandriz in the Sobral unit, clearly overlying the Corálico and Oóito units. To the present author's opinion, either the finding site must have been confused or a locality with the same name exists elsewhere in the level indicated by the ammonite. Reworking from the older Cabaços beds and transport from the east seems to be rather unlikely.

To further illustrate the stratigraphic confusion, it should be also mentioned that the clastic sequences along the coast of Sta. Cruz were primarily taken for Kimmeridgian by R. WILSON (1979), but in a note »added in proof« to the same paper, the author guesses a Lower Cretaceous are based on palynological investigations. FÜRSICH (1981) dated the same sequence as late Kimmeridgian (sensu Gallico)/early Tithonian on grounds of a diagnostic ostracod (cf. to following chap.).

5.1.2 Micropaleontological Classification

The best results in classifying shallow marine sequences which lack ammonites are achieved by zonations based on microfauna and microflora. RAMALHO's (1971) thorough analysis of the Upper Jurassic around Lisbon led to the establishing of six zones, divided into further subzones. His zonation, however, was also partially based on lithostratigraphic correlations so that for large-scale application this classification had to be simplified (e.g., FELBER et al. 1982:322).

Foraminiferal Biozonation

Generally accepted for Upper Jurassic platform facies are the following biozones based on benthic foraminifers (see HOTTINGER 1969, BENEST et al. 1975, AZEMA et al. 1977, GARCÍA–HERNANDEZ & LÓPEZ–GARRIDO 1979, RAMALHO 1981, PÉLISSÉ & PEYBERNÈS 1983):

- *Lusitanica* biozone (Upper Portlandian to lowermost Cretaceous?)
- *Virguliana* biozone (uppermost Lower Kimmeridgian to Lower Portlandian)
- *Jaccardi* biozone (Upper Oxfordian to Lower Kimmeridgian)

The *Jaccardi* zone is a taxon range zone, based on the complete stratigraphic range of *Alveosepta jaccardi*, whereas the *Virguliana* zone is a mixed interval/acme zone, based on *Everticyclammina virguliana* occurring frequently now, and further characterized by the non-appearance of *A. jaccardi* and *Anchispirocyclus lusitana*.

The *Lusitanica* zone is another taxon range zone which according to the mentioned authors begins in the late Portlandian. SEPTFONTAINE (1981), however, whilst avoiding a *Virguliana* interval zone, starts the *Lusitanica* zone already in the Kimmeridgian with the appearance of the precursor form *Anchispirocyclus praelusitana*. This, however, is not followed here, since a *Virguliana* zone is well developed and precursor forms of *A. lusitana* are hardly to identify in unoriented thin-sections.

No general agreement exists about the upper boundary of the *Lusitanica* zone. Though most authors assume a final Portlandian or lowermost Berriasian upper limit, some extend the zone up to the lower Valangian (REY 1979, SEPTFONTAINE 1981).

Thus, the Jurassic–Cretaceous boundary has to be defined by other markers, such as ostracods (e.g., REY 1979), dasycladaceans (e.g., BENEST et al. 1975, DRAGASTAN et al. 1975), or other foraminiferal assemblages (e.g., GARCÍA–HERNANDEZ & LÓPEZ–GARRIDO 1979).

Further Informations Provided by Algae

All sequences under study clearly belong to the *Virguliana* zone and the *Lusitanica* zone. A further biostratigraphic subdivision, however, is difficult.

The first appearance of the dasycladacean *Campbelliella* (»*Vaginella*«) *striata* which is very useful in the Serra da Arrábida (cf. to RAMALHO 1971, FELBER et al. 1983), is of no importance here because of the form's rarity. On top, its occasional occurrence in the treated sequences fairly close to the base of the *Lusitanica* zone surely does not represent the taxon's first possible appearance. A very useful tool, however, is the sudden appearance of the gymnocodiacean? alga *Permocalculus* n.sp. (cf. to chap. 4.5) in the upper part of the *Virguliana* zone (cf. also to RAMALHO 1971:tab. 7).

The *Lusitanica* zone in the study area is further characterized by the diagnostic (RAMALHO 1971, BASSOULET et al. 1978) *Macroporella espichelensis* and *Terquemella*(?) *triangularis*, whereas typical forms such as *Macroporella embergeri* or *Triploporella neocomiensis*, known from the lower Cretaceous of the Iberian Peninsula (GARCÍA–HERNANDEZ & LÓPEZ–GARRIDO 1979, REY 1979) are not occurring. Thus, the examined sections do not surpass the Jurassic upper boundary.

Further Informations Provided by Ostracods

Ostracods, derived from marls of the Sobral, »Pteroceriano« and Freixial units, do not permit exact biostratigraphic classification. However, they allow the general separation of the Upper Portlandian from older strata.

Ostracod assemblages from the Sobral and »Pteroceriano« units are rather identical in qualitative composition, composed mainly of *Cytherella* gr. *suprajurassica*, *Asciocythere* sp., *Cytheropteron* sp., aff. *Theriosynoecum* sp. (non *wyomingense*) and indiscriminated taxa.

Marls of the Freixial unit exhibit *Cytherella* gr. *suprajurassica*, *Paracypris* sp. 1, *Schuleridea* sp. 1, *Protocythere* sp. 1 (all sensu RAMALHO 1971).

Cetacella armata, typically occurring in the Upper Kimmeridgian of Portugal (cf. to HELMDACH 1971, FÜR-SICH 1981, WERNER 1984) could not be detected.

5.1.3 Stratigraphic Use of Macrofauna

The lithological units are partially well characterized by macrofaunal elements. *Eomiodon securiformis*, *Gervillia sobralensis* (pl. 15/4) and *Nerinea turbinata* (pl. 15/1) are typical forms of the Sobral unit and of siliciclastic intercalations in the lowermost part of the »Pteroceriano« unit, whereas comparable environments are characterized by *Trigonia freixialensis* in the Freixial unit (chap. 3.3.6, pl. 16/9).

Arcomytilus morrissi (pl. 14) and *Myophorella lusitanica* (pl. 16/4) occur in nodular limestones of the »Pteroceriano« unit but not of the Freixial unit. The distribution of these two forms may seem to be caused both phylo-

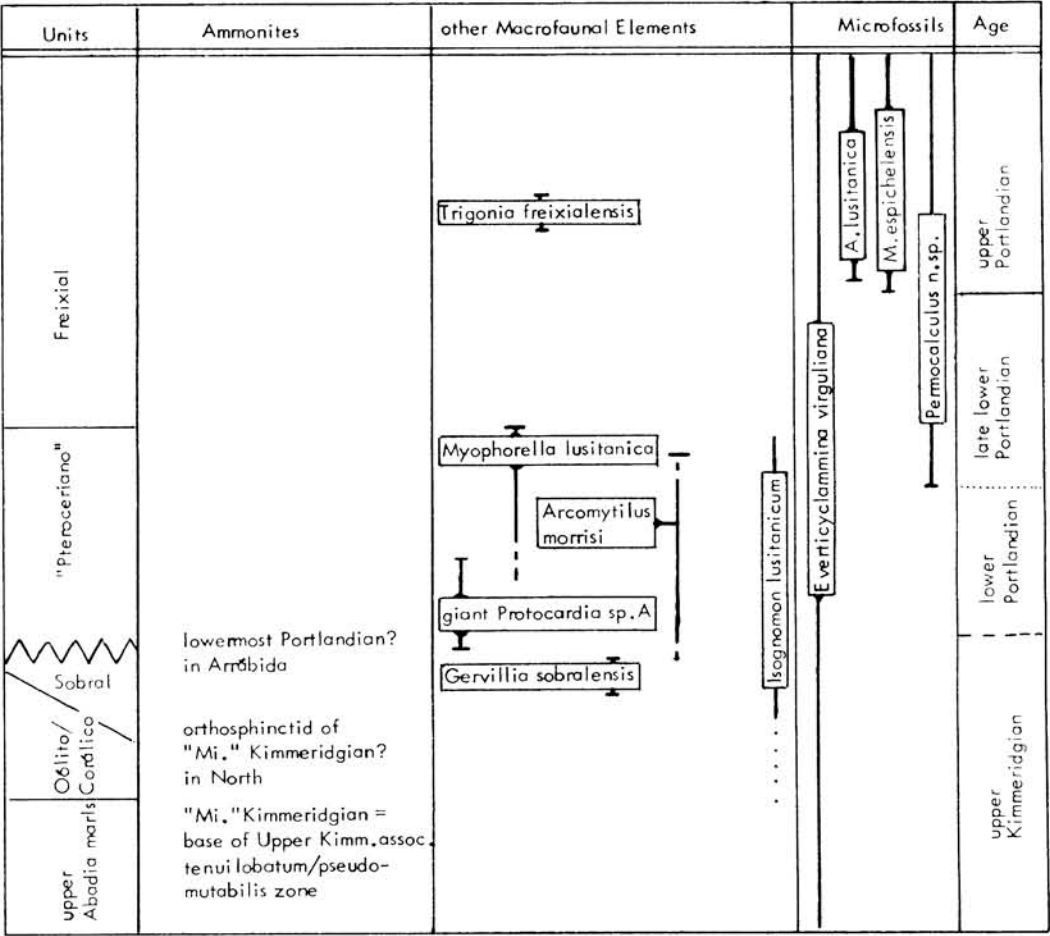


Table 2: Biostratigraphic tools in the study area (southern part). For discussion see text.

genetically and environmentally. Hence, lower or upper limits of occurrences are of no further stratigraphic value, since they are strongly controlled by facies distribution and should not be correlated.

The giant *Protocardia* sp. A, however, occurs mainly in a narrow zone from the higher Sobral unit to the lower-most »Pteroceriano« unit south of Arruda dos Vinhos and might represent a fairly short—living form of considerable stratigraphic value (F. FÜRSICH, Munich, kind pers. commun.).

Using this hypothesis the thin levels of nodular limestones exhibiting this form, intercalated in the coastal clastics of Sta. Cruz can be well correlated (cf. to chap. 5.2.2.4). The occurrence of the level with giant *Protocardia* sp. A fairly high in the »Pteroceriano« sequence in the southeast (section Bom Jesus, chap. 8) would then indicate the earlier establishment of »Pteroceriano« facies in this region.

5.2 Lithostratigraphy

5.2.1 Local Lithostratigraphic Correlations

The available biostratigraphic tools, unfortunately, are not precise enough to enable satisfying stratigraphic correlation of individual sections. Thus, lithostratigraphy has to serve for further refining. Additionally, correlations of individual sedimentary units with sequences outside the central study area are only feasible mainly by lithostratigraphic means (cf. to chap. 5.2.2.4).

The major obstacle for a lithostratigraphic approach are diachronous facies boundaries which are particularly time—ignorant in marginal marine environments. In the Serra da Arrábida, south of Lisbon, for instance, the lower boundary of a lithological unit comparable to the »Pteroceriano« unit in age and facies development crosses two different micro—biozones (FELBER et al. 1982:326). In the study area, the occurrence of probably age—equivalent ammonites in the basal part of the Sobral unit in the north and in the upper Abadia marls further south indicates either a very short—termed development of the interbedded Corálico/Oólito beds or, more likely, once more rather diachronous facies boundaries. Additionally, the upper boundary of the Sobral unit could be proved to be intercalatory with the overlying »Pteroceriano« unit. This sort of diachronous limitation is naturally not astonishing for a delta complex as represented by the Sobral unit.

Renewed input of clastics, characterizing the »Pteroceriano«—Freixial and the »Pteroceriano«—Upper Sandstone boundaries (see chap. 5.2.2.3), is also highly diachronous: The higher part of the »Pteroceriano« unit contains *Permocalculus* n.sp. in the south, whereas further north this form is not yet appearing in the limestones underlying the clastics.

Another correlation instrument are marker beds, particularly extensive shell beds, many of which are recently often re—interpreted as storm deposits. *Isognomon* shell beds were used for correlation by TRZESNIEWSKI & SEIFERT (1958) in the surroundings of the Vimeiro diapir. However, they do not serve for correlation in the study area, since their lateral extension is very restricted in most cases. More suitable are the mixed storm coquinas as described in chap. 3.2.4 which extend over larger parts of the sedimentation area. Several neighboured sections can be well linked by such isochronous key beds.

Oncolite beds also may be of advantage for correlation, if their formation was due to a general regional lowering of sedimentation rates. Local oncolite development caused by locally favourable conditions must be excluded for this purpose.

The extensive development of the, mainly freshwater, oncolite of Alenquer (LEINFELDER 1985) in the northeast can be tentatively connected with marine oncolites further south (fig. 11).

Generally, regressive boundaries tend to be much more diachronous than transgressive onlaps. Transgressions are normally accompanied by low sedimentation rate what leads to sharper and considerably less diachronous transgressional contacts (e.g., DULL et al. 1967). Actually, the upper regressive boundary of the »Pteroceriano« unit is heavily diachronous (see above), whereas a rapid transgression was held responsible by CHAUMEAU (1962) for its lower limitation (but see also chap. 6.5.1).

To the present author's opinion, the peak of »Pteroceriano« transgression is marked by the widespread nodular limestones with *Arcomytilus*, *Trichites* and giant *Protocardia* sp. A which appear in the lower »Pteroceriano«

limestones (see chap. 5.2.2.3) of the central area and are the only marine representatives of calcareous »Pteroceriano« facies in the northwest and west. Originated under low sedimentation rate, these beds represent the largest extension of the »Pteroceriano« sea and are certainly fairly isochronous.

Northward correlation of this »Pteroceriano« transgression is more difficult to perform, since there exist occasionally two marine limestone horizons which are separated by up to 40 meters of marginally marine and terrestrial clastics: In the S. Quitéria section (chap. 8), the lower, very sandy horizon exhibits *Arcomylus morrisoni* and *Trichites* sp., whereas the upper one, superimposed to the Alenquer Oncolite, consist of pure mudstones exhibiting occasional birdseyes (LEINFELDER 1985).

Correlating the lower horizon to the main spreading of »Pteroceriano« facies would imply a possible lower Portlandian age for the higher situated Alenquer Oncolite. This, however, is not too well in consensus with the old age of the Sobral unit, as implied by an ammonite finding (cf. to chap. 5.1.1.). Most probably, this maximum spreading of »Pteroceriano« facies is related to the peak of global eustatic sea level rise at the Kimmeridgian/Portlandian boundary (cf. to chap. 6.5.1). Due to the pronounced local subsidence pattern of this area, expansion of limestone facies was most probably already taking place earlier in this area, represented by the sandy beds with *Trichites*. The second progradation, the thin marine limestone beds overlying the Alenquer Oncolite, should then be correlated with the beds with giant *Protocardia* sp. A, thus implying most likely an uppermost Kimmeridgian age for the Alenquer Oncolite.

5.2.2 Suggestions on Lithostratigraphic Terminology and Classification under Consideration of Basinwide Application

5.2.2.1 Terminological Situation

Like anywhere else, regional geological research is encountered by plenty of stratigraphic notions in the Upper Jurassic of the Lusitanian Basin as well (see also tab. 1, chap. 1.2). A particular problem in Portugal was the common mixture or non-separation of lithostratigraphic and biostratigraphic terms, like the »Pteroceriano« which was formerly understood as a chronostratigraphic notion. This reflects the old layer-cake conception of stratigraphy, in which for beds of identical facies also an identical age was assumed regardless their regional distribution.

Meanwhile, the »Pteroceriano« and the »Freixialiano« could locally be biostratigraphically defined (particularly RAMALHO 1971); the above outlined diachrony of these units, however, prohibits their general dating.

R. WILSON (1979) submitted an attempt to correlate Upper Jurassic sedimentary units, an useful approach which though is not completely satisfying because of lacking definition of terms: The term »Sobral«, formerly introduced by H.W. ROBBINS (fide CHAUMEAU 1962) for the clastics between the Amaral Coral Limestones and the »Pteroceriano« was substituted by the so-called »Upper Sandstones« by WILSON (1979). RUGET-PERROT (1961), however, used this latter item for the clastic equivalence of »Pteroceriano« and »Freixialiano« further north. Moreover, MOUTERDE et al. (1979:48) applied the name »Grès Supérieures« (translation Upper Sandstones) for the clastics between the Abadia marls *sensu strictu* and the Amaral Coral Limestones.

Another insufficiently defined and non-uniformly used though very colloquial stratigraphic term is the »*Lima pseudoalternicosta* Beds«. The beds are a Sobral equivalent according to CHAUMEAU (1962) or an equivalent of the Amaral Coral Limestones according to WILSON (1979). On top, the diagnostic bivalve *Lima pseudoalternicosta* could not be found in the beds in question.

Actually of greatest use for the region treated here is the original classification of CHOFFAT/CHAUMEAU (see tab. 1, chap. 1.2), if exclusively considered lithostratigraphically. Consequently, the terms Sobral, Freixial and »Pteroceriano« should be maintained because of their wide distribution in the Portuguese literature, but should be understood only as lithostratigraphic, facies-connected notions (see also chap. 5.2.2.3).

5.2.2.2 Prerequisites for Stratigraphic Classification

In the nineteenth and early twentieth century, the establishing of stratigraphic classifications was the main target of geological research in sedimentary basins, though hampered by the lack of knowledge on diachronism and facies substitutions and thus leading to a flood of very locally restricted stratigraphic names and wrongly correlated units.

During the last decades, the Lusitanian Basin, as many others, was examined by modern facies analysis methods, both under sedimentological and biological aspects, mainly to yield paleo–environmental and paleogeographic results. Simultaneously, biostratigraphic classification was improved.

What is still missing for the Upper Jurassic Lusitanian Basin is a standardized lithostratigraphic re–definition (see also FÜRSICH & WERNER 1984) which should be established only after a completely exercised multi-spectral basin analysis (cf. also to MIALL 1984:73).

Meanwhile, this present study, leading to a three–dimensional sedimentary analysis of larger parts of the basin (see chap. 6) as well as other works dealing with biostratigraphy (particularly RAMALHO 1971) or local facies analysis (e.g., FÜRSICH 1981, WERNER 1986) permit exact definition of a lithostratigraphic framework at least for the study region.

5.2.2.3 Suggestions on Formal Lithostratigraphic Units

The study region is a key area for understanding the stratigraphic situation of the late Upper Jurassic due to the widespread interfingering of clastic and carbonaceous deposits. Hence, a stratigraphic classification established in this area should be applicable to larger parts of the Lusitanian Basin.

Here suggested is a regional classification according to the norms of the International Subcommittee on Stratigraphic Classification (HEDBERG 1976), i.e., the concept of normative defining of lithostratigraphic Formations, Members, etc..⁴

The proposed stratigraphic formal units and their vertical and lateral arrangement are given in fig. 7.

The units are characterized and defined as follows:

Abadia mega – unit (Abadia Group, Grupo de Abadia)

Though the »Abadia beds« and the superimposed »Corálico/ Oólito« were no matter of detailed study here, it is suggested to establish a formal Abadia Group composed of the Cabrito Formation (Formação de Cabrito, marine sandstones), the Arruda Formation (Formação de Arruda, marls), the Alcobaça Formation (Formação de Alcobaça, marine sandstones) with the Consolação Member (Membro de Consolação, deltaic and bay sandstones, marls and limestones), the Amaral Formation (Formação do Amaral) with the Trancoso Member (Membro de Trancoso, coral limestones) and the Oólito Member (Membro Oólito), and the Ota Formation (Formação de Ota, shallow marine limestones) (see below).

Upper sandstone mega – unit (Upper Sandstone Group, Grupo dos Gres Superiores s.l.)

Overlying the Abadia Group in the northern part of the study area is a clastic sequence termed here formally as the Upper Sandstone Group (note that this term comprises a larger range than the so–called gres superiores sensu RUGET–PERROT 1961, yet coincides with the upper sandstones as understood by R. WILSON 1979).

Footnote⁴: The author is aware of the fact that only with further cooperation of stratigraphic workers and after a final formal establishing of type sections and publication in an adequate scientific medium such an approach is valid. This is a suggestion towards this direction. Contacts are already established in this aspect. To indicate the provisional character, units are still assigned as informal (formation, not Formation) outside this and the following suggestive chapter.

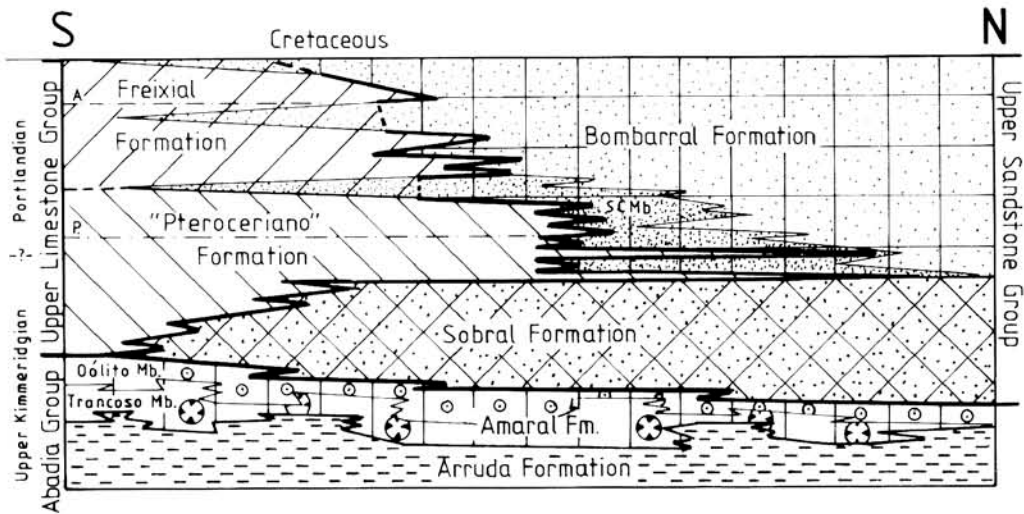


Fig. 7: General arrangement of (proposed) formal stratigraphic units in the study area.

Abbrev.: SC Mb: Santa Cruz Member, P: Onset of *Permocalculus* n.sp., A: Onset of *Anchispirocyclina lusitanica*

The lithological term is preferred here to a geographic term because of its colloquial use, although the Portuguese version »Gres Superiores« should be avoided because of narrower original definition, or used with the suffix »sensu lato«.

From bottom to top the group is divided as follows:

Sobral unit

Proposed formal rank: Formation (Sobral Formation, Formação de Sobral). The Sobral unit gains its rank »Formation« due to its wide distribution and its good mapping ability.

Derivation nominis: from the town Sobral de Monte Agraço, where the Formation is largely outcropping.

Though no type section is possible in the surroundings of Sobral, the name is maintained because of historic reasons (introduced by H.W. ROBBINS, fide CHAUMEAU 1962).

Holostratotypus: Mata section, m 18 – 66, southwest of Arruda dos Vinhos, from lower to upper Formation boundary; see chap. 8.

Hypostratotypus: Section at coast of Sta. Cruz, as given in FÜRSICH (1981: fig. 2, up to m 42 in subsection C).

Remarks: The Sta. Cruz section is more complete, yet lacking the lower Formation boundary. Therefore the Mata section is preferred to define the holostratotypus.

General characteristics (summary, for further treatment see chap. 6.2): Sequence of predominantly marginal marine (deltaic) siliciclastics with micaceous, lignitic, ocre-coloured silts and sandstones bearing *Eomiodon securiformis*, *Isognomon lusitanicum*, *Gervillia sobralensis*, etc.. Common oolite strings of beds with quartz-cored ooids and marls. Further north, red terrestrial siliciclastics in middle part of Formation (see fig. 10, chap. 6.2).

Thickness: 65 meters around Sobral, outwedging towards south and southeast.

Lower boundary: Onset of sandstone/oolite sequence overlying oolite unit (Oolito Member of Amaral Formation).

Upper boundary: Calcareous facies, in part only represented by one bed (»Pteroceriano« Formation). Further north: superposition of a thick series of red coarse clastics (Bombarral Formation).

Approximate age: Boundaries heavily diachronous. Mainly Upper Kimmeridgian, eventually down to Oxfordian? in the north (see chap. 5.1.1.).

Bombarral unit

Proposed formal rank: Formation (Bombarral Formation, Formação de Bombarral).

Derivatio nominis: from the town Bombarral, type area

Stratotypus: Because of poor outcrop conditions and the homogeneity of the unit (except for the lower part, see below), the designation of a type area suffices to characterize the Formation.

General characteristics: Red terrestrial sequence of siliciclastic silts, sandstones and a large amount of coarse conglomerates, often with considerable quantity of feldspar and metamorphic pebbles. In lower part, rare marine clastic intercalations (Santa Cruz Member, see below).

Thickness: Several meters to several hundreds of meters, thickening northwards.

Lower boundary: Marine deposits, normally clastics, rarely limestones of the »Pteroceriano« or Freixial Formations.

Upper boundary: Coarse, whitish kaolinitic clastics, attributed to the lowermost Cretaceous.

Approximate age: Upper? Kimmeridgian to uppermost Portlandian.

Santa Cruz unit⁵

Proposed formal rank: Member (Santa Cruz Member, Membro de Santa Cruz), belonging to the Bombarral Formation.

Derivatio nominis: Town Santa Cruz, type area.

Holostatotypus: Section at coast of Sta. Cruz, as given in FÜRSICH (1981: fig. 2, m 45 of subsection C to m 3 of subsection E).

Hypostatotypus: Benfica section, west of Torres Vedras (not comprising the complete Member), see chap. 8.

General characteristics: Fine-grained, mainly terrestrial clastics with marine clastic and marl intercalations, commonly with *Isognomon lusitanicum*, *Eomiodon securiformis*, *Myophorella lusitanica* and tiny soft bottom fauna, at base of Bombarral Formation.

Thickness: Several meters to tens of meters.

Lower boundary: Several beds of limestone representing the vestiges of the »Pteroceriano« Formation (see below).

Upper boundary: Last marine clastic bed.

Remarks: The Santa Cruz Member is grading laterally and vertically into the Bombarral Formation s.str. without a distinct mappable boundary. Consequently, the rank Member is attributed to identify the unit as subordinate to and included in the Bombarral Formation.

Intercalations of marine silts and sandstones with, e.g., *I. lusitanicum* within and on top of the »Pteroceriano« Formation, occurring particularly in the southwest, are vestiges of the Santa Cruz Member.

Approximate age: Upper? Kimmeridgian to Lower Portlandian?

Upper limestone mega – unit (Upper Limestone Group, Grupo dos Calcários Superiores)

The southern representative of the Upper Sandstone Group is a complex of limestones and marls with sandstone intercalations in the upper part. To accentuate its counterpart role to the Upper Sandstone Group, the formal name Upper Limestone Group is suggested here. A lower limestone mega – unit would be represented by the Middle Jurassic to early Upper Jurassic shallow marine limestones.

Footnote⁵: Corresponds to »Torres Vedras unit« in LEINFELDER (1985: 254).

»Pteroceriano« unit

Proposed formal rank: Formation (»Pteroceriano« Formation, Formação »Pteroceriano«).

Derivationominis: The term Pteroceriano, Pterocérien or Pterocerian is commonly used in the literature on the Portuguese Jurassic and thus should eventually not be abolished. Formerly understood as a West European chronostratigraphic item, it is considered here only as a facies—connected, lithostratigraphic term. To avoid confusion it is suggested to use the Portuguese version, pointing out the unit's local distribution, always together with the notion Formation to clarify its lithostratigraphic character. Quotation marks should additionally prevent any confusion with chronostratigraphy.

Holostratotypus: Alcubela—Freixial section, m 5 – 185, south of Arranhó (comprising complete range of Formation).

Parastratotypus: Arranhó—Bemposta section, m 12 – 136 (comprising complete range of Formation).

Hypostratotypes: Sections Tesoureira, S'Tiago dos Velhos (m 0– 47, upper part of Formation, up to upper boundary), Bom Jesus (lower part of Formation); see chap. 8 for all sections.

General characteristics (summary, for further treatment see chap. 6.3): Sequence of marls, calcareous marls and limestones.

Based on CHOFFAT/CHAUMEAU (see fig. 1, chap. 1.2) the »Pteroceriano« Formation can be further subdivided into the following informal subunits, from base to top:

- Lower »Pteroceriano« limestones (calcário »pterooceriano« inferior, m 5 – 33 of holostratotypus)
- Lower »Pteroceriano« marls with limestone intercalations (marga – calcário »pterooceriano« inferior, m 33 – 94 of holostratotypus)
- Alrota limestones (calcário de Alrota, m 94 – 145 of holostratotypus)
- Upper »Pteroceriano« marls with limestone intercalations (marga – calcário »pterooceriano« superior, m 145 – 185 of holostratotypus)

This subdivision is not possible in regions away from the type section, so that no formal subdivision is suggested.

The most characteristic faunal elements are *Arcomylus morrisi* (lower part), *Myopholas multicostata*, *Trichites* aff. *saussurei* and *Myophorella lusitanica* (upper part).

Remarks: The »Pteroceriano« Formation is to be understood as a calcareous – marly unit. The marly – siliciclastic sediments substituting the »Pteroceriano« Formation laterally and sometimes also called Pterocerian (e.g., FÜRSICH 1981, WERNER 1986) should not be termed as such.

Thickness: 150 – 250 meters, decreasing up to zero towards north and west and then represented by a few beds only.

Lower boundary: Distinct, formed by clastics and marls of the underlying Sobral Formation. Uppermost Sobral Formation often represented by marls with *Gervillia sobralensis*.

Upper boundary: Onset of siliciclastics belonging to the Freixial Formation (see below) or the Bombaral Formation (Santa Cruz Member).

Approximate age: Lower Portlandian, situated in the upper part of the *Everticyclammina virguliana* interval biozone. Further biostratigraphic division possible by the appearance of *Permocalculus* n.sp. in the upper part (cf. to chap. 5.1.2). In the south and east possibly already beginning in the uppermost Kimmeridgian (cf. to chaps. 5.2.1 and 6.5.1).

Freixial unit

Proposed formal rank: Formation (Freixial Formation, Formação de Freixial).

Derivationominis: Village Freixial, west of Bucelas, site of type section. Current stratigraphic term in Portuguese literature, also often used as Freixialiano. The latter item implies a chronostratigraphic range, so that it is avoided here.

Holostratotypus : Section Alcubela–Freixial, m 185 – 350 (comprising complete range of Formation), see chap. 8.

Hypostratotypes : Section Tesoureira–Casais da Serra, west of Freixial, lower part, m 66 – 122, and upper part, m 0 – 123 (comprising complete range of Formation), see chap. 8, and section »Freixial« of RAMALHO (1971), along the same roadside.

General characteristics (summary, for further treatment see chap. 6.4): Sequence of marginal marine siliciclastics, marls and limestones.

Considering CHOFFAT/CHAUMEAU (see tab. 1, chap. 1.2), the Freixial Formation can be further subdivided into the following informal subunits, from bottom to top:

- Lower Freixial interbeds (camadas interstratificadas inferiores de Freixial, limestones, marls, sandstones, m 185 – 210 of holostratotypus).
- Lower Freixial sandstone (grés inferior de Freixial, m 210 – 217 of holostratotypus).
- Middle Freixial interbeds (camadas interstratificadas médias de Freixial, m 217 – 242 of holostratotypus).
- Main Freixial sandstone (grés principal de Freixial, m 242 – 274 of holostratotypus).
- *Anchispirocyclina* limestone (calcário com *Anchispirocyclina*, m 274 – 296 of holostratotypus).
- Upper Freixial interbeds (camadas interstratificadas superiores de Freixial, m 296 – ca. 310 of holostratotypus).
- Upper Freixial sandstone (grés superior de Freixial, ca. m 310 – 350 of holostratotypus).

Further west only few horizons of limestones are intercalated into a predominantly clastic series (see chap. 6.4). The occurrence of thin limestone intercalations should serve as diagnostic criterion to attribute this sequence to the Freixial Formation, thus separating it from the Bombarral Formation.

The most characteristic, though rare, macrofaunal element of the Freixial Formation is *Trigonia freixialensis*.

Thickness : 150 – 200 meters, if measureable.

Lower boundary : Onset of siliciclastics on top of the underlying »Pteroceriano« Formation which latter may be represented by few beds only in the west.

In regions marginal in the distribution of the »Pteroceriano« Formation, i.e., with sandstone intercalations representing vestiges of the Santa Cruz Member, the boundary to the Freixial Formation is nevertheless clear because of the disappearance of typical »Pteroceriano« and Santa Cruz fauna such as *Arcomylus morrisi* and *Isognomon lusitanicum*.

Upper boundary : North: Onset of reddish, terrestrial coarse clastics without any marine calcareous intercalations (Bombarral Formation). South: Onset of whitish coarse clastics, attributed to the lowermost Cretaceous (cf. to REY 1979).

Approximate age : »Middle« to final Portlandian (upper part of the *Everticyclammina virguliana* interval biozone with *Permocalculus* n.sp.; *Anchispirocyclina lusitanica* taxon range biozone). Boundaries probably slightly diachronous.

5.2.2.4 Lithostratigraphic Basinwide Correlation

In this chapter it is attempted to test the proposed lithostratigraphic concept by its application on the Upper Kimmeridgian and Portlandian of the entire Lusitanian Basin (fig. 8).

Base for this attempt was the evaluation of existing detailed examinations and additional informations from personal field trips.

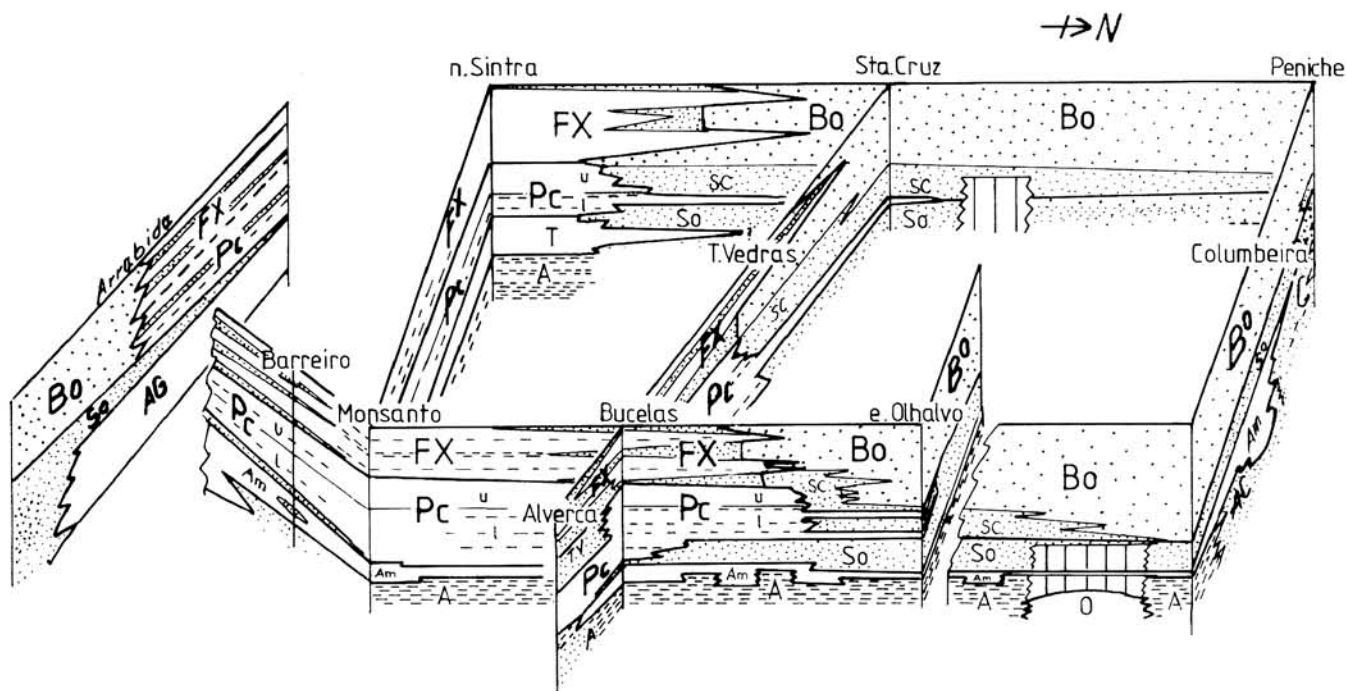


Fig. 8: Correlation of Upper Kimmeridgian to final Portlandian sediments in the southern and central Lusitanian Basin.

Based on this study, further personal examinations and evaluation of FELBER et al. (1982), FÜRSICH (1981), FÜRSICH & SCHMIDT-KITTLER (1980), LEINFELDER (1983), LEINFELDER & RAMALHO (in prep.), MOUTERDE et al. (1972), RAMALHO (1971), WERNER (1986), WILSON (1979).

White: limestones; dashes: marls; narrow-dotted: terrigenous siliciclastics; wide-dotted: terrestrial siliciclastics; vertical lines: hiatuses;

AG Abadia Group: A Arruda Fm (Abadia marls), AC Alcobaça Fm, C Consolação Mb, Am Amaral Fm, O Ota Fm; Upper Sandstone Group: So Sobral Fm, Bo Bombarral Fm, SC Santa Cruz Mb; Upper Limestone Group: Pc »Pteroceriano« Fm (u upper, l lower part), FX Freixial Fm.

Not at scale.

Correlation towards south

Sintra region:

RAMALHO's (1971) sections north of Sintra are here suggestively correlated to the proposed scheme as follows:

The base of the Littoral section, the »Schistes de Ramalhão« are to be correlated to the lower part of the Arruda Formation (Abadia marls). Superimposed is the »Marno-Calcaire Schisteux« (481 m). The marl-limestone intercalations at the base and on top of this unit represent respectively the upper part of the Arruda Formation (Abadia marls) and the lower part of the »Pteroceriano« Formation. In between intercalated is a thick intraclastic-reefal limestone lenticle (300 m), very similar to the Amaral Formation. The Sobral Formation is not extending so far to the southwest.

The »Calcaire à Oncolites« (126 m) with common corals is following next, representing the upper part of the »Pteroceriano« Formation (Alrota limestone).

The overlying 65 meters of »Calcaire noduleux«, continuing to another 362 meters of nodular limestones in nearby section Murches represent the Freixial Formation, here occurring without sandstone intercalations which only appear in the overlying Purbeck beds (60 m).

Lisbon region:

Correlation to this area is again based on RAMALHO (1971) who examined borehole samples.

In borehole Monsanto 1 a situation similar to the Sintra region is obvious:

Superimposing the Arruda Formation (Abadia marls, on top with thin limestone intercalations) is a reefal limestone (64 m), easily to attribute to the Amaral Formation. The overlying micritic limestones with occasional corals and stromatoporoids (130 m) are attributed to the lower part of the »Pteroceriano« Formation, whereas its upper part is represented by 109 meters of micritic limestone with oolitic and intraclastic levels (Alrota limestone). The Freixial Formation is developed in a marly–micritic sequence, with only 15 meters attributable to its lower, but 346 meters to its upper part (*Anchispirocyclina* limestone).

As in the Sintra region, clastic intercalations (Sobral Formation, sandstone beds in the Freixial Formation) are not developed.

The situation is different already some kilometers further south (Barreiro boreholes):

In log Barreiro 2, already the Arruda Formation (Abadia marls) is strongly sandy. The superimposed intraclastic, oolitic and dolomitic limestones (70 m) are easily attributable to the Amaral Formation. They already contain sandstone intercalations which thicken towards south. The Sobral Formation is represented by the »Complexe greseux inferieur« (70 m), a sequence of sandstones and marls with rare limestone levels.

The overlying »Complexe marno–calcaire« (130 m) is clearly identical with the »Pteroceriano« Formation.

Finally, the »Complexe greseux supérieur« (154 m) with limestone intercalations represents the Freixial Formation.

Arrábida region:

In the cliff section at Cabo Espichel, westernmost Arrábida region, the »Pteroceriano« and Freixial Formations are not divisible by lithostratigraphic means, since sandstone intercalations are not only restricted to the upper part (cf. to RAMALHO 1971, FÜRSICH & SCHMIDT–KITTLER 1980).

Correlation to the entire region is, however, possible when regarding a combination of Arrábida sections rather than an isolated example (cf. to FELBER et al. 1982, LEINFELDER 1983):

The Abadia Group is included in the mentioned authors' »Micrite Series«, thus being completely calcareously developed here. Only in the extreme southeast, contamination by clastic input is obvious already in this level (Micrite/Sandstone Intercalation Series sensu LEINFELDER 1983). The superimposed »Arenite Series« may be correlated with the Sobral Formation, the overlying »Siliciclastic Series« (eastern Arrábida) with the Bombarral Formation. Further west limestone intercalations increase so that comparison to the Upper Limestone Group (»Pteroceriano« Formation plus Freixial Formation) is rendered possible.

General trends in the south of the Lusitanian Basin:

Two trends are obvious when pursuing the sedimentological units to the south:

1. The importance of sandstone intercalations, particularly in the Upper Limestone Group, is decreasing until Lisbon, to augment again further south towards the Arrábida.
2. Limestone development in the upper part of the Abadia Group (analogue to the Amaral Formation) is heavily increasing towards southwest (Sintra).

Further south, towards the Arrábida, limestones completely substitute the marly Arruda Formation (Abadia marls).

Correlation towards west and north

Sta. Cruz:

Coastal sections along the beach of Sta. Cruz are examined by FÜRSICH (1981): The terrestrial–deltaic clastic–marly sequence exhibits a narrow level (6 m) with thin limestone intercalations (op. cit., fig. 2, columns B,

C, and figs. 14, 15) bearing the giant *Protocardia* sp.A (F.FÜRSICH, Munich, kind pers. commun.). These micritic nodular limestones clearly represent the outthinning »Pteroceriano« Formation⁶, thus attributing the underlying clastics to the Sobral Formation, whereas the superimposed, fauna-rich marls, silts and sandstones account for the Santa Cruz Member (Bombarral Formation).

R. WILSON (1979, fig. 7) gave sketch columns of the Sta. Cruz sequence which can be interpreted in the same way.

Consolação region:

A minute study of the coastal section along the cliffs of Consolação, nearby Peniche, is worked out by WERNER (1986). The section is already tentatively correlated to nearby areas by the same author. This correlation is followed here, with some additional suggestions on affiliation of lithostratigraphic units.

The 750 m-thick, almost exclusively siliciclastic sequence may be subdivided as follows:

Prodelta, delta and bay sediments with intercalations of marly limestones and marly coral biostromes (80 m) are attributed to the Abadia level due to ammonite findings by WERNER (1986) (suggestion here: Consolação Member of the Alcobaça Formation). The superimposed delta front, beach and lagoonal siliciclastic deposits (now without *Alveosepta jaccardi*) are correlated to the Corálico do Amaral (here, to the Amaral Formation) by the same author (m 80–150), but should eventually be attributed to the Sobral Formation in formal classification because of their lithologic similarities.

Above these beds, siliciclastics turn soon into terrestrial deposits (also equivalent to the Sobral Formation). Between meter 580 and 630, marine deposits occur once again (Forte Pai Mogo). According to WERNER (1984), they represent the »Cetacella armata beds« sensu HELMDACH (1971) and are correlated by the former author to the Pterocerian (cf. to footnote ⁶). Applying the definition suggested here, these beds should be termed Santa Cruz Member. Superimposed terrestrial clastics (up to m 750) would represent the rest of the Bombarral Formation.

In the hinterland, the section of Columbeira is developed differently, most probably due to an at that time active salt diapir ridge (e.g., WERNER 1986). Superimposed to Upper Oxfordian/Lower Kimmeridgian limestones (RUGET–PERROT 1961) are ca. 150 m of marly, siliciclastic beds with oncolite and oolite intercalations (personal examination, also WERNER 1986) (here tentatively Alcobaça Formation of the Abadia Group). These beds are overlain by a thick sequence of mostly high energetic limestones which are correlated, e.g., by R. WILSON (1979) with the Corálico do Amaral (here Amaral Formation).

S. Martinho do Porto:

R. WILSON (1979) examined a coastal sequence at S. Martinho do Porto (between Peniche and Nazaré):

Superimposed to calcareous Upper Oxfordian/Lower Kimmeridgian beds are clastics which he termed Abadia beds. Because of their exclusively sandy terrestrial development they should be attributed to the deltaic Alcobaça beds (sensu MOUTERDE et al. 1972, here tentatively Alcobaça Formation), possibly under the establishment of a subunit (tentatively S. Martinho Member).

The overlying 50 meter-thick sequence of marls and sandstones with limestone intercalations is assigned as Corallian/Sobral (here Trancoso–Sobral Formations) by R. WILSON (1979).

Superimposed are the Upper Sandstones (sensu R. WILSON, here Bombarral Formation).

Cabo Mondego:

North of Nazaré, at the Cabo Mondego, a coastal sequence of corresponding beds was examined by R. WILSON (1979).

Footnote⁶: Bear in mind the different use of the term Pteroceriano by FÜRSICH and WERNER, as outlined in the foregoing chapter.

Calcareous Oxfordian beds are overlain by a thick set of terrestrial clastics (Upper Sandstones sensu WILSON). They exhibit two marine horizons, the first one represented by fine clastics and marls between m 342 – 450, and the second by a thin micritic intercalation around m 665 of the given section (op. cit., fig. 3). Without additional data about their approximate age, it is not possible to decide whether the limestone intercalation represents the Trancoso Formation, herewith considering the lower marine level as a thin vestige of marine Abadia – Alcobaça beds, or whether it even could be attributed to the »Pteroceriano« Formation.

General trends in the west and north of the Lusitanian Basin

Regarding the Upper Jurassic sediments from the Abadia Group onwards, an intensive shallowing and rapid increase of clastic influence towards west and north becomes evident. Thus, the main part of the Abadia Group is intensively shallowing in these directions, with the marly Abadia beds (here Arruda Formation) being substituted by the deltaic Alcobaça Formation (including the Consolação Member) which grades into terrestrial deposits further north.

The Amaral Formation, however, shows different behaviour. After its outthinning north of Alenquer (cf. to chap. 6.5.2), the calcareous Amaral Formation is again intensively developed further north, though mainly around and east of the Vimeiro – Caldas da Rainha diapir (see also R. WILSON 1979, WERNER 1986), substituting major parts of the Alcobaça Formation. It still remains unclear whether the Amaral Formation forms a continuous, though possibly diachronous calcareous platform, or whether it is composed of isolated lentils, possibly in slightly different stratigraphic levels.

Northward shallowing again becomes evident by the rapid outwedging of the »Pteroceriano« Formation, whereas the vestiges of the responsible transgression remain distinct by the correlatable sandy Santa Cruz Member.

6. BASIN INTERPRETATION

6.1 Facies Models – Theoretical Approach and Methods

Facies interpretation generally leads to the establishment of facies models, in a way that horizontally and vertically co-existing postulated depositional environments are arranged in the most logical fit. From these models paleogeographic patterns are concluded, either with or without additional stratigraphic and structural data.

Facies models are always based on the assumption of actualism, both in respect of sediment-creating mechanisms and general depositional settings. While the first assumption is beyond doubt, the second is only applicable with large restrictions: On one hand, Recent polar ice caps prohibit development of major shelf areas, on the other, the post-Pleistocene sea level rise still causes world-wide unequilibria in depositional conditions, such as the sudden stop of reef growth or the Recent predominance of high energy coasts.

Therefore, comparisons with modern case studies are not always fully satisfactory, particularly if paleogeographic conclusions should be drawn. Moreover, many facies models and concluded paleogeographic constellations are based on only one or few lithological sections, leading to a rigid steady-state model regardless its stratigraphic position and the lateral arrangement of facies types.

For the carbonaceous realm and also deduced from modern examples, J.L. WILSON (1975) established 24 »Standard Microfacies Types« which are furthermore arranged and associated in nine standardized »Facies Belts«. Additionally he gave examples for fossil analogues, demonstrating that his zonation also gives good environmental interpretation for former wide epicontinental seas, such as, say, the early Tethys during Triassic times. However, for small-scaled environmental patterns and for mixed clastic-carbonate sequences which is both the case in the Upper Jurassic of the Lusitanian Basin, his method is not applicable.

The most modern approach for environmental and paleogeographic interpretation, a more flexible way of combining modern case studies and postulating distribution patterns for nowadays not realized depositional conditions, is termed by BRENNER (1980) »Process-Response Modelling«. Although the notion is rather new, the method is at least partially used since a longer time, particularly when interpreting Ancient biofacies patterns, a field where direct modern analogues are not existing.

To yield satisfying paleogeographic results, all the below mentioned steps should be carried out (table 3):

6.2 The Development of the Sobral Formation

Distribution:

Whilst only forming a thin stripe along the Corálico/Oórito outcrops (Amaral formation) south of Arruda dos Vinhos, the Sobral formation covers most of the study area west and northwest of Sobral de Monte Agraço. Unfortunately, the only moderately undulating morphology prohibits extensive sections. In this area, complete sections extending from the Corálico up to the onset of calcareous »Pteroceriano« facies only could be reached around Sobral (sections SO, AQ), Olhalvo (sections OE, Q), Runa (section ZB) and west of Torres Vedras (section EN) (see fig. 9, location of sections see fig. 1, chap. 1.1).

The best exposed section is close to Mata (proposed holostratotypus), along the road from Arruda dos Vinhos to Bucelas (section MA). Further south, the Sobral formation is rapidly outwedging (sections CH and AD

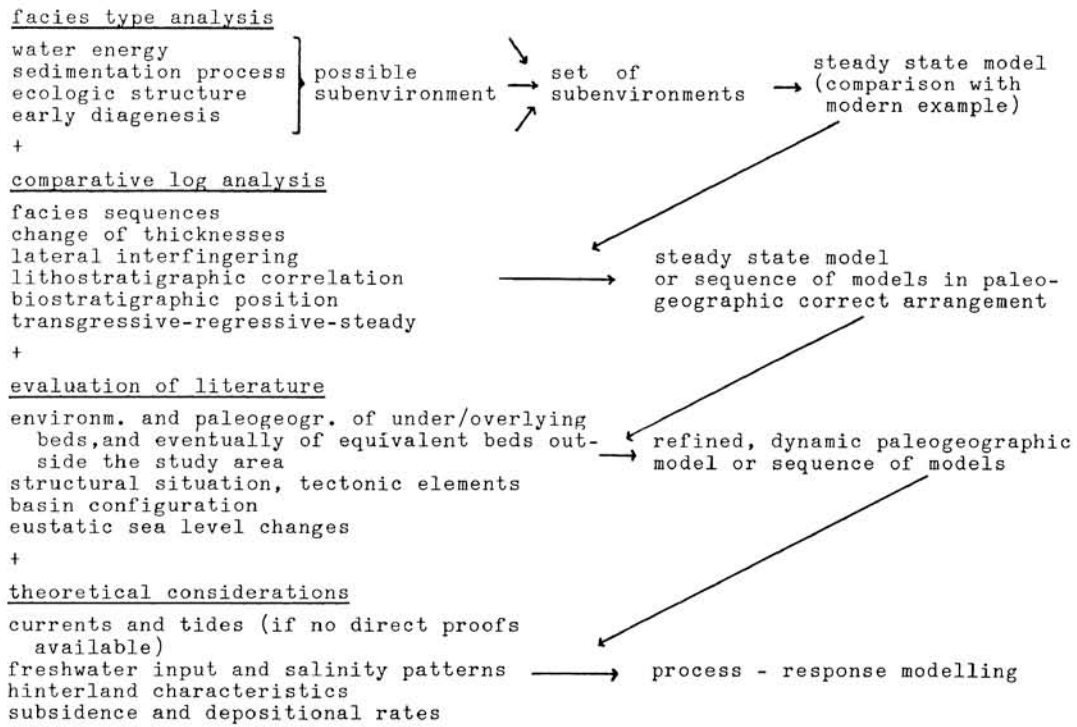


Table 3: Development of environmental models from steady—state models to process—response modelling in order to yield paleogeographic informations.

around Calhandriz), in part by intensive interfingering with the »Pteroceriano« formation (section GT, south-west of Sapataria).

Maximum thickness occurs between Arruda dos Vinhos and Sobral de Monte Agraço (ca. 65 m), rapidly thinning towards south and particularly southeast, where already five kilometers SE of section Mata the Sobral formation disappears completely.

In the north, thickness is also slightly lowered (ca.50–60 m), diminishing to 40 meters on both sides of the Matacões diapir.

Development :

In fig. 9, 10 simplified sections are shown in their spatial correct arrangement. (Description of sections see chap. 8.) Environmental interpretation is both concluded from facies analysis (cf. to chap. 3.1) and from sequence interpretation. Since no biostratigraphic or lithostratigraphic marker beds are occurring within the So-

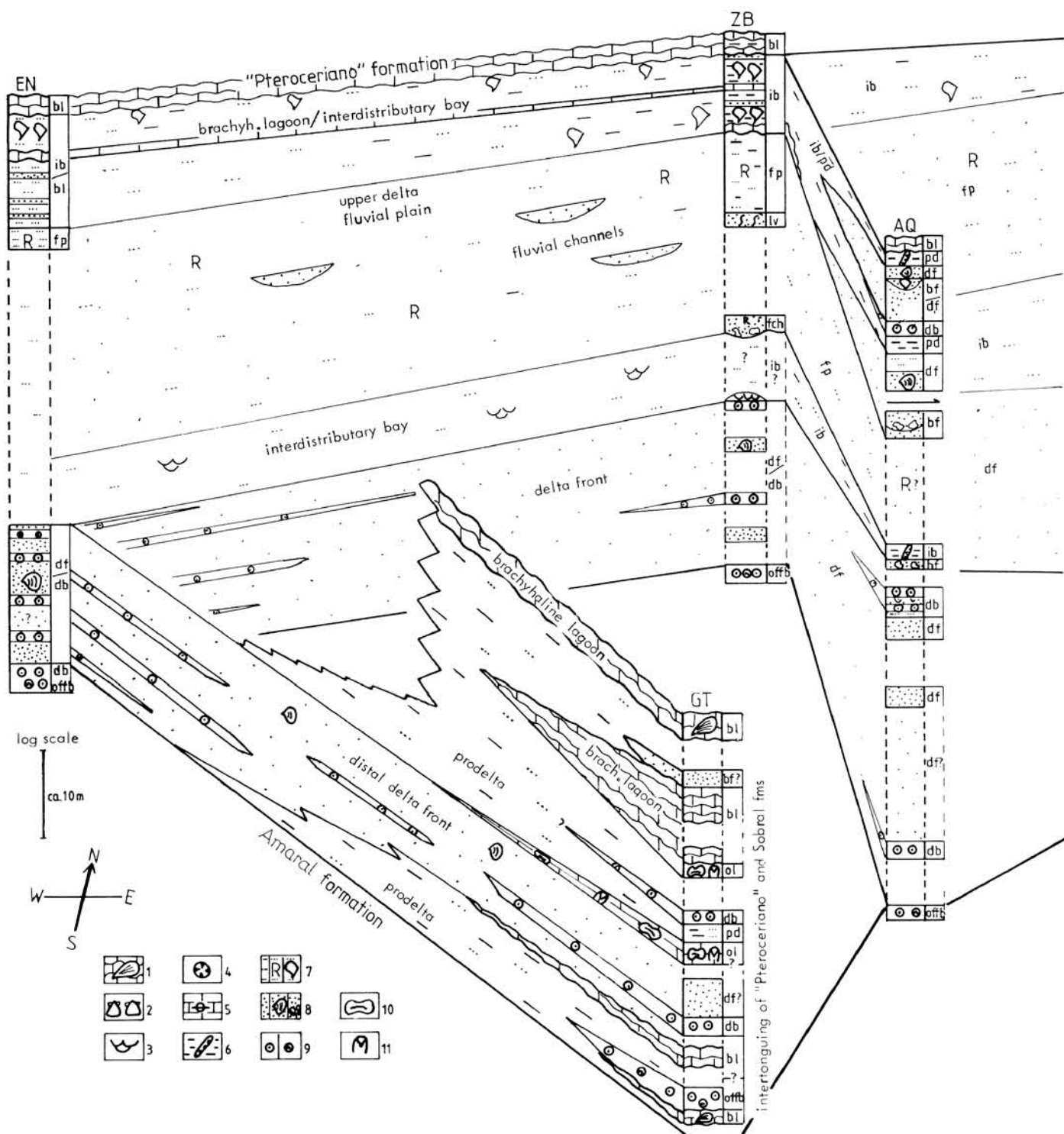
Fig.9 (next page): The Sobral Delta Complex

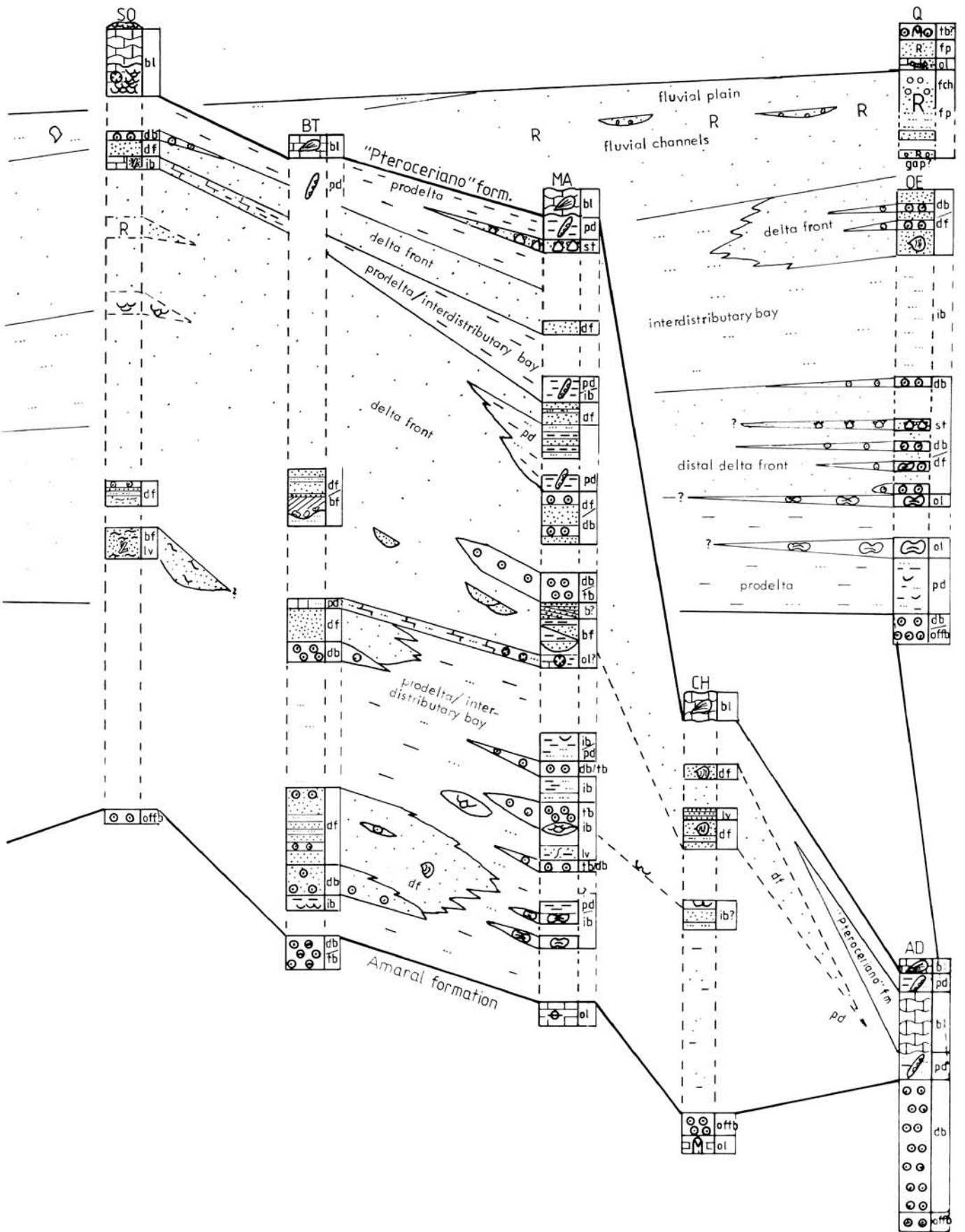
Simplified lithological sections and their environmental interpretations. Correlation between individual columns is somewhat interpretative. Spatial arrangement of logs is equidistant to actual positions (location see fig. 1, chap. 1.1).

Legend: 1 nodular limestones, e.g., with *Arcomytilus*; 2 shell coquinas; 3 oyster patch reefs; 4 coral facies; 5 lagoonal cortoid limestones; 6 marls, e.g., with *Gervillia sobralensis*; 7 silts/red silts/silts with *Isognomon lusitanicum*; 8 sandstones/sandstones with *Eomiodon securiformis*/sandstones with downcutting surface and channel lag of lime clasts; 9 oolites with quartz—cored ooids/oolites with bioclast—cored ooids; 10 oncolitic facies; 11 rhodolith facies.

Abbrev.: ol open lagoon; ib interdistributary bay; bl brackish lagoon/bay; df delta front; db distal bar; tb tidal bar; off b offshore bar; bf bar finger; pd prodelta; b beach; fch fluvial channel; fp flood plain; lv levee; st storm deposit.

Sections: EN Engenheiro; GT Gotleis; ZB Zibreira; AQ Alqueidão; SO Sobral; BT Batalha; MA Mata; CH Chão da Vinha; Q Sta. Quitéria; OE Oerca; AD Adanaia.





bral formation, individual sections are to be linked by environment correlation. Although this attempt is to some degree speculative, a clear picture is pointed out:

In the north, the Corálico/Oólito units are superimposed by a 15 to 20 meter thick distal delta front sand complex with *Eomiodon* sandstones dominating and common intercalated strings of dirty oolite. At its base, a marly—silty prodelta sequence with intercalations of oncolites appears in the northeast.

The delta front sands are apparently overlain by a several meter thick layer of marly—silty interdistributary bay deposits with common small oyster patch reefs. This layer is thickening towards east. There delta front sands are intercalated on its top, what can also be expected throughout the entire layer.

Following is an up to 20 meter thick terrestrial, fine—grained series representing floodplains with common intercalations of coarser, often conglomeratic fluvial channels. This series can be well traced by its red colouring.

Superimposed are brown, fine—grained interdistributary bay deposits with very widespread banks of *Isognomon lusitanicum* and thin horizons of marly nodular *Arcomytilus* limestones, grading into the few meters or decimeters of »Pteroceriano« formation existing in this area (see following chapter).

The basal delta front sand complex is reaching south until Sobral de Monte Agraço where on its top thick bar-finger sands with downcutting surfaces, lime clast channel lags and associated submarine levees grading into beach sands are developed. Good outcrops of this level are north of Sobral de Monte Agraço (e.g., church of Via Galega, hill north of Freiria).

Further south, the front sands are extensively interfingering with prodelta, interdistributary bay and even calcareous lagoonal oncolites, nodular mudstones and coral facies (section GT).

The red terrestrial level of the northern part is also rapidly outwedging towards south, not reaching further than to the surroundings of Sobral de Monte Agraço. Instead, delta front sands with oolite strings and common intercalations of interdistributary bay and gradational prodelta marls and silts are occurring. The transition to the superimposed »Pteroceriano« formation is always formed by few meters of prodelta marls with *Gervillia sobralensis*.

M o d e l (fig. 10):

When considering the variety of existing facies types and, above all, their kind of interbedding, the question regarding the type of the Sobral delta arises.

Particularly of interest are the thin intercalations of sandy—marly oolites with quartz—cored ooids within delta front, prodelta and interdistributary bay deposits, indicating widespread very shallow highs with bidirectional currents suitable for oolite formation within deeper environments.

As well puzzling is the common transition from interdistributary bay to prodelta environments. Moreover, prodelta environments also display clear signs of shallow water as already outlined in chap. 3.1.3. Additionally, both clastic and brackish influence fade away over a very short distance.

This all implies a type of delta characterized by a very flat offshore slope and common lower shoreface or offshore bar which shelter a set of semi—enclosed lagoons. The best explanation for all facts is given by a delta model transitional between the types III and IV of WRIGHT (1978). For the formation of this kind of deltas, intermediate wave energy and moderate tidal influence are required besides very gentle offshore slopes. Flat slopes, landward wave action and tides may easily lead to oolite formation. Additionally, oolite development is also dependent from homopycnal outflow conditions of the river water. This means that the lighter issuing freshwater gets rapidly mixed up with the denser marine water in a fairly turbulent zone, a process which is favoured by flat delta slopes, tidal influence and original high density of the river water due to high sediment charge. Ooids could form in the zone where outflow jet and landward waves were meeting. According to REIJERS & ten HAVE (1983), radial ooids often form in slightly deeper settings than tangential ooids, where a constant moderate turbulency keeps the ooids in suspension and thus permits radial crystal growth. The common radial ooids in the Sobral formation may strengthen this explanation (cf. to chap. 3.1.1).

Homopycnal outflow also explains well the rapid transition to almost normal marine salinity conditions and the restricted extent of clastic influence. Yet, seasonal heavy rainfalls may have changed outflow to hypopycnal conditions, with a thin sheet of issuing buoyant freshwater affecting vast parts of the depositional area for a

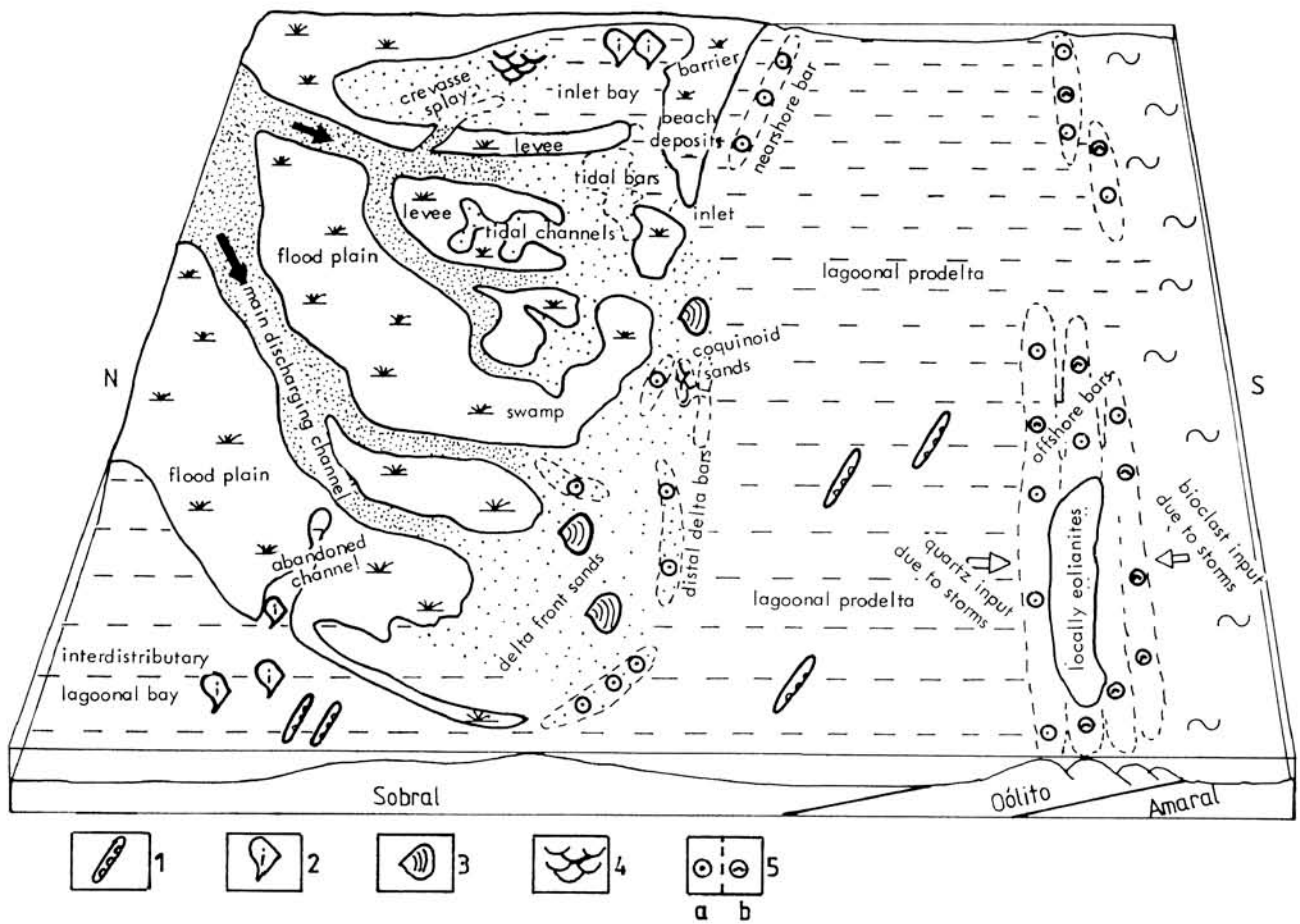


Fig. 10: Theoretic depositional model for the Sobral formation:

Association of facies types evokes a bar—sheltered estuarine delta model transitional between type III and IV of WRIGHT (1978). Characteristic are moderate tidal and wave influence, flat offshore slopes and dominating homopycnal outflow conditions (see text).

1 *Gervillia* marls; 2 *Isognomon* facies; 3 *Eomiodon* facies; 4 oyster patch reefs; 5 oolite facies, a) with quartz—cored ooids, b) with bioclast—cored ooids.

short time. This also caused interruption of ooid formation and possibly landward ooid transport by now dominating wave action.

Flat offshore slopes and tidal action are also responsible for the common connection of prodelta areas with interdistributary bays and estuarine enclosed lagoons. Bidirectional tidal currents also may have turned offshore and shoreface bars into tidal oolite bars, explaining the common oolite strings even in estuarine bay deposits.

No direct signs of the postulated tidal influence exist in the region under study, since the tidal zone is most probably completely represented by clastics which lack diagnostic tidal features. However, in the Upper Oxfordian of Cabo Mondego (R. WILSON 1975a), the Upper Oxfordian to Kimmeridgian of the eastern Serra da Arrábida (FELBER et al. 1982, LEINFELDER 1983), as well as in the Upper Portlandian of Cabo Espichel (FÜRSICH & SCHMIDT—KITTLER 1980), extensive intertidal calcareous algal laminites and loferites are developed, so that already R. WILSON (1975a) postulated a mesotidal regime (i.e., 2 – 4 m tidal range) for the Upper Jurassic Protoatlantic and its connected Lusitanian Basin.

Sediment input in distal delta areas must have been fairly low at times to allow coral growth, oncolite formation and even development of lime mud.

Finally, it has to be kept in mind that the base of the Sobral formation is considerably diachronous (cf. to chap. 5.1.1), so that the lower distal bar/tidal ridge development in the north is contemporaneous with the Corálico coral bank and Oórito beach/barrier ridge accretion zone further south (cf. also to chap. 6.5.2).

These above mentioned characteristics of the Sobral formation are compiled in a depositional model in fig. 10.

6.3 The Development of the »Pteroceriano« Formation

The »Pteroceriano« formation, biostratigraphically situated within the *Virguliana* biozone, is subdivided here into a lower part without *Permocalculus* n.sp. and an upper part containing this alga (cf. to chap. 5.1.2).

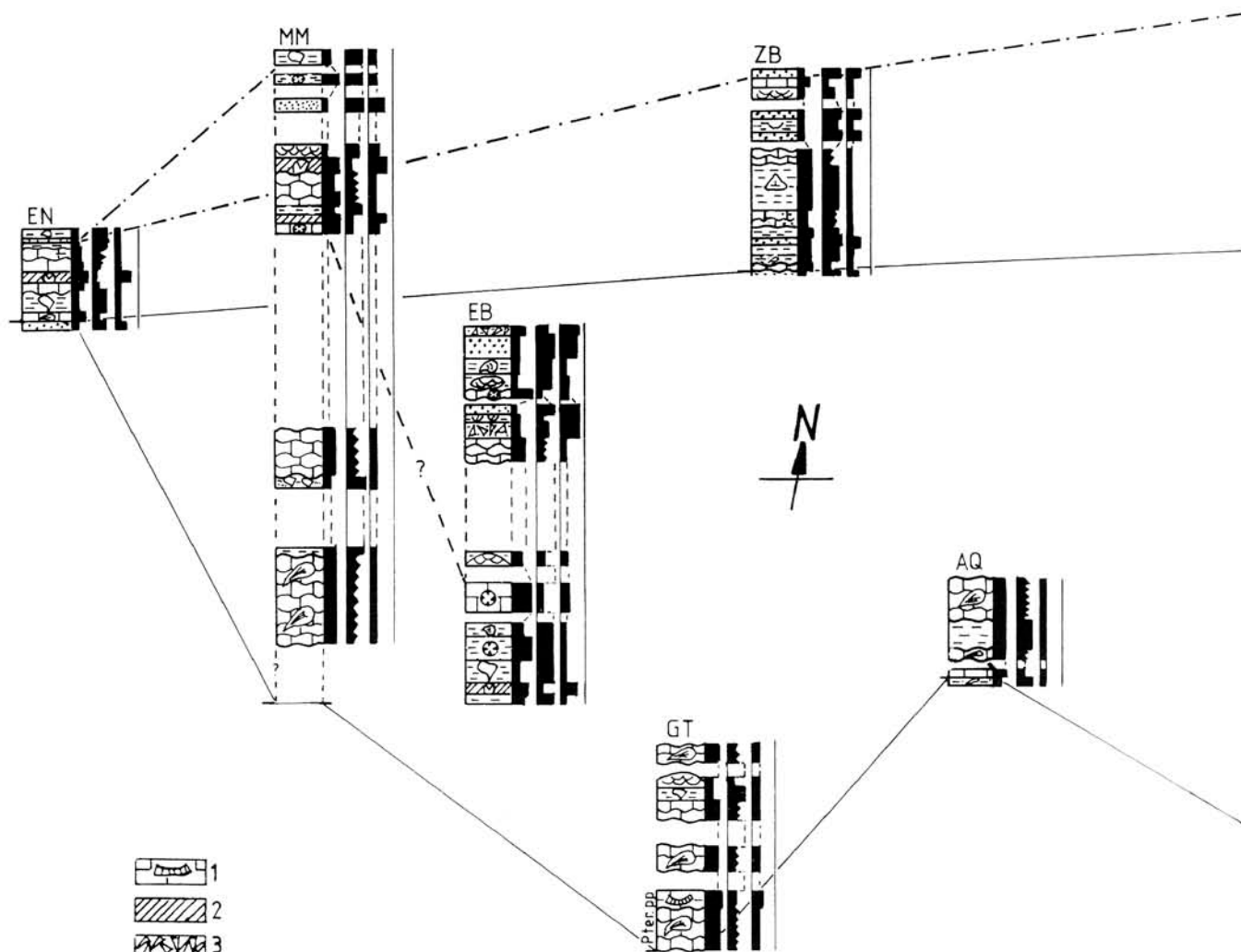


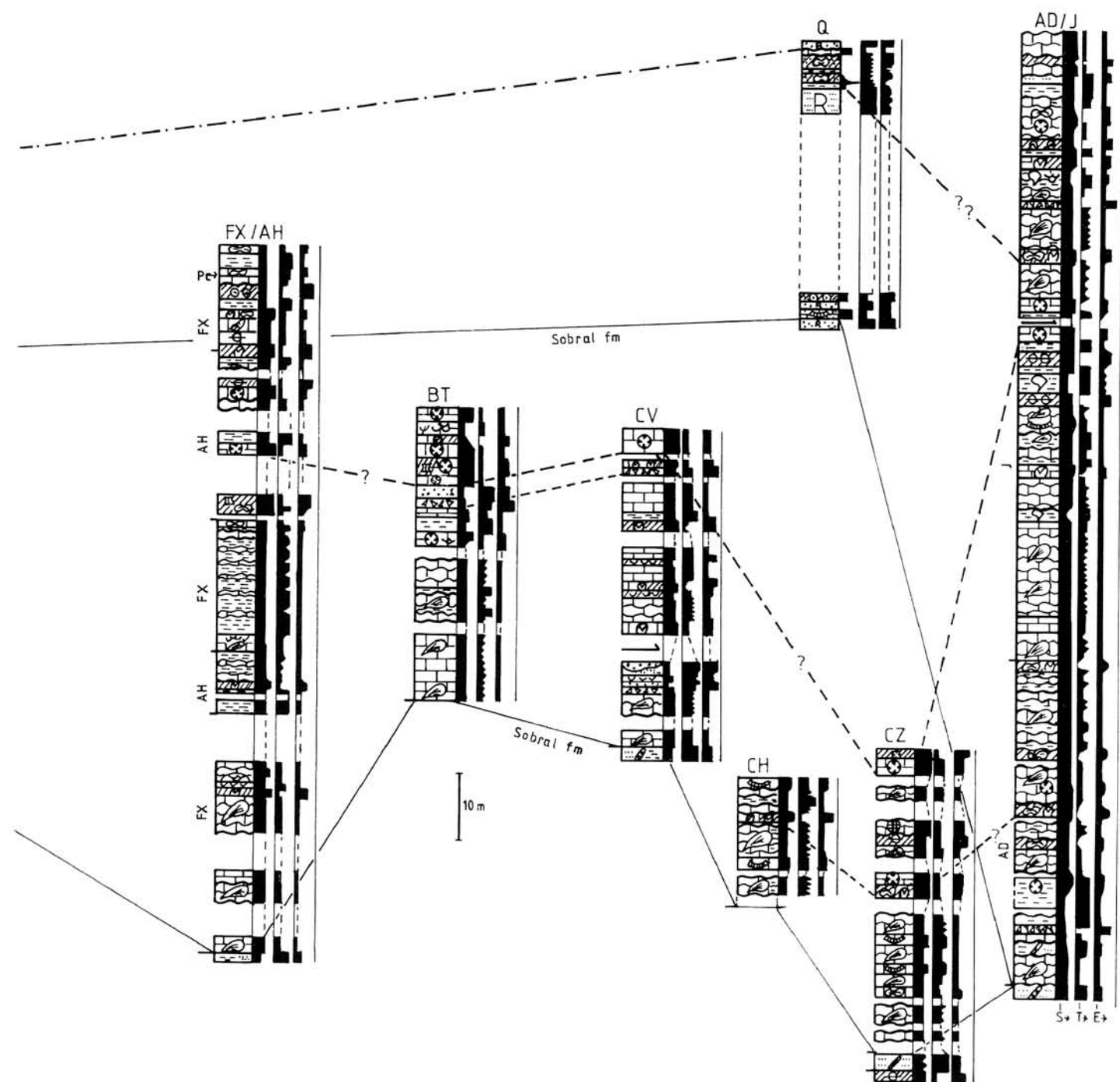
Fig. 11: Simplified lithological sections of the »Pteroceriano« formation, lower part.

Spatial arrangement is roughly equidistant.

Legend: 1 limestones, open fabric, e.g., with *Trichites*; 2 limestones with closed fabric; 3 storm coquinas; Pc appearance of *Permocalculus*;

Black logs: S salinity (freshwater to upper euhaline), T terrigenous input, E energy level, all three increasing from left to right.

Further symbols as in fig. 9.



Sections from left to right:

EN Engenheiro; MM Moinho do S. Miguel; EB Enxara do Bispo; GT Gotleis; ZB Zibreira; AQ Alqueidão; FX/AH Alcubela–Freixial/Arranhó–Bemposta composite section, lower part; BT Batalha, upper part; CV Carvalha; CH Chão da Vinha, upper part; Q Sta. Quitéria, upper part; CZ Calhandriz; AD/J Adanaia/Bom Jesus composite section.

Location of sections see fig. 1, chap. 1.1.

6.3.1 The Lower Part of the »Pteroceriano« Formation

Distribution:

Most of the »Pteroceriano« outcrops belong to the lower part of the formation. Being extensively developed and covering large areas south of Arruda dos Vinhos (e.g., sections FX pp, typus section, AH pp, BT, CV, CH, TS, location see fig. 1. chap. 1.1) with a thickness of 90 meters, it outthins rapidly towards the west and north (fig. 11): Around Enxara do Bispo, in the southwest, the unit is still well developed though more and more marine sandstones become intercalated, representing vestiges of the Santa Cruz member (Bombarral formation) (sections EN, MM). This sequence is thicker than 70 meters.

Several hilltops north of Sobral de Monte Agraço (e.g., Moinho do Sobral, Via Galega—Maceira, Carmões, Cabeço do Rei, Corujeira, Força 2^a, location see ZBYSZEWSKI & TORRE DE ASSUNÇÃO 1965) have caps of nodular *Arcomylus* and *Trichites* limestones representing the base of the »Pteroceriano« formation and peeping out from a clastic plain which is constituted of the Sobral formation. Towards north, the unit wedges out rapidly: Few meters of »Pteroceriano« limestones with *Trichites* at Cadafais hilltop (800 m north of Cadafais village) diminish to a few beds around Cabreira hilltop (2.5 km southwest of Alenquer), still being traceable until Meca, where they disappear completely.

To the northwest, the »Pteroceriano« formation also diminishes heavily in thickness, but apparently holds on until the coast at Sta. Cruz. Lack of *Permocalculus* n.sp. and occasional occurrences of giant *Protocardia* sp. A also attribute the beds to the formation's lower levels: In section ZB, 2 km northeast of Runa, only a few, decimeter-thick »Pteroceriano« beds are occurring, as is the case at Cucos, 2 km west of Matacães. Further off from the Matacães diapiric structure, thickness is again slightly increasing (section EN, 8 m, with sandstone intercalations, 4 km SSW Torres Vedras; Charnais hilltop, further west). Tracing further west is not possible, mostly because the corresponding beds are either eroded or paleo-eroded by the overlying clastics, or simply not outcropping. However, the nodular limestones at the coast of Sta. Cruz belong most likely to the same level (cf. to chap. 5.1.3).

In the southeast, towards Alverca, the lower part of the »Pteroceriano« formation has its maximum development (sections CZ, AD, J). Between Adanaia and Alhandra (2 km north of Alverca) the thickness of the lower part is apparently more than 130 meters.

Development:

In fig. 11, 13 lithological sections (derived from 15 main sections; complete description see chap. 8) of the lower part of the »Pteroceriano« formation are presented in equidistant arrangement.

Main reference level for correlation is the top of the Sobral formation, i.e., the onset of continuous calcareous-marly »Pteroceriano« facies. Except for the extreme south (section GT, see also foregoing chapter), this boundary is well developed. In the southeast, several strings of Sobral sandstones and silts are still occurring in the lowermost part of the »Pteroceriano« formation, documenting the somewhat intertonguing boundary between both formations.

Further correlations are difficult to achieve: Most sections do not extend up to the onset of *Permocalculus* n.sp.. Subdivision of the holo- and hypostratotypus into lower »Pteroceriano« limestones, lower »Pteroceriano« marl with limestone intercalations and Alrota limestones (extending into the upper part of the »Pteroceriano« formation) is not transferable to other sections. The start of intensive coral limestone development (Alrota limestones) is tentatively used for correlation towards east. This points out an enormous reduction in thickness of the underlying beds between Arranhó and Calhandriz, with the complete disappearance of the lower »Pteroceriano« marl with limestone intercalations. On the other hand, the start of coral bank formation is certainly slightly diachronous, starting earlier in the east with its apparent generally better environmental conditions (see below) and thus developing on costs of the underlying beds.

Further tools for correlating neighboured sections are also storm coquinas and oncoid beds (cf. to chap. 5.2.1).

The following picture of stratigraphic development can thus be outlined:

»Pteroceriano« facies reached its maximum lateral extension (as given above) already at the formation's base with uniform, slightly marly, partly nodular *Arcomylus* and *Trichites* limestones (see also chap. 6.5.2). Only in

the extreme east, »Pteroceriano« facies apparently established already earlier, since this area was hardly affected by the Sobral delta complex. Findings of giant *Protocardia* sp. A fairly high above the »Pteroceriano« base (cf. to section Bom Jesus, chap. 8) may support this conception (see chap. 5.1.3). This would also partly explain the high thickness in this region. Even further north, along a structural subsidence zone, »Pteroceriano« facies established eventually earlier (see chap. 5.2.2.3). In the south, »Pteroceriano« facies interfingering with the Sobral formation also occurred earlier.

Environmental conditions improved towards east, so that locally isolated coral growth could take place. A general facies uniformity is, however, remarkable. Yet, contemporaneous sedimentation of clastics in farther surroundings is evidenced by admixture of siliciclastics in storm coquinas, by rare intercalations of clastic horizons and by the complete return to clastic sedimentation after the initial »Pteroceriano« beds in the north and north-west (Santa Cruz member). These clastics also commonly reworked the underlying »Pteroceriano« level completely. Terrigenous influence then increased again over the entire region so that in the »Pteroceriano« type area the sequences become highly marly. Contamination was again minor in the Tejo region where facies did not change considerably. Common oncolite and rhodolith beds in this interval may indicate longer stillstands of deposition.

The region between the two depo-centers (sections FX/AH, J/AD, see chap. 8) is characterized by heavily lowered sediment thicknesses and almost complete lack of marl horizons (sections BT, CV, CH, CZ).

Simultaneously with the renewed decrease of terrigenous clay input, coral limestone banks suddenly started to develop in the type area (Alrota limestones) (cf. to chap. 6.5.2) Coral banks are of minor extent, turning after few meters into still dominating nodular limestone facies (fig. 12).

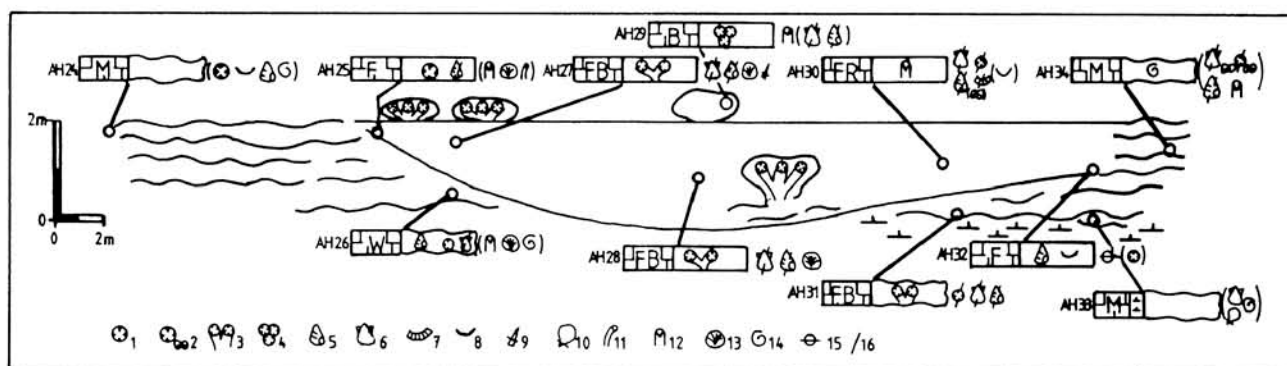


Fig. 12: Facies of coral bank in the »Pteroceriano« formation, lower part along road from Sobral de M. Agraço to Bucelas, northern boundary of Arranhó village.

Legend: M Mudstone, W Wackestone, F Floatstone, R Rudstone, B Boundstone.

Facies—dominating components in rectangular frame (frame with wavy lines = nodular fabric), further components right of frame (in brackets if rare).

Components: 1 corals, indiff.; 2 corals, superficially encrusted by cyanophytes (analogously for other symbols); 3 branching corals; 4 massive corals; 5 gastropods; 6 bivalves, indiff.; 7 *Trichites*; 8 oysters; 9 echinid spines; 10 *Pseudocidaris* spines; 11 serpulids; 12 *Marinella lugeoni*; 13 »cayeuxiid« algae, mostly *Solenopora cayeuxiformis* n.sp.; 14 lituolids; 15 cortoids; 16 fragmented components (in connection with other symbols).

In the generally better conditioned east, coral growth started more gradually, so that coral clusters already occurred in lower horizons. The upper levels of »Pteroceriano« beds in the west should also correspond to these improved conditions. Coral development took place as well in the southwest (Enxara do Bispo), although a rather high background sedimentation of terrigenous clastics favoured coral marl rather than limestone development.

Model (fig. 13):

The assemblage of facies types clearly points out a general quiet water lagoonal environment for the development of the lower »Pteroceriano« formation. True euhaline stable conditions were apparently rarely achieved, as the highly tolerant fauna reveals. Most constant and normal salinity values are represented by limestones and marls with *Trichites* and corals. *Arcomytilus* limestones and marls with bivalve-like fossils, *Isognomon lusitanicum* and oysters could then be simply arranged along a declining salinity gradient, so that easily a stripe pattern could be modelled with the determining parameters being decreasing salinity versus increasing terrestrial influence, also expressed by the increase of clay input.

The occurrence of storm coquinas would not be contradictory to such a model. Very difficult, however, is in which position to place the common formation of oncoids and rhodoliths in such a bi-parameter model. Frequent marl intercalations, particularly with upward transitions to calcareous facies, would also not fit in the picture.

Hence, further parameters for modelling have to be taken into account: Heavily varying sediment thicknesses point to a differentiated subsidence pattern and thus to structural elements active at the time of deposition of the lower »Pteroceriano« formation.

The central area clearly shows two intensively subsiding depo-centers, one along the Tejo valley (Alverca), the other, broader one, around Arranhó–Tessoureira, southwest of Arruda dos Vinhos. In between was a structurally higher block, prohibiting the development of a thick sedimentary sequence. Sediment thicknesses also decrease considerably towards the Enxara do Bispo – Matacães region further west, due to active diapirism (see chap. 6.5.1).

In the rapidly subsiding areas, particularly in the western one, sedimentation could not keep pace completely, so that paleomorphology, though less pronounced, apparently coincided with the differentiation in subsidence: Oncoids and rhodoliths, both often occurring in hostrocks of very shallow, mostly high energetic origin, developed preferably on the uplifted block and are related to lacking or very minor background deposition. Stop of

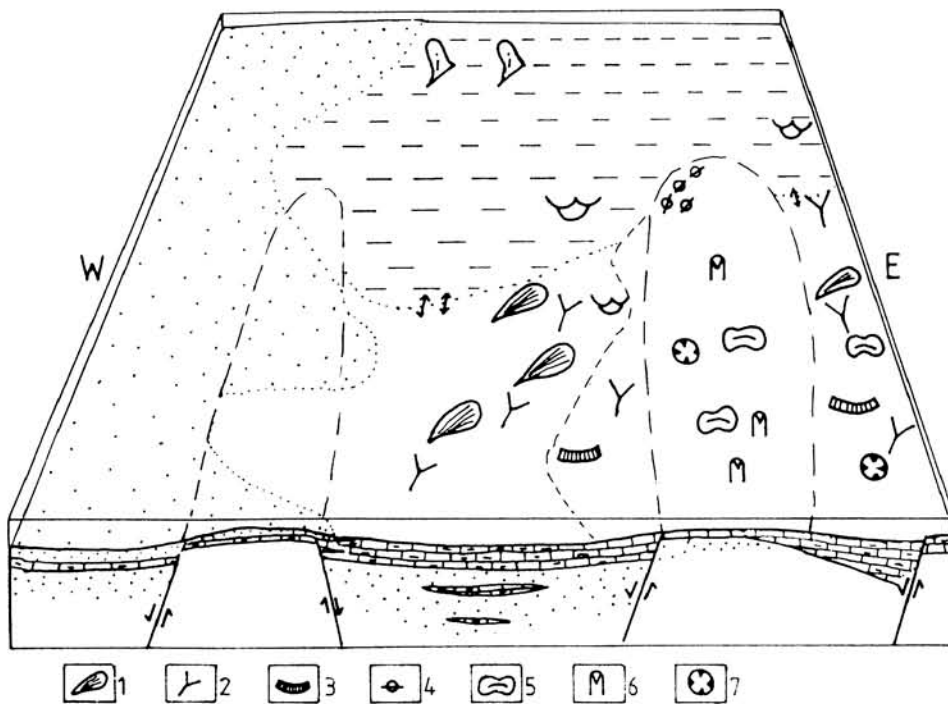


Fig. 13: Depositional model of the »Pteroceriano« formation, lower part.

1 *Arcomytilus* limestones; 2 nodular limestones; 3 *Trichites* limestones; 4 cortoid pack/grainstones; 5 oncolite facies; 6 rhodolith facies; 7 coral limestones. Further symbols as in fig. 10.

background sedimentation, however, also happened in the subsiding areas, particularly in the eastern one, eventually indicating a differentiated subsidence pattern there.

Yet, occurrence of some oncolites and rhodoliths in the subsiding settings may also be related to more general stillstands of background deposition (see chap. 6.5.1) or even be due to roll-down of algal nodules from the gentle slopes of the adjacent elevated block, a not uncommon event in oncolite formation (HOTTINGER 1983).

Terrigenous fine-grained input settled down mainly in the quiet water environments in the structurally lower part to form extensive marl sequences which are lacking on the uplifted block. Apparently, input of clay from the north was somewhat channelled between the uplifted block in the east and the diapiric swell further west. Astonishingly, no input of sand-sized siliciclastics took place from the east. Sand input from the north was intensive (Santa Cruz member), representing the temporal continuation of the Sobral delta complex. Possibly, a clastic trap prohibited continuous sand input from the north (cf. to chap. 6.5.2).

Despite their massive development west of the Enxara do Bispo – Matacães diapir, siliciclastics derived from the west do rarely disturb the »Pteroceriano« development in the south. Only in section Enxara do Bispo itself, still situated east of the diapiric apex, siliciclastic input is more pronounced, though also restricted to some horizons. Obviously, the diapir acted as a morphologic fence, allowing sand sheets to pass only occasionally, possibly during storms.

Salinity was certainly not constant, in a way to simply impoverish towards north and west, but rather underwent frequent undulations. This is not only indicated by sequences of facies types from different salinity regimes, but eventually also by the spreading and withdrawing of marls, possibly related to phases of respectively higher and lower riverine clay and thus freshwater input (cf. also to chap. 6.5.1). The common algal nodule facies from coralline algae to cyanophyte overgrowths also points out variable salinities (cf. to chap. 3.2.9). However, as already outlined, salinity is not the dominant factor for determining facies distribution.

6.3.2 The Upper Part of the »Pteroceriano« Formation

Distribution:

The distribution of sediments attributable to the upper part of the »Pteroceriano« formation is much less expanded than that of the formation's lower part.

Deposits are restricted to the southernmost part of the study area, extending from S'Tiago dos Velhos (section SV) about seven kilometers to the west and being best developed around Alrota and Tesoureira (sections ALR, AH pp, TS). The non-occurrence of the formation's upper part in the west and north is not due to Quaternary erosion of the corresponding beds but rather to primary lack of deposition or paleo-eroding (see below).

Development:

In fig. 14, three lithological sections of the upper level of the »Pteroceriano« formation are given.

A change in the sedimentary pattern was already obvious in the uppermost part of the lower »Pteroceriano« formation with the beginning of coral bank sedimentation. This development becomes more pronounced now in the central type area, resulting in intensive calcareous coral patch reef and coral bank formation.

Often they are additionally associated with high energy sediments such as oolites, rhodolitic–oncolitic rudstones, cortoid grain/packstones and circumreefal skeletal pack/rudstones as well as with low energy nodular limestones (fig. 15). Marls are still well developed, forming thick layers between the individual limestone lentils and commonly bearing huge quantities of corals and bivalves (cf. to chaps. 3.2.3 and 3.2.5). Individual lentils and banks are of restricted lateral extension, not surpassing several hundreds of meters or few kilometers.

Thickness of the coral patch reef complex around Alrota is 40 meters, decreasing towards east and west, where only isolated beds of coral floatstones or boundstones are rarely occurring.

These Alrota limestones are overlain by the poorly outcropping upper »Pteroceriano« limestones with marl intercalations, measuring about 40 meters in thickness.

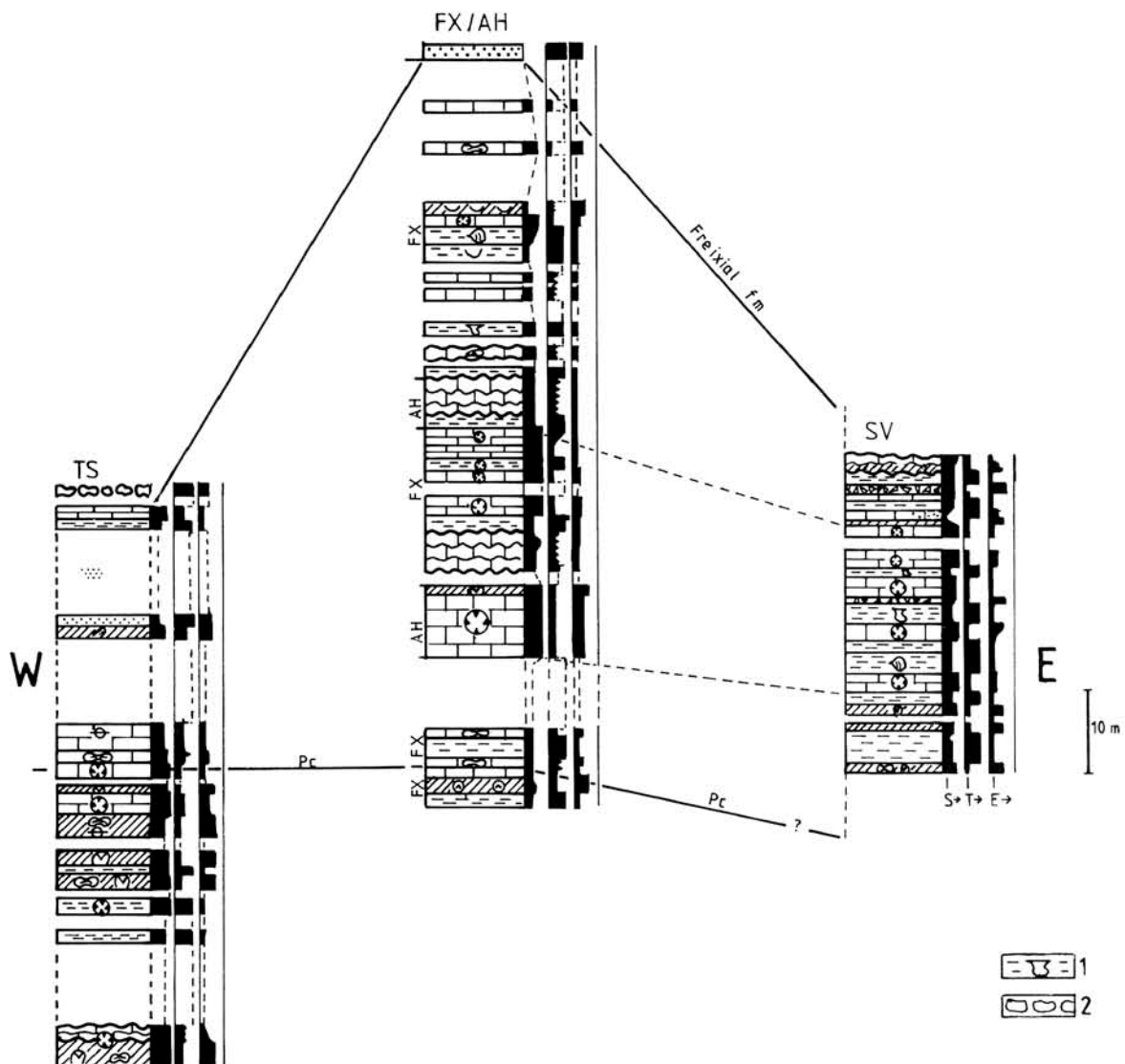


Fig. 14: Simplified lithological sections of the »Pteroceriano« formation, upper part.

1 marls with bivalve fossils and *Pteroperna*; 2 caliche. Further symbols as in figs. 9, 11.

Sections: Ts Tesoureira – Casais da Serra, lower and middle part; FX/AH Alcubela–Freixial/Arranhó–Bemposta composite section, middle part; SV S' Tiago dos Velhos.

Location of sections see fig. 1, chap. 1.1.

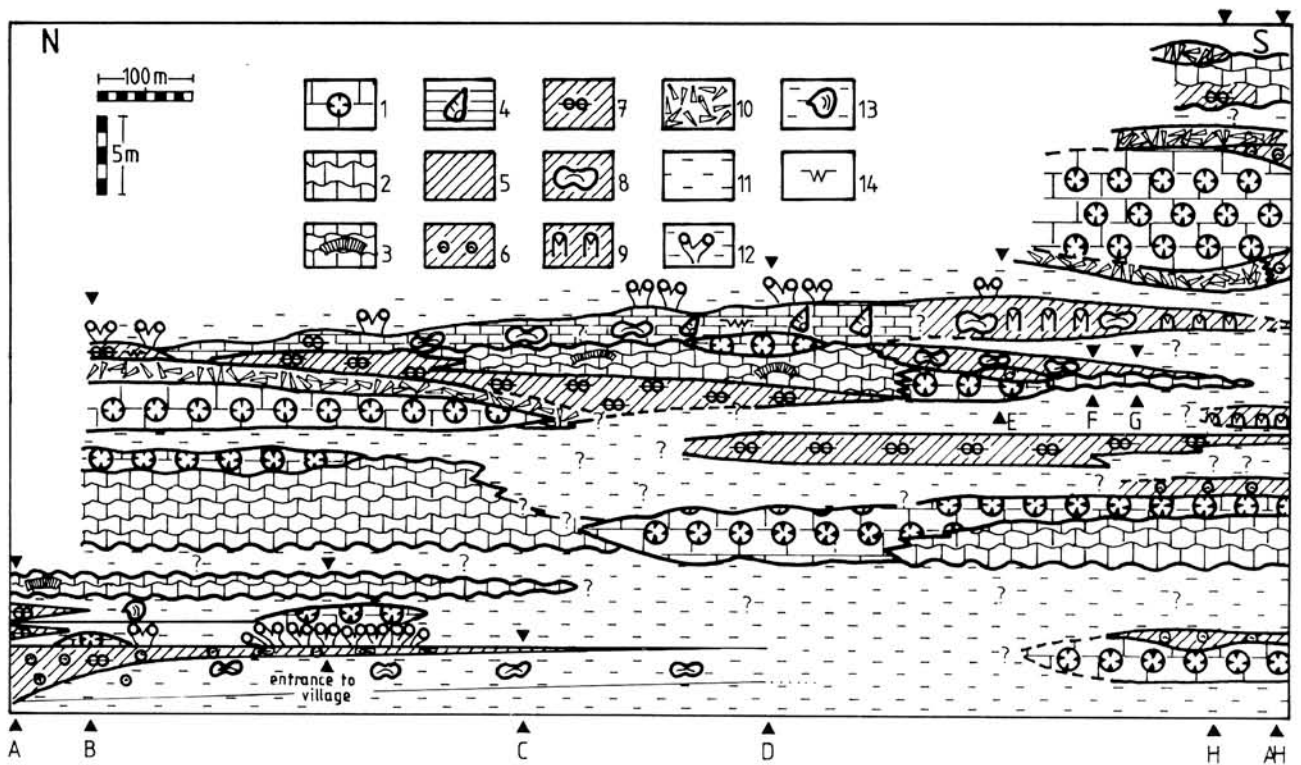


Fig. 15: Intertonguing of coral patch reefs and associated sediments around Alrota (mainly based on Alrota sections A–H and Arranhó–Bemposta section AH, see chap. 8).

1 coral boundstones; 2 nodular limestones with open fabric; 3 *Trichites* limestones; 4 nerineid floatstones; 5 limestones with closed fabric; 6 oolitic grainstones; 7 cortoid pack/grainstones; 8 oncolitic rudstones; 9 rhodolith rudstones; 10 reefoid debris facies; 11 marls; 12 coral marls; 13 marls with bivalves; 14 early vadose cracks.

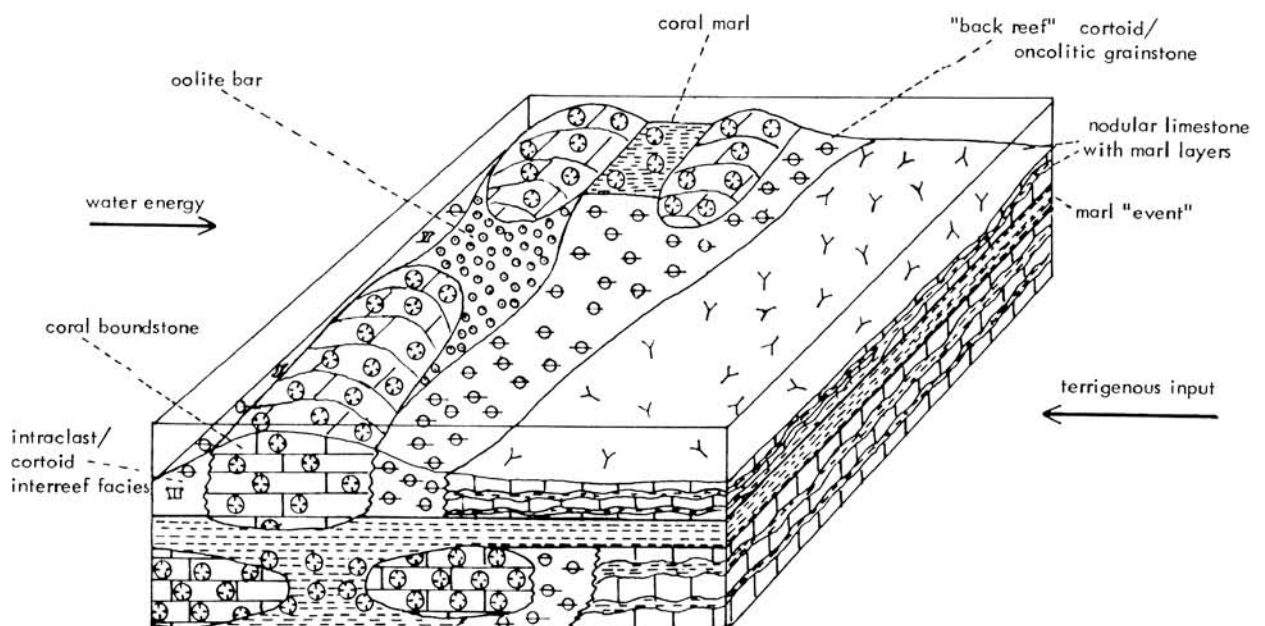


Fig. 16: Facies model of the coral limestones around Alrota.

Model (figs. 16, 17):

The Alrota limestones are principally composed of facies types attributable to reefal environments.

Coral boundstones of a »reef core« would be embedded in and surrounded by »central to fore reef« rhodolith facies, »circumreefal« talus facies, »interreefal« oolites, »back reef« corallgal/skeletal cortoid grainstones and lagoonal nodular limestones, if stereotypically arranging them to facies belts, e.g., using the J. WILSON (1975) model.

However, the frequent occurrence of marls and, above all, the geometry of facies type arrangement to a small-scale intertonguing complex evoke a completely different model, thus being a good example against steady-state models based exclusively on facies type variety.

Although there commonly occur high energy sediments such as grain/packstones and rudstones, coral boundstones are dominated by micritic types, pointing out the prevalence of fairly tranquil environments for coral growth. Marly coral patch reefs, commonly preserved in-situ, strengthen this interpretation.

A generally high, though intermittent clay input is also a very important factor in determining the development and geometry of sediment types. Terrigenous clay input was one main factor for limiting coral growth, though analysis of coral types reveals that many forms were adapted to tolerate low, some even higher background deposition (cf. to chap. 3.2.5). When contamination by clay was not too high, lime patch reefs could establish, leading to an accentuated morphology of patch reef knobs. Terrigenous material was channelled between these patches and could settle down in protected depressions. Often, however, clay input was too high (»marl event«) causing the stop of patch reef formation.

Larger reef patches were surrounded by high energy sediments: Skeletal debris facies was forming the direct talus ring; oolites and rhodolith rudstones developed in swell regions between individual coral reef lentils, and oncoïd-cortoid grain/packstones were possibly oriented in stripes leeward to the reef knobs in respect of the prevailing water energy. The latter sediments were deposited in an extremely shallow environment, as evidenced by common desiccation cracks and arrangement of oolites in cross-bedded lateral accretion deposits (cf. to chap. 3.2.7).

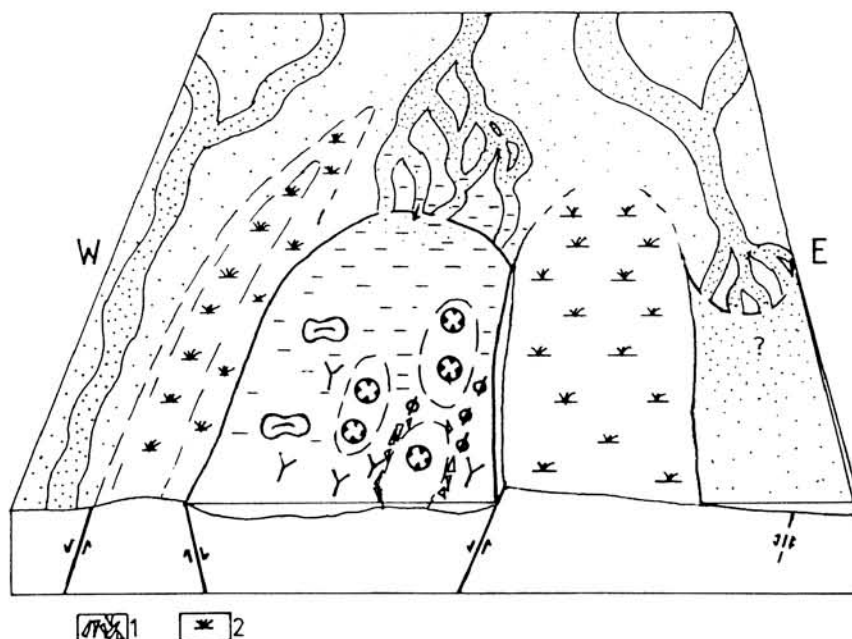


Fig. 17: Depositional model of the »Pteroceriano« formation, upper part.

1 reefoid skeletal debris facies; 2 positive, emerging areas without sedimentation.

Further symbols as in fig. 13.

All reef patches and associated arenite facies developed within a lagoonal environment which is generally characterized by the formation of nodular limestone and marl development.

Place of development of this patch reef complex corresponds to the central heavily subsiding area of the lower part of the »Pteroceriano« formation between Alrota (Arranhó) and Tesoureira. A general shallowing compared to the formation's lower part is a good explanation for the facies development and the restricted extent of calcareous deposits. Surprising, however, is the lack of contamination by siliciclastics despite the surrounding wide distribution of dominantly terrestrial clastics (Atlantic borderland, northern region, Tejo valley): In the west, the Enxara do Bispo – Matacães – Montejunto high was again acting as a clastic fence, now apparently forming a mainland hill range, preventing any clastics to pass over. The north is the presumed source area of terrigenous clay derived from river input. Coarser clastics were apparently filtered, most probably by a flat floodplain development where rivers lost most of their transport force (cf. to chap. 6.5.2). Again there is no coarse clastic supply from the east (Tejo region), completely contrasting to what will take place in the superimposed Freixial deposits (see below). Due to the general shallowing, the structurally and morphologically elevated block further east apparently underwent subaerial exposure, thus prohibiting any eventual transport of siliciclastics from the west (fig. 17).

The upper »Pteroceriano« marls with limestone intercalations are already transitional to the development in the Freixial formation (see below).

6.4 The Development of the Freixial Formation

Distribution:

The Freixial formation is characteristically developed east and west of its type section at Freixial village, northwest of Bucelas (sections FX, TS/BA/CA–CM, location see fig. 1, chap. 1.1). To the west it is traceable until the coast around Cambelas, although in the coastal hinterland limestone intercalations are of very minor importance. The formation is not recognizable further north than Alverca. More in the north it is substituted by the Bombarral formation.

Development:

In fig. 18, the two main sections of the Freixial formations are given. The formation is easily to be divided into two subunits by the main Freixial sandstone, separating a lower calcareous—marly—clastic sequence without, and an upper one with *Anchispirocyclina lusitanica* and *Macroporella espichelensis*, evidencing the beginning of the *Lusitanica* biozone.

The main Freixial sandstone and the other sandstone intercalations are thickening heavily towards northeast and northwest on costs of the calcareous parts of the sequence. A thin marine intercalation within the main sandstone in the south is, however, thickening towards southwest (fig. 18), illustrating the general gradual substitution of sandstones by limestones towards this direction (cf. to chap. 5.2.2.4).

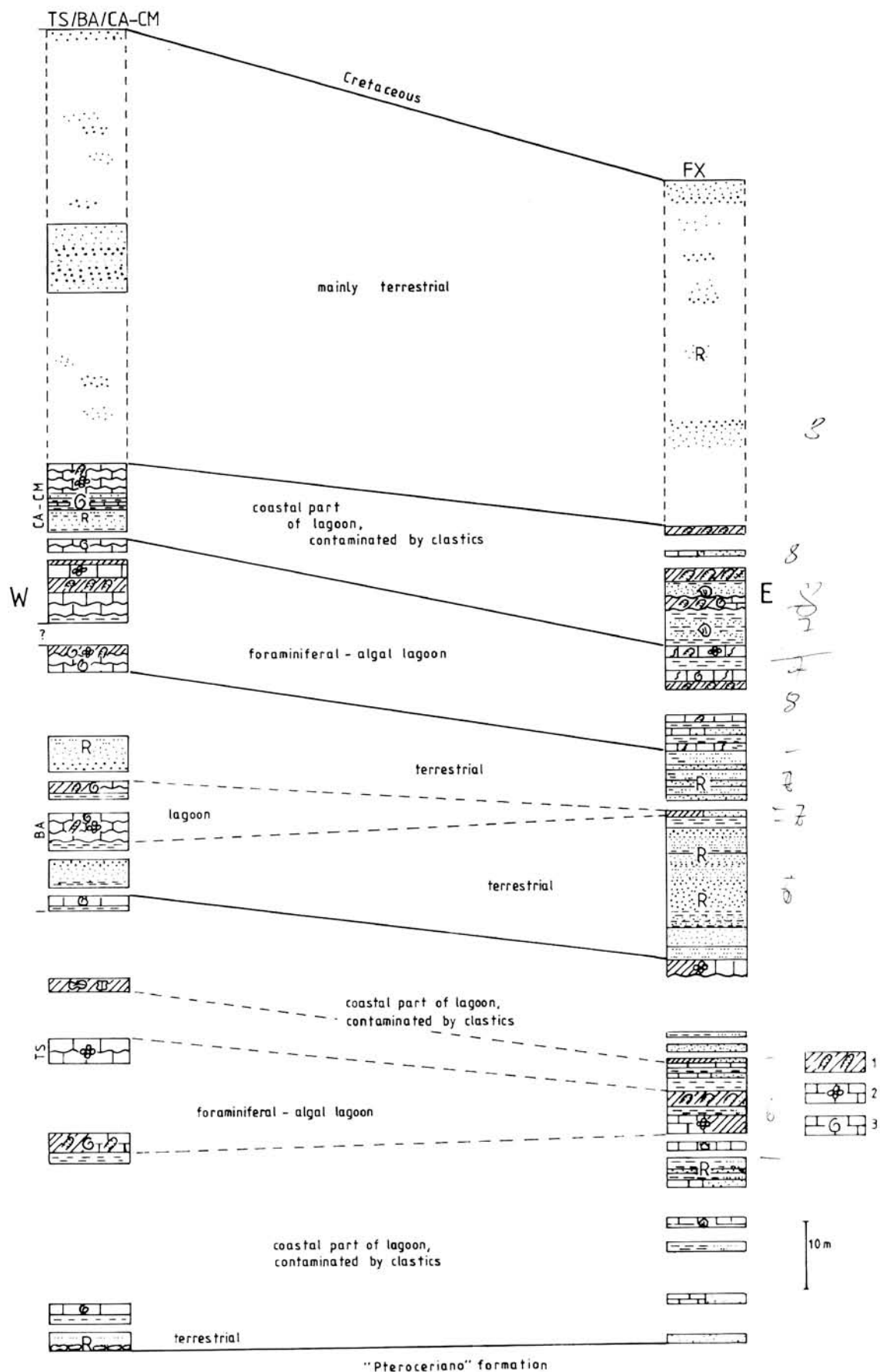
Limestones are composed of low energetic micritic nodular mudstones and common, though thinner, horizons of bioclastic, foraminiferal, dasycladacean and gymnocodiacean packstones as well as oolitic and intraclastic grainstones.

Most types are very different to »Pteroceriano« facies types. Particularly the algal and foraminiferal packstone facies occur very rarely in the underlying unit. The frequent intraclastic grainstones composed of well rounded grains are fairly uncommon in the »Pteroceriano« formation.

Fig. 18 (see next page): Simplified lithological sections of the Freixial formation.

1 *Permocalculus* facies; 2 dasycladacean facies; 3 foraminiferal facies. Further symbols as in figs. 9, 11.

Sections: FX Alcubela–Freixial; TS/BA/CA–CM Tesoureira–Casais da Serra composite section, upper part; location see fig. 1, chap. 1.1.



Also very typical for the Freixial formation are mixture types between limestones and sandstones, such as wackestones with a high quartz amount or very sandy *Permocalculus* packstones.

Marls are rarely outcropping in the Freixial formation, so that no direct comparison with the »Pteroceriano« marls is possible. Often, they contain huge amounts of small oysters.

Another important difference to the »Pteroceriano« formation is the lateral persistence of limestone levels, although their thickness is heavily diminishing.

In the formation's lower part only one limestone horizon reaches the coast at Cambelas, whereas in its upper part intercalations are more common also in the marginal areas of development (southwest of study area, Tejo region). Only towards north, limestones seem to outwedge rapidly, so that the Freixial formation is substituted by the Bombarral formation. Because of erosion no exact northern limitation of Freixial development can though be given.

Model (fig. 19):

As already outlined (see chap. 3.3.2/3.3.3), the sequence of Freixial limestones can for modelling be well arranged into a stripe pattern when regarding the foraminiferal or algal assemblages. Thus, a shallow zone of a mixed lituolid and miliolid assemblage is followed landwards by a belt dominated by miliolids alone. Algal assemblages coincide largely with this zonation. The algal belt can be subdivided into a seaward dasycladacean zone with additional nodules of encrusting algae and a more landward one with a high amount of clastic contamination and the dominance of *Permocalculus*. Arrangement of sediment types evokes a similar pattern. The basinwards situated lagoonal micritic limestones with open fabrics are landwards followed by a narrow high ener-

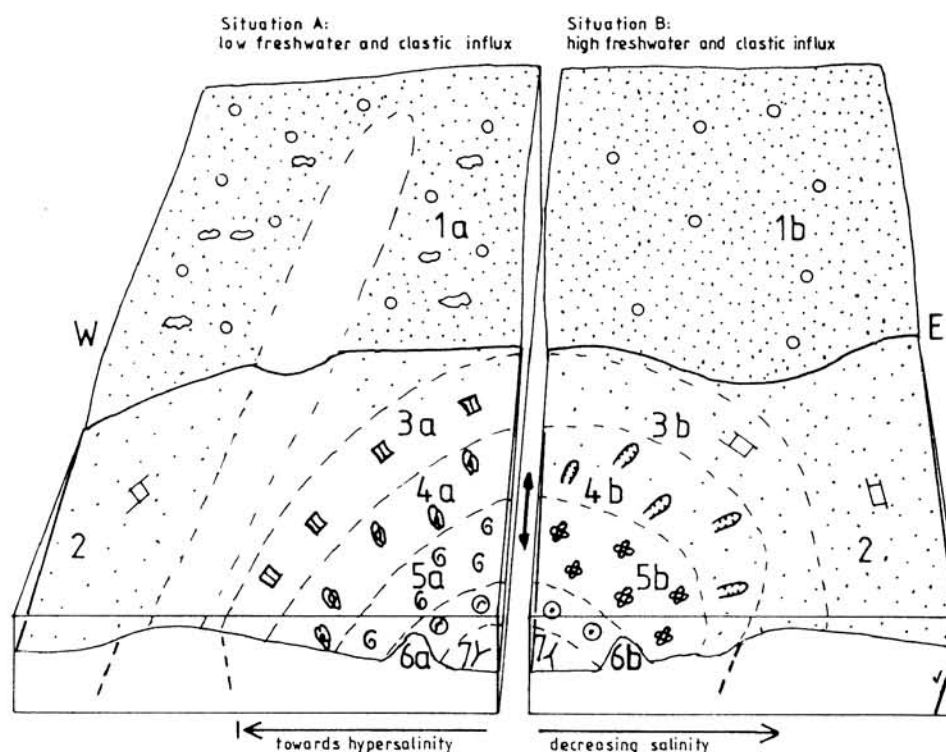


Fig. 19: Depositional model of the Freixial formation.

Left side: situation during low freshwater and clastic input.

Right side: situation during high freshwater and clastic input.

1a fluvial environments with caliche formation in fluvial plains; 1b fluvial environments; 2, 3b coastal clastics with rare limestone intercalations; 3a intraclast belt; 4a miliolid belt; 4b *Permocalculus* belt; 5a mixed foraminiferal belt; 5b dasycladacean belt; 6 oolite belt, a with bioclast-cored, b with quartz-cored ooids; 7 lagoonal micritic limestones.

gy belt where grainstone formation took place. Micritic microfossil packstones with increasing amount of sand follow landwards and are substituted by marginal marine sandstones.

The enormous lateral persistence of facies types endorses such simple modelling and enables explanation of facies sequences solely by oscillations of the sea level and/or by varying degree of hinterland influx.

In contrast to the »Pteroceriano« formation there did not exist major clastic fences during the depositional time of the Freixial formation. A minor exception is the *Permocalculus* belt which, though marginally situated, was morphologically slightly depressed (occurrence of silicisponges, cf. to chap. 3.3.3) and thus acted as a clastic trap.

In principal, clastic supply contaminated the entire depositional area with decreasing influence towards the basin center. Clastic input and thus also freshwater admixture was, however, augmenting periodically. Consequently, during times of low hinterland influence salinities raised in the enclosed basin, to give rise to the dominance of foraminiferal limestones, grading to hypersalinity in shallow coastal areas with low water circulation (miliolid assemblage with dolomites, see chaps. 3.3.1, 3.3.2).

Analogously, during times of higher freshwater input the more central basin areas were in equilibrium in respect of salinity (evaporation versus input), so that dasycladacean meadows could establish. More landwards, the increasing influence of freshwater and quartz sand led to the sandy *Permocalculus* facies type. Occasional occurrence of charophyte gyrogonites in this zone indicate a more landward, subsequently eroded charophyte belt.

6.5 Paleogeographic Evolution of the Central Lusitanian Basin during the Upper? Kimmeridgian and Portlandian

In this chapter, summarized informations from facies and sequence analysis are combined with model conceptions to yield an impression of the paleogeographic evolution of the central Lusitanian Basin during Upper? Kimmeridgian and Portlandian times.

6.5.1 Paleogeographic Parameters

6.5.1.1 Local Structural Parameters

Several active structural elements existed during Upper Jurassic times in the study area.

The Enxara do Bispo – Matacães – Montejunto Diapiric High and the Vimeiro Diapir

Active diapirism in the Lusitanian Basin started somewhere in the late Middle Jurassic (e.g., SEIFERT 1963), becoming very active during the Upper Jurassic (R. WILSON 1975a, FÜRSICH & SCHMIDT–KITTLER 1980, LEINFELDER 1983).

Particularly the Caldas da Rainha diapir with its southern prolongation to the Vimeiro diapir was apparently strongly influencing the paleogeography, probably forming an island chain during the Middle Kimmeridgian (R. WILSON 1979, WERNER 1986).

For the Matacães – Montejunto high, activity was also suggested already for the early Upper Jurassic (e.g., MEMPEL 1955). Its influence is also very obvious in the sequence under study, causing enormous reductions in thicknesses and acting as a clastic fence during the depositional time of the »Pteroceriano« formation. Influence in the Freixial formation is less distinct, yet perceptible.

Arruda Depo – Center

An isopachous map for Kimmeridgian sediments, i.e., mainly the Abadia group, reveals an enormous thickening of deposits around Arruda dos Vinhos and Sobral de M. Agraço (the Arruda sub–basin sensu R. WILSON 1979). Maximum thickness of 2.5 km appears several kilometers NNW Arruda, diminishing rapidly to 500 meters towards all directions, particularly rapidly towards east.

The intensive subsidence of the Arruda depo–center is possibly due to active faulting further west and east, resulting in a graben–like structure (see below). Subsidence is most likely pronounced by lateral creeping of Upper Triassic/Liassic salts (Dagorda beds) towards the diapir regions.

During the uppermost Kimmeridgian and Portlandian, i.e., during the deposition of the Sobral and »Pteroceriano« formations, this constellation remained fixed, apparently with the maximum subsidence area gradually passing south. This is eventually caused by differential compaction of the Abadia group which is distinctively more marly in the south than in the north. The Sobral delta complex was apparently channelled in the subsiding area. Distribution of calcareous facies also seems to be strongly related to this structure.

Another Kimmeridgian depo–center, the Bombarral sub–basin (R. WILSON 1979), northwest of the Montejunto high, is not recognizable in the Portlandian by means of facies analysis, since clastic sedimentation exceeded even an eventually high subsidence rate in this area.

Vila Franca Fault System and Bordering Highs

The Vila Franca fault system is not only a Tertiary/Quaternary structure, bounding the Cainozoic sediments of the Tejo valley and the Jurassic–Cretaceous bedrocks further west, but was already active during the Upper Jurassic (R. WILSON 1979). This fault system was strongly controlling siliciclastic hinterland input from the east which was high in the Abadia group and Freixial formation but low to lacking in the Sobral and »Pteroceriano« formations.

The Ota limestone, nowadays appearing as a morphologically elevated hill range, is almost completely bounded by young faults (ERBENICH 1984). Geophysical data suggest that its eastern limitation is a continuation of the Vila Franca fault system and that the Ota limestone is situated on a structurally higher basement block (R.C.L. WILSON, Milton Keynes, kind pers. commun.). The heavily paleokarstified limestone with an age older than Portlandian (LEINFELDER & RAMALHO in prep.), underwent partial subaerial exposure already in the uppermost? Kimmeridgian/Portlandian, serving as lime resource for hardwater rivers which gave rise to the development of freshwater limestones further west (LEINFELDER 1985).

Thus, the faults west of the Ota hill range are also paleostructures belonging to the Vila Franca fault system (s.l.) and most possibly extending further south to border also the horst structure west of Alverca which is responsible for the obvious reduction in sediment thicknesses or even the total lack of sediments in the »Pteroceriano« formation (fig. 20).

In the Upper Jurassic, the fault system was normally accompanied by structural highs, what is obvious by the eastward shallowing character of sediments (Abadia beds, R. WILSON 1979), by the eastward increase of siliciclastic influence (Freixial formation), by the eastward reduction or outthinning of sediments (»Pteroceriano« formation) or even by erosion of older strata (Ota block). Yet, it also exhibited structural downfaulted blocks at certain times. This is evidenced by the local increase of sediment thicknesses during the lower »Pteroceriano« formation and possibly by the lack of contamination by Sobral siliciclastics around Alverca, eventually even indicating a morphologic depression trapping clastics from eastern sources (cf. to chap. 6.5.2).

Synsedimentary movements along the fault system are also obvious by slight angular bedding unconformities (pl. 1/2).

There is also a possibility that Upper Triassic salts were uprising along this fault system and thus modifying the subsidence and uplift patterns of individual blocks. Salts were, eventually already during the Upper Jurassic, leached by deeply percolating groundwaters, causing hypersaline interstitial waters in some sediments what occasionally resulted in early diagenetic formation of authigenous idiomorphic quartz crystals as occurring in »Pteroceriano« marls around Alverca. For discussion of authigenous quartz findings along the Portuguese diapirs and references see WERNER (1986).

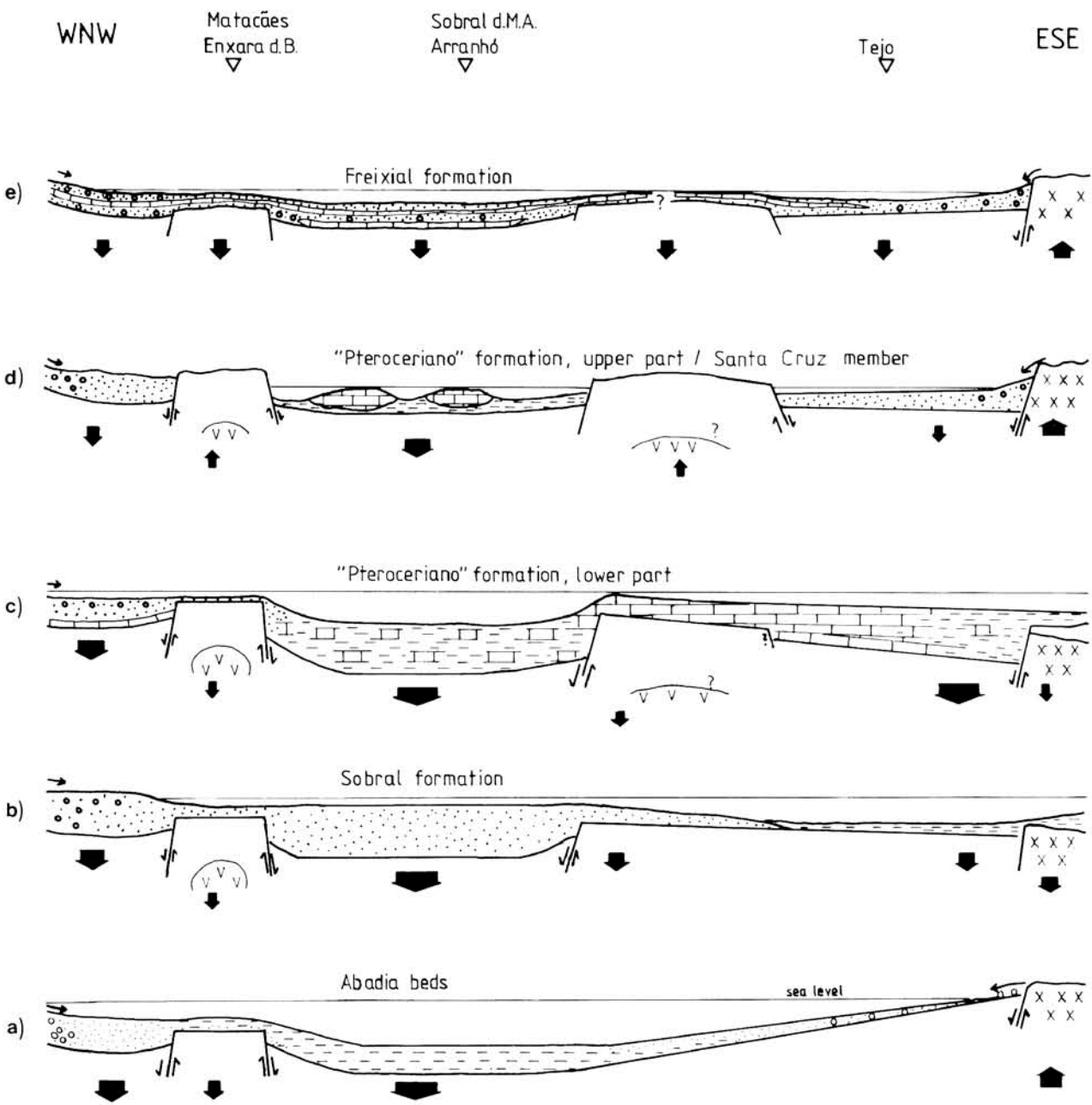


Fig. 20: Sketch-like subsidence pattern of the study area during the Upper Kimmeridgian and Portlandian, as reconstructed by facies distribution and sediment thicknesses. Tejo region simplified. East of Tejo hypothetical reconstruction, since sediments are not outcropping.

Black vertical arrows: subsidence/uplift in relation to sea level. Width of arrows corresponds to rate of movements.

x = basement; v = uprisings salt diapirs; bricks = limestones; dashes = marls; dotted = sands; circles = gravels.

6.5.1.2 Regional Structural Parameters

Pelagic sediments were already deposited during the Upper Jurassic off the Recent Portuguese coast (BALDY et al. 1977), whereas the Lusitanian depositional area was contemporaneously a gulf-like shallow part of the Protoatlantic (R. WILSON 1975a).

The rather enclosed character of this basin was due to a graben-like subsidence within hercynic basement rocks, bounding the basin during its entire history in the north and east as well as partially in the west (e.g., RAMALHO 1971, RIBEIRO et al. 1979) and in the southeast (LEINFELDER 1983). Like the other bordering highs, also the western uplifted block, with rests nowadays represented by the hercynic basement rocks of the Berlengas Islands and their surrounding sea floor (e.g., BALDY et al. 1977:fig. 3), caused intensive siliciclastic input into the basin.

In the Recent shelf off the central Estremadura coast, a still higher position of the hercynic basement compared to other Portuguese shelf areas is indicated by the broad and shallow character of this part (cf. to VANNEY & MOUGENOT 1981:fig. 16), by the dominance of Mesozoic outcrops contrasting to other offshore districts (cf. to BALDY et al. 1977:fig. 3; BOILLOT et al. 1975:fig. 4), and by high gravimetric Bouguer anomalies (cf. to LAUT et al. 1981). VANNEY & MOUGENOT (1981), by means of combined geomorphological – seismic methods, reconstructed the Mesozoic – Cainozoic morphostructural evolution of the shelf area, also claiming an uplifted basement block emerging during the entire Jurassic in the area in question (op. cit., fig. 40, 3–5).

Down south, the basin was not bounded by westward situated basement blocks; active diapiric highs, however, also partially restricted the water exchange with the open proto-ocean during the Upper Jurassic (FÜRSTICH & SCHMIDT-KITTLER 1980, FELBER et al. 1982).

The Lusitanian Basin is clearly a marginal basin related to Atlantic opening. Yet, tensional stress did not lead to a simple graben-like subsidence but rather to a further basin differentiation by wrench tectonics due to the re-activation of Ancient oblique NNE–SSW hercynic elements. These were also the prevailing directions of structural elements active during the Upper Jurassic. The Vila Franca fault system and the general trend of the diapiric highs correspond largely to these directions (see also R. WILSON 1979).

Alignment of salt diapirs along Ancient re-activated structures clearly relates salt diapirism to tectonics. In many places of the Lusitanian Basin, where Ancient diapirism is obvious, sediment load was actually much too little to trigger uprise of salt. This, for instance, is true for the Sesimbra diapir which was burdened by only few hundreds of meters when uprise started (cf. to SEIFERT 1963). This means that, at least in the Lusitanian Basin, no halokinesis s.str. is realized. In other words, it was not the salt which created a fault pattern due to its uprise, but at least the initial uprise was triggered by tensional faulting.

6.5.1.3 Sediment Interrelationships

Contemporaneous Siliciclastic – Carbonate Sedimentation

A striking characteristic of the present sedimentary sequence is the contemporaneous deposition of both siliciclastics and lime/marl sediments, either in a highly intertonguing way or along fairly distinct boundaries (»Pteroceriano« versus Sobral formation and Santa Cruz member; Freixial formation). This implies fairly potent »clastic fences« of various forms controlling the sedimentation.

One sort of fences are morphological elevations bound to structural highs. As outlined, the diapiric highs were almost unpassable swells at certain times. The structural high west of Alverca, most probably extending to the Ota block, also acted in this respect. Occasional halts of clastic input from eastern hinterland sources could eventually also be related to such morphological elevations.

Strongly subsiding areas are another kind of clastic traps if supply is in equilibrium with the rate of subsidence and sea level movements, so that no starvation of sediment occurs which would cause local progradings of transgressive lime facies. Distribution of the Sobral delta and input of siliciclastics from the north during deposition of the »Pteroceriano« formation are apparently controlled by such structures (cf. to chap. 6.5.2).

A primary, tectonically induced, subsidence pattern may subsequently become modified by differentiated load

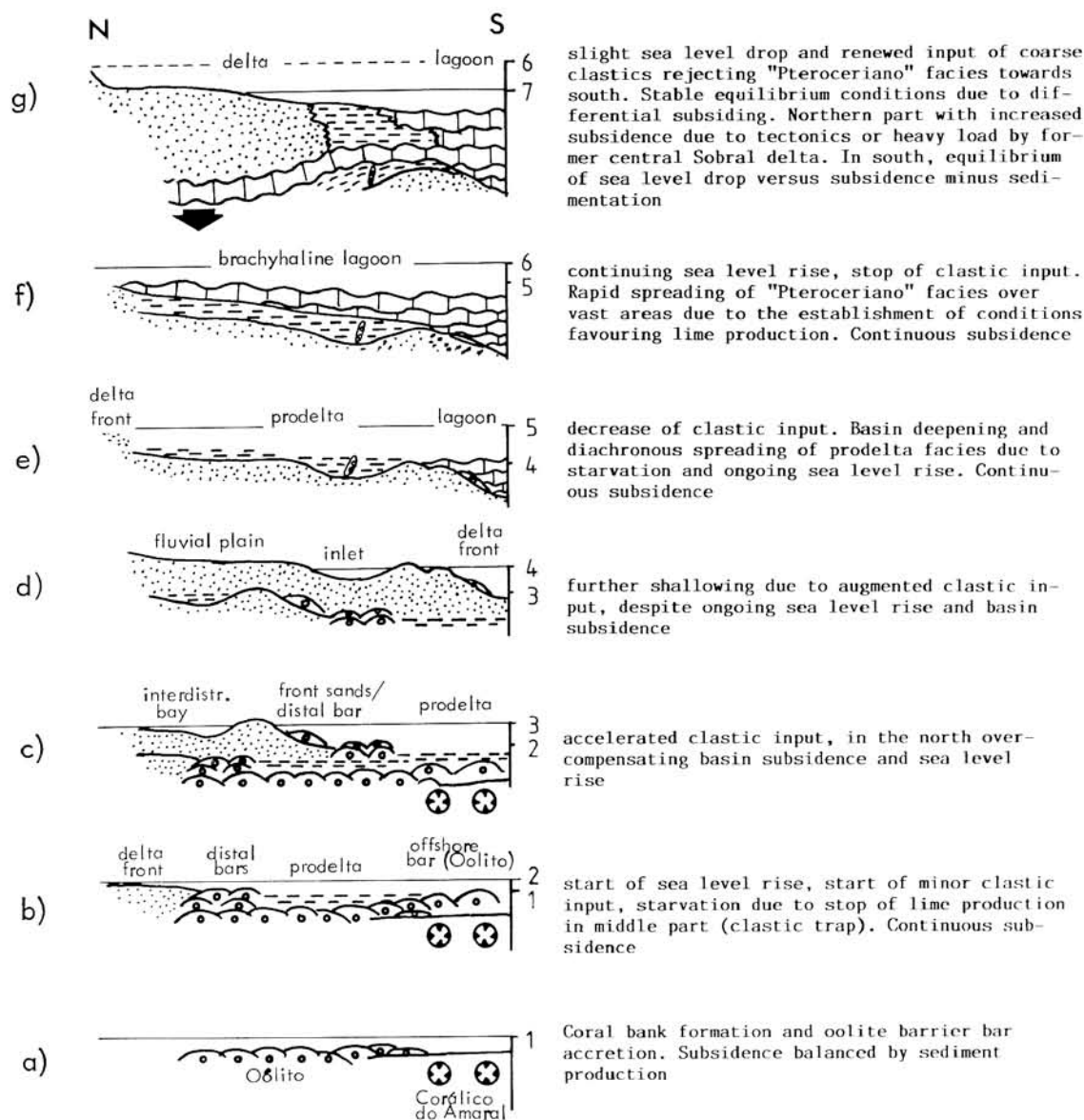


Fig. 21: Basin development in the study area with regard to sediment interrelationships, depositional rates subsidence pattern and sea level changes.

pressures due to differing thicknesses (e.g., WALKER et al. 1983). The possible interference of a structurally related subsidence pattern with load-induced subsiding and sea level movements is tentatively summarized in fig. 21.

Strong coastal boundary currents may be another perfect clastic fence, restricting contamination by even high amounts of terrigenous clastics and freshwater entirely to a narrow longshore belt (ROBERTS & MURRAY 1983). However, the rarity of high energy sediments and the general basin configuration in principle excludes this possibility in the present case. Only to some extent, currents might have controlled the influx of clay-sized clastics from the eastern hinterland.

The Freixial formation is characterized by sandstone intercalations extending over the entire depositional area. In some cases this may be due to supply of sand into the very shallow basin during storms. Generally, however, push-like tectonic hinterland uplifts should account for the extensive spreading of siliciclastics.

Short-lived transgressions followed by rapid regression; are also able to incorporate clastic sediments from the surrounding coastal areas into the entire basin, resulting in thin sheets of sandstone intercalations. The common gradations from sandstones to limestones in the Freixial formation strengthen such an interpretation.

Marl – Limestone Intercalation Sequences

Both the »Pteroceriano« formation and the Freixial formation are characterized by the dominance of, often small–scaled intercalations of marls and more or less marly limestones. This gives reason to ask for the mechanism leading to such sequences.

HALLAM explained many marl–limestone interbedding sequences of the British and Portuguese Liassic as a diagenetic disintegration of, primarily fairly homogenous, marly limestones into marl and limestone beds (for references see HALLAM 1975:70).

Since nodular limestones develop their pronounced nodular fabric only during diagenesis due to differential compaction and diagenetic overgrowth of burrows (cf. to chap. 3.2.1), some small–scale carbonate depletion of intercalated marls in favour of burrow accretion may have taken place in respective parts of the sequence.

Though, preservation even of aragonitic shells in marls and faunal differences between marl and limestone assemblages clearly exclude a general diagenetic explanation of »Pteroceriano« and Freixial marl–limestone sequences.

Often, marls are understood as the coastal facies representative of a more basinward limestone province free of terrigenous clay influx (e.g., TALBOT 1973). This would evoke hundreds of very short–lived transgressions and regressions, so that such a conception is not acceptable in the present case.

In other cases marls may have been deposited in deeper, more quiet settings than associated lime regions characterized by higher water energy preventing deposition of terrigenous clay (e.g., HALLAM 1975:fig. 4.6). This explains many of the small, lentic–like marl/limestone intercalations of the upper part of the »Pteroceriano« formation (cf. to chap. 6.3.2) but is not valid for the bulk of laterally persistent limestone and marl beds which all were deposited in about the same water depth.

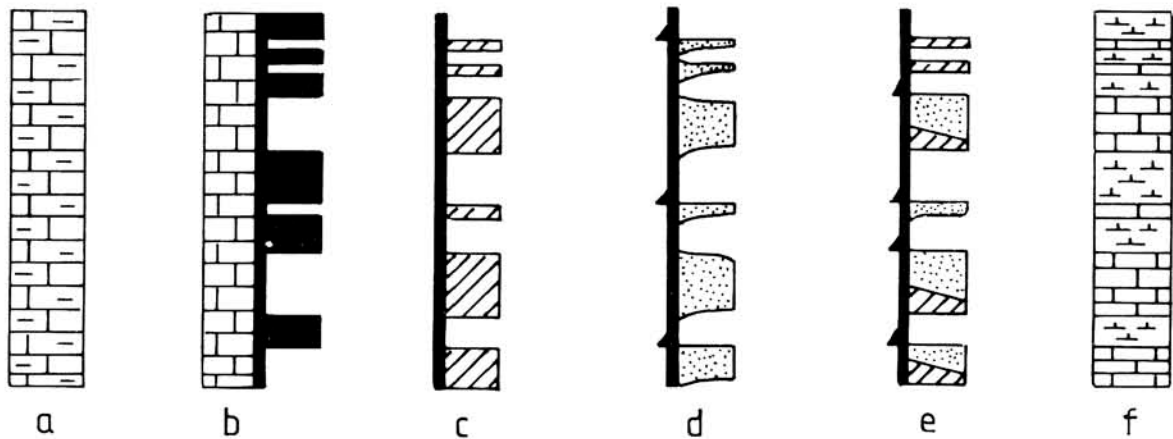


Fig. 22: Possible ways leading to a marl – limestone – intercalation sequence (f).

- (a) Diagenetic segregation of homogenous calcareous marl sequence.
- (b) Episodic terrigenous clay input (black) into area with continuous lime sedimentation (bricks).
- (c) Episodic input of allochthonous lime clouds (cross–hatched) into area with continuous clay background sedimentation (black).
- (d) Episodically rapidly accelerated autochthonous lime production, due to external, non–sedimentological, or internal biologic control of the ecosystem (dotted). Continuous low clay background deposition (black). Collapse of lime producing biologic association caused by internal parameters or by slightly elevated clay input.
- (e) Combined model: continuous low clay background sedimentation (black). Episodic input of allochthonous lime (cross–hatched), aiding in the establishment of autochthonous lime production (dotted). Autochthonous lime production breaking down due to episodically slightly elevated input of clay.

Model (e) is favoured here; for discussion see text.

The easiest explanation is a periodical hinterland uplift in accentuated steps, causing short—termed vast lateral spreading of marl facies. Facies analysis of nodular limestones and functional analysis of the dwelling fauna, however, reveals that also lime mud sedimentation was apparently intermittent, varying from stillstands to very rapid accumulations (cf. to chap. 3.2.1). Moreover, the breakdown of lime production already through minor pollution with terrigenous clay (e.g., WALKER et al. 1983) should not be underestimated.

Hence, a combined model accounts best for the present limestone/marl sequences (fig. 22e):

Organic productivity of limestones is not only very high in reefal areas but also in lagoonal environments like the present basin (autochthonous lime mud production due to disarticulated calcareous algae amounts up to 250g $\text{CaCO}_3/\text{yr} \cdot \text{m}^2$ in modern examples, FLÜGEL 1982: 114).

Decrease in productivity may be related to seasonally higher clay input or to minute tectonic uplifts. This partial collapse of carbonate production allows relative enrichment of terrigenous clay, although supply is not necessarily high.

The almost total lack of pure, uncontaminated limestones suggests that there was apparently a continuous low terrigenous background sedimentation, so that the degree of autochthonous lime productivity was possibly not too high. One should not neglect the importance of carbonate admixture in form of lime mud clouds derived from contemporaneously developing reefs further south (e.g., reef of Cascais, R. WILSON 1979: tab. 4) and swept into the lagoon during storms. Such an initial deposition of allochthonous lime mud possibly re—stabilized physico—chemical and organic conditions supporting the re—start of autochthonous carbonate production.

6.5.1.4 Global Sea Level Changes and Diachronism

Shallowing and upsanding of basins may even take place during general sea level rise in regions overcompensated by terrigenous input. On the other hand, basin deepening may also occur during sea level fall due to depositional starvation and local subsidence. Thus, the degree of local basin subsidence and hinterland activity can only be estimated by comparison with global sea level curves.

Evaluation of global sea level stands in pre—Cainozoic times is mainly based on proportional distribution of land versus sea area, resulting in determination of relative sea level changes. Methodically, regional estimations from stratigraphic sequences of ocean—marginal basins and epicontinental seas are considered together and averaged (e.g., HALLAM 1975).

A curve of relative sea level changes (VAIL et al. 1977) gained by these methods also summarizes all regional tectonic effects and is consequently highly dependent upon selection and quantity of summarized data. Thus, curves of relative sea level changes, such as the Exxon global sea level curve (ZIEGLER 1978: fig. 2, based on VAIL et al. 1977) show a general rise during the entire Kimmeridgian, Portlandian and Berriasian, exceeding in extent the Callovian—Oxfordian transgression. This coincides with the situation in the northern part of the North Atlantic but is contradictory to the state in many more southward basins surrounding the Atlantic (cf. to chap. 6.6) and to the situation in Portugal, pointing out the locally and regionally strongly differing degree of hinterland uplifts or basin subsidence.

A better estimate is the attempt to gain curves of eustatic, rather than relative change of sea level, i.e., drop or rise due to input or consumption of water by polar ice caps and, more important, due to a general change in the shape and thus volume of ocean basins, mainly caused by different rates of sea floor spreading. VAIL et al. (1977: 91) also gave a curve of eustatic sea level changes by using calculated sea level curves, e.g., of PITMAN (1978). The resulting curve points out that sea level was rising only during the Kimmeridgian, whereas in the Portlandian a slow drop was initiated.

Even when basing on such a modified sea level estimation, it remains clear that the shallowing character of Upper? Kimmeridgian sediments in the Lusitanian Basin (Abadia basinal marls, Amaral shallow water limestones, Sobral fluvio—marine sandstones) is due to a high input of terrigenous sediments overcompensating basin subsidence and the general sea level rise. On the other hand, transgressive »Pteroceriano« facies developed during the Lower Portlandian despite a slow drop in the global sea level.

The development of a »regressive« (better: shallowing) sequence accompanied by global sea level rise during the Kimmeridgian suggests a highly diachronous character of superimposed sediments.

The base of maximum extension of »Pteroceriano« facies, eventually coinciding with the peak of global sea level rise at the Kimmeridgian/Portlandian boundary is, however, most likely rather synchronous. This is possibly evidenced by the short-living bivalve *Protocardia* sp. A (cf. to chap. 5.1.3). It is assumed that the sudden onlap of limestone facies is not related to the slow rising sea level but is more likely due to a certain stop of hinterland input, improving the conditions for carbonate establishment, so that lime facies appeared rather penecontemporaneous in all concerned parts of the lagoon (cf. to fig. 21).

The following silting and sanding up of the basin fits to the picture of a dropping global sea level, though it is overprinted by a varying terrigenous supply due to episodic uplifts and subsequent erosion of the hinterland.

6.5.2 Paleogeographic Reconstruction of the Central Lusitanian Basin during the Upper Kimmeridgian and Portlandian

By evaluating all data as achieved from facies interpretation, spatial stratigraphic analysis, environmental models and structural parameters, it should be possible to summarize all informations in order to reconstruct the paleogeographic development of the considered region. The obvious handicap of an only rough biostratigraphic framework can be partially balanced by theoretic considerations on sedimentary models and on influence of global sea level changes and by estimation of diachronism.

Although herewith adding a modelling component to reconstruction, the outlined picture should be a valid approximation to the original development (fig. 23: cf. also to figs. 10, 13, 17, 19, 20, 21).

To give a more complete impression, the units under- and overlying the examined sequence are also briefly taken into consideration.

Kimmeridgian p.p.: the Abadia Group

While during the Kimmeridgian a thick sequence of basinal marls was deposited in the Arruda depo-center, sand beds and even conglomeratic intercalations increased considerably towards the east (R. WILSON 1979), so that a shallowing in this direction should be indicated. At the same time intensive reef development was taking place around Sintra in the southwest (see chap. 5.2.2.4 and R. WILSON 1979), possibly on structurally and morphologically elevated blocks.

Shallowing of the basinal parts due to filling up with terrigenous material then led to the non-synchronous establishment of coral lime facies over major parts of the central Lusitanian Basin, particularly along the structural highs in the western vicinity of the Vila Franca fault system. Lime facies possibly spread in mere horizontal accretion, i.e., coral banks are getting younger in southward and southwestward direction.

Maximum development of the Amaral formation east of Arruda dos Vinhos (Trancoso, Amaral) actually coincides with a structural border, obviously separating depositional areas in the later »Pteroceriano« formation (see below). Along the Tejo valley, oolite formation and marly coral patch reef formation took place. Contemporaneously, oolites were also deposited along the active Matacães–Montejunto high and west of Alenquer.

After the growth of corals up to the sea level, oolites spread also over coral bank areas, possibly in highly diachronous lateral beach/barrier ridge accretion.

Fig. 23 (see next page): Sketch maps of sediment distribution and paleogeography in the study region. For discussion see text.

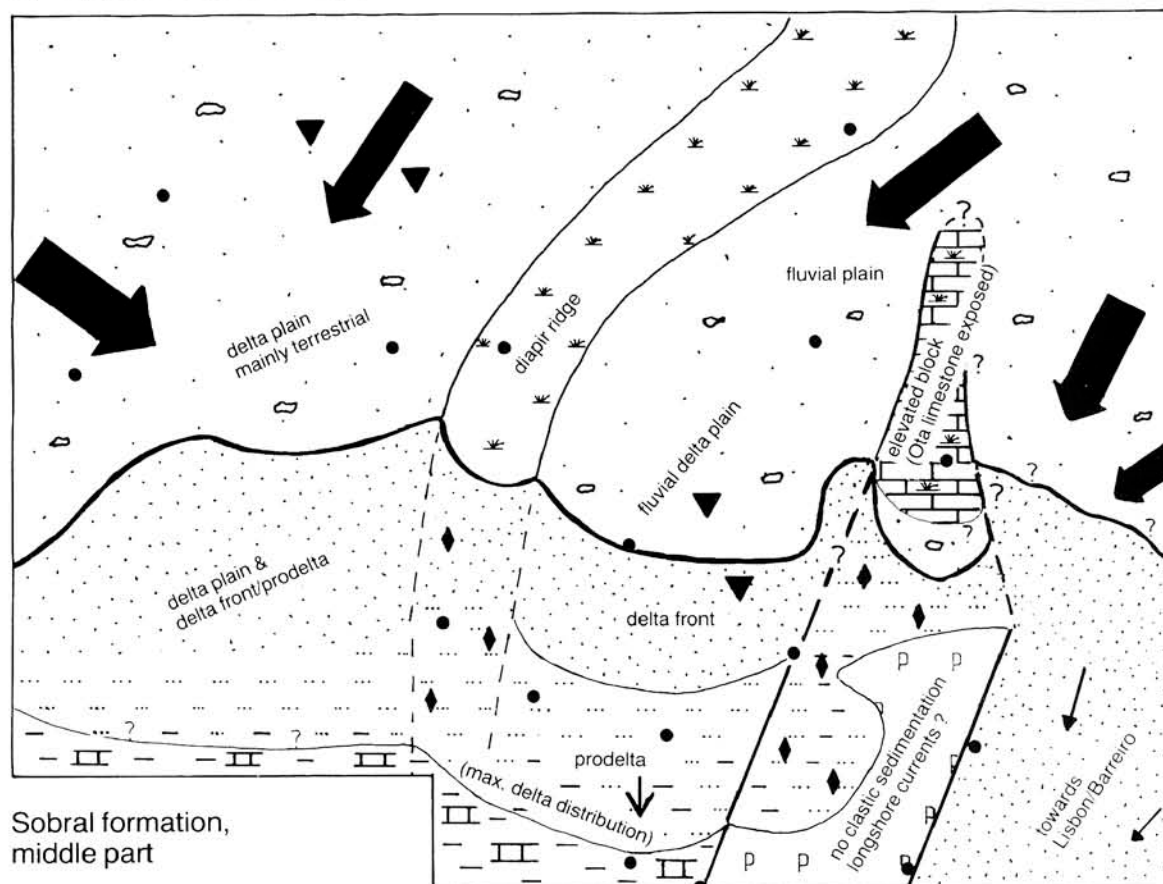
Recent geography also incorporated in (d).

Legend: wide-dotted = terrestrial clastics; narrow-dotted = marine clastics; dashes = marls; bricks = limestones.

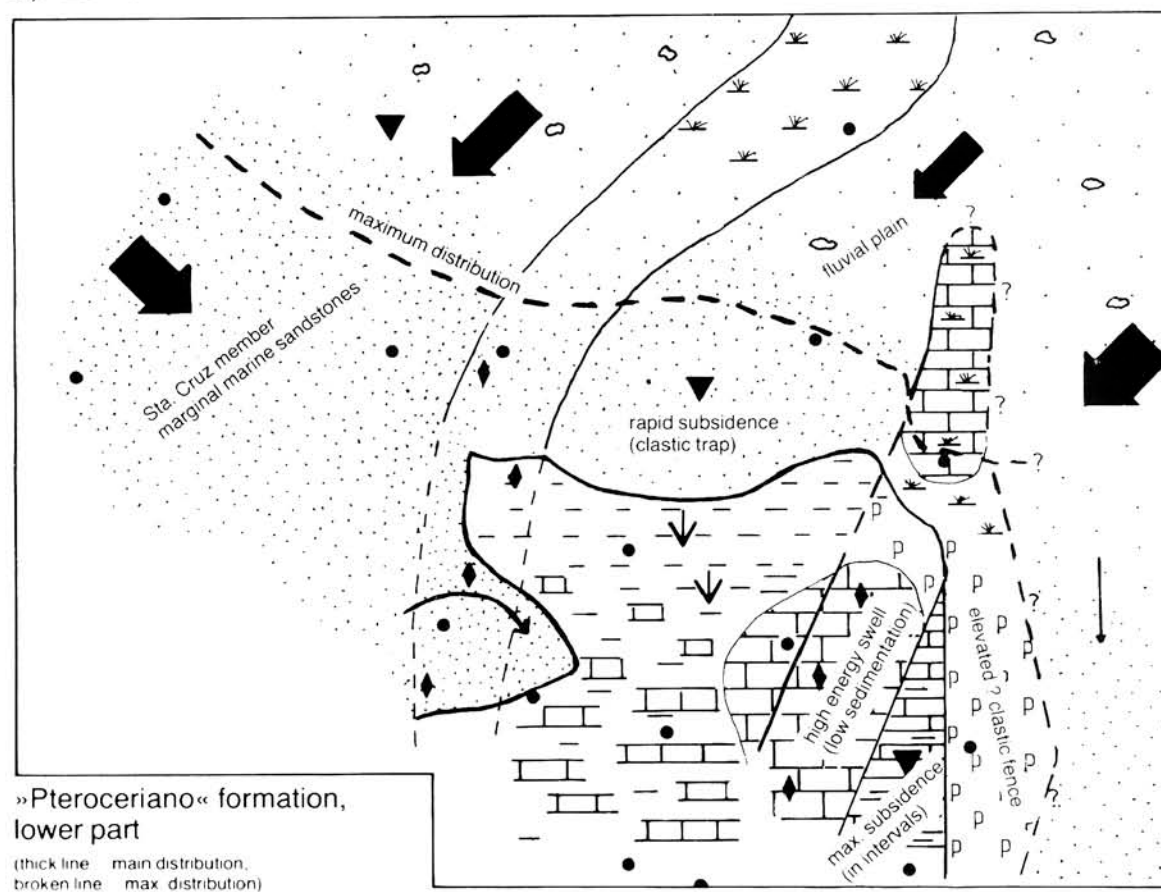
✕ emerged area with erosion; ♦ very low subsidence, minor submarine sedimentation (swell); p p positive submarine area without sedimentation (swell); ↓ main subsiding area with starving sedimentation; ▼ main subsiding area, compensated by sedimentation.

Large black arrows: Main input of siliciclastics.

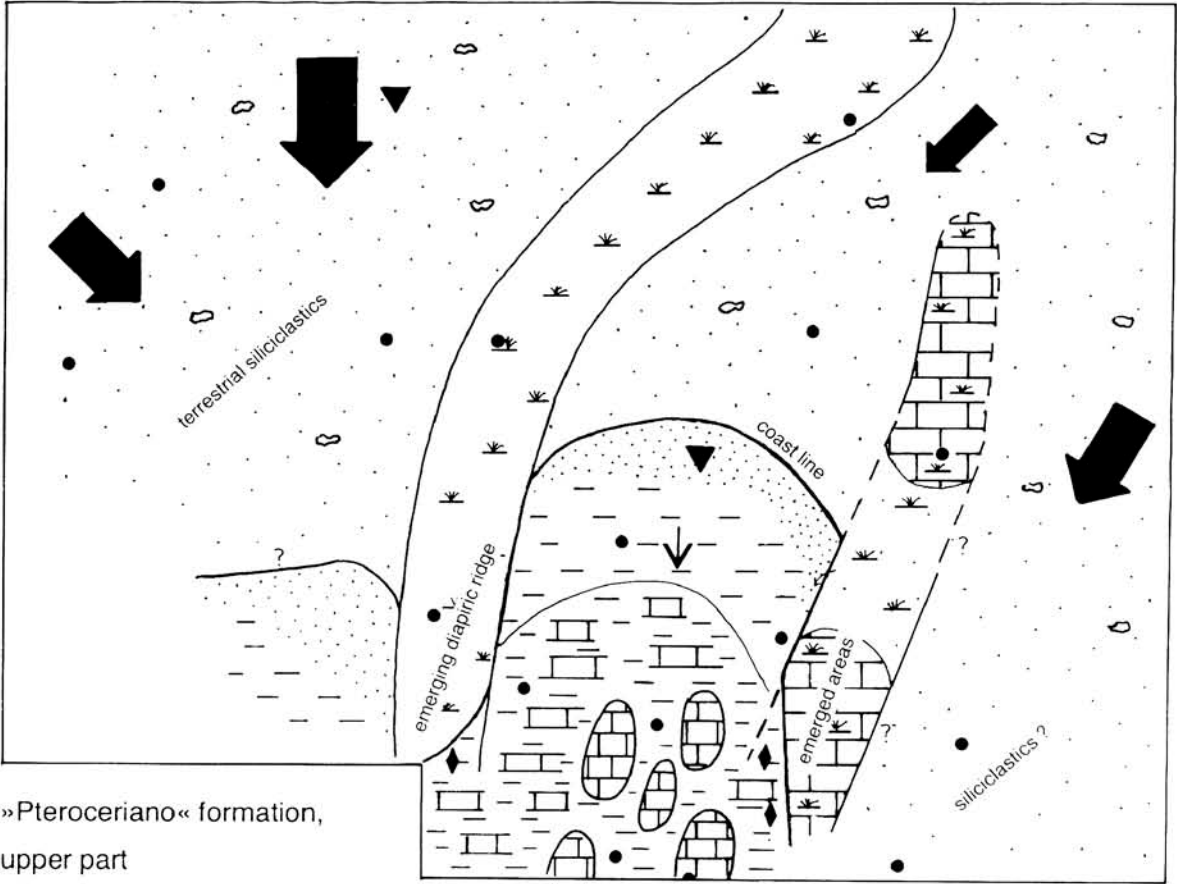
a) Upper? Kimmeridgian



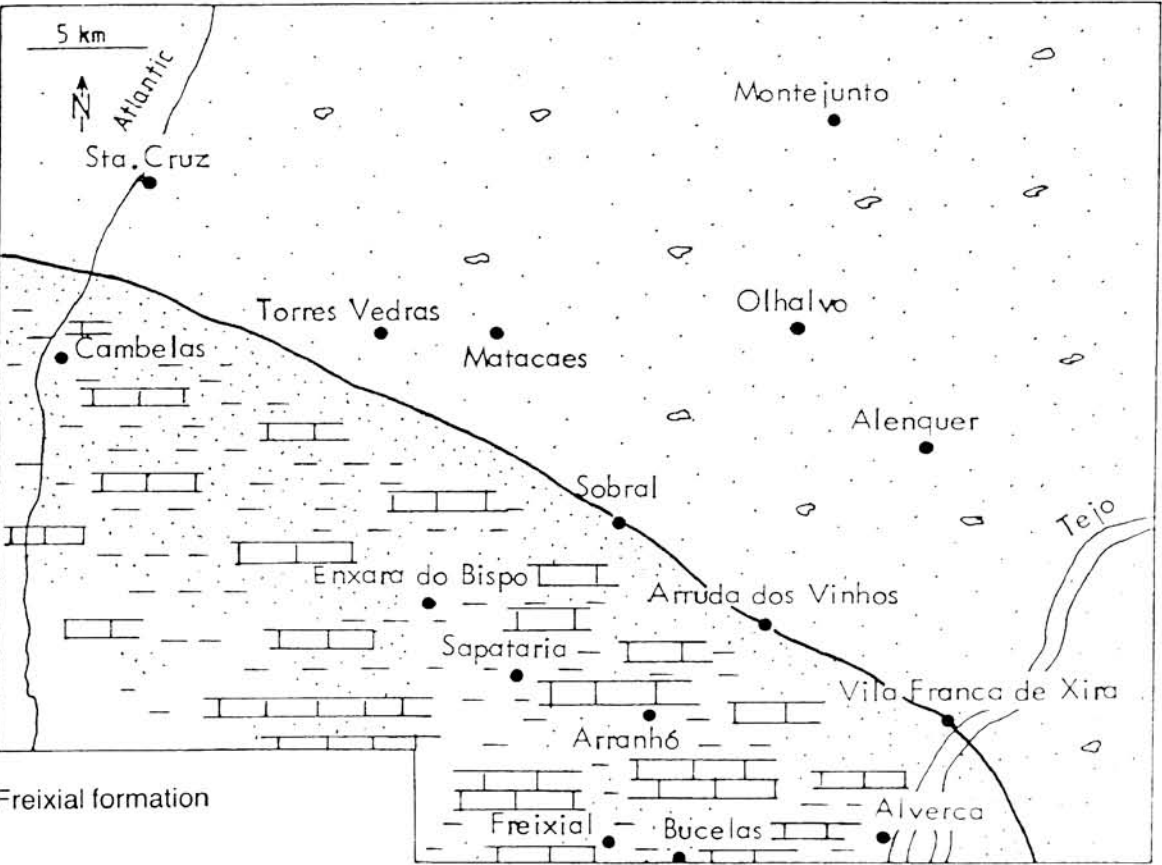
b) Lowermost Portlandian



c) late Lower Portlandian



d) final Lower & Upper Portlandian



Late Upper Kimmeridgian: The Sobral Formation (fig. 23a)

Further north, the Sobral delta complex was contemporaneously slowly prograding southwards. It was biparted by the mentioned diapiric high.

Though enormously developed along its western border, the Ota block is covered only by a thin sheet of delta sandstones, indicating its high structural position at the time of the Sobral delta formation, when it possibly underwent subaerial exposure at certain times.

Outwedging of the delta complex towards southeast (Alverca) may be due to an elevated tilted block. This block caused an only minor or lacking onlap of a marginal delta lobe in contrast to the subsiding area further west and eventually also acted as a clastic morphological fence for potential east-derived clastics. Such clastics may also have been channelled further south in a narrow graben or half-graben-like wrench zone along the later Tejo valley. Actually, east-derived clastic supply is again obvious in the Lisbon region, increasing intensively towards south (cf. to chap. 5.2.2.4).

In the central area, the Gotleis section allows to roughly determine the southern boundary of the Sobral delta complex.

The largest part of the introduced sands was trapped by the heavily subsiding Arruda depo-center. Apparently, input versus subsidence plus ongoing global sea level rise was in perfect equilibrium to restrict the main delta development to this area, simultaneously allowing the establishment of lime facies further south. Oolite swells incorporated in the distal delta complex were a further filter for supplied sands (cf. to chap. 6.2).

Kimmeridgian/Portlandian Boundary and Early Lower Portlandian: The »Pteroceriano« Formation, Lower Part and Contemporaneous Deposits (fig. 23b)

The early establishment of lime facies (nodular limestones, oncolite/rhodolith facies) in the south (thus »Pteroceriano« facies) was initially disturbed by several progradings of sand sheets. This was either related to accentuated hinterland uplifts or to lowerings in the subsidence rate of the depo-center, causing episodic spreading of sand facies further south.

The main delta complex closes up with prodelta marls, spreading diachronously from south to north over vast parts of the lagoon. In shallower parts, oyster patch reefs developed commonly. This situation is apparently related to a strong decrease in hinterland efficacy, resulting in the input of only fine-grained terrigenous particles. Since subsidence remained, the ongoing sea level rise could not be compensated any longer by the now low amount of added siliciclastics, causing gradual basin deepening from south to north.

A further decrease in clay supply then led to the rapid, largely penecontemporaneous spreading of micritic nodular limestone facies over the entire lagoon, in an extension which was never again reached subsequently during the Upper Jurassic. This main »Pteroceriano« spreading should coincide with the maximum highstand of global sea level at the Kimmeridgian/Portlandian boundary (cf. to chap. 6.5.1.4).

Particularly in the east, the widespread *Trichites*/rhodolith lime muds as well as the establishment of coral growth indicate a rather fully marine character of the sea at that time. *Trichites* facies occurs as far as Olhalvo in the north, so that maximum extension of lime facies reached most likely still further.

Renewed start of terrigenous contamination, accompanied by a now gently dropping global sea level, led to a more or less sudden breakdown of calcareous facies in almost all regions of the study area. The limestone/marl development of the »Pteroceriano« formation was now confined to a 20 kilometer large stripe between the Enxara do Bispo Matacães diapiric high and the Tejo valley. (Further extension to the region east of the Tejo is not to exclude but certainly of minor extent, if considering the paleogeographic pattern of the superimposed beds, see below.)

In the west and north, marginal marine to deltaic fine siliciclastics (Santa Cruz member of the Bombarral formation) analogous to the Sobral delta, or terrestrial sands (Bombarral formation s.str.) were deposited. The »Pteroceriano« lagoon was fairly well sheltered from coarse clastic input by the Enxara do Bispo – Matacães diapiric swell and eventually by an elevated block east of the Tejo. From the north, supply of fine-grained terrigenous detritus was continuing in varying rates. Sand-sized grains, however, were completely trapped further north, most possibly because the thick deposits of the underlying Sobral delta caused accelerated subsidence,

so that a vast fluviomarine, low energetic peneplain could develop, where coarse particles were filtered before they could reach the limestone province.

Local subsidence along the western faulted borders of the emerged Ota block led to a further, very minor spreading of marginal marine bioturbated lime muds, overlying predominantly brackish to freshwater cyanophyte deposits (LEINFELDER 1985).

In the southern continuation of the subsiding areas, deeper and thus more quiet marine settings were realized to give rise to a thick development of marls with intercalations of nodular limestones according to the outlined model (cf. to chap. 6.5.1.3).

Further east (between Arranhó and Calhandriz), purer lime sediments with corals and rhodoliths were deposited under more elevated hydraulic conditions. Minor thickness in development is caused by distinctly lower subsidence rates. This structurally higher block also caused a submarine morphological elevation, what explains the shallower character of sediments and the lack of clay settlement due to the elevated energy conditions.

Enormous sequence thickening in a narrow stripe bordering the Recent Tejo valley indicate a rapidly subsiding wrench block in this area. It is not astonishing for a fault-bounded subsiding block that subsidence rate was varying considerably: During times of rapid subsidence, a certain starvation of sediments took place, so that this area was also morphologically deeper situated than the bordering levels, to give rise to slightly marly, low energetic nodular limestone and marl development. Halts in subsidence were followed by morphological levelling, so that facies types of the neighbored block, such as oncolitic and rhodolitic sediments could spread further east at certain times. Another possibility to explain oncolitic/rhodolitic beds in this downthrown block is downslope rolling from the adjacent morphological elevation (cf. to chap. 6.3.1.).

Late Lower Portlandian p.p.: The »Pteroceriano« Formation, Upper Part, and Contemporaneous Deposits (fig. 23c)

A general shallowing, eventually due to the global eustatic sea level drop, explains best the paleogeographic pattern of the superimposed sediments:

Marine clastics were no longer deposited west of Torres Vedras; instead, fluvial sediments were spreading largely (Bombarral formation s.str.).

The Enxara do Bispo – Matacães diapiric swell which was still occasionally pervious for clastics from the west during the depositional time of the lower »Pteroceriano« formation, apparently underwent subaerial exposure, thus representing an elevation not surmountable for terrigenous deposits.

The morphologically higher block bordering the western side of the Tejo valley apparently also emerged partially. This is not directly evident by hiatuses in corresponding sections, since erosion in this region went down to the lower »Pteroceriano« formation. It would, however, fall in with the concept of general shallowing and would particularly explain the lack of siliciclastic input from the east which became so obvious in the overlying Freixial formation.

Thus, marine deposits were apparently restricted to a narrow bay. This open lagoonal bay exhibited a very shallow character, with common occurrence of high energetic calcareous sediments. Occasional oolite beds were formed by lateral accretion mechanisms, evidencing their tidal character (cf. to chap. 3.2.7). Coral patch reefs developed largely, indicating a fairly normal salinity regime of the lagoonal bay which was due to its complete connection to southward situated marine regions and apparently to only low freshwater input from adjacent lands. It seems possible that the main fluvial systems, transporting riverine cargo and thus also freshwater towards south, were confined to the regions west of the Enxara do Bispo – Matacães – Montejunto high and east of the Vila Franca fault system.

Coral associations were, however, adapted to some input of fine siliciclastics (cf. to chap. 3.2.5) which were additionally channelled between the individual patch reefs (cf. to chap. 6.3.2).

Clay and thus freshwater input increased again subsequently, so that coral growth collapsed and the lagoonal floor was covered by marly sediments with only minor intercalations of lime mud deposits.

Final Lower and Upper Portlandian: The Freixial Formation (fig. 23d)

In the final Lower and Upper Portlandian, the paleogeographic pattern changed considerably, leading to principally different sediment sequences:

Swell regions related to diapiric uprise were less distinct during the Upper Portlandian, what resulted in the development of a vast, uniform, very shallow lagoonal environment with a regular zonation into different lagoonal facies belts. According to varying salinities, foraminiferal—dominated or algal—dominated carbonaceous facies types were deposited in a generally shallowing arrangement (cf. to chap. 6.4).

Accentuated stepwise hinterland uplifts, probably caused by the onset of Late Cimmerian movements in the Atlantic borderlands (see, e.g., ZIEGLER 1978), resulted in, at times very high siliciclastic input into the lagoon, overcompensating basin subsidence and thus pushing away the sea. Fluvial environments occasionally conquered the entire region (particularly main Freixial sandstone, see chap. 6.4), to be subsequently overcome again by the sea. Distribution of limestone intercalations both in the west and east is much minor in comparison with the area between the Enxara do Bispo — Matacães high and the Vila Franca fault system.

This should be due to the shallower character of the lagoon's marginal parts allowing the sea to prograde less often, as well as to a primarily thinner development of marine lime sediments which could be easier eroded by onlapping clastics.

Recent distribution of lime deposits in the north is limited along a line Cambelas (Atlantic coast) — Sapataria (SE Enxara do Bispo) — Vila Franca de Xira (Tejo valley), although the original extension possibly reached somewhat further north.

At the end of the Jurassic, the entire lagoon was slowly sanding up by the development of strongly freshwater—influenced »Purbeck«—type facies.

Cretaceous

»Purbeck« facies reached the Sintra region in the lowermost Cretaceous, where subsequently marine lagoonal facies re—established. Further north terrestrial development with deposition of very coarse arcose sediments remained until the uppermost Valanginian, after which during the Hauterivian marine facies again spread over large parts of the Lusitanian Basin (REY 1979). This transgression was not extending far to the north (cf. to REY 1979:figs. 4, 6, 7), coinciding with the transgressive patterns during the Upper Jurassic, whereas in the Upper Cretaceous extension of the sea was reaching much further, yet without surpassing the eastern extent of Portlandian sediments (cf. to BERTHOUS & LAUVERJAT 1979:figs. 2–5). This clearly indicates that the Lusitanian depositional area changed from a marginal basin with its own symmetry characteristics to a simple off-shore province incorporated to the young Atlantic ocean during the Cretaceous.

6.6 The Upper Jurassic Lusitanian Basin in Comparison with Other North Atlantic Marginal Basins

While the North Sea Basin exhibits a fairly different geological evolution due to regionally important structural elements (for survey see ZIEGLER 1978), other North Atlantic marginal basins further south (in respect to a paleo—continental fit may, e.g., op.cit.:fig. 12) show a development principally comparable with the Lusitanian Basin.

Thus, the Northwest African basins, such as the Tarfaya—Aaiun Basin of southern Morocco and the Mauritania—Senegal Basin as well as the Canadian and northeastern U.S. basins (Scotian, George Bank and Blake Plateau Basins) are also in principal structurally bound to Paleozoic lineaments. They exhibit the same Upper Triassic/Liassic initial rifting development with precipitation of evaporites and subsequent, mainly Early Jurassic/Middle Jurassic spreading of carbonate platform facies which coincides with the first sea floor spreading in central parts of the young Atlantic (cf. to LANCELOT & WINTERER 1980, JANSÁ & WIEDMANN 1982).

With the onset of the Atlantic transgression in the Callovian/Upper Jurassic, a second phase of reef development started throughout nearly all basins under a strong structural differentiation due to widespread Cimmerian

tectonics and under the competition of prograding clastic delta wedges. This figure coincides with the Upper Jurassic development in the Lusitanian Basin. The main difference to the latter is the larger asymmetry of the other basins, i.e., outthinning of deltaic clastic wedges respectively towards west along the American margin and towards east along the North African margin, thus indicating general basin deepening towards the central Proto–Atlantic. The northern and central Lusitanian Basin was more independent during the Upper Jurassic, showing general basin deepening towards southwest, i.e., parallel to the Proto–Atlantic.

The marginal basins of Northern Morocco (Atlas Basins) exhibit a somewhat different development due to their geotectonic setting intermediate between Atlantic and Tethys development (cf. to JANSÁ & WIEDMANN 1982, STETS & WURSTER 1982, HÜSSNER 1985).

The Algarve was also in such a transitional position, what explains the mutual occurrence of talus sediments, platform carbonates and pelagic deposits during the Upper Jurassic (cf. to MOUTERDE et al. 1979, RAMALHO 1981). Hence, it obviously connected the Atlantic province to the Tethyan Betids (cf. to SEYFRIED 1980), a seaway which already existed during the entire Jurassic (e.g., THIERRY 1982, ENAY & MANGOLD 1982).

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for Section 8. Appendix (Lithological Sections),
pp. 109 - 173, see file Leinfelder1986_partB.pdf

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