

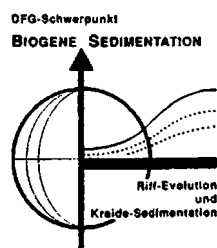
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Siliceous sponge facies from the Upper Jurassic of Portugal

By

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With 25 figures in the text



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Abstract: Siliceous sponge facies is widely developed in the Upper Jurassic sedimentary basins of Portugal. Most occurrences are situated in the eastern Algarve basin, and can be considered as part of the Upper Jurassic sponge facies belt extending across Europe along the northern Tethyan shelf. The Portuguese occurrences of siliceous sponges range from Middle Oxfordian to Middle Kimmeridgian in age. They characterize a variety of facies, namely (1) sponge meadows and biostromes, (2) sponge/microbial crust mud mounds, (3) microbial thrombolites containing siliceous sponges, (4) thrombolites with corals and siliceous sponges, and (5) coral/siliceous sponge debris facies and muddy boundstones. Siliceous sponge groups comprise dictyids, lychniscids, tetractinellids and "lithistids". These groups vary in their proportions depending on the sponge facies type. The sponge genera and species are characteristic of the Tethyan realm.

The major factors controlling the occurrence and composition of sponge facies are bathymetry, sedimentation rate and fluctuations in oxygen content. Bathymetric interpretation is based on position of sponge facies within shallowing-upwards successions and on faunal gradients established by semiquantitative palaeoecological analysis. Low sedimentation rate is a prerequisite for the occurrence of sponge facies, particularly the crust-rich types. Indicative for low sedimentation rates are glauconite content, faunal incrustations and association with distinct condensation levels. Glauconite enrichments, the occurrence of the dysaerobic bivalve *Aulacomyaella* and strong impoverishment of fauna in some levels indicate low to fluctuating bottom water oxygenation responsible for the growth of sponge-bearing thrombolites and for rapid transitions from thrombolite facies to coral facies.

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The controlling factors are directly linked to sea level fluctuations and their influence on climate and ocean water circulation. Lowering of sedimentation rate during sea level rise enabled establishment of reef facies across a wide bathymetric range. From shallow to deep, the coral facies is followed by a mixed coral-siliceous sponge facies, by pure siliceous sponge facies and, finally, by oxygen-controlled sponge thrombolites. In the balanced greenhouse climate of the Late Jurassic, larger sea level rises resulted in additional climatic equilibration and hence slacking of oceanic circulation. This induced major rises of oxygen deficient waters, which explains the occurrence of shallow-water sponge-bearing thrombolites and rapid transitions from sponge thrombolites to coral facies.

Introduction

Siliceous sponge facies is well known in the Upper Jurassic succession of Southern Germany where it forms the spectacular rocky landscape of the Franconian and Swabian Alb. The most fundamental studies about the sponge facies were carried out in the Swabian Alb, particularly by our admired, but much too early deceased colleague, Prof. Dr. MANFRED GWINNER (e.g. GWINNER 1958, 1962, 1976, GEYER & GWINNER 1984, 1991), to whom we dedicate this contribution.

European Upper Jurassic siliceous sponge facies is known from the entire northern shelf of the Tethyan Sea, in a belt extending from Romania (Dobrugea: BARBULESCU 1974, DRAGANESCU 1976) to Poland (Polish Jura Chain: SIEMIRADZKI 1914, TRAMMER 1979, 1991), Southern Germany (Franconian Alb: e.g. FLÜGEL & STEIGER 1981, FLÜGEL et al. 1992, MEYER & SCHMIDT-KALER 1990, BRACHERT 1992, and Swabian Alb: e.g. GWINNER, loc. cit., WAGENPLAST 1972), Switzerland and France (Jura chains: GAILLARD 1983, GYGI & PERSOZ 1986) down to Southeastern Spain (Celtiberian and Prebetic zones: BEHME 1970, FEZER & GEYER 1988, GEYER & PELLEDUHN 1979, DEUSCH et al. 1990) (Fig. 1). Some



Fig. 1. Occurrence of Upper Jurassic siliceous sponge facies in Europe. Modified and expanded after TRAMMER (1982).

reports mention local siliceous sponge or mixed sponge - coral occurrences further to the west, i. e. from southern Portugal (RAMALHO 1985, TERMIER et al. 1985a, b) and from the subsurface of the eastern and southeastern US shelf (ELIUK 1978, ELLIS 1984, JANSÁ et al. 1983). However, up to the present date, data from this area are very scarce.

Our comparative studies on European Upper Jurassic reef facies revealed a lot of to date unknown siliceous sponge-bearing facies particularly in the eastern Algarve Basin (southern Portugal). This indicates that the north Tethyan Upper Jurassic sponge belt actually persisted further west. To a lesser extent, siliceous sponge-bearing facies also could be detected in the Upper Jurassic of the central Portuguese Lusitanian Basin. Both Portuguese basins are particularly known for their rich shallow-water mollusc and coral facies (e. g. ROSENDAHL 1985, FÜRSICH & WERNER 1986, 1991, WERNER 1986, LEINFELDER 1986, 1992, 1993, ELLIS et al. 1990). The rather widespread occurrence of siliceous sponge-bearing facies was not recognized.

Some of the Portuguese occurrences of siliceous sponge facies are comparable with, others are in considerable contrast to, the well known South German sponge facies. Their study should therefore be of particular value for the recently revived discussion on the controlling factors of Upper Jurassic sponge facies (cf. KEUPP et al. 1990, MEYER & SCHMIDT-KALER 1990, SELG & WAGENPLAST 1990).

Geological framework

The eastern part of the Algarve Basin can be interpreted as a part of the northern shelf of the western Tethyan ocean (RAMALHO 1972-73, 1985). The western Algarve is in a transitional position between the Tethys shelf and the central Portuguese Lusitanian Basin which is a marginal basin heralding the opening of the North Atlantic ocean (WILSON 1979, LEINFELDER & WILSON 1989) (Fig. 2).

Sedimentation in both basins started with an initial graben rift phase leading to uppermost Triassic to Hettangian red beds, volcanics and evaporites. Lower and Middle Jurassic sediments are represented by shallow-water and hemipelagic carbonates and marls, mirroring a quiescent sagging phase. The transition from the Middle to the Upper Jurassic is characterized by a regional, uppermost Callovian to Lower Oxfordian hiatus, which is developed as a subaerial unconformity in the Lusitanian Basin and major parts of the Algarve Basin (RAMALHO 1972-73, 1985 ROCHA 1976, LEINFELDER 1987, WILSON et al. 1989) and a marine phosphoritic condensed horizon in the westernmost Algarve (ROCHA 1976, RAMALHO & RIBEIRO 1985). Upper Jurassic sediments of both the eastern Algarve and the central Lusitanian Basin are largely developed as mixed carbonate - siliciclastic shallowing-upwards successions. Yet, these

successions are much more differentiated in the Lusitanian Basin than in the eastern Algarve Basin, due to a second extensive rift phase affecting central Portugal (VANNEY & MOUGENOT 1981, LEINFELDER & WILSON 1989, NOSE in prep.).

Both the western Algarve and the southern Lusitanian Basin, as well as a narrow outcrop area in between (Sines - São Tiago do Cacém), exhibit dominance of Upper Jurassic carbonate platform facies with faunal elements indicative of a restricted connection of both basins (cf. MOUTERDE et al. 1979, FELBER et al. 1982, RAMALHO in OLIVEIRA 1984).

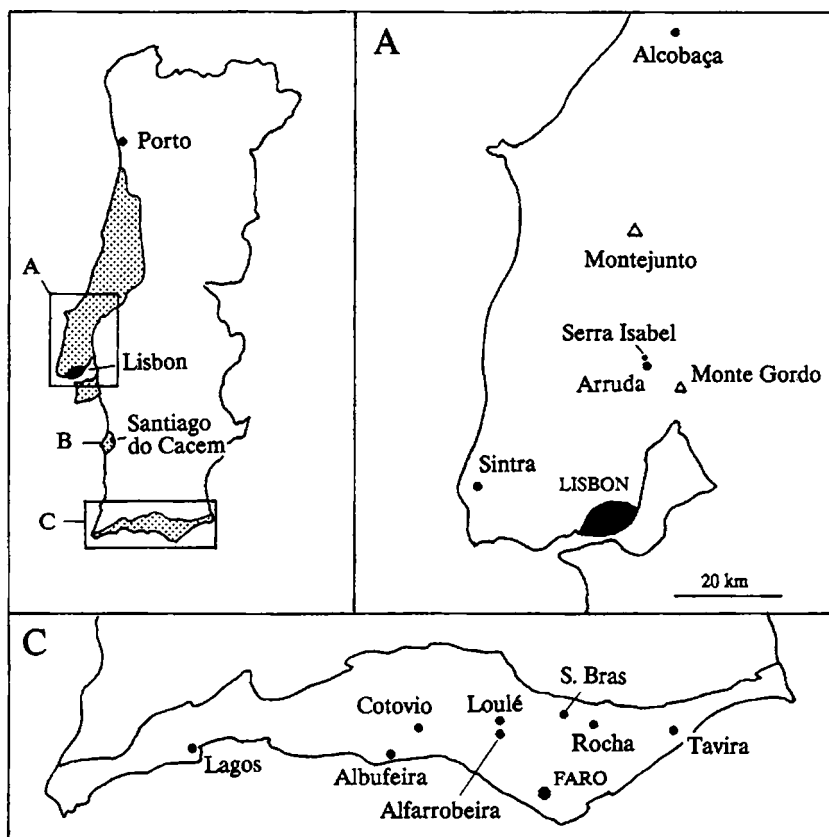


Fig. 2. Position of the Lusitanian Basin (A), the Sines-São Tiago de Cacém area (B) and the Algarve Basin (C) of Portugal, with localities mentioned in the text.

The Upper Jurassic succession of the eastern Algarve Basin

Fig. 3 shows the generalized stratigraphic framework of both the Algarve and the Lusitanian Basin. In the eastern Algarve Basin a clear shallowing-upwards succession is developed (RAMALHO 1985, NOSE in prep.), with the only exception of the São Ramão shallow-water platform which is surrounded by deeper water facies.

Peral beds: The Peral beds represent a shallowing-upwards alternation of ammonite-rich marls and bedded marly limestones with occasional intercalations of sandstones. This alternation and the repetitive occurrence of marl- and limestone-dominated intervals indicate cyclicity at various scales, although outcrop conditions do not allow closer examination. The minimum thickness of the Peral beds is 200 metres, however, the base of the units is commonly not exposed. Around Loulé, dense micritic limestones occur beneath the succession ("hydraulic limestones").

Condensed, glauconitic ammonite and brachiopod shell beds are frequent. Some horizons are rich in allochthonous shallow-water particles (ooids, oysters, corals). Coarser debrites and olistoliths occur at several localities. Bindstones and mud mound facies containing siliceous sponges were detected at various levels within the Peral beds, but are most common in its uppermost part.

According to MARQUES & OLORIZ (1992), the Peral beds span the Middle and Upper Oxfordian and may include the entire Lower Kimmeridgian (including the divisum zone), although the degree of heterochroneity is not clear (cf. MARQUES 1983, ROSENDAHL 1985).

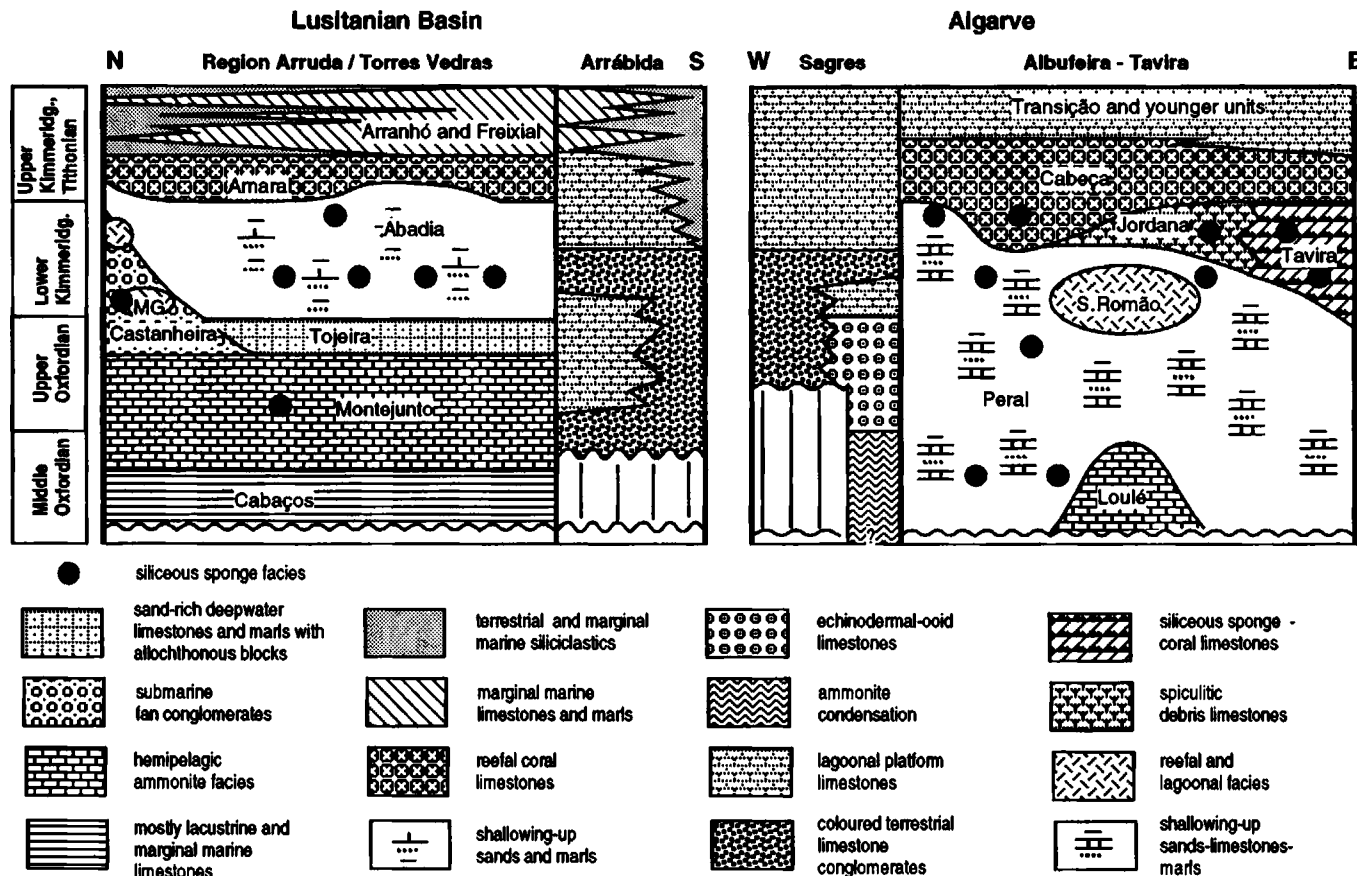
Jordana beds: The Jordana beds are only developed in the eastern part of the Eastern Algarve, where their thickness ranges from 20 to 160 metres.

The beds are almost exclusively composed of fine- to medium-grained intraclastic bioclastic grainstones, packstones and wackestones. Coarse rudstones and floatstones are occasionally intercalated. Intraclasts represent reworked micritic and organic microbial clotted limestone partly containing relics of siliceous sponge skeletons. This internal structure as well as their irregular shape makes these intraclasts comparable with the so-called "tuberoids" of the South German sponge facies (cf. FRITZ 1958, GEYER 1962, WAGENPLAST 1972, GWINNER 1976). The transported bioclasts are largely composed of crinoidal and echinoidal fragments. Coralline sponges (e. g. *Eudea*, *Neuropora*, *Corynella*) and corals, the latter also forming small bafflestones, occur occasionally. Siliceous sponges appear isolated or within small bioherms; spicules are at places extremely common (cf. RAMALHO 1985). The faunal elements are often completely or marginally silicified. Silica nodules also occur isolated, sometimes exhibiting branching, resembling *Thalassinoides* burrows. The silica material is thought to be derived from dissolved skeletons of siliceous sponges occurring in the uppermost Peral beds.

The Jordana beds have been placed in the transition zone between the Lower to Upper Kimmeridgian (divisum / acanthicum zones) by MARQUES (1983).

Cabeça beds: The shallow-water platform limestones of the Cabeça beds attain a maximum thickness of 150 to 200 metres. They are dominated by reefal coral facies rich in bioclastic debris, intraclasts, ooids and oncoids. The dominant fabric is grain supported with various grain size and lime mud content, although the mud supported fabric is frequent at places. Corals occur in boundstone patches but are more frequently fragmented and incorporated as clasts in the high-energy debris facies. The diversity of coral taxa and growth forms is very high. Stromatoporoids, coralline sponges, chaetetids, as well as benthic molluscs are also common (NOSE in prep.; cf. RAMALHO 1985, ROSENDAHL 1985). At places, siliceous sponges occur frequently.

Fig. 3 (Legend see p. 205)



Clearly situated above the Peral and the Jordana beds, a Lower to Middle Kimmeridgian age is likely for the Cabeça beds, an interpretation which is consistent with micropalaeontological data given by RAMALHO (1985). The Foupana beds (*sensu* MARQUES 1985, RAMALHO 1985) at the base of the Cabeça contain some silicified fossils which is possibly caused by dissolution and reprecipitation of silica gels from sponge skeletons. The unit is included here in the Cabeça beds due to their facies similarities. Around Loulé, the Cabeça beds are known as "Dolomite of S. Barbara de Nexe", because they underwent late diagenetic dolomitization (*cf.* ROSENDAHL 1985).

Tavira beds: The Tavira beds occur locally in the area of Tavira beneath the Cabeça beds. They replace the Jordana and lower Cabeça beds, to both of which they exhibit facies similarities. Scarce ammonite data indicate that this carbonate unit existed earlier than most of the other carbonate units (possibly as early as earliest Kimmeridgian, according to MARQUES 1983). This is most likely due to its position on a salt pillow / structural high. The Tavira beds are characterized by very thick beds of detrital floatstones, rudstones and packstones, which are intercalated with very thick, often brecciated boundstone beds. This mixture of alloclastic limestones and autochthonous to parautochthonous reefal facies reflects a deposition on a gently inclined slope. The detrital limestones are very similar to the Jordana beds, although faunal content and faunal size is often greater. The boundstone beds are dominated by siliceous sponges at the base and by a co-occurrence of siliceous sponges and corals in the upper part. Due to continuous grading into coral boundstone facies, the boundary to the superimposed Cabeça beds is transitional. The Tavira facies is restricted to a maximum thickness of 10 metres.

São Romão beds: This local unit is composed of up to 400 metres thick, coral-rich shallow-water ramp carbonates (SCHMID 1992). It shows facies similarities with the Cabeça beds but developed earlier than the latter, i. e. within the Peral beds. The platform establishment occurred through a rapid transition from Peral facies to Jordana-type allochthonous debris limestones to autochthonous bioclastic sands including many coral patch reefs rich in stromatoporoids and coralline sponges (*cf.* RAMALHO 1985). Locally, siliceous sponges occur in a Tavira-type facies at the base of the unit. The progradational ramp architecture and the lateral waning of the unit are characteristic of a development on an active salt pillow (Loulé salt diapir).

Younger units: Units superimposing the Cabeça beds are mostly calcareous and represent inner shelf areas. Their "lagoonal"-type facies is characterized by dasycladacean and lituolid foraminiferal limestones; Purbeck-type facies with sandstone intercalations occur more commonly towards the upper Tithonian (RAMALHO 1985, ROSENDAHL 1985). No siliceous sponges were detected in these units.

The Upper Jurassic succession of the western Algarve Basin and the southern Lusitanian Basin

Both the western Algarve (area of Sagres) and the southern part of the Lusitanian Basin (Serra da Arrábida, to the South of Lisbon), and a narrow outcrop

Fig. 3. Simplified lithostratigraphic framework of the Portuguese Upper Jurassic succession and occurrence of siliceous sponge facies. After FELBER *et al.* (1982), MARQUES (1985), RAMALHO (1985), ROSENDAHL (1985), LEINFELDER (1986, 1987), LEINFELDER & WILSON (1989) and unpubl. results.

situated halfway between both (area of Sines - São Tiago de Cacém) (Figs. 2, 3) exhibit similar carbonate platform development. This is characterized by low to high energy carbonates containing coral and stromatoporoid patch reefs, by the frequent occurrence of terrestrial multicoloured carbonate breccia, and by some intercalations of mollusc and coral-rich marls and siliciclastics (e. g. FELBER et al. 1982, LEINFELDER 1983, RAMALHO 1971, 1972-73, 1985, RAMALHO in OLIVEIRA 1984; see Fig. 3 for stratigraphic framework). Facies containing siliceous sponges were only detected in drill cores in the vicinity of São Tiago de Cacém (TERMIER et al. 1985a, b).

The Upper Jurassic succession of the central Lusitanian Basin

The general succession of the Upper Jurassic of the central Lusitanian Basin shows similarities with the development of the eastern Algarve, and can hence also be described as a large-scale shallowing-upwards megasequence (RAMALHO 1971, 1985, NOSE in prep.). However, the influence of syndimentary tectonics and sea level fluctuations was tremendous and led to very rapid lateral and vertical facies changes (LEINFELDER & WILSON 1989), which are much more pronounced than in the eastern Algarve.

Cabaços beds: After the regional Lower Oxfordian hiatus which is, at places, again overlain by terrestrial multicoloured carbonate breccia, the Middle Oxfordian Cabaços beds with a thickness of 200 to 400 metres (WILSON et al. 1989) are widespread. The carbonates and, to a lesser extent, marls comprise freshwater, brackish water, hypersaline and, subordinately, normal marine shallow water environments without siliceous sponges.

Montejunto beds; deep-water and shallow-water facies: The typical Montejunto beds, of late Middle to Upper Oxfordian age are represented by evenly bedded limestones with rare marl intercalations, which are rich in ammonites and commonly contain a high amount of isolated sponge spicules. They represent a deeper shelf hemipelagic lime mud environment and may attain thicknesses of 400 to 1200 metres (WILSON et al. 1989). Towards the area of the Montejunto mountain (type locality), intercalations of allochthonous bioclastic packstones and grainstones increase, which were generated at the margin of the coeval Montejunto shallow-water platform. This platform developed on a fault block-related salt pillow. It is slightly progradational and rimmed by a grainstone shoal. Patch reefs occur in the inner platform area (mostly coral bafflestones) and on the upper slope (crust-rich coral-chaetetic boundstones with occasional siliceous sponges) (ELLIS et al. 1990; unpubl. results).

Abadia beds and equivalents: The Upper Jurassic second rifting phase of the Lusitanian Basin had its maximum peak in the uppermost Oxfordian to Lower Kimmeridgian and led to the onset of siliciclastic sedimentation over formerly carbonate-dominated areas. In the Montejunto region, the deeper water marl/sandstone/limestone succession of the ammonite-rich Tojeira facies (lower Abadia beds) superimposes the Montejunto ammonitic limestones. The Tojeira beds contain blocks of karstified shallow-water limestones derived from the now partly or completely exposed Montejunto platform. The overlying Abadia (s. str.) succession is composed of clays and marls, partly with ammonites, and a subordinate amount of sandstone intercalations. Turbiditic sandstones, mud pebble breccia, gravitational slumps and clinoforms observed in seismic sections (LEINFELDER & WILSON

1989) are indicative for a huge progradational slope system. The Abadia beds shallow upwards, as is obvious by an increasing content of benthic fauna. In the higher part of the unit, around Arruda-dos-Vinhos, a condensed level occurs, which is characterized by local ammonite enrichments, iron-impregnated limestones, and a peculiar coexistence of microbial limestones, coral meadows, siliceous sponges and benthic mollusc fauna (Serra Isabel level, cf. Fig. 20). Also, coral meadow and crust-rich facies which may contain siliceous sponges are locally frequent in the uppermost part of the Abadia beds.

Towards the east, the lower Abadia beds pass laterally into thick and coarse siliciclastic arcotic conglomerates, containing basement pebbles and large clay boulders. These Castanheira conglomerates represent a local, though huge alluvial / submarine fan system. Relics of local coral reefs (Monte Gordo and Castanheira) are preserved within and on top of the fan system (LEINFELDER & WILSON 1989, LEINFELDER 1993). The Monte Gordo reef contains siliceous sponges associated with corals in its middle part.

Towards the northeast, on an uplifted basement block, another coral-reef rimmed narrow carbonate platform (Ota Limestone) developed during the time of the higher Abadia (LEINFELDER et al. 1988, LEINFELDER 1993). No siliceous sponges were detected from the Ota coral reef (LEINFELDER 1992).

The thickness of the Abadia beds is in the order of 800 metres. From seismic interpretation, the thickness of the prograding unit is 500 metres, the Castanheira conglomerates below reach a local thickness of 2200 metres in a structural low at Arruda (LEINFELDER & WILSON 1989).

The lower part of the Abadia beds (s. l.) is well dated in the Montejuno area, where the late Upper Oxfordian to Upper Kimmeridgian (bimammatum to acanthicum zone) is well established (ATROPS & MARQUES 1986, 1988). Around Arruda most ammonites from the upper part of the Abadia indicate the hypselocyclum to divisum zone (particularly within the Serra Isabel level) and, possibly, acanthicum zone. The exact age of the upper boundary is not clear: ATROPS & MARQUES (1988) postulate an extended duration of the Abadia beds into the Lower Tithonian, on grounds of ammonites of the hybonotum zone. These ammonites were found in the supposed top of the Abadia beds in the eastern part of the Arruda sub-basin. Structural and facies relations are complicated in that area (cf. LEINFELDER & WILSON 1989) and we assume that the specimens stem from the Sobral unit or younger units exhibiting similar facies.

Amaral beds: The Amaral beds can be differentiated into a lower unit rich in coral boundstones (Corálico), and an upper unit of oolitic grainstones with occasional intercalations of marine sandstones and marls (Oólito). Thicknesses are highly variable; the average thickness is around 30 to 40 metres. Within the Corálico, coral boundstones rich in microbial crusts, coral-stromatoporoid framestones and bioclastic, oncolitic wackestones, packstones, grainstones and rudstones are intercalated. Although coralline sponges are frequent, no siliceous sponges could be detected (Nose in prep.). Based on ammonite datings derived from under- and overlying units, the Amaral unit should comprise the eudoxus zone, although the exact age of its upper and lower boundary is not clear.

Younger units: The younger Upper Jurassic units overlying the Amaral beds are represented, from base to top, by (1) marls and marine to terrestrial sandstones of the Sobral estuarine delta, (2) the Arranhó nodular shallow-water marly limestones and marls which are rich in bivalves and locally contain coral biostromes (formerly termed "Pteroceriano" beds), and (3) the Freixial beds, a Purbeck-type sequence of foraminiferal and dasycladacean shallow-water limestones and marls of a variable salinity regime which intercalate with red beds (RAMALHO 1971, LEINFELDER 1986, 1987). No siliceous sponges could be detected.

Siliceous sponge-bearing facies from Portugal

In the Portuguese Upper Jurassic, siliceous sponges are characteristic and diagnostic, sometimes even dominating members of a variety of reef facies. We interpret siliceous sponges as important environmental indicators and hence use the term "siliceous sponge facies" in a broad sense, where siliceous sponges may but need not dominate the macrofauna. Likewise, the term "reef facies" is understood in a broad sense. It includes level-bottom fossil communities characterized by epibenthic reef fauna (potential reef-building organisms, such as corals and sponges) as well as buildups mainly produced by reef fauna or by microbial crusts together with varying amounts of reef macrofauna and lime mud.

To date, siliceous sponge taxa of the Portuguese Upper Jurassic were only determined from a well at Sines and from the Algarve Basin (ROSENDAHL 1985, TERMIER et al. 1985a, b). Our collections yielded the first entirely preserved specimens of siliceous sponges, from marly deposits, particularly from one level at Rocha (Fig. 4). At Cotovio, a similarly rich horizon could be detected. Additional entire, partly determinable sponges from hard limestones were obtained by means of a portable motorized rock saw.

The "Lithistida" represent a polyphyletic group (e. g. BURTON 1929) and presently are splitted into different taxonomic units. These are distinguished by morphological differences of their microscleres. However, such differentiation is not possible using fossil material. Therefore we still use the term "lithistids", though in a purely descriptive sense, i. e. all siliceous demosponges with "desmas" as skeletal elements. The siliceous sponge groups Dictyida and Lychniscida, both members of the Hexactinellida, are also known today as Hexactinosa and Lychniscosa, respectively (MEHL 1992).

Preservation of the sponges is occasionally good, but most of the time poor. The sponge skeletons were diagenetically altered in different ways. Dictyid and lychniscid skeletons were mostly calcified but sometimes show partial dissolution or micritization. The skeletons of "lithistid" sponges are altered through accretionary crystallisation. Desmas thickened and the skeletons sometimes appear very atypical in thin section. Hence, siliceous sponges from unorientied thin sections can be only attributed to a certain sponge group or

Fig. 4. Siliceous sponges from the Upper Jurassic of Portugal.

(a-c) the dictyid *Tremadictyon* sp., Rocha meadow, eastern Algarve

(d-f) the dictyid *Craticularia* sp., Rocha meadow, eastern Algarve

(g) the lithistid *Cnemidiastrum* sp., Alfaroibeira Section, eastern Algarve (polished slab)

(h) long shafted, isolated monaxons and tetraxons, probably representing a tetractinellid sponge, associated with corals (upper left and lower right), Arruda-dos-Vinhos, Serra Isabel level, Lusitanian Basin (thin section)

(i) lychniscid sponge, Tavira beds, eastern Algarve (thin section)

Length of bar: a-f: 10 mm; g: 5 mm; h: 0.5 mm; i: 1 mm, for close-up: 0.15 mm.

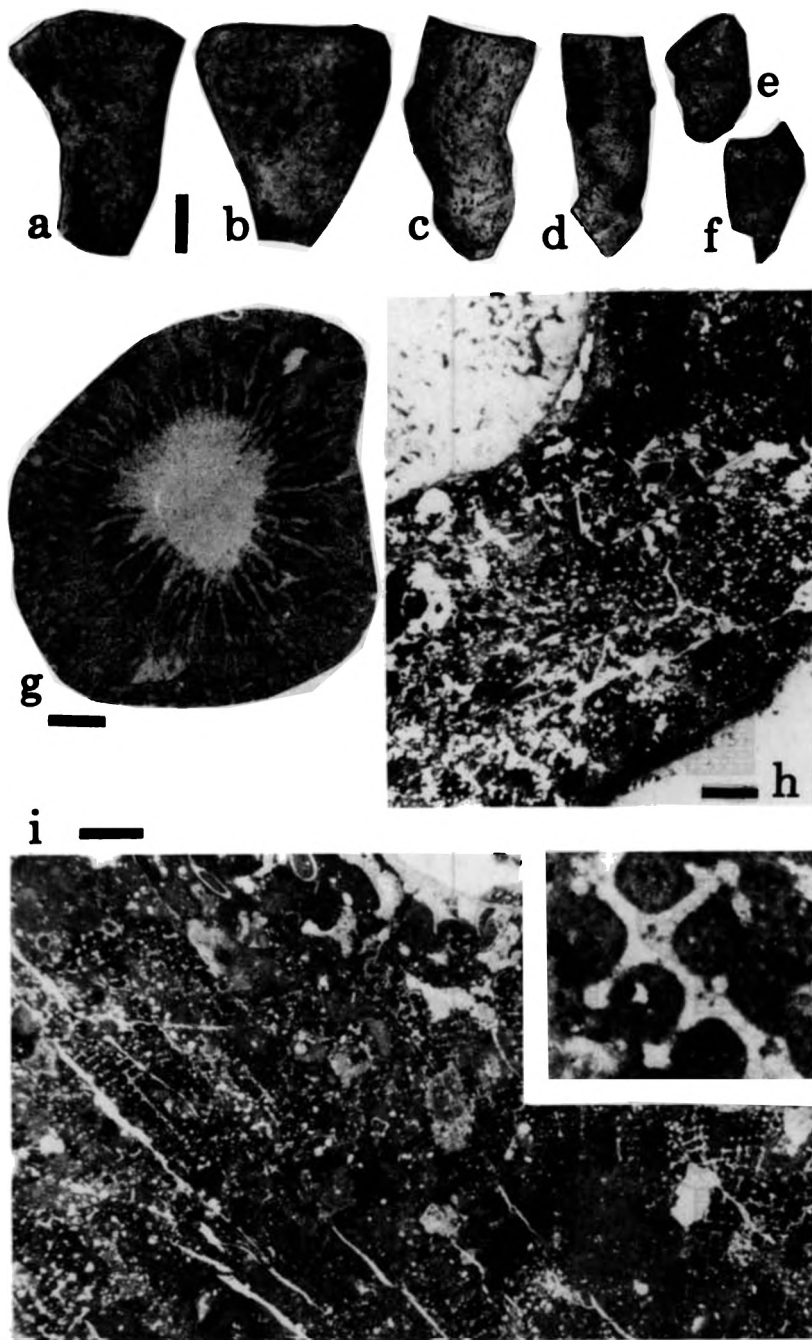


Fig. 4 (Legend see p. 208)

subgroup, if any. Concentrations of long shafted, isolated spicules, which are either monaxons or tetraxons, occur frequently at some localities. Most likely, they represent relics of tetractinellid siliceous sponges (e. g. Choristida) (GERLOFF 1983, KEUPP et al. 1989). Since monaxon spicules do, however,

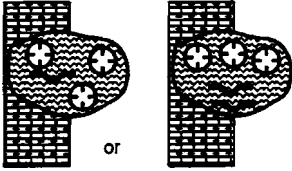
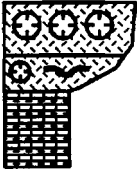
	dimensions	distribution of siliceous sponge types	type example in section:
1 sponge meadow - facies crusts subordinate or lacking 	dm - 3 m	low-diversity hexactinellid or lithistid association	Rocha, Tavira (Algarve)
2 sponge-crust-mud - facies 	1 - 20 m	frequent lithistids + hexactinellids	Alfarrobeira (Algarve)
3 sponge-bearing thrombolites 	dm - 30 m	rare hexactinellids, occasionally additional lithistids	Rocha (Algarve)
4 coral-sponge thrombolites 	up to a few m	lithistids, rarely with hexactinellids	Serra Isabel (Lusitanian Basin)
5 sponge-bearing coral-debris - facies 	up to tens of m	lithistids, rarely with hexactinellids	S. Bras (Algarve)

Fig. 5. General characteristics of siliceous sponge facies types from the Upper Jurassic of Portugal.

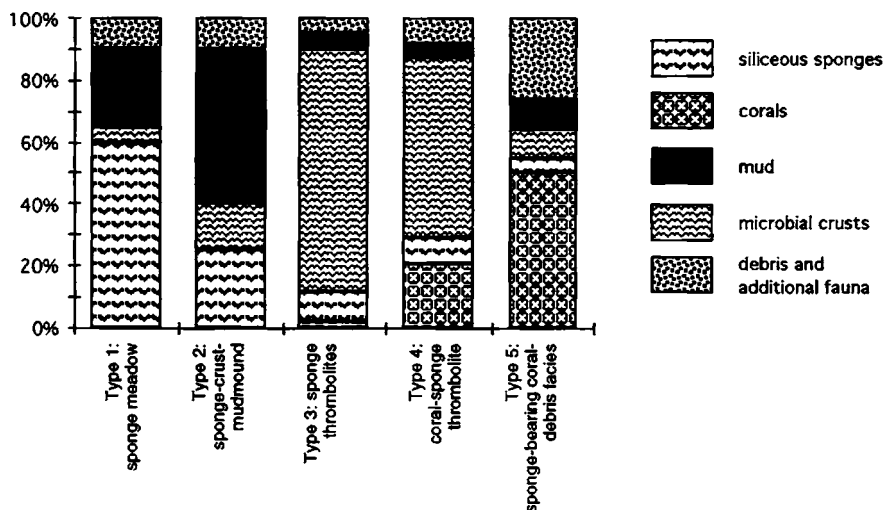


Fig. 6. Composition of siliceous sponge facies types, based on semiquantitative analysis and estimations using thin sections, polished slabs and field cuts.

Locality	Type	Relative frequency	determinable taxa	Glaucinite
Rocha	1		<i>Craticularia parallela</i> (GOLDFUSS), <i>Tremadictyon</i> sp., <i>Stauroderma</i> sp., <i>Tremadictyon reticulatum</i> (GOLDFUSS), <i>Craticularia?</i> sp., <i>Tremadictyon</i> sp., <i>Stauroderma lochense</i> (QUENSTEDT), <i>Walcotella?</i> sp., <i>Platychonia auriformis?</i> (QUENSTEDT)	+
Alfarrobeira	2		<i>Cnemidiastrum</i> sp.	++
various localities	3		<i>Pachyleichisma</i> sp., <i>Craticularia?</i> sp.	++++
Serra Isabel	4		<i>Cylindrophyma milleporata</i> (GOLDFUSS), <i>Hyalotragos?</i> sp., <i>Craticularia</i> sp., <i>Cypellia rugosa</i> (GOLDFUSS)	+
São Bras d'Alportel	5		<i>Platychonia?</i> sp., <i>Cylindrophyma?</i> sp., <i>Hyalotragos?</i> sp.	-

Dictyida Lychniskida "Lithetida"

Fig. 7. Composition of siliceous sponge fauna, determinable sponge taxa and glauconite content from various examples.

occur in many other sponge groups, these isolated spicules are not regarded in the semiquantitative analysis of sponge faunas given here (cf. Fig. 7).

The determination of siliceous sponges presented in Fig. 7 shows that apparently no endemic species occur. All sponges identified at the generic as well as at the species level are known from the sponge facies belt extending along the northern Tethyan shelf (e. g. TRAMMER 1979, 1982, PISERA 1991, KRAUTTER in prep.).

Facies types

The Portuguese siliceous sponge occurrences allow to establish five major sponge-bearing facies types, which can be defined according to (1) faunal composition, (2) degree of reefal organisation (meadow - biostrome - rigid framework), and, to a lesser degree, (3) framework morphology (Figs. 5, 6, 7);

The relative compositional proportions were estimated by using field cuts and polished slabs.

Facies Type 1: Siliceous sponge meadows

As sponge meadow facies or biostromal facies we classify bedded spiculites of the Jordana beds and the Montejunto deep-water facies (1a) as well as marly or

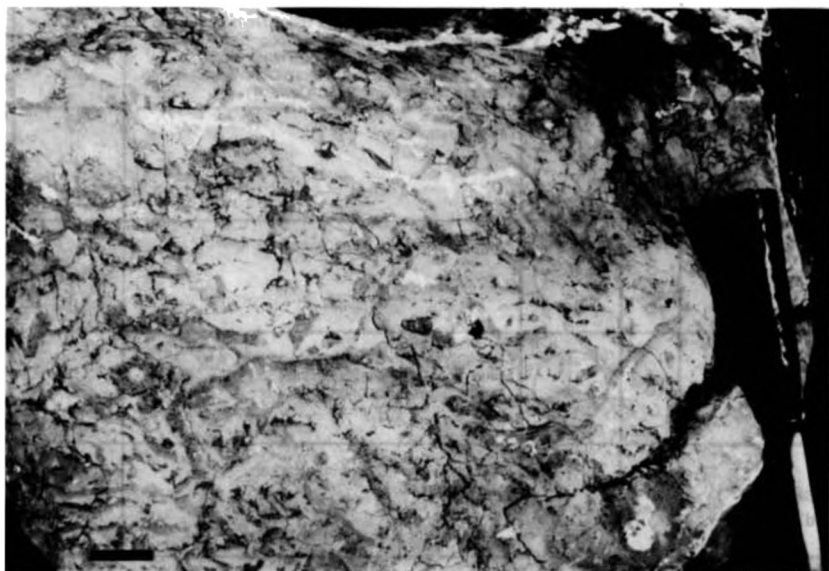


Fig. 8. Siliceous sponge meadow facies (facies type 1c). Platy "lithistid" sponges are embedded in a micritic matrix. Microbial crusts occur subordinately. Length of bar is 4 cm. Tavira quarries, eastern Algarve.

calcareous siliceous sponge meadows without (1b; Rocha) or with crusts (1c; Cotovio, lower Tavira beds). The benthic fauna is largely dominated by siliceous sponges. Specimens may be small or large, but show similar size distribution within one meadow. Within one locality, one morphotype and one sponge group dominate largely (e. g. small cup-shaped hexactinellids at Rocha; large platy "lithistids" at Tavira; Fig. 8). Type 1 sponge facies sometimes contains varying amounts of authigenic glauconite. Thickness of the sponge meadow facies varies from 10 cm (Rocha) to 3 metres (Tavira).

Facies Type 2: Siliceous sponge mud mounds

This type develops gradually from bedded hemipelagic limestones and marls. Mounds have an indistinct low-relief shape and are composed of small massive lenticular bodies situated within irregularly waxing and waning beds. Heights vary from 1 to a few metres to a maximum of 25 metres. Type 2 occurs at several sites within the Peral beds, particularly at Alfarrobeira.

The richness of lime mud (up to 50 vol.%, Figs. 6,9) together with the indistinct buildup morphology justifies a classification as mud mound. Siliceous sponges amount to about 25% and are dominated by dictyids, although "lithistids" and some lychniscids occur as well (Fig. 7). Long shafted, isolated spicules

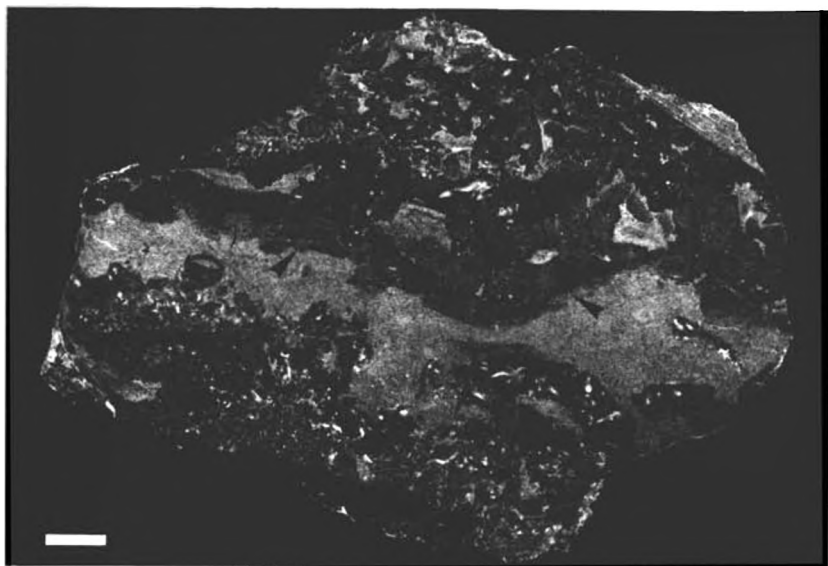


Fig. 9. Siliceous sponge mudmound facies (facies type 2). Platy sponge (arrows) is intensively overgrown by microbial crusts exhibiting clotted fabric. White dots represent *Tubiphytes*. Note richness in lime mud. Polished slab. Length of bar is 1 cm. Alfarrobeira Section, eastern Algarve.



Fig. 10a



Fig. 10b

Fig. 10a, b. Large cup-shaped thrombolitic biohermal structures (facies type 3) standing close to each other. The horizon is intercalated in the marly Peral beds, rich in ammonites. (a) Oblique view of bedding plane; (b) lateral view of one thrombolitic cup. Length of hammer is 28 cm. Cotovio Section, eastern Algarve.

which are not attributable to a certain sponge group are also common. Microbial crusts are typically developed both on sponges and within the mud, but do normally not exceed 15-20%. Additional elements are ammonites, brachiopods which often occur in clusters, pectinacean bivalves, bryozoans, serpulids and the coralline sponge *Neuropora spinosa*.

Authigenic glauconite is common in the type 2 facies (Fig. 7).

Facies Type 3: Siliceous sponge-bearing thrombolites

Type 3 is the dominant siliceous sponge-hosting facies in the eastern Algarve Basin, but also occurs in the central Lusitanian Basin (facies type 3). The very distinct reef bodies range from 10 centimetres up to 30 metres (Rocha) in height; smaller examples may occur in clusters (Cotovio; Fig. 10). The reefs are almost exclusively composed of dense ("micritic") to peloidal crusts with a typical thrombolitic clotted fabric (cf. AITKEN 1967, RIDING 1991) (Figs. 6, 11). Sometimes, an indistinct stromatolitic lamination occurs. The microbial origin of these crusts is substantiated by their dome-shaped to branching upwards

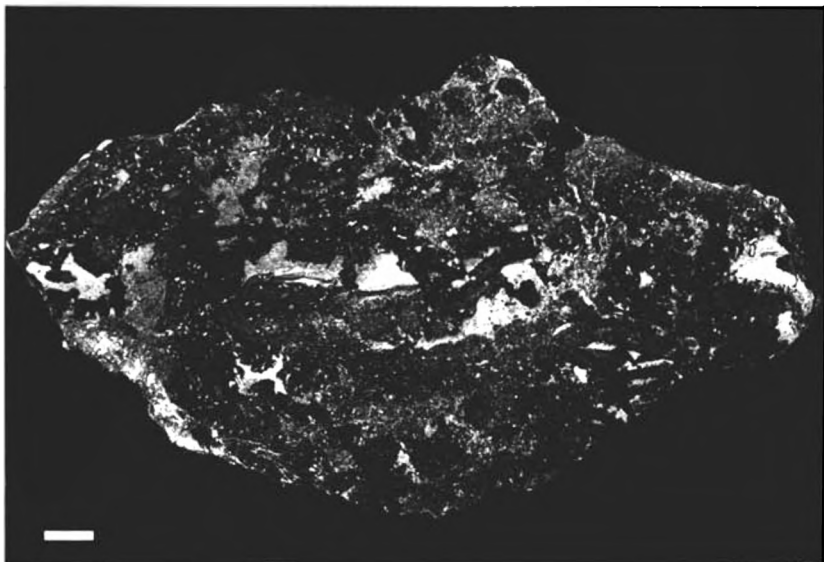


Fig. 11. Thrombolite containing rare siliceous sponges (arrow), exhibiting the typical clotted fabric (facies type 3). White dots are *Tubiphytes*. Lime mud, which is rich in glauconite, only occurs within cavities formed by the microbial crusts. Polished slab. Length of bar is 1 cm. Rocha thrombolite, eastern Algarve.

growth, by peloids aligned in rows and arrays, and by their intimate association with encrusting organisms such as thecideidinid brachiopods, bryozoans or *Tubiphytes*. The latter often seems to be integrated within the dense crusts. The lithified nature of the microbial crusts is evident by occasional to frequent overgrowth by serpulid worms and occasional borings made by lithophagid bivalves. Siliceous sponges, amongst these almost exclusively dictyids, occur in percentages up to about 15% of rock volume, but are commonly only accessory though characteristic dwellers. Generally, their body size is small, not exceeding a few centimetres. Long shafted, isolated spicules occur occasionally. Larger thrombolites may show some levels with rare, small solitary corals. These thrombolites contain lime-mud only in crust-constructed, up to dm-sized cavities. Another characteristic feature of the thrombolites is the enormous richness in authigenic glauconite, which is finely distributed throughout the bioherms, but particularly enriched in mud-filled cavities and on the outer surfaces of the buildups, giving some of them a grass-green colouration. Type 3 bioherms were detected at certain levels within the Peral beds (Algarve), particularly in the upper and topmost part (Rocha, Albufeira, Tavira, Cotovio, São Bras) and at some sites within the Serra Isabel level (Lusitanian Basin).

Facies Type 4: Siliceous coral- sponge thrombolites

Type 4 is the dominant siliceous sponge-hosting facies type in the Lusitanian Basin (particularly Serra Isabel level), but also occurs in the Algarve Basin (Tavira, São Bras, Cotovio). Bioherms are again thrombolitic and may attain sizes up to several metres. Authigenic glauconite occurs in low amounts. The characteristic feature of this type is the co-occurrence of siliceous sponges together with hermatypic corals, the latter of which outnumber the sponges. Dictyid, lychniscid and "lithistid" sponges occur likewise. Long shafted, isolated spicules are also common.

Two subtypes occur:

a) Coral-rich thrombolites containing, in addition, siliceous sponges in a notable number (Fig. 12). Corals and siliceous sponges may overgrow each other. This type occurs at Serra Isabel (Abadia beds, Lusitanian Basin), Tavira (Tavira beds, eastern Algarve), Cotovio (Peral beds and base of Cabeça, eastern Algarve) and West of Rocha (Peral beds, eastern Algarve), and forms structures up to 4 metres, rarely up to 10 metres thick.

b) Thrombolites with upward transition from siliceous sponge facies to coral facies. This type is characterized by representing a small scale succession from sponge-bearing thrombolites to coral-rich thrombolites, which are devoid of siliceous sponges. Sponges may attain fairly large sizes, up to 20 centimetres. The transition occurs (in one bioherm or biostrome) within a vertical distance of several decimetres (Fig. 13). Type 4b examples are up to 6 metres thick (Serra Isabel level, Lusitanian Basin).

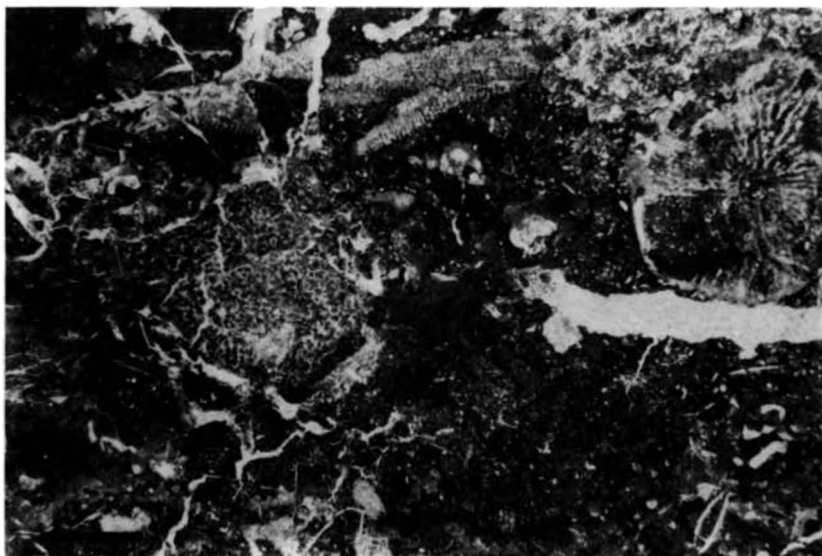


Fig. 12. Coral / siliceous sponge facies, rich in microbial crusts (facies type 4a). Corals (at right margin and top centre) and "lithistid" sponges (centre left) occur together within dense microbial crusts. Thin section. Length of bar is 5 mm. West of Rocha, eastern Algarve.

Facies Type 5: Mixed coral - siliceous sponge debris facies

The mixed coral - siliceous sponge facies differs from type 4a in the lesser occurrence of microbial crusts which may be frequent yet do not dominate. Corals and, to a lesser extent, stromatoporoids of various types and growth forms occur with siliceous sponges in variable proportions and sizes (Fig. 14). Siliceous sponges are dominated by "lithistids", but lychniscids and dictyids as well as long shafted, isolated spicules also occur. Common are also the coralline sponges *Neuropora spinosa*, *N. lusitanica*, *Corynella* aff. *quenstedti* and *Thalamopora lusitanica*. *Tubiphytes*, *Terebella* and serpulids are frequent in the occurring crusts. Decimetre-sized boundstone patches are rare: mostly, the reefal organisms and additional biogenic elements (e. g. thick-shelled bivalves, gastropods, some brachiopods) are fragmented and embedded in a bioclastic to intraclastic, unsorted, allodapic sediment which varies between rudstone and floatstone fabric (depending on the site). Type 5 facies is widespread in the Upper Tavira beds (Algarve), and occurs at the base and within the Cabeça beds (São Bras; Algarve), as well as in the entire Lusitanian Basin and the S. Tiago do Cacém area. Type 5 facies and partly, type 4a facies, largely correspond to the "microfaciès récifal à organismes encroûtants" described by RAMALHO (1971) from the Lusitanian Basin.



Fig. 13a



Fig. 13b

Fig. 13a, b. Details of a lenticular reefal limestone bed, with siliceous sponge-bearing thrombolite at base (a; with the "lithistid" *Cylindrophyma* sp.), grading into a highly diverse coral association a few decimetres above (b) (facies type 4b). Sponge in (a) is 20 cm long; hammer in (b) is 15 cm long. Serra Isabel level, northeast of Arruda-dos-Vinhos, Lusitanian Basin.



Fig. 14. Mixed coral-siliceous sponge debris facies (facies type 5). Siliceous sponge (left), coral (right) and chaetetid (centre) occur together within a mud-rich bioclastic matrix. Thin section. Length of bar is 5 mm. Tavira quarries, eastern Algarve.

Siliceous sponge distribution pattern

The relative frequency of basic siliceous sponge groups from the different facies types is given in Fig. 7. A remarkable trend is the decrease of dictyid sponges from facies type 2 and 3 towards type 5 in favour of an increase of "lithistid" sponges. "Lithistid" and, to a lesser extend, lychniscid sponges are particularly common in types 4 and 5 which are characterized by a high content of hermatypic corals. This can be interpreted as a bathymetric trend, with dictyid sponges preferring deeper water, whereas "lithistid" and lychniscid sponges tolerate shallower environments (see below). Preservational bias can be largely ruled out, since all sponge groups occur, with varying proportions, in all compositional types.

The distribution pattern of sponge groups for facies type 1 is represented by the Rocha meadow in Fig. 7. The sponge fauna is mainly composed of dictyids and hence coincides well with the above mentioned bathymetric trend. However, this cannot be regarded as a general feature for sponge meadows, since type 1 meadows and biostromes are variably dominated either by dictyid or by "lithistid" forms. Thus no characteristic overall pattern can be given for type 1. The other examples based on quantitatively collected specimens (Fig. 7)

clearly reflect an overall trend, since similar patterns can be also verified in sponge localities which only can be studied by qualitative to semiquantitative thin section and polished slab analysis.

Occurrences and successions of siliceous sponge facies

Eastern Algarve Basin

Siliceous sponge-bearing facies of the eastern Algarve Basin occur at distinct levels within the Peral, Jordana, Tavira and, to a lesser extent, Cabeça beds. Maximum occurrence of sponge facies is at the Peral/Jordana transition and within the Tavira facies.

Albufeira: The Albufeira section shows the upper Peral and the superimposed Cabeça coral limestones. It was described by ROSENDAHL (1985) who mainly focused on the coral limestones. Due to a large landslide, the Cabeça outcrop is meanwhile mostly destroyed. However, the landslide caused a better outcrop situation of the Peral beds and revealed a large thrombolitic bioherm rich in siliceous sponges about 20 metres below the Cabeça base. The type 3 thrombolitic body is 7 metres long and 4 metres high. It is very rich in glauconite and contains frequent *Tubiphytes* and serpulids. Parts of the crusts exhibit a tuberolitic fabric. The thrombolite contains small cavities which are filled with a detrital facies rich in echinoid and mollusc debris, also containing lignitic debris. The walls and particularly roofs of the cavities are encrusted by serpulids, bryozoa ("*Berenicea*"), thecideidinid brachiopods and cementing bivalves (*Atreta*), which also occur occasionally throughout the thrombolite. The content of, exclusively dictyid sponges (e. g., craticulariid forms) is very low. They are sometimes infested by coelobitic foraminifera ("*Thurammina*"). Furthermore, rare and small terebratulids, some cidaroid spines, rare gastropods and lithophagids and very rare solitary corals were detected. Ammonite fragments were found in the surrounding Peral beds.

Alfarrobeira: A part of the Alfarrobeira section, taken along the road from Loulé to Faro is shown in Fig. 15. The section displays a typical Peral facies development of bedded limestones and marls, with intercalations of quartz-rich intraclastic packstones and extends to the top part of the unit. Typical faunal elements are ammonites and planktic crinoids (*Saccocoma*). The superimposed Jordana and Cabeça beds are extensively dolomitized (Dolomite of S. Barbara de Nexe). Spiculitic layers (type 1a facies) occur at various levels within the Peral beds. A fairly high number of siliceous sponges (e. g. the "lithistid" *Cnemidiastrum* sp.; Fig. 4g) occurs in the middle and top part of the section where the bedding becomes indistinct and grades into 25 metres of type 2 mud mound facies characterized by a high content of microbial crusts rich in *Tubiphytes* (Fig. 9). Glauconite is fairly common both in the micritic matrix and the crusts. Within the micrite, tuberooids are frequent. Dictyid sponges, partly with "*Thurammina*" infestation, dominate, but "lithistids" and lychniscids occur

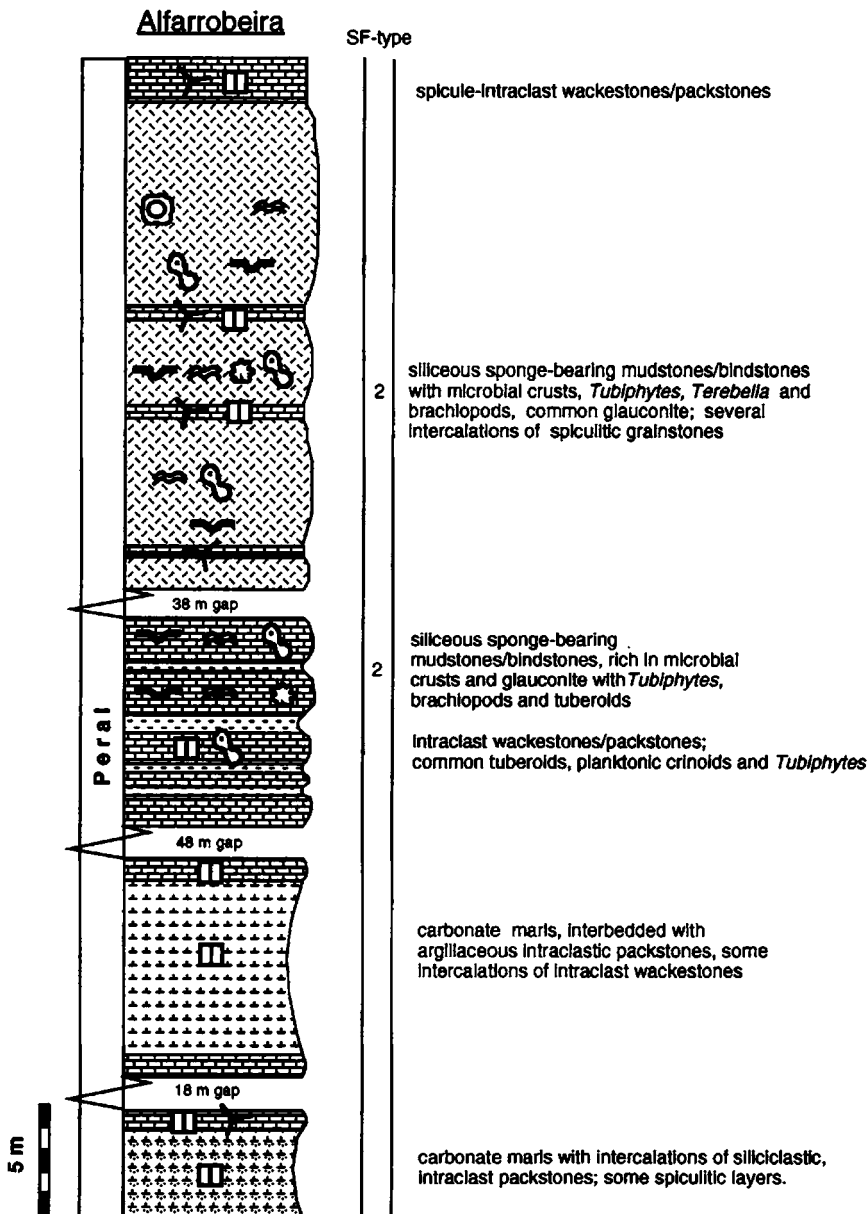


Fig. 15. Alfarrobeira Section, upper part, eastern Algarve (for location see Fig. 2). SF-type: sponge facies type (also for other sections).

occasionally. Serpulids and *Terebella lapilloides* are common. Terebratulid and rhynchonellid brachiopods occur in clusters. One solitary coral and *Neuropora spinosa* were also detected. A similar facies and fauna also occurs in the lower part of the section (Fig. 15).

Rocha: A situation similar to Albufeira, yet at a much larger scale, exists at the site Rocha (Fig. 16). Here, sponge-bearing thrombolites (type 3) with a thickness of 30 metres are intercalated between the Peral and Jordana units. The bioherm was discovered and first described by RAMALHO (1988) who mentioned the enormous amount of algal (i. e. microbial) crusts and the fairly low content of siliceous sponges. Additional sampling allows now to present a more detailed section of the spectacular thrombolite succession. In addition, a level with three, slightly marly horizons which are very rich in small, mostly cup-shaped dictyid sponges was discovered.

The thrombolites are underlain by the marly to micritic Peral unit which contains abundant ammonites. A find of *Creniceras dentatum* within the thrombolites is diagnostic for the hyselocyclum to eudoxus-zone. The top of the Peral beds is characterized by a marly limestone bed with a considerable content in glauconite, which is particularly enriched in sediment-filled *Planolites* burrows. Fine bioclastic debris is also common. Cauliflower and pillow-type thrombolites very rich in glauconite compose the majority of the section (Fig. 11). The amount of *Tubiphytes*, serpulids and siliceous sponges varies considerably; *Tubiphytes* is extremely abundant in some levels, whereas siliceous sponges only occur very subordinately within the thrombolites. They are dominated by dictyids, although lychniscids (e. g. *Pachyteichisma* sp.) and, rarely, "lithistids" occur as well. Crusts in the middle and topmost part of the thrombolites commonly display a stromatolitic columnar habitus and are partly rich in additional encrusting organisms (cf. RAMALHO 1988). Rare and small corals (*Goniocora*, cf. *Stylosmilia*) have been found between metre 6 and 9. As in the Albufeira example, lignite debris can occur within cavities. Small ammonites are also concentrated in some cavities. Particularly in the middle part, the thrombolite development is occasionally interrupted by Peral-type or Jordana-type micritic and debris facies, containing ammonites, belemnites, small mollusc and echinodermal debris, planktic crinoids (*Saccocoma*), abundant tuberooids and again lignite debris. Most of these intercalations seem to wedge out after a short lateral distance and apparently represent debris aprons channeled downslope between thrombolite pillows. Between metre 18.5 and 22 the marly intercalations contain abundant, up to 5 centimetre large, cup-shaped dictyid sponges (*Craticularia* sp., *Stauroderma* sp., *Tremadictyon* sp., Fig. 4a-f), representing a single-population type 1b meadow. Additional meadow elements are the coralline sponge *Neuropora spinosa*, *Isocrinus* and echinid skeletal parts as well as many small ammonites. The intercalation in the middle is the most complete. The composition of the sponge fauna of this level is given in Fig. 7. The top of the thrombolite is overlain by 1 metre of dark marls, followed by Jordana beds which are very rich in spicula and silica nodules (type 1a facies).

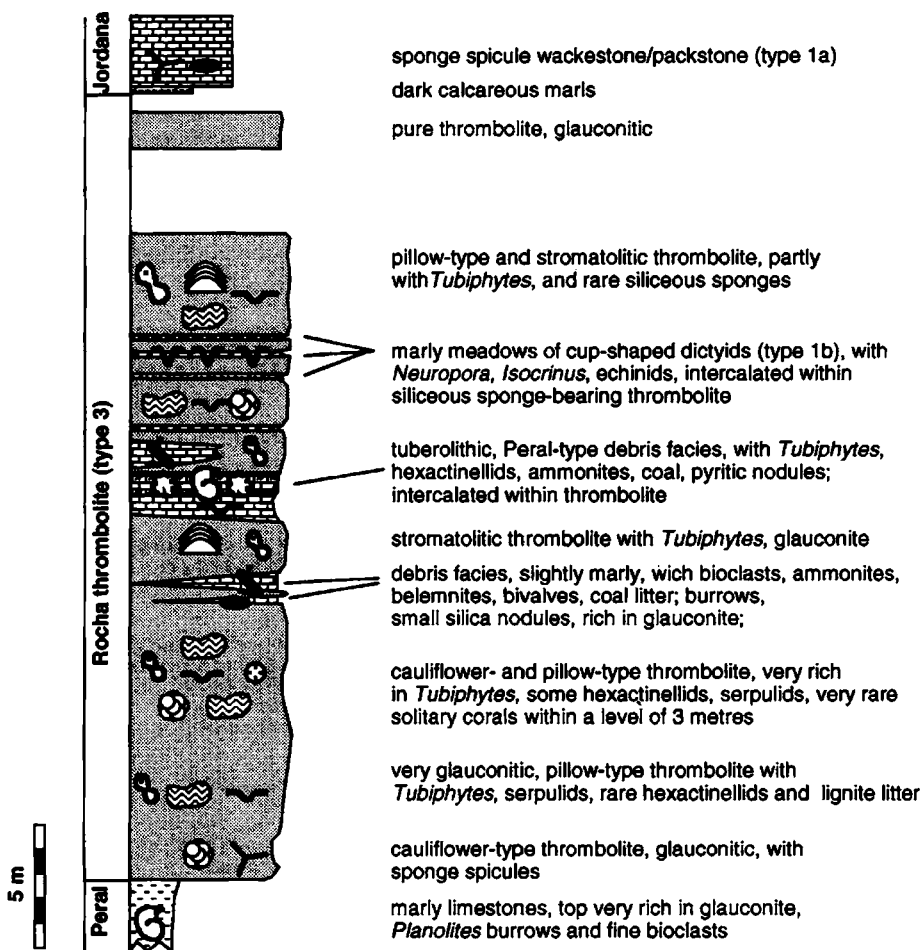
Rocha

Fig. 16. Rocha Section, upper part, eastern Algarve (for location see Fig. 2).

West of Rocha: 300 m to the west of the above site, more thrombolitic sponge bearing facies was detected within the Peral beds. Although containing orthosphinctids, no age-diagnostic ammonites were found. According to structural evidence we assume a position in the middle part of the Peral unit.

Decimetre to metre-sized allochthonous, irregularly distributed boulders, associated with some beds of allochthonous grainstones and packstones are situated within a Peral marl-sandstone succession. Due to suitable cuts a three-dimensional outcrop examination was possible revealing that blocks lie within

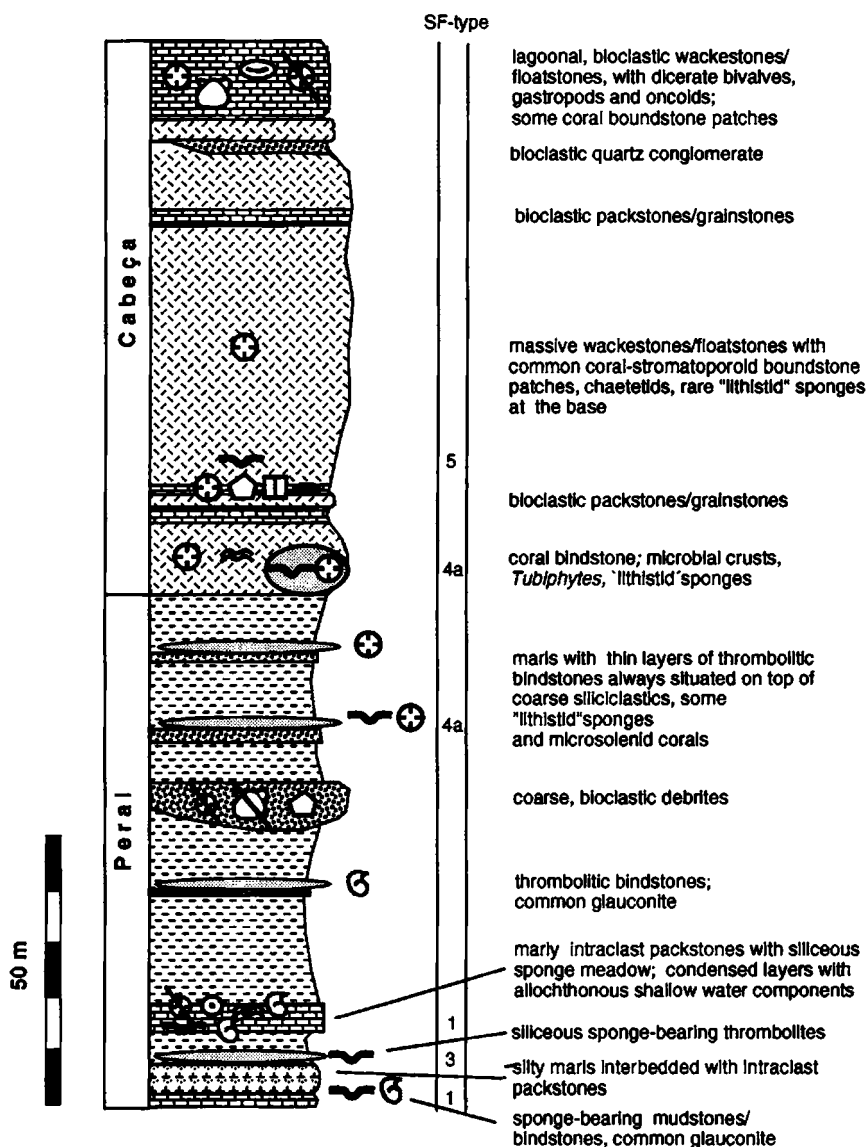
Cotovio

Fig. 17. Cotovio Section, eastern Algarve (for location see Fig. 2).

a shallow channel several tens of metres wide, which gently slopes towards WSW. Some blocks represent crust-rich coral bafflestone and boundstone facies, others show a mixed coral-siliceous sponge-crust association (type 4a; Fig. 12), whereas some are purely thrombolitic, containing additional sponges (type 3). The mixture of different boundstone facies suggests that the blocks are derived from different water depths and were transported along a canyon system towards deeper water, where they are preserved in the distal part of the channel. Possibly, the walls of the proximal canyon were covered by bioherms at different water depths. The allochthonous nature of the largest boulder could be additionally proven by an upside-down geopetal fill within a brachiopod shell.

Cotovio: The section at Moinho de Cotovio (Fig. 17) comprises a major part of the Peral beds, which exhibit a wide range of facies at this locality, and the Cabeça beds. The predominantly marly Peral succession contains several horizons of bioclastic sandstones as well as bioclastic quartz debrites with quartz pebbles up to 20 centimetres in diameter. The lower part is limestone-dominated and contains a glauconitic bioclastic packstone layer, rich in allochthonous ooids and debris of hermatypic corals, a crust-rich ammonite-brachiopod shell concentration with hardground characteristics, and a siliceous sponge meadow (type 1b). The sponge meadow is dominated by cup-shaped dictyids, though some "lithistids" occur as well. The dictyids *Tremadictyon reticulatum*, *Tremadictyon* sp., *Craticularia parallela*, *Stauroderma lochense*, *Stauroderma* sp., *Walcotella?* sp. and the "lithistid" *Platychonia* cf. *auriformis* were determined. Additional elements are *Tubiphytes*, some serpulids, several ammonites and very rare small solitary corals. Thrombolitic bindstones are intercalated at various positions within the Peral: Thrombolites from the lower part of the Peral are of type 3 and contain occasional dictyid sponges. In the lowermost thrombolite levels, 30 to 40 centimetres high, isolated thrombolite cups are developed which stand close to each other (Fig. 10), giving an appearance similar to modern Shark Bay stromatolite cups (cf. GOLUBIC 1991), although the surrounding ammonite facies proves a much deeper growth position than its modern counterpart (see below). *Tubiphytes*, *Terebella lapilloides* and authigenic glauconite is common both within and on the outer surfaces of the cups. Thrombolites from the upper Peral measure 1 to 2 metres in height. They are of type 4a and contain some "lithistid" and many coralline sponges (*Neuropora spinosa*, cf. *Myrmecidium*) together with hermatypic corals (mostly microsolenids). The superimposed Cabeça beds are characterized by high-diversity coral-stromatoporoid wackestones and floatstones with boundstone patches, and intercalations of bioclastic limestones. They locally comprise siliceous sponges, so as to form small patches of sponge-bearing type 5 facies. At the base of the unit, the coral boundstones are rich in microbial crusts and contain metre-sized patches with a mixed coral-"lithistid" sponge fauna (type 4a sponge facies). Superimposed are lagoonal limestones with diceratid bivalves, nerineids, oncooids and small coral boundstone patches, which are devoid of siliceous sponges.

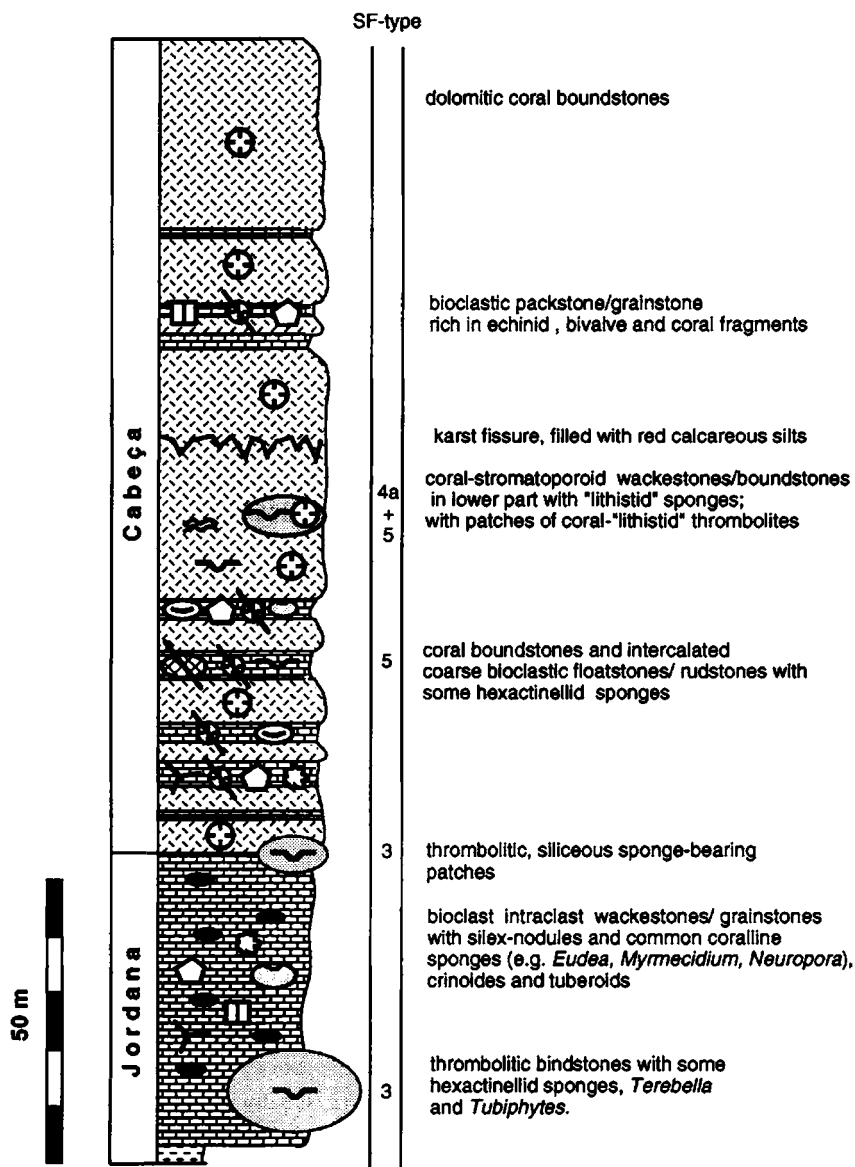
São Bras de Alportel

Fig. 18. São Bras de Alportel Section, eastern Algarve (for location see Fig. 2).

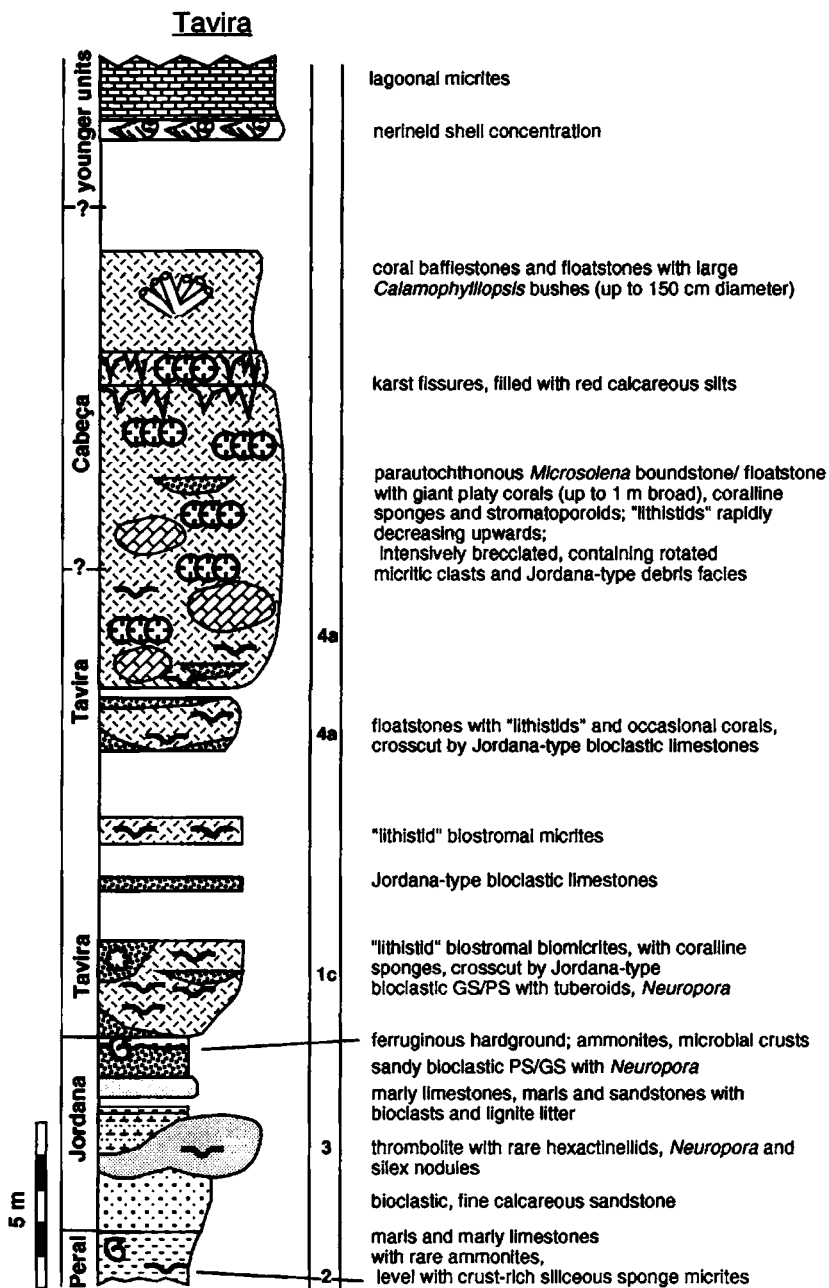


Fig. 19. Tavira Section, eastern Algarve (for location see Fig. 2).

São Bras de Alportel: This section was taken along the road from São Bras to Faro. It comprises the Jordana beds and the major part of the Cabeça beds (Fig. 18). The Jordana beds are typically composed of bioclastic intraclastic wackestones to grainstones containing silica nodules, coralline sponges and echinodermal fragments. Intercalated is a 10 metre thick thrombolite rich in *Tubiphytes* and *Terebella*, which contains some dictyid sponges (type 3). The lateral margins of this thrombolite are very steep, so that the allochthonous debris material obviously could bypass the thrombolite buildup. Another small type 3 thrombolite containing some lychniscid sponges is situated at the transition from the Jordana to the Cabeça beds. The Cabeça beds are represented by coral-stromatoporoid boundstone and bioclastic limestones. Locally, "lithistid" sponges occur both in crust-rich boundstones (type 4a) as well as in the debris facies (type 5). The latter occurrences are fairly rich in very thin, encrusting rhizomorphine sponges. Many other subgroups of the "lithistids" are also represented.

Tavira: Fig. 19 shows a composite section from the Tavira area taken in the quarries to the west of the Sequa river, and two parallel sections taken to the east of the river. 3 to 5 metres below the top of the Peral beds occurs a horizon containing isolated, waxing and waning, up to 2 metres thick thrombolites with dictyid sponges (type 3). Occasionally, the thrombolites are developed on top of a fine-bioclastic, Jordana-type sandstone. An iron-crust rich hardground and channeled Jordana debris facies (fine packstones and grainstones) occur just below the base of the Tavira unit. The Tavira unit exhibits rapid small-scaled facies transitions. Typically it starts with a micritic biostrome facies of platy, rarely columnar "lithistid" sponges which are partly overgrown by thin microbial crusts (type 1c; Fig. 8). Elsewhere, this biostrome facies seems to have gravitationally collapsed and have been incorporated as large, indistinct blocks within sparitic, Jordana-type grainflows and micritic debris flows. These allochthonous sediments contain a high percentage of microsolenid and other corals as well as stromatoporoids, chaetetids and coralline sponges. Jordana-type grainstone and rudstone facies rich in *Neuropora* commonly fills channels cut within the autochthonous sponge biostrome facies as well as within the parautochthonous to allochthonous micritic debris flow facies.

Further up, the biostromal sponge facies grades into a micritic, mixed microsolenid-"lithistid" sponge facies (type 5; Fig. 14) developed as an up to 10 metre thick hard limestone bed. The platy *Microsolena* attains sizes larger than 1 metre, although being only 5 centimetres thick.

Coralline sponges are common and siliceous sponges rapidly disappear. The transition to the Cabeça unit occurs within this bed. The lower part of the bed contains decimetre-sized indistinct micritic areas which appear to be transported, semi-consolidated blocks of sediments. At the top of the massive bed a karst horizon, characterized by reddish carbonate material infilling secondary cavities and fissures, can be widely traced. The age of this horizon is to date

unclear. The Cabeça unit of the Tavira area exhibits a micritic low-energy character, containing up to 2 metres large bafflestones of *Calamophylliopsis* which do not contain siliceous sponges. Lagoonal, diceratid, oncolitic and nerineid limestones represent the top part of the section.

Lusitanian Basin

Montejunto beds: Horizons rich in spicules are common in the bedded deep-water limestones of the Montejunto beds (type 1a). Furthermore, at the mountain road to Pragança below the Montejunto hilltop, siliceous lychniscid

Arruda valley (northern part)

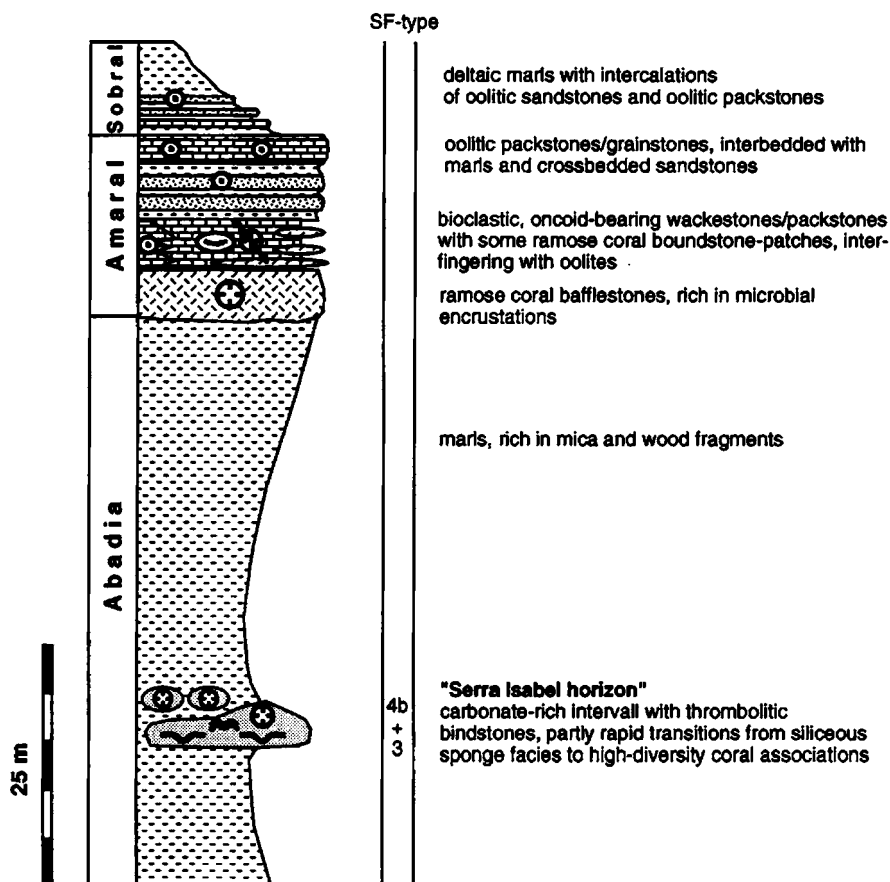


Fig. 20. Section to the North of Arruda dos Vinhos, Lusitanian Basin (for location see Fig. 2).

and "lithistid" sponges occur in coral-dominated patch reefs (SCHERER 1991), situated on the upper slope of the Montejunto shallow-water platform (type 5).

Monte Gordo reef: The 60 metres thick relic of the Monte Gordo reef is intercalated within the Castanheira fan (Abadia beds). It is dominated by corals (e.g. microsolenids, *Calamophylliopsis*, *Stylina*) and contains additional stromatoporoids, molluscs and a high proportion of microbial crusts (LEINFELDER 1993). In its middle part, "lithistid" siliceous sponges and long shafted, isolated spicules occur frequently together with the corals (type 5).

Serra Isabel level: Fig. 20 shows the upper part of the well developed Abadia-Amaral-Sobral shoaling-upwards succession. Different sponge facies types were encountered at various localities within the Serra Isabel level, situated about 30 metres below the top of the Abadia beds. At Serra Isabel decimetre-sized coral-rich thrombolites occur, containing "lithistid" and lychniscid (e.g. *Cypellia rugosa*) siliceous sponges, long shafted, isolated spicules (Fig. 4h) as well as frequent coralline sponges, *Millericrinus* roots, serpulids, *Tubiphytes* and bryozoa (type 4a) (WERNER et al. in press). Further east and west type 4b facies is well developed: At Casal da Lapa, a lenticular biostromal bed with a maximum thickness of 150 centimetres is, at the base, developed as a thrombolite with rare, up to 20 centimetres large siliceous sponges (e.g. the dictyid *Craticularia* sp. and the "lithistids" *Cylindrophyma milleporata* and ?*Hyalotragos* sp: Fig. 13a). Within the same bed and over a vertical distance of only 20 centimetres this assemblage passes into a crust-rich highly diverse coral association containing *Microsolena*, *Trochophlegma*, *Dermosmilina*, *Calamophylliopsis*, *Isastrea*, *Thecosmilina* and others as well as coralline sponges (*Thalamopora lusitanica*, *Neuropora spinosa*, *Myrmecidium*, *Peronidella*), echinids, terebratulids and some bivalves (Fig. 13b). Similar situations exist further west, where type 4a facies attains a thickness of 6 metres. Elsewhere, *Tubiphytes*-rich thrombolites containing extremely rare to occasional siliceous sponges (type 3) occur as lateral equivalents and form bioherms up to 7 metres high (Casal do Carvalho). The highly differentiated sedimentology and palaeoecology of the Serra Isabel level will be the target of a more detailed case study (in prep.).

Sintra area (outcrops): The dictyid *Craticularia* and spicules occur in shales and bedded limestones within the Ramalhão and, particularly, Mem Martins beds, which are partial equivalents of the Abadia beds. They represent sponge meadow facies (type 1b) situated on a limestone-dominated muddy low energy ramp (RAMALHO 1971, ELLIS et al. 1990).

Other localities and borehole occurrences: Siliceous sponges occur very rarely as additional elements within coral / coralline sponge-dominated facies in the shallow-water carbonates of the Montejunto unit at Serra d'el Rei and Columbeira (to the north of the Montejunto). Similar type 5 facies is more widespread towards the south where it was encountered in the Upper Oxfordian to Lower Kimmeridgian from the Lisbon area (borehole Monsanto #1 and

Barreiro #2, #4, RAMALHO 1971 and unpubl. results). The Barreiro buildup represents a coral-rich structure capped by spicule-rich *Tubiphytes* wackestones and siliceous sponge-bearing thrombolites, which is interpreted to represent a drowning event by ELLIS et al. (1990). Further south, at S. Tiago do Cacém, situated halfway between the Lusitanian Basin and the Algarve, mixed coral-siliceous sponge facies (type 5) could be dated as Upper Oxfordian to Lower Kimmeridgian (cf. RAMALHO in OLIVEIRA 1984).

Remark on coralline sponge facies

Coralline sponges are very widespread in a large variety of environments within the Portuguese Upper Jurassic (cf. TERMIER et al. 1985a, b). They occur in thrombolitic and non-thrombolitic sponge facies, and may be abundant in both marly and calcareous coral facies. At places, shallow-water facies is dominated by coralline sponges (FÜRSICH & WERNER 1991). Hence, the general occurrence of coralline sponges is of no diagnostic value, particularly for bathymetric interpretation. They are, as a whole however, certainly more frequent in coral facies. A partial exception to this rule are the common sclerosponges *Neuropora spinosa* and *N. lusitanica* which are fairly eurytopic, and often occur in large numbers not only in coral facies but also in siliceous sponge facies. On the other hand, diversity and distribution pattern of coralline sponges at the generic or species level and, to a larger extent, their growth form pattern are valuable tools for establishing environmental gradients between coral and siliceous sponge facies (WERNER et al. in press, and below).

Discussion

Controlling factors

The variety of Portuguese Upper Jurassic siliceous sponge reef facies occurring within different environmental and sequential settings is favourable for the study of various controlling factors, related to each other, which determine the growth and type of siliceous sponge faunas.

Some potential controlling factors can be completely or to a large part excluded:

- (1) All types of siliceous sponge facies occur together with stenohaline elements, particularly ammonites, belemnites, echinoids and brachiopods, so that compositional and diversity differences in sponge facies cannot be explained by differences in salinity regimes.
- (2) Structural control is of paramount importance for the occurrence of many coral reefs and coral-dominated platform carbonates in the siliciclastically dominated succession of both the Lusitanian Basin and the Algarve Basin (LEINFELDER & WILSON 1989, ELLIS et al. 1990, SCHMID 1992, LEINFELDER 1993).

However, most of the examined occurrences of sponge facies are not related to a position on structural highs. It rather seems, that their lateral distribution is mostly driven by chance and self-reinforcement on poorly structured ramp-type shelf areas. Exceptions are the Tavira sponge facies developing on a salt pillow and, possibly, the very large Rocha thrombolite, whose growth seemed to have favoured by the position on a fairly steepened slope, possibly enforcing bypassing of sediment around the structure. The existence of sediment-filled cavities within the Rocha thrombolite are evidence of bypassing of sediments. The large olistoliths at the adjacent site Rocha-West also prove the existence of steep slopes in the Rocha area. The general position of all Portuguese sponge reef occurrences on slope settings is partly responsible for the vicinity of both coral and siliceous sponge facies (see below).

(3) Water energy can also be ruled out as a controlling factor. Almost all siliceous sponge facies types display low-energy characteristics. The carbonate debris facies of most type 5 examples is clearly allochthonous and was deposited in a tranquil setting. However, some type 5 examples do occur within a high-energy, coral-dominated environment, but seem to represent protected local settings in these cases (NOSE in prep.).

Water depth

Portuguese siliceous sponge-bearing facies are intercalated in well developed thick shallowing-upwards successions. Most of the time, different compositional types can be attributed to different positions within these successions. Fig. 21 shows the generalized Upper Jurassic succession of the eastern Algarve and the intercalations of siliceous sponge-bearing facies. Type 5 (mixed coral facies with additional siliceous sponges) occurs above type 4 (coral-sponge thrombolites). The position of types without hermatypic corals (type 1,2) normally is below types 4 and 5, though over a wide range within the ammonite-rich deeper shelf facies. In WALTHER's sense of facies interpretation (WALTHER 1893/94), this seems to reflect a clear bathymetric separation of a deeper zone with the exclusive occurrence of siliceous sponges, an intermediate zone of co-occurrence of siliceous sponges and corals, and a shallow-water zone where corals are largely prevailing. However, this trend is weakened by the fairly irregular distribution of type 3 reefs (siliceous sponge-bearing thrombolites) and, to a lesser extent, type 1 and 2 facies. These types occur in a variety of positions between the lowermost parts of the sections and the dominance of coral-rich types (Fig. 21).

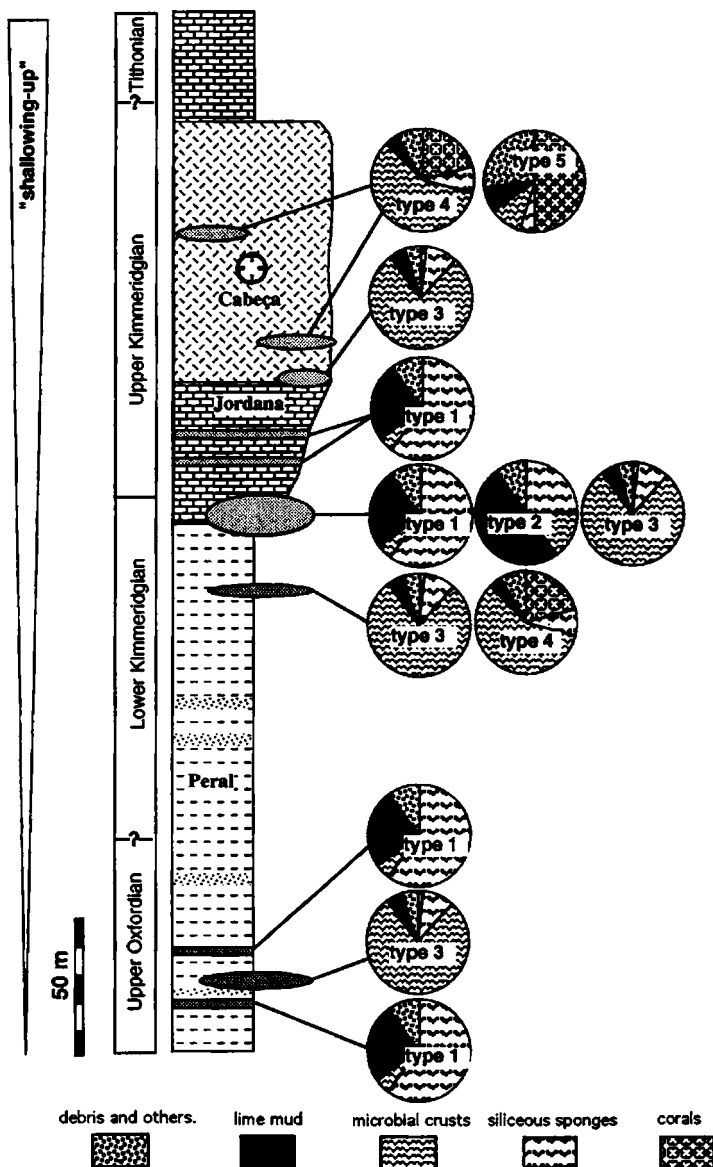


Fig. 21. Generalized composite section of the Upper Jurassic succession in the eastern Algarve. The succession represents a clear shallowing-upwards trend from ammonite marls (Peral) to allochthonous intraclastic bioclastic limestones (Jordana) to coral platform facies (Cabeça) to lagoonal biomicrites. Note that coral-rich siliceous sponge facies (types 4, 5) is restricted to the upper part, whereas thrombolites (type 3) and siliceous sponge meadows (type 1) occur over a wide range.

This schematic interpretation of bathymetry according to WALTHER's law (WALTHER 1893/94) can be corroborated and refined by obvious ecologic gradients. Such gradients can be established by comparative quantitative and semiquantitative analysis of reef communities (WERNER et al. in press and unpubl. results). Depth distribution data of bivalves are derived by independent analysis of non-reefal benthic mollusc communities from the Upper Jurassic of Portugal (cf. FÜRSICH & WERNER 1984, 1986, WERNER 1986). Fig. 22 displays the most prominent bathymetric trends. Both the composition and diversity of sponge fauna changes drastically. Towards greater depths, coralline sponges diminish both in individual and species number, whereas siliceous sponges increase. Although hexactinellid (particularly lychniscid) sponges also occur at moderate depths, they clearly outnumber the "lithistids" in the deep settings. However, deeper water hexactinellid sponges are almost exclusively represented by dictyids rather than lychniscids. The bathymetric range of some coral species (e. g. *Microsolena agariciformis*, *Convexastrea sexradiata*) is rather broad. Although its functional advantage is yet not fully understood, some of them change their growth form from massive knobby in shallow-water towards columnar in deeper water. The opposite is true of the cementing bivalves which maintain their oyster-type growth form at all depths, whereas the genera and species change: *Praeexogyra pustulosa* is restricted to the shallow water and is substituted by *Plicatula ogerieni* and *Atreta unguis* towards the deeper water (WERNER et al. in press). Lithophagid bivalves also decrease towards greater depths, despite the abundance of secondary hardgrounds (skeletal hardparts, lithified microbial crusts) even in the deeper reefs. Based on the data presently available, the distribution of encrusting bryozoa and foraminifera seems to be similar at any depth. The standard type of microbial crusts, meaning the dense to peloidal, clotted thrombolitic type, is clearly eurybathic, occurring at any depth. On the other hand, the diversity of accompanying encrusting algae and microporobionts clearly diminishes towards greater depths. For instance, *Bacinella irregularis*, typically occurring with *Lithocodium*, is restricted to the very shallow water, whereas *Tubiphytes morronensis* occurs over a very wide bathymetric range, yet having its maximum distribution in moderately deep water.

The bathymetric gradients of reefal and non-reefal organisms given in Fig. 22 allow to relate some sponge facies types to distinct water depths. We assume that the pure coral facies occurs down to 30–40 metres, mixed coral-siliceous sponge facies (type 5, 4a) extends from the very shallow down to 70 metres, and siliceous sponge facies without hermatypic corals occurs below these zones. However, the growth depth of the type 4b and type 3 reefal facies (thrombolites with transitions from siliceous sponge to coral macrofauna, and siliceous sponge-bearing thrombolites, respectively) cannot be determined by comparative palaeoecology. For instance, type 3 thrombolites may or may not have high numbers of lithophagid bivalves, *Tubiphytes* or coralline sponges. Obviously, type 3 and, to a lesser extent, type 4b thrombolites seem to occur

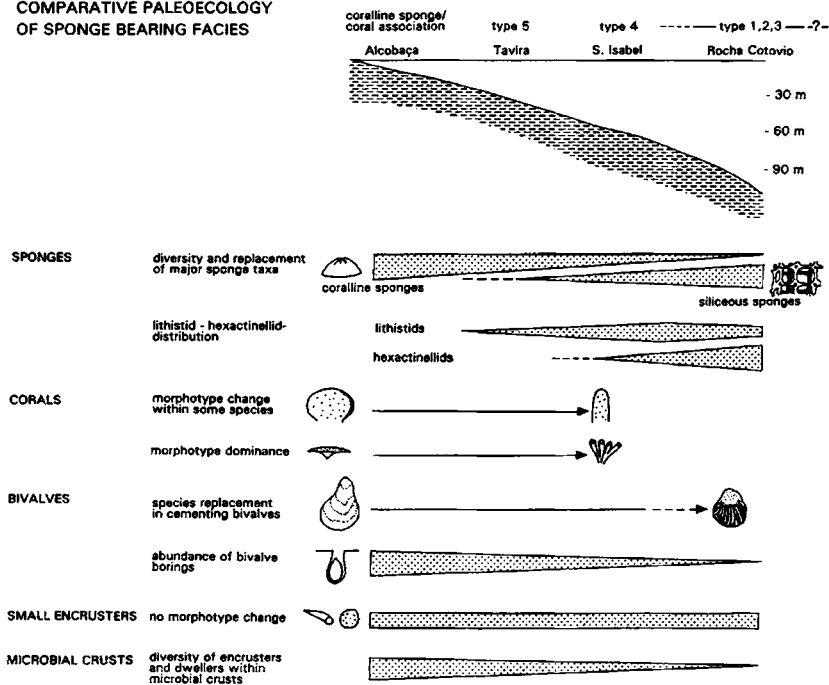
COMPARATIVE PALEOECOLOGY
OF SPONGE BEARING FACIES

Fig. 22. Comparative palaeoecology of sponge-bearing facies (modified and expanded from WERNER et al. in press). See text for explanation.

over a fairly wide bathymetric range. Likewise, within the facies without hermatypic corals, the development of thrombolites, mud mounds and meadows cannot be attributed to differences in bathymetry.

Sedimentation rate

The general occurrence of siliceous sponge reef facies is clearly related to a starved to zero sedimentation regime. The sponge facies-containing parts of the Portuguese shallowing-upwards successions are characterized by a dominantly siliciclastic, fine-grained regime with a general high sedimentation rate. Within this high-sedimentation regime, sponge facies is clearly related to some very distinct levels (such as the Serra Isabel level of the Lusitanian Basin described above). These levels show all signs of very low to lacking sedimentation. The Serra Isabel level, for instance, represents a dominantly calcareous intercalation within the marl and clay dominated Abadia succession and exhibits a condensed

development of an infauna-dominated soft-bottom to an epibenthic firm-ground association. It also shows an enormous enrichment of iron oxide in one distinct layer. In the Algarve, a level accompanied by thrombolitic sponge facies at Cotovio exhibits hardground characteristics such as oysters and serpulids attached to the hardened substrate as well as borings of lithophagid bivalves. Authigenic glauconite, which is diagnostic of very low sedimentation rates (ODIN & MATTER 1981), is particularly abundant in some horizons containing sponge-bearing thrombolites. Within and on top of the thrombolites serpulid worms may be frequent, substantiating the very slow growth of thrombolites in a zero sedimentation regime. Once sedimentation has ceased, microbial crusts develop very rapidly. An extended period of zero sedimentation in order to allow accumulation of skeletal hardparts as secondary hardgrounds or to ensure diagenetic hardening of the substrate was not necessary. This is demonstrated by the following process: Crust growth commonly started on very small hardparts and then built out laterally. This greatly facilitated rapid local stabilization of the substrate, in a way that even marly and clayey sediments could be overgrown immediately after the lowering of sedimentation rates. Hence, the occurrence of microbial crusts within fine-grained successions allows the detection of breaks in sedimentation at a high resolution.

As discussed above, the position of most, if not all occurrences of Portuguese sponge facies on slopes was also partly responsible for keeping sedimentation rates low by enabling bypassing of sediments. However, the exclusive occurrence of sponge reef facies in laterally persistent and correlatable horizons is a strong argument for a general regional lowering of sedimentation rate at the times when siliceous sponge facies occurred (see below).

Oxygenation and nutrient levels

Not interpretable by the above control mechanisms is the occurrence of thrombolites containing only accessory siliceous sponges (type 3 facies) over a wide bathymetric range and thrombolites with siliceous sponges rapidly passing into coral thrombolites (type 4b facies). Particularly in the Algarve the type 3-containing levels are very rich in glauconite. Authigenic glauconite not only occurs within the thrombolites but also on top and at the margin of the structures as well as in the thrombolite-bearing beds. The richness in glauconite often results in a very intensive green colour of these horizons. Authigenic glauconite forms at zero sedimentation rate on the sea floor and due to its content of both ferric and ferroan ions needs slightly reducing conditions on the sea-floor (DEER et al. 1966, ODIN & MATTER 1981). Particularly, the richness of glauconite on top and between thrombolitic structures, rather than within the thrombolites is a strong indicator for generally lowered (dysaerobic) or commonly

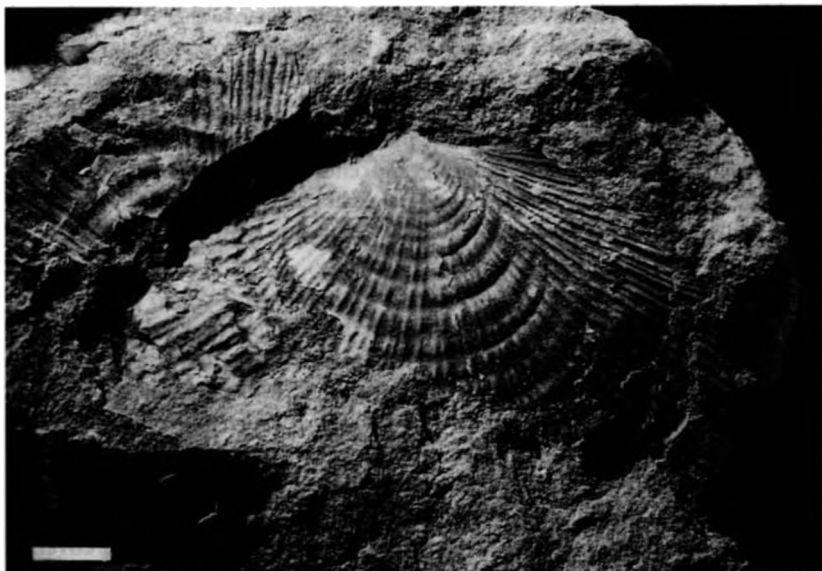


Fig. 23. The epibyssate flat clam *Aulacomyella abadiensis*, which is typical for dysaerobic environments. Length of bar is 5 mm. Serra Isabel level, northeast of Arruda, Lusitanian Basin.

shifting (poikiloaerobic, cf. OSCHMANN 1991) oxygen concentrations at the sediment-water interface.

In the Lusitanian Basin, the Serra Isabel level is rich in both type 3 and type 4b thrombolites. Glauconite is also common in many structures. In others, glauconite seems to have been substituted by pseudomorph pyrite which partly was later oxidized to goethite by weathering processes. The same is true for early diagenetic framboidal pyrite concretions which now are also preserved as goethite. Oxygen depletion is also indicated by the frequent occurrence of the very thin-shelled, flat pectinacean bivalve *Aulacomyella abadiensis* (Fig. 23). The species was described by FRENEIX & QUESNE (1985) from the Abadia beds of the Arruda area. The genus has a worldwide distribution from the Kimmeridgian to the top of the Tithonian. It exclusively occurs in fine-grained, mostly slightly bituminous facies, where it dominates the communities and often occurs as monospecific clusters. Consequently, it is interpreted by KELLY & DOYLE (1991) as an epibenthic form living in a dysaerobic environment, an interpretation which is corroborated by its functional shape, similar to that of "posidoniids". Presently unresolved is whether *Aulacomyella* had a chemo-

sympatric lifestyle (KAUFFMAN, pers. comm. 1991) or whether it was adapted to fluctuating oxygen levels through an extended planktotrophic larval stage (OSCHMANN in press; OSCHMANN in prep.). In the Serra Isabel level, *Aulacomyella* mostly occurs as monospecific clusters at distinct bedding planes which is consistent with its dysaerobic interpretation. Occasionally, however, it is associated with other epibenthic and endobenthic elements which we interpret as a time-averaged, telescoped succession of different benthic communities (dysaerobic and aerobic) caused by very low sedimentation rates (in prep.).

Lowered bottom water oxygenation is commonly related to productivity blooms in the surface waters. Hermatypic corals need both high oxygen and low nutrient levels (e. g. KÜHLMANN 1984, HALLOCK & SCHLAGER 1986). Siliceous sponges normally also grow under low nutrient levels and in oxygenated waters (REITNER, pers. commun. 1992), so that the occurrence of rich siliceous sponge faunas should indicate high oxygen/low nutrient environments. However, the simple structure, large surface and internal skeleton of sponges makes it likely that many could survive times of poor oxygenation. This seems to be particularly plausible for the hexactinellids whose internal skeletons are covered only with a very thin soft body (THOMSON 1868 in MEHL 1992). Actually, sponges are known from oxygen-depleted waters of the Black Sea (BAÇESCO 1963, RHOADS & MORSE 1971). Some sponges do seek higher nutrient levels, as is demonstrated by the increase of siliceous and non-siliceous sponges in some of today's coral reefs undergoing environmental pollution (KÜHLMANN 1984, 1988, SCHUHMACHER 1991, SCHLAGER 1992, GEISTER, pers. commun. 1992) or around river mouths which discharge nutrient-rich waters (SARA & VACELET 1973). Hexactinellid sponges are characteristic members of bathyal settings characterized by enrichments of nutrients and organic matter, as well as by thriving of bacteria (TUZET 1973). Generally, sponges seem to be better adapted to fluctuating nutrient levels than hermatypic corals. Modern sponges from nutrient-rich lagoonal reefs develop a much greater biomass than sponge faunas from nutrient-poor "clean-water" offshore coral reefs where sponges can only survive by containing abundant cyanobacterial symbionts (WILKINSON & TROTT 1985, WILKINSON & EVANS 1989). Another example for adaption of modern sponges to fluctuating trophic conditions are cold-water siliceous sponge - microbial mat associations recently discovered in the central Greenland Sea. The sponge-microbial mat association is situated on the crest and flanks of a seamount whose top is - 133 m below sea level. The site is characterized by oligotrophic waters which are seasonally affected by highly elevated nutrient levels and associated plankton blooms. Short-termed nutrient release is caused by ice-cover retreat during summer; the particulate and suspended organic matter is rapidly transferred to the benthic organisms by a downwelling Taylor current (HENRICH et al. 1992).

Hence, lowered or fluctuating bottom water oxygen concentrations were responsible for the suppression of most of the reef macrofauna, particularly

hermatypic corals and siliceous sponges at some levels. This explains the frequent dominance, in these levels, of microbial crusts and thus the development of thrombolites with little or no macrofauna. Bathymetric change alone can be excluded as the responsible factor for the growth of and differences between thrombolites since the following observations cannot be explained by rapid, major changes in water depth: (1) the existence of very rapid, decimetre-scaled upwards transitions from pure or siliceous sponge-bearing thrombolites to crust-rich coral facies (observed at several localities within the Serra Isabel level; (2) the restriction of specimen-rich dictyid sponge meadows to thin intercalations within the Rocha thrombolite, and (3) the occurrence of thrombolites over a wide range within the clearly shallowing-upwards succession (e. g. at Cotovio and São Bras).

Consequently, differences of thrombolite composition should mostly reflect differences in oxygen/nutrient levels rather than bathymetric differences. Thrombolites rich in corals and siliceous sponges indicate high oxygen/low nutrient conditions. Their richness in microbial crusts is here due to a starved sedimentation regime. The type 3 thrombolites or the basal part of the type 4b thrombolites, i. e. the examples with a subordinate content of siliceous sponges are indicative of fluctuating nutrient and oxygen levels. Some of the siliceous sponges within the microbial crusts might have been adapted to generally higher nutrient/lowered oxygen conditions. This might be particularly true for large forms, such as some specimens of *Cylindrophyma milleporata*. However, the majority of siliceous sponges within thrombolites is small and might have grown during the more favourable, though short phases of lowered nutrient and elevated oxygen levels. The accompanying fauna fits such an interpretation of fluctuating oxygen/nutrient conditions. The occurrence of small solitary, probably asymbiotic corals in some horizons at the Rocha thrombolite might indicate elevated nutrient levels accompanied by still normally oxygenated bottom water. Annelids are known to be euryoxic and are able to switch their metabolism under low oxygen or even anoxic conditions (SCHÖTTLER & BENNET 1991). Brachiopods are difficult to interpret. Modern lingulids are adapted to low oxygenation, although the majority of articulate taxa occurs in well oxygenated waters. The rare occurrences of brachiopods within the thrombolites hence seem to be connected with short times of improved environmental conditions. The same is true for the occasionally occurring coralline sponges, particularly *Neuropora* spp.. Actually, the indicators for better oxygenation (brachiopods, corals, coralline sponges and lithophagid bivalves) only occur at distinct horizons or intervals within the thick Rocha thrombolite, a fact which strongly supports the fluctuating oxygen/nutrient model.

Upper Jurassic microbial crusts are very eurytopic. They occur in low and, more rarely, high energy regimes (LEINFELDER 1992), in shallow and deep water as well as in oxygenated and oxygen-depleted environments. The problem is that the basic crust type, which is characterized by a dense to peloidal, clotted

thrombolitic to irregularly laminated fabric, is identical in all settings. However, differences in water depth are indicated by the nature and diversity of accompanying algal-like microencrusts (LEINFELDER 1992, WERNER *et al.* in press), whereas differences in oxygen levels are not directly visible by the crust fabric. Apparently, the calcifying pattern of coccoidal cyanobacterial and bacterial clots is similar for oxygenated and dysaerobic as well as for autotrophic and heterotrophic forms (cf. GERDES & KRUMBEIN 1987, RIEGE *et al.* 1991). This is not surprising, since modern shallow-water stromatolites growing in an oxygenated environment are oxygen-depleted already a few millimetres below their surface, where heterotrophic or chemolithoautotrophic anaerobic bacteria thrive (e.g. GERDES & KRUMBEIN 1987). Consequently, oxygen depletion at the crust-water interface, as postulated for many of the Portuguese examples, can be only proved by referring to the composition and richness of epibenthic macrofauna.

The lowering of oxygen concentration was possibly coupled with an increase in alkalinity, favouring the rapid calcification and hence, general development of crusts (cf. KEMPE 1990, KEMPE *et al.* 1991). However, the occurrence of peloids in filament-type, partly branching rows and the occasional columnar phototactic upwards growth of crusts excludes a purely inorganic origin of the Portuguese crusts. Because thrombolites do not represent local features but rather occur at distinct and widespread levels, we also rule out a seep or hydrothermal vent origin. Cold seep pseudobioherms rich in inorganically precipitated, crust-like carbonate are known from the Upper Jurassic of France. Contrasting the Portuguese examples these are dominated by lucinid bivalves (up to 30% of rock volume) and serpulid worms (GAILLARD *et al.* 1985, 1992).

Sea level fluctuations - the major driving force

Siliceous sponge facies commonly occurs in beds deposited during periods of regionally lowered sedimentation rates (e.g. the Serra Isabel level) which can be interpreted as condensed levels or transgressive systems tracts in a sequence stratigraphic context. Also, other criteria for sequence stratigraphic interpretation are widespread: Besides condensed levels, karst horizons on shallow-water platforms (sequence boundaries), the time-dependent occurrence of coral reefs within a high sedimentation siliciclastic environment (transgressive to early highstand), or the progradation-backstepping patterns of coarse or terrestrial facies can be used to establish a sequence stratigraphic framework. Fig. 24 includes a simplified sequence stratigraphic interpretation of the Upper Jurassic succession from the Lusitanian Basin (cf. LEINFELDER 1993, LEINFELDER & WILSON 1992, LEINFELDER & WILSON in prep.). These local results match the latest version of the VAIL Group sea level curve (PONSOT & VAIL 1991, RIOULT *et al.* 1991, JAQUIN *et al.* in prep.). Although age determinations are partly insufficient, the horizons characterized by siliceous sponge facies, ammonite condensation layers as well as channelized and olistolith-rich horizons

are easily correlatable between the Lusitanian Basin and the eastern Algarve Basin. Irrespective of whether this sea level curve represents global eustatic sea level fluctuations or, rather, regional Europe-wide, rift-tectonic dominated relative sea level fluctuations, the control of third order sea level fluctuation on the occurrence of sponge reef facies is apparent. Moreover, we believe, that due to climatic feedbacks the development of oxygen-controlled thrombolite facies also depends, to a large part, on sea level fluctuations of third order and lower scale (Fig. 25):

In the siliciclastically dominated sedimentation regime of both the central Lusitanian Basin and the eastern Algarve Basin, sedimentation rates *during times of low sea level* were too high to enable growth of reefal benthic communities in deeper waters. Due to bypassing of sediment towards distal areas, coral reef growth was, at places, possible in the winnowed high-energy zone. Type 5 siliceous sponge facies (i. e. mixed coral-siliceous sponge facies) could occur in protected or deeper settings within or at the base of coral reefs.

During sea level rise sedimentation rates were considerably lowered in the deeper water, allowing the establishment of benthic reefal communities which show a clear bathymetric zonation: Below the coral belt, a zone of mixed coral-siliceous sponge facies existed (type 5 and type 4a facies), which was followed by a deeper zone dominated by siliceous sponges (type 1 and 2; meadows and mounds, respectively) and by the still deeper, oxygen-controlled zone characterized by type 3 facies (thrombolites with subordinate amount of siliceous sponges).

We assume that during the Late Jurassic, the nature and position of the oxygen-controlled zone was different from today. The apparent lack of polar ice caps and the general high global sea level should account for a greenhouse-type climate which was much more equilibrated than today. This caused a more sluggish water exchange system and the lack of pole-derived, oxygen-rich ocean bottom waters. Dysaerobic to anaerobic waters could have developed in depths shallower than today. The upper boundary of this zone was certainly undergoing strong seasonal fluctuations due to productivity blooms, similar to

Fig. 25. A sequence stratigraphic model for the sponge facies of the siliciclastically dominated Upper Jurassic succession of Portugal, combining the controlling factors bathymetry, sedimentation rate and oxygen content fluctuations.

Upper panel: During low sea level, high sedimentation rates in deeper settings prevent reefal benthic associations. Coral reefs and mixed coral-siliceous sponge associations may occur in the shallow, partly agitated water.

Middle panel: During sea level rise, sedimentation rates are lowered and a clear bathymetric zonation of reef fauna is established.

Lower panel: In extreme cases, most likely during major sea level rise, equilibrating effects on climate and ocean circulation patterns strongly raised the oxygen-depleted zone, so that siliceous sponge-bearing thrombolites occur at fairly shallow depths and may pass rapidly into coral facies.

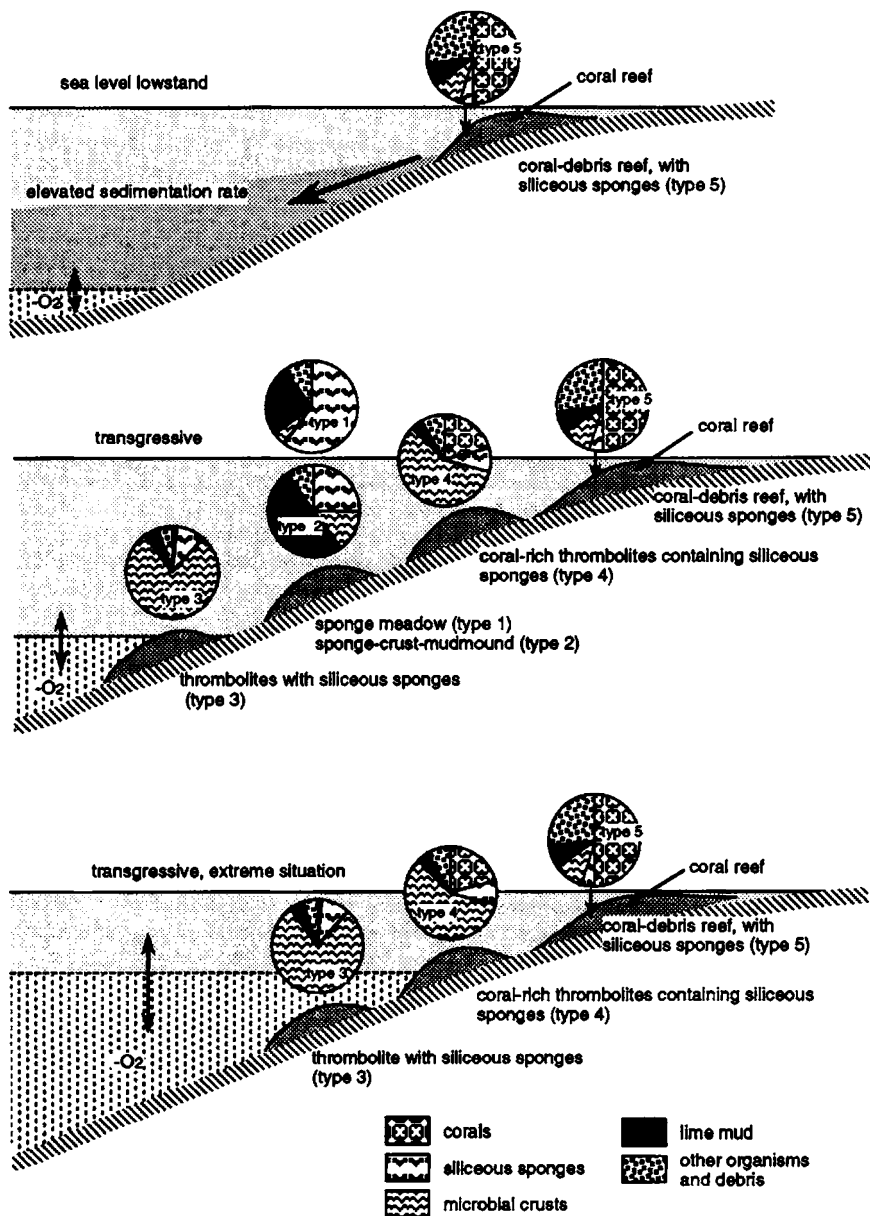


Fig. 25 (Legend see p. 242)

modern shelf sea algal "pests" as commonly occurring in the North Sea or Adriatic Sea.

Sea level rise caused an additional equilibration of the already maritime climate leading to further slackening of water exchange. Hence, a given rate of sea level rise could have raised the dysaerobic zone by a much greater rate.

During very pronounced sea level rise, this multiplying effect raised the upper boundary of the dysaerobic zone into the fairly shallow water (though well below the wave-agitated zone). Such a model explains the occurrence of type 3 sponge-bearing thrombolites also at fairly shallow depths and the rapid transition from sponge-bearing to coral-rich thrombolites (type 4b facies). The bathymetric zone of dominance of siliceous sponges (type 1 and 2) is generally oppressed in this case. Short-termed improvement of oxygenation, possibly coupled with sedimentation events are, however, responsible for the intercalation of single-population siliceous sponge meadows within the thrombolites.

Such a model is in good accordance, with predictive model calculations of present day and future climate-hydrosphere interactions. The modern sea level rise, caused by enhanced, man-made CO₂ emissions will result in a positive feedback since the enlarged ocean surface will cause higher evaporation of water, which itself is a strong greenhouse gas (cf. CHAHINE 1992). For the Kimmeridgian, OSCHMANN (1990) postulated a very equilibrated climate characterized by a sluggish ocean circulation pattern and a summer low-pressure system at the ice-free North Pole, in order to explain the widespread occurrence and cyclicity of oxygen fluctuations of the Kimmeridge Clay of northwestern Europe. This matches well with the numerical palaeoclimate model for the Kimmeridgian recently established by VALDES & SEELWOOD (1992). They identify an equilibrated climate with global annual surface temperatures of 20° C (present day: 14°C), an average cloud cover of 72% (present day 55%) and a total rainfall of 2.6 mm/day (present day: 2.3 mm/day). Under such general conditions, enhanced bottom water oxygen-depletion can be easily explained by additional climatic equilibration occurring during sea level rises. For the Upper Jurassic, climatic equilibration and related slackening of ocean circulation during high sea level also was recently taken into consideration by MARTIRE (1992). It should be noted that climatic equilibration and the related extension and pulling up of the oxygen-depleted zone in the course of sea level rise was already considered in the seventies in a milestone article by FISCHER and ARTHUR in order to explain the widespread and partly shallow-water occurrence of black shales at certain times in the earth's history (FISCHER & ARTHUR 1977).

Comparison of Portuguese siliceous sponge facies types with other European sites

Although siliceous sponge facies is widely described from other European sites (see above), no descriptive or genetic classification exists as yet. We therefore base our comparison mainly on own examinations from southwestern Germany, Switzerland and Spain. Our classification of sponge facies established for the Portuguese occurrences naturally cannot match all situations elsewhere. Application of the Portuguese classification is a first step towards an integrated comparative description and interpretation of Upper Jurassic sponge and reef facies as a whole.

Type 1: The dominant sponge facies type from the Oxfordian of the Prebetic and Celtiberian range of Spain is a sponge meadow facies comparable with type 1c. It shows considerable differences to the Portuguese occurrences. Particularly their enormous lateral distribution, dominance of very large-sized platy sponges, and their faunal composition is different (KRAUTTER in prep.; cf. DEUSCH et al. 1990, PISERA 1991). Comparable sponge meadow facies exists subordinately in southern Germany (Treuchtlingen "marble" with a considerable proportion of crusts; (type 1c; cf. KOTT 1989); marly sponge meadows (type 1b, e. g. Faulenhau: WERNER et al. in press) and the spiculitic marls (type 1a, e. g. Zementmergel beds, GERLOFF 1980). Crust-poor, type 1b sponge meadow facies is the dominant sponge facies type in the Oxfordian of the Swiss Jura (e. g. EGGER 1991).

Type 2: The lime mud-rich sponge mud mound facies (type 2), which is not very widespread in Portugal, appears to be the dominant type in southern Germany. It has been known for a long time, that many if not most of the spectacular sponge mounds are composed of a high percentage of lime mud besides microbial crusts and siliceous sponges (e. g. GWINNER 1976, WAGENPLAST 1972, FLÜGEL & STEIGER 1981, KEUPP et al. 1990, FLÜGEL et al. 1992). Similar to the observations from Portugal, the large mounds are commonly composed of smaller, lentil-like units which due to stacking and clustering produce the larger complexes (unpubl. results). However many such structures cannot be observed due to the strong diagenetic overprint and dolomitization. Oxygen fluctuations are also considered as a control mechanism for the growth of small sponge-microbial crust mudmounds by BRACHERT (1992). Most of the Swiss and French Upper Jurassic sponge mounds also belong to the type 2 category (cf. GAILLARD 1983, GIGY & PERSOZ 1986). Crust-rich small mudmounds and stromatolitic to thrombolitic bodies exist in the deep-water succession of the western Subalpine Basin in France (DROMART 1989). These bodies share similarities with the type 2 and 3 facies from Portugal, although they are apparently devoid of sponges. Siliceous, particularly hexactinellid sponges occur, however, scattered throughout the succession, occurring with ammonites, belemnites and radiolarians. Some type 2 mounds also have been found in the Oxfordian of the Celtiberian and Prebetic range of Spain.

Types 3, 4 and 5: Thrombolites containing low sponge quantities (type 3) are locally developed in southern Germany (e. g. WOITKE 1992) and are rare in the Celtiberian range. The siliceous sponge-coral microbialites (type 4a and b) are frequent in the Kimmeridgian of the Celtiberian range (unpubl. results). Type 5 (mixed coral-siliceous sponge facies) is comparable with the so-called "coral facies" of Southern Germany, which is rich in particles and includes packstone, grainstone and rudstone facies, besides containing siliceous sponges as well (e. g. the locality Arnegg; PAULSEN 1964).

New results by KOCH (KOCH in FLÜGEL et al. 1992; KOCH et al.; in prep.) show, that some of the large Upper Kimmeridgian to Tithonian buildups of

Southern Germany may represent another sponge reef facies type which to date could not be found elsewhere. Such buildups are predominantly composed of fine-grained particles, many of which can be regarded as superficial ooids, in a packstone to grainstone fabric where sponge facies occurs subordinately. The fabric is partly comparable with some type 5 mixed coral-siliceous sponge reefs. The grain-supported character of such structures, some diagenetic evidence (KOCH & SCHORR 1986, WIRSING & KOCH 1986) and fabrics of microborings (GLAUB 1988, VOGEL 1992, GLAUB in prep.) led to the interpretation that some sponge reefs from Southern Germany might have grown in fairly shallow water. Contradictory to such an interpretation is, however, the apparent lack of hermatypic corals and green algae as well as the richness of ammonites and belemnites in and around such structures.

Conclusions

1. Portuguese Upper Jurassic siliceous sponge-bearing facies, which to date was only known from a small number of outcrops and drillholes, occurs widespread in the eastern Algarve Basin and, to a lesser extent, in the Lusitanian Basin. In the eastern Algarve Basin it occurs within the Peral, Jordana, Tavira and Cabeça units; in the Lusitanian Basin it was mostly detected in the Montejunto, Ramalhão/Mem Martins and Abadia units. Yet the siliceous sponge facies is restricted to distinct horizons within these units.

2. Based on faunal composition and degree of reefal organization five basic reefal siliceous sponge-bearing facies can be discriminated. Type 1 represents meadow and biostrome facies which is either dominated by dictyids or "lithistids". Type 2 can be termed siliceous sponge/microbial crust - mud mound facies and is characterized by the dominance of dictyid sponges. Additional elements are mainly brachiopods, epibenthic bivalves, serpulids, bryzoans and small ammonites. The very widespread type 3 can be characterized as microbial thrombolites with additional siliceous sponges, almost all of which are dictyids. Their frequency is variable but always low. Type 3 is particularly rich in authigenic glauconite. The thrombolite structures range from a few decimetres to 30 metres in thickness. Type 4 facies are thrombolites containing both corals and siliceous sponges. They may occur together (4a) or as a small-scale succession from a basal sponge-bearing thrombolite to a crust-rich coral facies (4b). Siliceous sponges are composed of dictyids, lychniscids and "lithistids". Concentrations of long shafted, isolated monaxons and tetraxons, probably representing relics of tetractinellid sponges, are particularly common in this type. The accompanying fauna is often rich (e. g. hermatypic corals, crinoids, echinoids, bivalves, serpulids). Type 5 is a mixed coral-siliceous sponge facies characterized by its subordinate amount of crusts and by a high percentage of biotrital material. Corals are more frequent than siliceous sponges. The latter are dominated by "lithistids", although lychniscids and dictyids are not uncommon.

3. Siliceous sponge genera of Portugal are not endemic but part of the general sponge belt fauna, which to date is particularly known from Southern Germany and Poland (e. g. SIEMIRADZKI 1914, SCHRAMMEN 1936, TRAMMER 1982, 1989, MÜLLER 1987, 1988). *Craticularia*, *Tremadictyon* and *Platychonia* were frequently found, although poor preservation of most sponges does not allow to establish dominance patterns at the species and generic level. Very common in Portugal are coralline sponges. They have their maximum distribution in the shallow-water, coral-dominated facies (FÜRSICH & WERNER 1991, WERNER et al. in press), although certain taxa frequently also occur in the siliceous sponge facies (particularly *Neuropora*; in the shallower types also *Corynella* and *Thalamopora*).

4. The dominant factors determining the occurrence and composition of siliceous sponge reef facies are bathymetry, sedimentation rate and oxygen/nutrient fluctuations. Bathymetric distribution can be well established due to the occurrence of different sponge facies at different positions within clearly developed shallowing-upwards successions. These trends can be substantiated and refined using bathymetric gradients established by comparative semi-quantitative palaeoecological analysis. Below and in between the pure coral facies mixed coral/siliceous sponge facies occurs, which is followed by siliceous sponge-dominated facies and by the oxygen-controlled sponge-bearing thrombolites. Within the siliceous sponges, the distribution of subgroups also reflects a clear bathymetric trend from the dominance of dictyids in the deeper water and the increasing importance of "lithistids" and lychniscids towards shallower settings. Concentrations of long-shafted, isolated spicules (hence probably tetractinellid sponges) also follow this trend and are much more common in shallower environments. Palaeoecological and sedimentological data (e. g. encrusting fauna, faunal enrichments, hardgrounds, glauconite richness) proves the dependence of sponge reef facies upon low to zero sedimentation rate. The occurrence of reef facies within distinct, correlatable horizons and their integration in a sequence stratigraphic framework indicates that sponge reef communities grew during the low sedimentation regime of regionally or globally rising sea level. Impoverishment of reefal macrofauna, glauconite richness and association with bivalves indicating low oxygen conditions (*Aulacommyella*) point to fluctuating oxygen/nutrient levels as the main factor for type 3 (thrombolites with subordinate siliceous sponges) and type 4b (thrombolites with rapid transitions from sponge to coral fauna). The general shallow bathymetric position of type 4b facies and the occasional shallow position of type 3 facies indicate that the dysaerobic or poikiloaerobic zone was raised to fairly shallow water during major sea level rise due to the related climatic equilibration.

5. All reefal siliceous sponge facies types established in the Upper Jurassic of Portugal can be detected in the Upper Jurassic successions of Southern Germany, Switzerland or Spain, although the dominance pattern of reefal types is clearly different.

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