

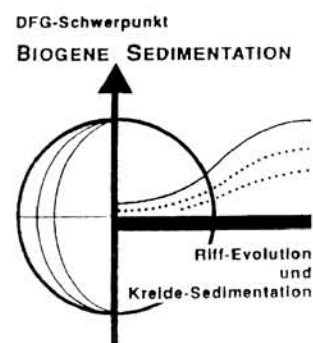
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Research Report 'Evolution of Reefs'

The Origin of Jurassic Reefs: Current Research Developments and Results

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SEQUENCE STRATIGRAPHY – AMMONITE STRATIGRAPHY –
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SUMMARY

In order to elucidate the control of local, regional and global factors on occurrence, distribution and character of Jurassic reefs, reefal settings of Mid and Late Jurassic age from southwestern Germany, Iberia and Romania were compared in terms of their sedimentological (including diagenetic), palaeoecological, architectural, stratigraphic and sequential aspects. Upper Jurassic reefs of southern Germany are dominated by siliceous sponge - microbial crust automicritic to allomicritic mounds. During the Oxfordian these form small to large buildups, whereas during the Kimmeridgian they more frequently are but marginal parts of large grain-dominated massive buildups. Diagenesis of sponge facies is largely governed by the original composition and fabric of sediments. The latest Kimmeridgian and Tithonian spongiolite development is locally accompanied by coral facies, forming large reefs on spongiolitic topographic elevations or, more frequently, small meadows and patch reefs within bioclastic to oolitic shoal and apron sediments. New biostratigraphic results indicate a narrower time gap between Swabian and Franconian coral development than previously thought. Palynostratigraphy and mineralostratigraphy partly allow good stratigraphic resolution also in spongiolitic buildups, and even in dolomitised massive limestones.

Spongiolite development of the Bajocian and Oxfordian of eastern Spain shares many similarities. They are both dominated by extensive biostromal development which is related to hardground formation during flooding events. The Upper Jurassic siliceous sponge facies from Portugal is more localised, though more differentiated, comprising biostromal, mudmound and sponge-thrombolite as well as frequent mixed coral-sponge facies. The Iberian Upper Jurassic coral facies includes a great variety of coral reef and platform types, a pattern which together with the analysis of coral associations reflects the great variability

of reefal environments. Microbial reefs ranging from coral-rich to siliceous sponge-bearing to pure thrombolites frequently developed at different water depths. Reef corals even thrived within terrigenous settings.

In eastern Romania, small coral reefs of various types as well as larger siliceous sponge-microbial crust mounds grew contemporaneously during the Oxfordian, occupying different bathymetric positions on a homoclinal ramp.

Application of sequence stratigraphic concepts demonstrates that onset or, in other cases, maximum development of reef growth is related to sea level rise (transgressions and early highstand) which caused a reduction in allochthonous sedimentation. The connection of reef development with low background sedimentation is corroborated by the richness of reefs in encrusting organisms, borers and microbial crusts. Microbial crusts and other automicrites can largely contribute to the formation of reef rock during allosedimentary hiatuses. However, many reefs could cope with variable, though reduced, rates of background sedimentation. This is reflected by differences in faunal diversities and the partial dominance of morphologically adapted forms. Besides corals, some sponges and associated brachiopods show distinct morphologies reflecting sedimentation rate and substrate consistency. Bathymetry is another important factor in the determination of reefal composition. Not only a generally deeper position of siliceous sponge facies relative to coral facies, but also further bathymetric differentiation within both facies groups is reflected by changes in the composition, diversity and, partly, morphology of sponges, corals, cementing bivalves and microencrusts.

Criteria such as authigenic glauconite, dysaerobic epibentic bivalves, *Chondrites* burrows or framboidal pyrite in the surrounding sediments of many Upper Jurassic thrombolitic buildups suggest that oxygen depletion excluded higher reefal metazoans in many of these reefs. Their position within shallowing-upwards successions and associated fauna from aerated settings show that thrombolitic reefs occurred over a broad bathymetric area, from moderately shallow to deep water. Increases in the alkalinity of sea water possibly enhanced calcification.

Reefs were much more common during the Late Jurassic than during the older parts of this period. Particularly the differences between the Mid and Late Jurassic frequencies of reefs can be largely explained by a wider availability of suitable reef habitats provided by the general sea level rise, rather than by an evolutionary radiation of reef biota. The scarcity of siliceous sponge reefs on the tectonically more active southern Tethyan margin as well as in the Lusitanian Basin of west-central Portugal reflects the scarcity of suitable mid to outer ramp niches. Coral reefs occurred in a larger variety of structural settings.

Upper Jurassic coral reefs partly grew in high latitudinal areas suggesting an equilibrated climate. This appears to be an effect of the buffering capacity of high sea level. These feedback effects of high sea level also may have reduced oceanic circulation particularly during flooding events of third and higher order, which gave rise to the

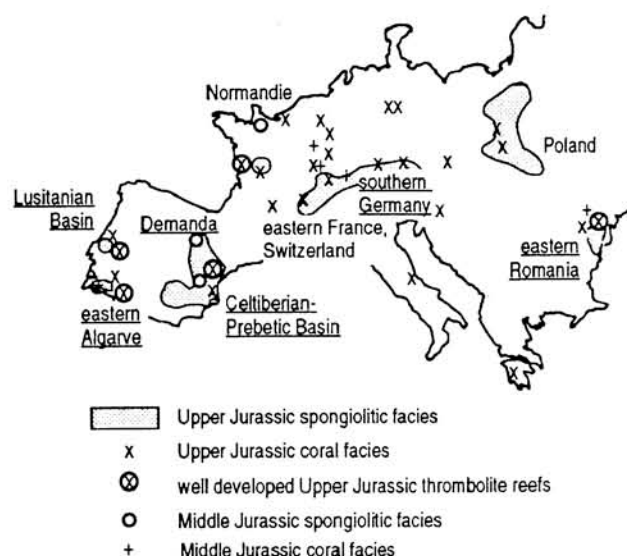


Fig. 1. The distribution of European Jurassic reefs. Underlined locations were studied in detail.

development of black shales and dysaerobic thrombolite reefs. Hence, the interplay of local, regional and global factors caused Jurassic reefs to be more differentiated than modern ones, including near-actualistic coral reefs as well as non-actualistic sponge and microbial reefs.

1 INTRODUCTION (Leinfelder)

During the Jurassic period reef growth became increasingly important. Earlier studies on Jurassic reefs focused particularly on the description of reef rocks. Reef development was explained by obvious factors such as overall water depth and general latitudinal position. However, the complicated pattern of reef occurrences, disappearances and expansion, as well as the large compositional and structural differences among Jurassic reefs suggests that more complex and interactive factors are involved. The analysis of this multifactorial frame controlling Jurassic reefs is the target of a large working group which collaborates under the umbrella of the Priority Program of the German Research Foundation (DFG) entitled 'Global and regional controls of biogenic sedimentation'. The preliminary results of the various subgroups are integrated in the present paper, a sequel to the state-of-the art outline from the beginning of these studies (KEUPP *et al.* 1990). Other recent reports focusing on general aspects of Jurassic, chiefly Upper Jurassic, reefal environments are MEYER & SCHMIDT-KALER (1990), SELG & WAGENPLAST (1990) (both on south German reefs) and LEINFELDER (1993a). For additional references of earlier studies on Jurassic reefs the reader is referred to these papers and to the exhaustive bibliography given by FLÜGEL & FLÜGEL-KÄHLER (1992).

In the present study, the evaluation of controlling factors is mostly based on detailed palaeoecological, sedimentological, diagenetic and sequential case studies of Upper Jurassic reefs, since reefs of this series are more

widespread and more differentiated than their Lower and Middle Jurassic counterparts. We base our interpretations largely on selected occurrences in southern Germany (section 3.1), Iberia (Portugal, Spain; section 3.2) and Romania (section 3.3) (Fig. 1), whereas other localities were visited for reconnaissance studies (Poland, Czechia, Austria, Switzerland, France). Additionally, Middle Jurassic spongiolitic reef facies was investigated in detail in eastern Spain (section 3.2.1) to allow comparison with Upper Jurassic spongiolites. Furthermore, published data on other Jurassic reef occurrences were incorporated for comparison and general evaluation.

Except for the Lusitanian Basin of central Portugal all investigated areas were parts of the pericontinental and epicontinental seas bordering the northern margin of the Tethys ocean. On a large scale, facies development and successions are fairly uniform, whereas at higher resolution, mosaic or belt-type facies differentiation is obvious. This is indicative of homoclinal (often nearly flat) to steepened ramp configurations which prevailed on the European part of the northern Tethyan shelf. All successions represent marl/limestone alternations with intercalation of siliceous sponge facies characteristic of homoclinal mid to outer ramp settings. Only in the eastern Algarve (southern Portugal), intercalations of turbiditic sandstones and breccia debrites are indicative of a steepened ramp configuration. In all Upper Jurassic examples, the reef-bearing successions shallow upwards into inner ramp deposits, with the occasional (southern Germany) or dominant occurrence of coral facies (other areas). In Romania the original updip situation is also partly preserved, with mid-ramp deposits grading laterally into coeval inner ramp sediments.

The Lusitanian Basin of west-central Portugal is an Atlantic marginal basin, which during the Late Jurassic underwent intensive rifting. Therefore, basin fill characteristics, including reef occurrences, are often structurally controlled and terrigenous sediments prevail. Reefs within ramp configurations coexisted with reefs growing on structural uplifts or within siliciclastic fan deltas, and reefs of different bathymetry often grew simultaneously in different parts of the basin (*cf.* LEINFELDER & WILSON 1989, LEINFELDER 1994; sections 3.2.2-4). Analysis of reefs from this basin was chosen to evaluate the effects of tectonics and terrigenous input on reef development (sections 5.4, 6.1).

Accuracy of stratigraphic correlation is crucial for interpreting occurrence patterns of reefs and differences in reef characteristics. This is why we also emphasised the improvement of bio-, mineralo- (sections 4.1-3) and sequence stratigraphic correlations (section 4.4).

The influence of bathymetry, sedimentation rate, oxygenation, microbial activity, auto-enhancement, basin structure, sea level change, oceanic circulation, climate and evolution on the development and occurrence of Jurassic reefs is discussed, in the hope that some of these results may help both in the understanding of the Jurassic world and in the interpretation of reefs from other periods of the history of the Earth.

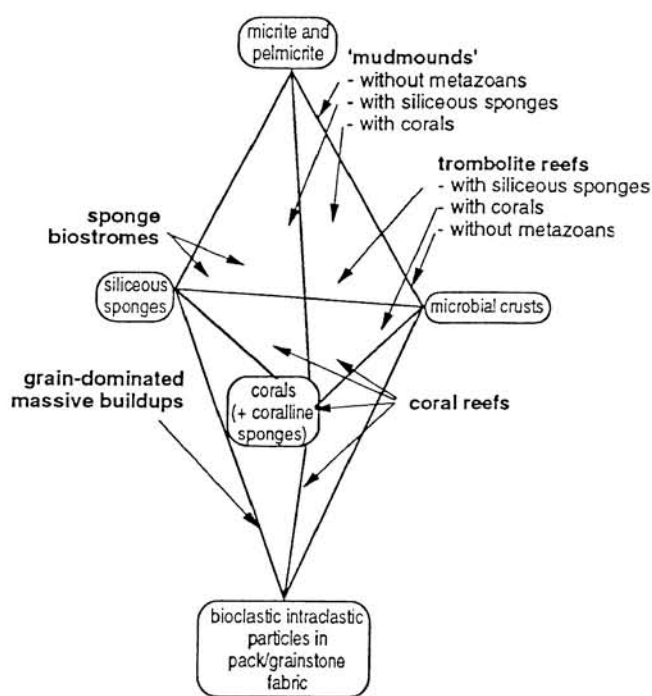


Fig. 2. Compositional types of Jurassic reefs and buildup types. The end members coral reefs, siliceous sponge reefs, microbialite reefs, mudmounds and bioclastic sand shoals frequently form transitional types. Arrows indicate the most common types (partly after LEINFELDER 1993a).

The authors of the individual sections are indicated in the respective headings. All contributions were edited by the coordinator in order to present the results in an integrated manner and to incorporate suggestions by other members of the Working Group. However, all authors double-checked the final version and are responsible for the results, views and reviews presented under their name.

2 OVERVIEW OF JURASSIC REEF ORGANISMS AND COMPOSITIONAL REEF TYPES (Leinfelder)

Jurassic reef facies comprise three basic compositional groups, namely coral reef facies, siliceous sponge reef facies and microbial, mostly thrombolitic, reef facies (Fig. 2). Many transitional types and successional pathways are developed (LEINFELDER 1993a). As an example, siliceous sponge reefs may grade upwards into mixed coral-sponge, then into coral reefs (section 5.2). Another frequent transition is the change from pure thrombolites to siliceous sponge or coral thrombolites (section 5.5).

The dominant reef building metazoans of the Jurassic were colonial scleractinian corals and siliceous sponges with a rigid skeleton (hexactinosa or dictyids, lychniscosa, and lithistid demosponges). Coralline sponges (particularly *Calcarea*, chaetetids, stromatoporoids and other 'sclerosponges') as well as non-rigid sponges (tetractinid demosponges and lyssakinosa) occasionally were of importance and sometimes even prevailing. These framebuilders were accompanied by a great variety of encrusting, boring and free-living epibenthic metazoans as well as free grow-

ing or encrusting algae or algal-type organisms, many of which are of problematic systematic position (LEINFELDER et al. 1993b). In muddy reefs, burrowing bivalves and other burrowers occurred sporadically. Microbial crusts participated in reef formation in various, often high proportions (section 5.1). Bivalve biostromes (e.g. oyster reefs, '*Lithiotis*' reefs or *Isognomon* meadows) are not included in this study.

Morphologically, Jurassic reefs include bioherms as well as biostromes or reefal meadows, all of which are considered here as reefs in a combination of geological and biological definition. In terms of fabric development Jurassic reefs comprise non-framework reefs, reefs with rigid metazoan framework and reefs with microbial crust framework. Most sponge bioherms occur as non-framework reefs forming mudmounds (section 3.1.1). Others are situated on the flanks or within grain-dominated buildups (section 3.1.2). Siliceous sponge reefs often also are termed spongiolites. The term siliceous sponge facies is used here in a broad sense and addresses sediment packages with frequent to occasional, yet characteristic, occurrence of siliceous sponges. Coral reefs comprise both non-framework and framework reefs. Non-framework coral reefs can be of the muddy mound or muddy biostrome type, but also include reefs dominated by bioclastic, originally un-stabilised debris (section 3.2.3).

3 REEF CASE STUDIES

The analysis of factors controlling occurrence and style of Jurassic reef growth demands refined case studies from different areas and structural settings. One of the classical European Jurassic reef sites is Swabia in southwestern Germany, where reefs were studied from different stratigraphic levels. Very good exposures and the availability of a dense network of cored boreholes pinpointed Geislingen as the most suitable area to elaborate a high-resolution study of the Upper Kimmeridgian part of the succession. Iberia, on the other hand, provides much more differentiated palaeogeographic settings which are mostly well known from previous investigations. Reef studies were performed here on a more regional scale, which allowed identification of a large number of different Upper Jurassic reef types in their palaeogeographic context. The occurrence of reefs mostly within large scale shallowing upwards successions provided independent sedimentologic and palaeoecologic calibration of reef settings. Middle Jurassic spongiolites of eastern Spain allow direct comparison with similar Upper Jurassic ones from the same basins, helping in deciphering a possible influence of evolution on reef development as well as deducing time-independent rules of spongiolite growth. In contrast to Iberia, no detailed palaeogeographic studies for the Upper Jurassic of Eastern Romania, the third case study region, are available. This region was chosen to test and substantiate the general validity of results on reef control as obtained from Iberia and southwestern Germany.

Case studies already presented elsewhere (particularly Portuguese sponge facies, Iberian thrombolite facies) are

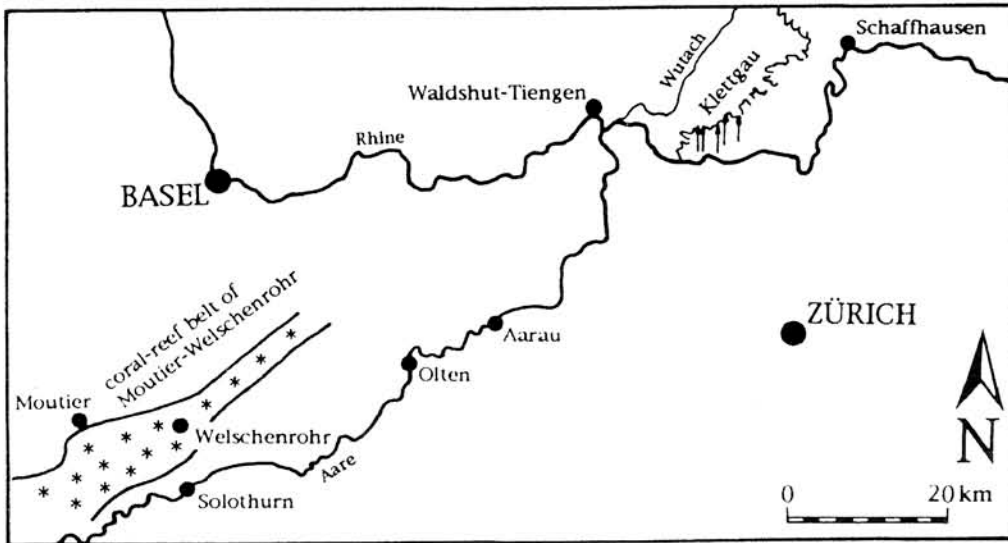


Fig. 3. Position of Oxfordian Klettgau sponge mounds and the Oxfordian coral reef belt of Moutier-Welschenrohr (Switzerland) (after GYGI 1969 and MÜLLER et al 1984).

only briefly summarised, whereas more space is given to hitherto unpublished examples in order to provide sufficient data for the evaluations presented in section 5 and 6.

3.1 Upper Jurassic reefs from southwestern Germany

For an overview of the Upper Jurassic geology and previous studies on the Swabian reefs of southwestern Germany the reader is referred to GWINNER (1976) and KEUPP et al. (1990). Our examination of reefs and adjacent sediments from this region focuses particularly on the poorly known ecology of reef faunas, on the character, spatial organisation and diagenesis of reef and reef-hosting deposits at a microscopic and macroscopic scale, as well as on stratigraphic correlation of reef-bearing successions (see section 4). The arrangement of case studies in a stratigraphic order will show that reef types partly have changed through time, which is interpreted to largely reflect a general shallowing of reefal environments. The new stratigraphic data are the base for future, more refined time-slice interpretations in order to assess the spatial distribution of reef types and reef-hosting deposits.

3.1.1 Upper Oxfordian sponge reefs from the western Swabian Alb (Krautter)

During the Oxfordian, deeper water ammonitic bedded limestones and marls were widely deposited in southern Germany. Local development of small to large spongiolitic bioherms further characterises this Swabian facies. In the westernmost part of the Swabian Alb, the Klettgau (Fig. 3), the transition from deeper water to the shallow water, oolitic Rauracian facies belt occurs (GEYER & GWINNER 1991). The Hornbuck Formation of Late Oxfordian age (Bimammatum Zone) is such a transitional unit.

The Hornbuck Formation reaches a thickness of up to 10 metres. It consists of micritic sponge-bearing limestones and marls. Small lenticular sponge bioherms are intercalated in a succession of well-bedded limestones and marls. The bedded facies is poor in sponges and other

fossils. In general the bioherms consist of thrombolitic microbial crusts, hexactinellid and 'lithistid' sponges as well as micritic, partly bioturbated mud. The sponge fauna is characterised by dictyid forms, such as *Craticularia parallela*, *Tremadictyon*, *Verrucocoelia verrucosa* and *Verrucocoelia gregaria*. 'Lithistid' sponges are mostly represented by *Platychonia schlottheimi*. *Chonelopsis striata* occurs rarely. The accompanying fauna consists of ammonites (Perisphinctidae, Haploceratidae, Glochiceratidae), belemnites, echinoderms (mostly cidaridechinoids), bivalves (e.g. *Chlamys*), brachiopods (both rhynchonellids and terebratulids), gastropods, coralline sponges (*Neuropora spinosa*), boring sponges (*Aka muelleri*), serpulids and *Terebella lapilloides*, *Tubiphytes*, foraminifera (e.g. *Len-*

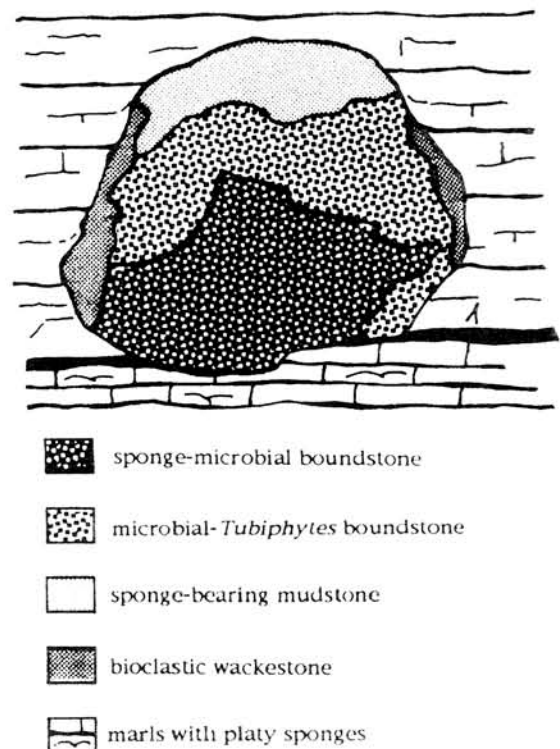


Fig. 4. Idealised section across a typical siliceous sponge - microbial mudmound of the Hornbuck Formation, Klettgau (Baden-Württemberg, Germany).

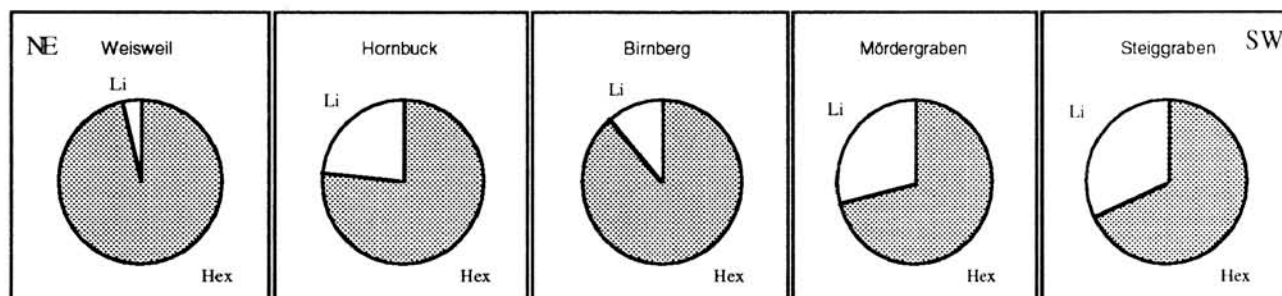


Fig. 5. The hexactinellid/lithistid-ratio from NW to SE in some outcrops of the Hornbuck Formation, Klettgau (Baden-Württemberg, Germany). Note that lithistid abundance increases relative to hexactinellids towards west, i.e. towards the shallower water.

ticulina, *Spirillina*, *Textularia*, *Nodosaria*, *Rheophax*) and bryozoans (*Berenicea*).

An idealised section (after HARTMANN 1993 and SADLER 1993) across a typical sponge microbial mudmound is shown in Fig. 4. The basal part consist of sponge-bearing marls. Hexactinellids, most of which are dictyids, are predominant. This facies type is replaced upwards by a sponge microbial muddy boundstone, characterised by a great amount of thrombolitic microbial crusts and hexactinellid sponges of all morphotypes (dishes, vases and tubes). Laterally as well as vertically a transition to a microbial crust-*Tubiphytes* boundstone occurs. Hexactinellid sponges are here less abundant. In most cases, sponge-bearing lime-mudstones form the top of the bioherm. The reef margin is represented by biodetrital wackestones with frequent fragments of microbial crusts ('tuberoids') and echinoderm detritus. The ratio of Hexactinellida to 'Lithistida' reduces from bottom to the top of the bioherms. At the bottom 'lithistid' sponges are very rare. Towards the top they become more abundant, although hexactinellid sponges still prevail.

Semiquantitative analysis of sponge groups from various locations shows a remarkable trend: towards the southwest, i.e. towards more proximal settings, the abundance of hexactinellids decreases, whereas 'lithistid' sponges become more frequent, although hexactinellids are still predominant (Fig. 5). This fits very well with the general paleogeographical situation. The shallow water coral reef belt of Moutier - Welschenrohr (Switzerland) was situated at this time only about 50 km to the southwest (GYGI 1969, MÜLLER et al. 1984) (Fig. 3). The ratio between hexactinellids and 'lithistids' also clearly reflects this shallowing trend towards the southwest. In modern seas, hexactinellids prefer deeper and colder water, whereas 'lithistid' demosponges are more common in tropical shallow water (e.g. LEVI 1964, 1991, REID 1968, VACELET 1988, VAN SOEST 1990).

Further to the east, i.e. towards the centre of the Swabian facies, sponge bioherms partly become larger and more complex. The quarry 'Klingenhalde' at Gosheim (western Swabian Alb) shows lenticular sponge buildups similar to the Hornbuck Formation (Pl. 1/5). An outstanding feature of the Klingenhalde locality is that small sponge microbial mudmounds (max 5 x 3 m) cluster to form a large scale, 30 m thick sponge reef structure (see Fig. 5 in LEINFELDER 1993a). This large sponge reef-complex shows its widest

lateral extension at the base which is a morphological form similar to most of the small buildups involved in the structure, though on a much larger scale. Towards the top, the sponge reef complex wanes continuously. The reef bioherms are rich in cryptocrystalline material, which in large part represents originally soft mud, as occasional bioturbation indicates. Bedded marls and marly limestones are intercalated between the small sponge bioherms and prevented diagenetic 'welding' to a macroscopical uniform, massive sponge-reef complex ('Massenkalk') as it is probably often the case for recrystallised saccharoidal, often dolomitised buildups in higher parts of the succession (see also section 3.1.2).

This reef complex is somewhat younger than the mounds of the Klettgau (cf. KOERNER 1963). In the Gosheim example crust-rich sponge-bioherms suddenly appear in the upper Malm α (Upper Oxfordian, Bimammatum Zone) over a lateral extension of about 200 metres. During the Malm β (Planula Zone), the siliciclastic input was reduced and micritic bedded carbonates predominated. Nevertheless, the sponge facies retreated continuously in favour of bedded lime mudstones onlapping the reef complex from all sides. Towards the upper part of the Malm β , the sponge facies was completely replaced by the bedded lime mudstone facies.

The sponges collected and analysed to date consists of about 70% dictyids, 10% lynchniscids and 20% lithistid demosponges, suggesting that the setting at Gosheim was not deeper than most of the Klettgau examples (cf. section 5.2). In the basal part of the sponge-complex giant dictyid vase-like sponges occur. They reach 2 m in diameter and are up to 1 m high (Pl. 1/1). The following sponge taxa were determined: *Verrucocoelia gregaria*, *Craticularia* sp., *Tremadictyon* sp. and *Cypellia rugosa*. The sponges are intensively covered with thick thrombolitic to dense microbial crusts. The accompanying macrofauna consist of various ammonites, belemnites, echinoderms, bivalves, brachiopods and serpulids. Similar composition of Oxfordian bioherms also can be found at other localities of the western Swabian Alb (e.g. Lochen).

3.1.2 Oxfordian and Kimmeridgian spongiolitic reefal environments from the Geislingen area, eastern Swabian Alb

The Geislingen area of the eastern Swabian Alb, as one

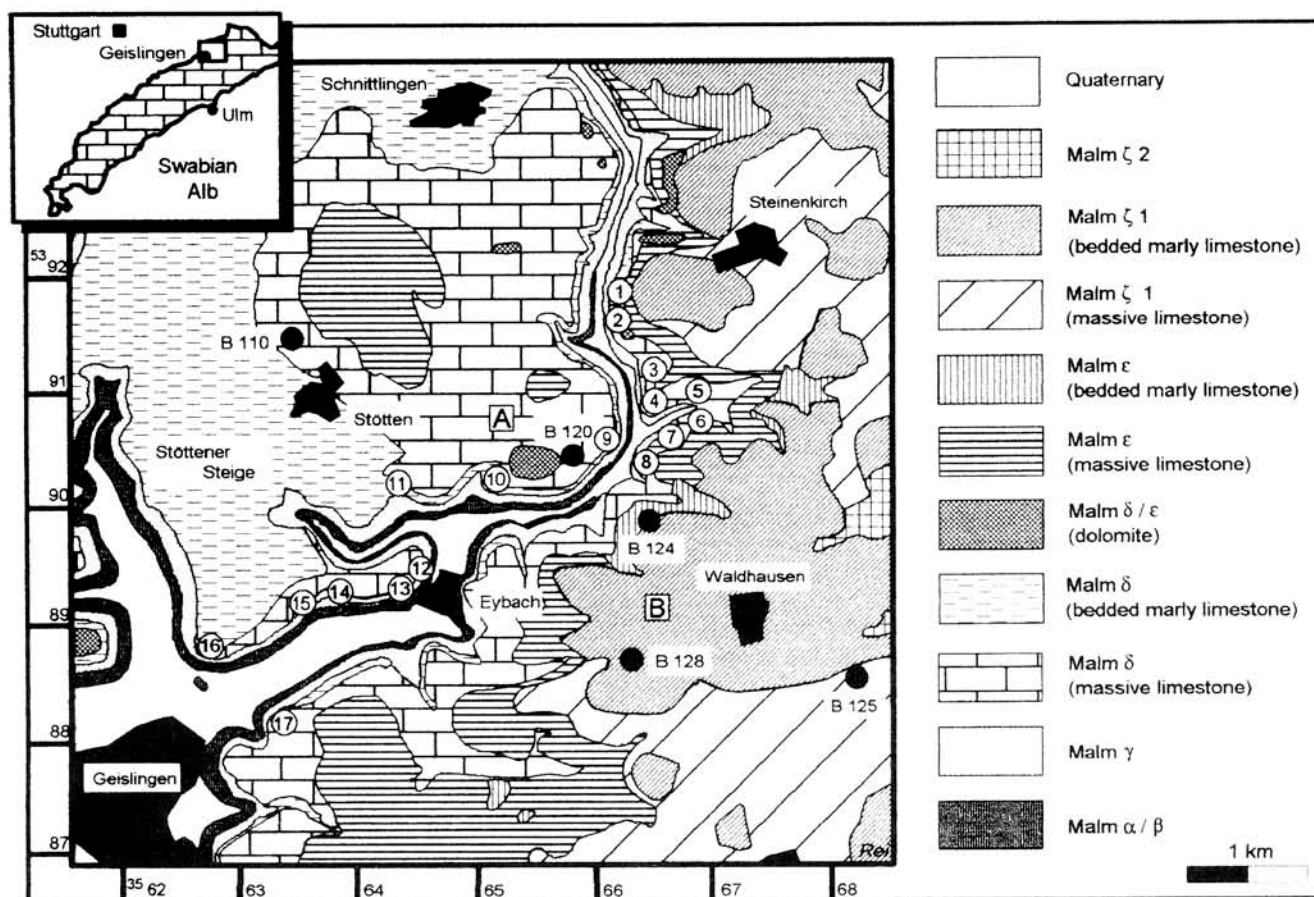


Fig. 6. Geological sketch map of the Upper Jurassic at the Geislingen - Eybatal area showing the locations of the investigated cores and major outcrops of massive limestones forming crags along the flanks of the Eybatal valley near Geislingen: 1.- Öhrnadel, 2.- Sphinx, 3.- Schulterfels, 4.- Gabelfels, 5.- Eislinger Wändle, 6.- Langer Schultes, 7.- Roggenstein, 8.- Lochfels, 9.- Albanus, 10.- Vergessene Wand, 11.- Franzosenstein, 12.- Himmelsfelsen, 13.- Spielerwand, 14.- Doppelüberhang, 15.- Drehfels, 16.- Anwandfels, 17.- Löwin

of the main targets within our project, is studied by three different working subgroups with the aim of establishing a high-resolution case study of the composition, diagenesis and architecture of reef and reef-hosting sediments of this area. The study is based on subsurface and outcrop data, the interpretation of which is facilitated by the newly available data on palynostratigraphy and mineralostratigraphy.

The spatial distribution of spongiolites in the Eybatal area (Koch)

Massive limestones ('Massenkalk') of varying stratigraphic position (Upper Oxfordian: Malm β, to Upper Kimmeridgian: Malm γ-ε) were mapped in the Eybatal valley in order to document the spatial distribution of spongiolite types. At the beginning of the study it was generally assumed that the massive limestones weathering out on the slopes of the Eybatal, would represent relics of spongiolitic bioherms of different size. The apparent synonymy of the terms 'massive limestones' and 'algal-sponge-reefs' is particularly based on GWINNER (1958). This interpretation was until recently generally accepted and appeared to be further substantiated by additional studies (ZEISS 1977; KEUPP et al. 1990; MEYER & SCHMIDT-KALER 1990, and SELG & WAGENPLAST 1990).

By examining about 200 mapped 'buildups' (Massenkalk), marked differences in facies development became apparent. Some buildups show more or less distinct, widely spaced bedding, whereas others show only very weak bedding. Many do not exhibit bedding but show a nodular fabric. Furthermore, in the upper part of the succession (Malm δ, early Late Kimmeridgian) abundant thick-bedded packstones and grainstones with peloids, lithoclasts and ooids were found. In some thick-bedded peloid-lithoclast-ooid carbonate sands, large micritic patches (up to some decameter in size) can be observed containing dish-shaped sponges.

The presently available results of ongoing microfacies analysis show that only about 30% of the 'massive limestones' in the study area can be considered as 'constructions with high biogenic contribution' (sponges, algae, 'crusts', brachiopods), whereas about 70% consist of peloid-lithoclast-ooid packstones and grainstones.

The Malm δ of the Eybatal valley shows pronounced lateral facies variation in response to accentuated morphologic differentiation of the sea floor. In area A (Fig. 6) the massive limestones are predominantly developed in nodular and irregularly bedded facies. The nodular character is caused by numerous sponge specimens preserved and partly enveloped by microbial carbonate. Larger micritic, sometimes nodular, spongiolite mounds up to 10 metre in

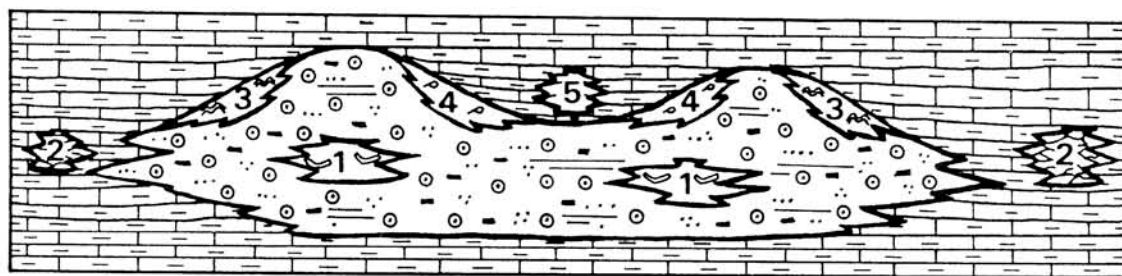


Fig. 7. Model of facies architecture of grain-dominated massive limestones for the lower part of Upper Kimmeridgian of the eastern Eybtl area. The model is thought to be valid for major parts of the Malm δ – $\zeta 1$ of southern Germany, where not developed in mud-dominated 'basinal' facies. Spongiolite mounds developed within and at the flanks of the peloid-lithoclast-oid sand facies.

(1) sponge-crust boundstone within the sand facies, (2) nodular, marly sponge-crust mounds in the marly facies between large sand areas, (3) crust-sponge mounds at the flanks of the sand facies towards the 'basins', (4) brachiopod-crust-sponge-mounds at the channel flanks between laterally amalgamated grain buildups, (5) sponge-crust mounds with internal zonation within the intra-buildup channels.

size are intercalated. This facies association is transitional to 'basinal' marly facies which also contains lenses of massive limestones of different size (dm to 10 m) which include nodular sponge-microbial crust muddy boundstones and up to 3 m thick lenses with nests of brachiopods. This 'basin' facies characteristically can be observed at the 'Stöttener Steige' near Stötten (Fig. 6). All facies types may occur together even within larger crags, as for instance the 'Himmelsfelsen' which has a size of about 60 m and formerly was thought to be spongiolitic massive limestone throughout but instead wholly consists of evenly bedded to nodular 'basinal' facies.

The Malm δ and ϵ of area B (Fig. 6) is generally characterised by the widespread development of peloid-lithoclast-oid sands. The massive limestones, formerly interpreted as spongiolites, consist of thick-bedded pure limestones rich in allochems (packstones and grainstones). Isopachous cements reflect primary interparticle porosity which later was clogged by marine phreatic cements. This suggests winnowing and, therefore, a moderate to elevated water energy level is assumed for the deposition of these carbonate sands. Intercalations of spongiolite lenses occur less frequently than in area A and encompass much smaller areas than the sand facies itself. Their place of formation was at the flanks as well as in interior settings of the high-relief sand bodies (Fig. 7). They comprise three different types, (1) micritic lenses rich in sponges (sponge-crust mounds, labelled 1 in Fig. 7), (2) mudmounds rich in brachiopods (labelled 4 in Fig. 7), and (3) crust-sponge boundstones (labelled 3 in Fig. 7), the latter stabilise the flanks of the huge sand bodies. Other additional spongiolitic types can occur (Fig. 7).

The examination of coeval massive limestones and associated sediments in other areas of the Swabian and southern Franconian Alb shows that the model of facies architecture developed in the Eybtl (Fig. 7) has a more regional validity. It can be concluded that during the Late Kimmeridgian, many if not most of the massive limestones ('Massenkalk') which generally were considered as sponge reefs, rather represent huge peloid-lithoclast-oid packstone/grainstone buildups, into which lenses of

sponge-bearing facies of various types are intercalated. A high particle content of massive limestone previously was recognised particularly for the latest Kimmeridgian and Tithonian and was thought to be largely related to coral facies (e.g. MEYER & SCHMIDT-KALER 1990). The abundance of these particles already during the early part of the Late Kimmeridgian, and possibly even earlier, as well as their association with siliceous sponge facies, was not known. However, the origin of these huge grain-dominated carbonate buildups is not clear to date. Possible interpretations are stacked submarine shallow sand dunes, large scale sand lobes, or microbial reefal buildups. The existence of microbial crust fabrics within the sands might indicate the importance of microbial mats in stabilising the structure (KEUPP et al. 1993). Hence, the carbonate grains could represent partly autochthonous microbial precipitates and partly allochthonous shallow water sediment.

Comparison of the Upper Oxfordian and Kimmeridgian massive limestones shows that both are highly differentiated in terms of facies organisation. Upper Oxfordian massive buildups represent single or stacked muddy mounds with variable abundance of crusts and sponges. This situation continues into the Kimmeridgian where it represents the 'basinal' facies. However, an additional and more dominant type of massive limestones occurred during the Late Kimmeridgian. This type represent huge grainstone buildups containing sponges and internal muddy or crust-rich siliceous sponge mounds.

Investigations of cores in the Geislingen area (Reinhold & Schroeder)

In the eastern Swabian Alb, between Stuttgart and Ulm, a large number of boreholes of 150 - 230 m depth were cored in preparation for a new high speed train track. In this project, facies types are studied in four cores from the Eyb Valley near the town of Geislingen/Steige, ranging stratigraphically from Lower Oxfordian to Lower Tithonian (Fig. 6).

In this section we particularly focus on the control of diagenetic features by facies and components.

Facies types Diagenesis			"massive limestone"			"bedded marly limestone"		Diagenetic environment
	Bioturbate Mudstone	Intraclast Filament Tubiphytes Wackestone/ Floatstone	Sponge-microbes Boundstone	Lithoclastic/ bioclastic Packstone/ Floatstone	Pellet Ooid Lithoclast Packstone/ Grainstone	"Filament" Mudstone/ Wackestone	Spicule Mudstone/ Wackestone	
stratigraphy	Malm β to lower γ	upper Malm γ to lower δ	Malm δ / ϵ	upper Malm δ	lower Malm ϵ	Malm ϵ	transition Malm ϵ / ζ	
depositional environment	below storm wave base, quiet water conditions, partly anaerobic substrate	below storm wave base, quiet water conditions, partly anaerobic substrate	deep ramp, below storm wave base, quiet water conditions	deep ramp, below storm wave base, quiet water conditions	shallow marine, above storm wave base, discontinuous sedimentation	quiet water conditions	quiet water conditions	
micritic envelopes	absent	absent	absent	plentiful	absent	absent	absent	m
bladed calcite	absent	absent	absent	absent	abundant	absent	absent	m
peloidal cement	absent	absent	abundant	abundant	abundant	absent	absent	m
pyritization	abundant	abundant	abundant	abundant	absent	absent	absent	m/b
chert nodules	absent	absent	absent	absent	absent	absent	abundant	m?
aragonite leaching	absent	absent	absent	absent	absent	absent	absent	b
calcification of sponges	absent	absent	absent	absent	absent	absent	absent	b
syntaxial rims	absent	absent	absent	absent	absent	absent	absent	b
scalenohedral cem.	absent	absent	absent	abundant	absent	absent	absent	b
fracture I (partly syngedimentary)	absent	absent	absent	absent	absent	absent	abundant	b
neomorphism of micritic matrix	absent	absent	absent	abundant	abundant	absent	absent	b
sparry calcite	absent	absent	abundant	abundant	abundant	absent	absent	b
vug formation	absent	absent	absent	abundant	absent	absent	absent	b
dolomite replacement in the matrix and along stylolites	absent	absent	absent	abundant	absent	absent	absent	b
(Fe)-dolomite cem.	absent	absent	absent	abundant	absent	absent	absent	b
saddle dolomite	absent	absent	absent	abundant	absent	absent	absent	b
vertical stylolites	absent	abundant	abundant	abundant	abundant	absent	absent	b
horizontal stylolites	absent	absent	absent	absent	absent	absent	absent	b
fracture II	absent	absent	absent	absent	absent	absent	absent	b
fracture III	absent	absent	absent	absent	absent	absent	absent	b
dedolomite	absent	absent	absent	abundant	absent	absent	absent	mp
sparry Fe-calcite	absent	absent	absent	abundant	abundant	absent	absent	mp
helectite	absent	absent	absent	absent	absent	absent	absent	mv
silicification	absent	absent	abundant	absent	absent	absent	absent	mp
quartz cement	absent	absent	absent	absent	absent	absent	absent	mp

absent ——— rare ——— moderate ——— plentiful ——— abundant ———
 m marin mp meteoric-phreatic mv meteoric-vados b burial

Fig. 8. Relations between diagenetic products and their genetic environments in different facies types, observed in Upper Jurassic cores from the Geislingen area. The lines illustrate the occurrence and frequency of diagenetic phenomena. The diagram shows that the diagenetic features are controlled by the primary rock fabric and the components. Note: in this table the diagenetic products are combined in order of the diagenetic environments.

Facies types: Seven facies types are distinguished in the core material by variations of dominant components and textures (Fig. 8).

The relatively high amount of matrix-supported small components in fine-grained marls and muddy limestones is an indication of quiet water conditions close to, but below storm wave base during the development of the bioturbated mudstones and intraclast filament *Tubiphytes* wacke- to floatstones. The common precipitative pyrite aggregates and *Chondrites* feeding traces indicate partly dysaerobic conditions (BROMLEY & EKDALE 1984, BROMLEY 1990).

In the 'massive limestone' facies ('Massenkalk-Fazies') three facies types occur (Fig. 8). The micro-encruster associations of microbial crusts indicate a deep ramp position, just below storm wave base for the formation of sponge-microbial boundstones and lithoclastic bioclastic pack- to floatstones. The microbial mats are encrusted by nubeculariid foraminifers, nodosariid foraminifers (e.g. *Bullopore tuberculata*) and *Terebella lapilloides* in combination with rare serpulids, bryozoans and brachiopods, an association which is similarly recognisable in deeper mid-ramp and outer ramp sponge-microbial mud mounds in Portugal (LEINFELDER et al. 1993b). In contrast, ooids and rounded lithoclasts in partly bedded carbonate sands indicate deposition above normal wave base. Some ooids were transported into deeper and calmer regions as suggested by ooid-packstones. Intercalated thin microbial mats with dense to peloidal fabrics and beds of baffled ooids suggest discontinuous deposition with intermittent calm periods: The microbial mats started growing at the sediment-water interface when accumulation had stopped and were covered by the next sediment influx.

The high amount of filaments and spicules in mud- and wackestones of the "bedded marly limestone" facies ('Bank-Fazies') also indicates quiet and deeper water conditions.

Diagenesis: The various diagenetic products, and their occurrence and abundance in specific facies types, are largely dependant on the primary facies development (Fig. 8). Their control by organisms, inorganic components and primary structures will be shown by some examples (Fig. 9; Pl. 2):

Dolomitisation and silicification are particularly controlled by fabric and particle composition. Dolomitisation is confined to the "massive limestone facies", whereby an early dolomitisation is related to the primary facies and a second dolomitisation is formed at dissolution seams and by replacement fronts (e.g. BRACHERT 1986, KEUPP et al. 1990, LIEDMANN & KOCH 1990). During early dolomitisation, first the micritic matrix is replaced by euhedral dolomite rhombs. In this process the components, especially the sponges and the dense microbial crusts, are more resistant to dolomitisation. In contrast, the second dolomitisation is related to pressure solution and vug formation.

The formation of chert concretions and quartz cement is confined to the spiculite facies where silica is available from sponges and spicules. Similarly, fossils are silicified in facies where siliceous sponges are abundant. Only sponges,

bryozoans and belemnites are frequently silicified, thus organisms are controlling factors for diagenetic features.

Pyritisation is primarily controlled by the depositional environment but, to a certain extent, possibly also by the primary mineralogy of the biogenic components. Pyrite often partly replaces skeletons, such as belemnites, bryozoans, echinoderms, sponges, worm tubes, brachiopod and mollusc shells, but is never observed in microbial crusts. Pyrite substituted the skeletons either with preservation of primary structures (e.g. sponge spicules, 'sieve plates' of echinoderms, pores of punctate brachiopod shells) or resulted in their destruction (e.g. belemnites, ammonites, mollusc shells). In addition, pyrite, cubic or irregular in shape, is precipitated in vugs, bioturbations and intraskeleton pores (e.g. sponges, brachiopod and pelecypod shells).

The examples described show that the diagenetic processes, the different pathways and successions are controlled by specific facies types, their complex interactions between biogenic, abiogenic components and matrices as well as earlier diagenetic products. One of the diagenetic sequences observed is presented in Fig. 9. Generally, the diagenetic record begins with an early marine phase with some bladed cement rims, micritic envelopes and pyritisation. Chert nodules with fractures filled by sediment indicate an early migration of silica under marine conditions. Aragonite leaching, various types of calcite cements and a first dolomitisation occurred during an early shallow burial diagenesis. In the core material we have no evidence in the diagenetic record for subaerial exposure during an early meteoric phase, contrary to observations in outcrop material from the Geislingen area (KOCH, pers. com. and own investigations). In addition, KOCH & SCHORR (1986), POMONI-PAPAIOANNOU et al. (1989) and LIEDMANN & KOCH (1990) described an early meteoric-vadose diagenesis from several Upper Jurassic localities in southern Germany, possibly indicating a small scale subaerial exposure of isolated carbonate sand bodies during the latest Jurassic.

Pressure solution, fracturing and a second dolomitisation with frequent saddle dolomite are developed during deep burial diagenesis. Following uplift, a second meteoric phreatic phase with karstification is indicated by dedolomitisation, homogenous sparry calcite cements and, rarely, helectite in fractures. In addition, goethite migrated from fracture walls into the sediment.

3.1.3 Swabian coral facies from the terminal Kimmeridgian (Latenser)

From the latest Kimmeridgian until the earliest Tithonian a relative fall in sea level created the precondition for coral reef growth in progressively shallowing waters on the entire south German ramp (LEINFELDER 1993a). For south-western Germany scattered occurrences of coral facies mostly exist in the eastern Swabian Alb (cf. SCHWEIZER-KLEMP 1982). Coral facies development continued into the earliest Tithonian (GEYER 1954), where it disappeared after a distinct shift towards the south and south-west (cf. SCHWEIZER-KLEMP 1982, SCHWEIGERT 1993a).

The 'Arnegg Reef' of late Kimmeridgian age is the only

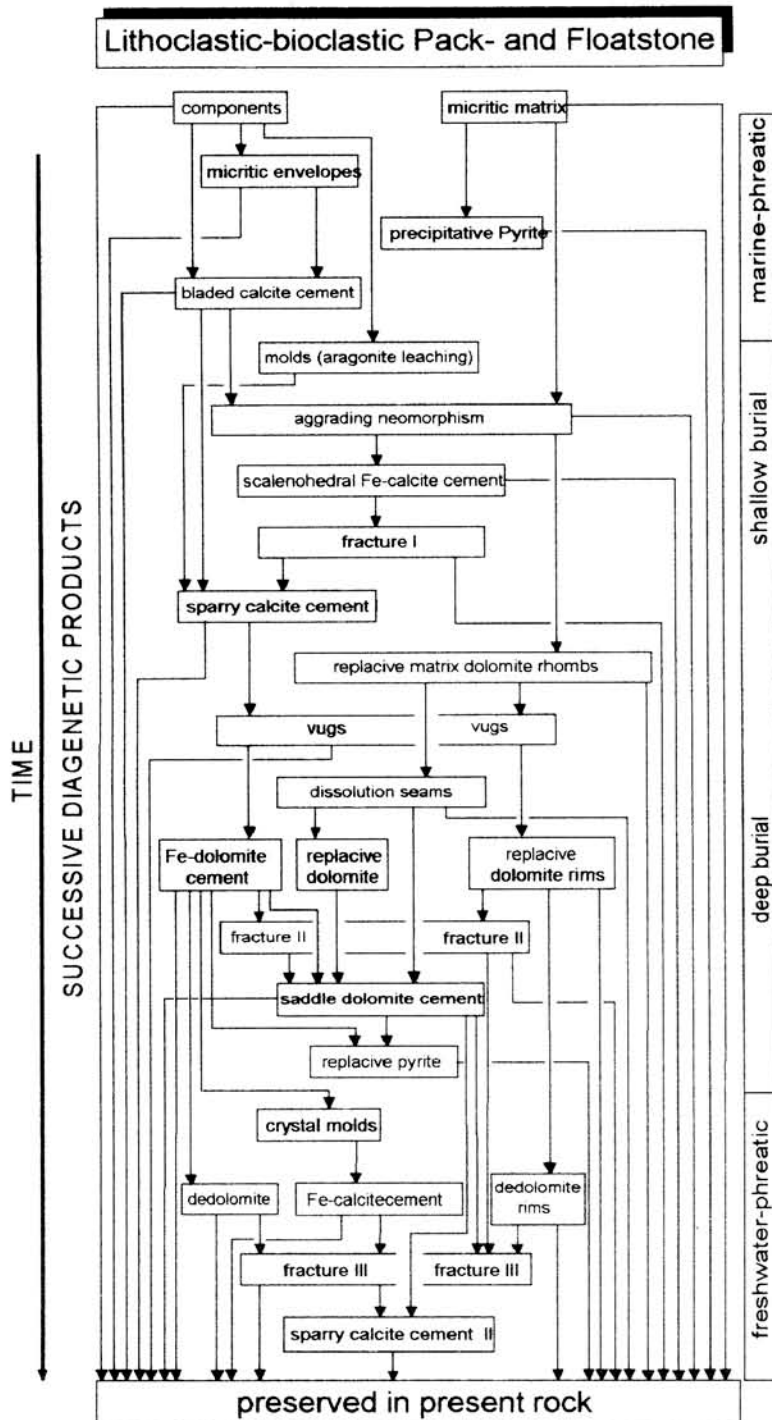


Fig. 9. Example for a facies controlled diagenetic sequence: Preliminary petrogenetogram of the lithoclastic-bioclastic pack- and floatstone facies showing the successive diagenetic development observed in the present rock. The connecting lines indicate the diagenetic sequences; diagenetic products of the same age are arranged in one level. On the right hand the interpreted diagenetic environment is shown.

example of a more fully preserved coral reef within the coral facies of the Swabian Alb. After the detailed study of PAULSEN (1964) a new investigation based on modern carbonate sedimentology is currently in progress. The 'Arnegg reef' grew on a topographic elevation represented by an Upper Kimmeridgian sponge-microbial crust bioherm which provided shallow water enabling growth of reef corals. The observable part of the 'Arnegg Reef' suggests

an original irregular circular geometry of the reef complex. The succession of facies types represents a distinct shallowing upward trend, evidenced by a gradual transition from siliceous sponge-microbial crust facies, to coral-siliceous sponge thrombolite facies (cf. PAULSEN 1964), and eventually to coral facies. In the associated calciclastic sediments a general coarsening upward trend from mudstones to peloidal/bioclastic wacke/pack/floatstones and finally grain/rudstones is detectable. This can be explained by both increasing production of coarser debris particles due to the shallowing into the wave agitated zone, as well as by progradation of the debris wedge. In the lower part of the reef debris apron, some intercalated thrombolitic coral - siliceous sponge bioherms occur. They contain massive, platy, solitary and branching corals in similar proportions. The top of the reef complex represents the central reef area with baffle/bindstone bioherms (2 to 6 m in diameter) which show lateral and vertical transitions with interreef debris in grain/rudstone fabric. The reef core is fringed by grain/rudstone debris facies with intercalated biostromes.

The coral bioherms of the Arnegg complex are composed of massive, platy and branching corals, whereas the biostromes of the debris facies largely contain massive to platy forms. Together with the corals, the dasycladacean green alga *Acicularia* (PAULSEN 1964), the microencruster *Lithocodium aggregatum* and the problematic chaetetid sclerosponge *Eurysoleenopora polypora* (cf. MOUSSAVIAN 1989) point to very shallow conditions at least for the topmost part of the reef. Microbial crusts are largely absent in the coral facies, whereas stromatolitic crusts occur in the underlying mixed facies.

From the basal sponge to the mixed coral-sponge facies, the composition of siliceous sponges changes towards an increasing frequency of lithistids, whereas hexactinellids decrease rapidly. Within the coral facies rigid siliceous sponges are extremely rare.

In other coral localities of the Swabian Alb, the corals are mainly found in debris beds. Rarely, biostromes and small reef knobs occur. Marly coral meadows also existed (LAUXMANN 1992). The debris facies shows high to low diversity associations with dominance of massive colonies over dendroid, phaceloid, foliose and solitary forms. In contrast, the marly facies is dominated by solitary, dendroid and phaceloid corals, and only contain low amounts of massive and foliose forms. Corals are accompanied by gastropods, bivalves, brachiopods, coralline sponges, echinoids, serpulids, bryozoans, *Tubiphytes*, foraminifera

and exceptionally siliceous sponges and chaetetids. During the latest Kimmeridgian (SCHWEIGERT 1993; see section 4.1), and hence simultaneously with neighbouring coral facies (SCHNEIDER 1957, REIFF, 1958, MALL 1968), locally large masses of obliquely stratified bioclast/intraclast-wackestones to rudstones up to 60 m thick (e.g. Brenztaltrümmersoolith') (REIFF 1958, SCHLÖSSNER 1987) were deposited, probably as storm-induced debris aprons. Despite the shallow water provenance of these sediments, coral fragments are rare in many localities. The detrital limestones laterally wedge out by interfingering with the 'Zementmergel', a succession of grey calcareous marls and limestones, which in turn are laterally associated with massive limestones with abundant siliceous sponges and microbial crusts (cf. Fig. 18). This situation clearly demonstrates that the coral facies did not develop extensively. Larger, though probably isolated, shallow-water areas were particularly characterised by the development of shallow water sands. Most likely, only small coral patch reefs and meadows developed in these shoal areas. Larger coral reef complexes such as the 'Arnegg Reef' were very rare and probably restricted to local topographic elevations extending into the shallow-water. Siliceous sponge facies thrived contemporaneously on the tops and at the flanks of less elevated grain-rich mounds (see section 3.1.2). Allochthonous shallow-water sands and marls accumulated in depressions between these buildup areas, indicating that a very accentuated and differentiated submarine topography had developed by the end of the Kimmeridgian.

3.2 Iberian Jurassic reefs

Jurassic reefs from Iberia were studied in three different basins, the Lusitanian Basin of west-central Portugal, the eastern Algarve Basin of southeastern Portugal and the Prebetic-Celtiberian-Demanda Seaway of eastern Spain.

Middle Jurassic siliceous sponge facies preceded a comparable Oxfordian development in eastern Spain. The common factor of the three Iberian basins is the development of a distinct large scale Upper Jurassic shallowing upwards succession, despite the fact that third-order sea level fluctuation and synsedimentary basin tectonics partly overprinted this trend. Siliceous sponge facies particularly developed during the Oxfordian, whereas mixed coral-sponge facies and coral facies predominated during the Kimmeridgian and, partly, Tithonian. Microbial reefs are a frequent constituent of Iberian Upper Jurassic reef facies, and had their peak of development in the eastern Algarve.

3.2.1 Middle Jurassic spongiolite and automicrite development from the NW-Iberian Chains (Sierra de la Demanda, Spain) (Rehfeld-Kiefer)

General setting and distribution of spongiolites

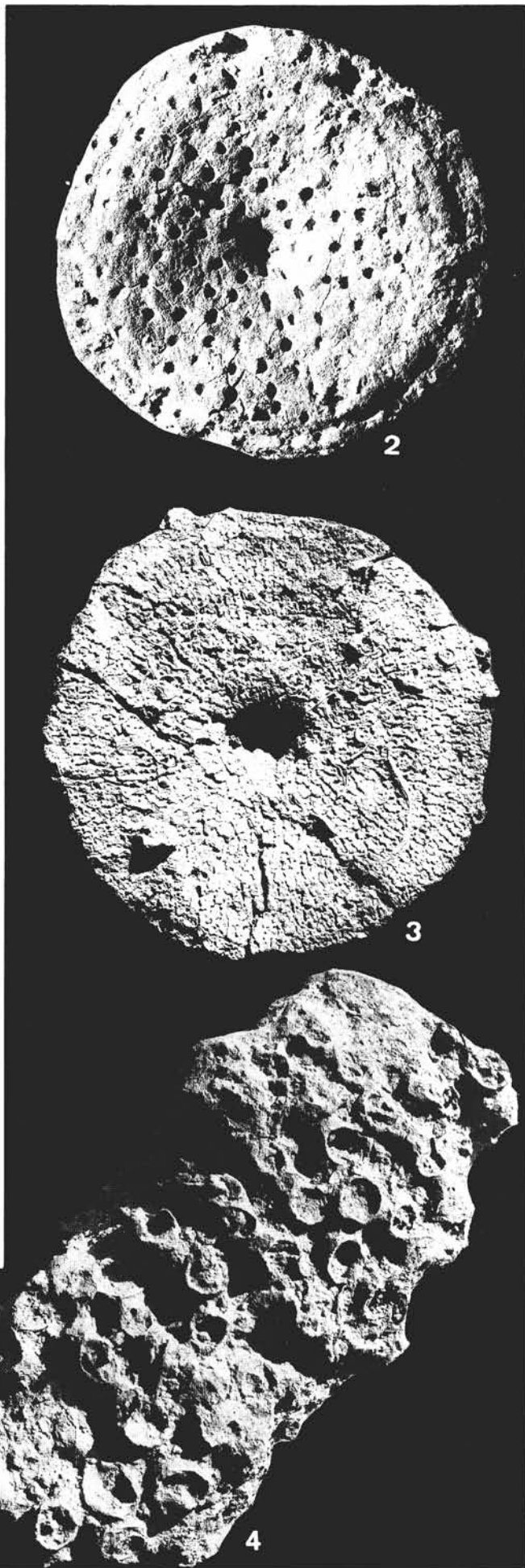
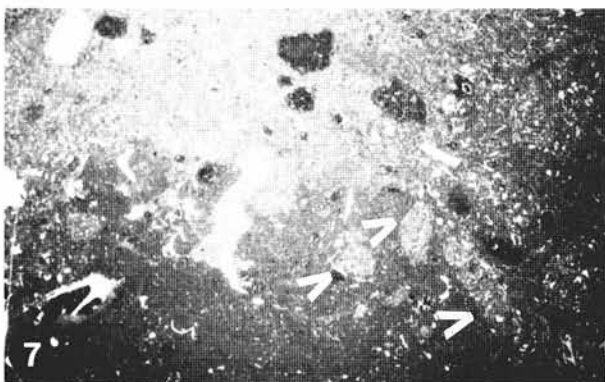
Middle Jurassic strata of Mid and Late Bajocian age are characterised by the widespread development of siliceous sponge facies. Their stratigraphic distribution ranges from the Sauzei to the Parkinsoni Zone.

In the Sierra de la Demanda (Fig. 10) a carbonate platform of moderate water depths was established at this time. Its facies and bathymetry were only faintly differentiated, representing an extended near level-bottom mid to outer ramp setting with a protected western and southern part and a more agitated central and eastern area. A slight general eastwards facies shift has occurred (WESTERMANN, 1955, MENSINK, 1966), since in the Upper Bajocian the onset of superimposed massive limestones seems to be somewhat earlier (Acris Subzone) in the west than in the east (Densicostata Subzone) of the Demanda area.

Sedimentation rate remained low throughout the entire time of deposition. Depositional conditions are characterised by hardground development and reworking as well as strong biostratigraphic mixing of ammonite faunas especially during

Plate 1 Siliceous sponge facies and siliceous sponges from southwestern Germany and Iberia (1-6: Krautter, 7: Rehfeld)

- Fig. 1. Giant vase-like dictyid sponge of the Klingenthalde-quarry near Gosheim (Oxfordian, western Swabian Alb, Germany). Height of sponge specimen: 80 cm.
- Fig. 2. *Staurodermalochense* (QUENSTEDT). Diameter of sponge: 14 cm. Oxfordian, El Cañigral, Prov. Teruel, Spain.
- Fig. 3. *Tremadictyon reticulatum* (GOLDFUSS). Diameter of sponge: 12 cm. Oxfordian, Jabaloyas, Prov. Teruel, Spain.
- Fig. 4. *Verrucocoelia gregaria* (QUENSTEDT). Height of sponge: 15 cm. Oxfordian, Jabaloyas, Prov. Teruel, Spain.
- Fig. 5. Small siliceous sponge bioherm (2,5 x 6 m) of the Klingenthalde-quarry near Gosheim (Oxfordian, western Swabian Alb, Germany).
- Fig. 6. Frías de Albarracín-section (Prov. Teruel, Spain). The figure shows a typical outcrop of the Oxfordian siliceous sponge-biostromal facies. A thick bed of sponge-bearing limestone at the base is overlain by an alternation of spongiolitic limestones and thin sponge-bearing marls. Thickness of the Oxfordian sponge-limestones (between arrows): 11 m.
- Fig. 7. Thin-section of Bajocian automicritic sponge facies from the Demanda area, Spain. Figure shows boundary between automicrite and overlying allomicrite. *Zoophycos* burrows (arrows) can be traced to the uppermost layers of the automicrite. Tuberoids probably result from burrowing activities in the surface layers of the automicrite. Most of the white dots within automicrite represent sponge spicules. Width of photograph is 2 cm.



the Upper Bajocian between the Niortense and Parkinsoni Zone (see also MENSINK 1966). The Humphriesianum Zone is reduced to an average of six metres. Carbonate production exceeded accommodation only in the upper part of the Parkinsoni Zone and massive shallow water limestones accumulated.

Facies development (cf. Fig. 23): The depositional units correspond to three depositional sequences, which can be assigned to three third order sea level cycles (see section 4.4.1). In the Sauzei and Humphriesianum Zone deposition started above a stratigraphic gap with 'biostratigraphic condensation' or even complete absence of the lower Sauzei Zone. Brecciated and pebbly limestones as well as clayey pebbles suggest reworking and terrestrial influence. In the western Demanda karstified carbonate breccia, bored by excavating bivalves, form the base of the sequence (WESTERMANN 1955). In some areas of the southern Demanda a distinct angular unconformity is developed. For this reason, tectonic causes for the formation of the break have been discussed (WESTERMANN 1955). Superimposed sediments largely consist of bioclastic allomicrites, generally enriched in echinoderm debris, and dense dark bioclast-bearing automicrites (see below), which thicken upward and alternate with thin marl layers. They are enriched in planktic and benthic foraminifera and are interpreted to be deposits of distal, open-marine conditions. Several beds developed hardgrounds on their surfaces which are covered by *Belemnopsis canaliculata* forming unoriented belemnite 'battlefields', as well as by large ammonites up to 20 cm in size with heavily dissolved shells (*Sonninia furticarinata* according to WESTERMANN 1955), and dense clusters of serpulids. Bioclasts are heavily bored and many of them are encrusted by miliolid foraminifera.

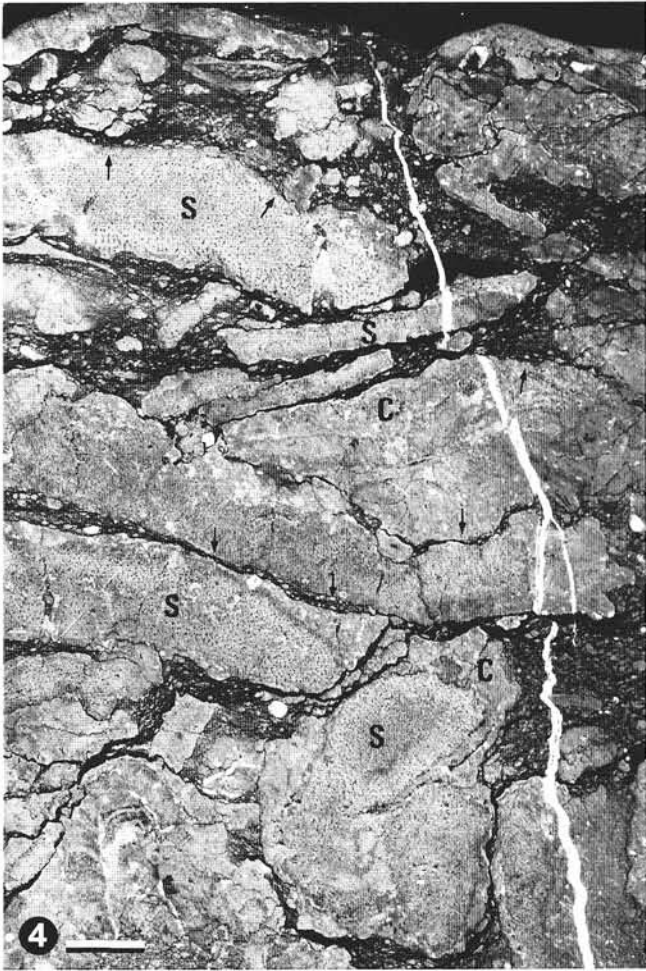
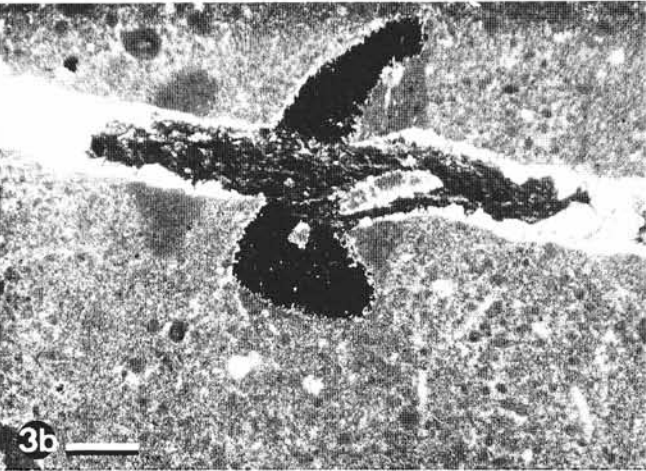
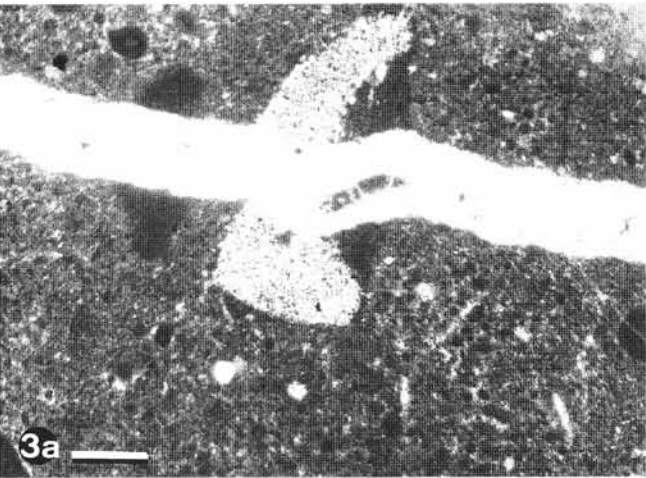
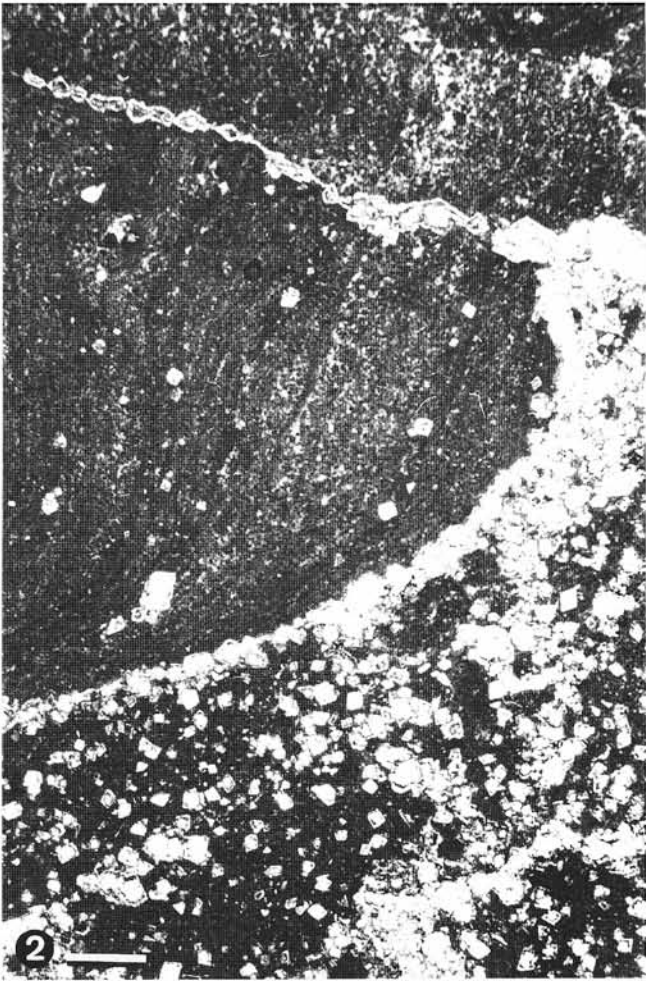
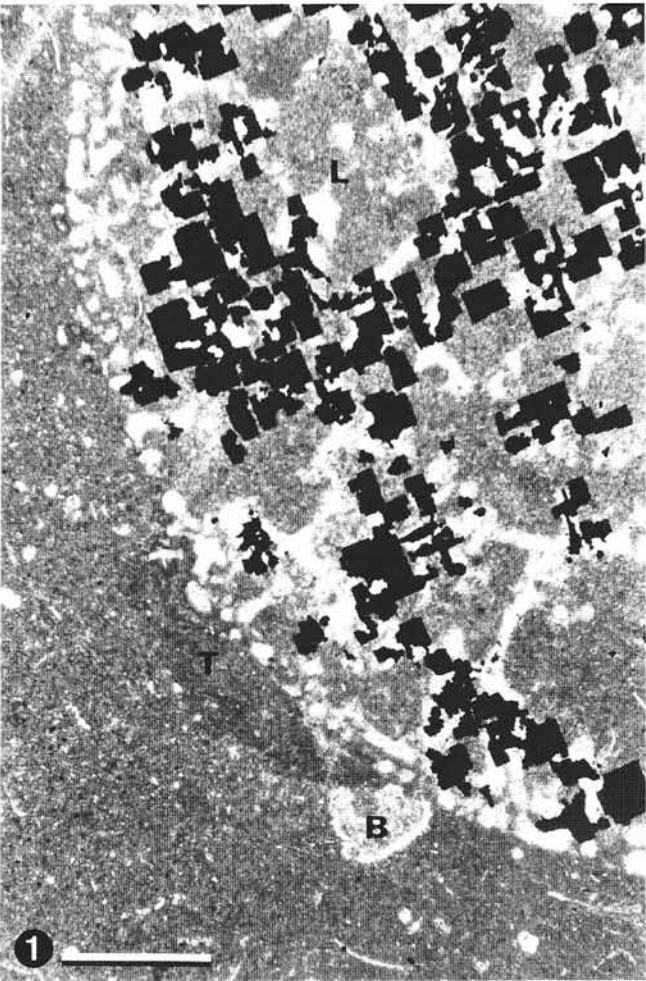
The upper beds of the Humphriesianum Zone and the base of the Upper Bajocian (biostratigraphically mixed Niortense-Garantiana Zone) suggest a short-term development of a second deepening/shallowing cycle. Sedimentation starts with moderately thick bioclastic limestone beds (still belonging to the Humphriesianum Zone according to MENSINK 1968) which grade into very thin bedded marl-limestone alternations. Within the upper part of the Niortense-Garantiana Zones, the depositional environment was suddenly subject to strong terrestrial influx comprising quartz sands, red sandy limestones, red clays and ferruginous and clayey concretions. Ammonites of both zones coexist in one layer. On top of the zone intense reworking of the underlying beds resulted in strong concentration of ammonites and other bioclasts. These reworked beds are heavily iron-stained. Above an iron-oolitic limestone bed, open-marine conditions were re-established.

Following gradual deepening within the Garantiana-Parkinsoni Zones a shallowing cycle initiated the development of a shallow-marine carbonate platform with little clastic influence. In the Parkinsoni Zone, massive, largely automicritic deposits with extensive void structures developed. Peloidal crusts are common in this facies. Upwards in the section, reworking of these automicrites initiated the development of massive tuberolitic pack- and grainstones.

Lithology, facies, and sediment thicknesses indicate that the evolving carbonate platform declined rather steeply first (Humphriesianum Zone) in the northeast, and somewhat later (Parkinsoni Zone) in the east. Sediment thicknesses attain three to four times the thicknesses with respect to the platform sediments. Along the platform margin well-sorted, cross-bedded oolitic limestones (100-150 m thick) interfinger with the platform carbonates (20-30 m thick) in the Upper Bajocian.

Plate 2 Control of diagenetic features by kind and fabrics of biogenic components: Examples from core 124 of the Geislingen area (Reinhold/Schroeder)

- Fig. 1. Skeletal pore preferentially cemented: Euhedral pyrite cubes are exclusively precipitated within the intraskeleton pores of a lithistid sponge during early marine diagenesis (sponge (L) encrusted by *Tubiphytes* (T) and *Bullopore tuberculata* (B)). Note that pyrite is not developed in the surrounding micritic matrix. Core B 124, 93,1 m depth, sponge-microbial boundstone facies, Malm, Geislingen area, eastern Swabian Alb. Sample 92-8, parallel nicols.
- Fig. 2. Skeletal pore preferentially preserved: Early meteoric dolomitisation affected the micritic matrix which is replaced by euhedral zoned dolomite rhombs. Note that only few dolomite crystals occur within the column-shaped stromatolitic-like microbial crust. Dolomite formation is controlled by content and distribution of primary clay minerals in the sediment as Mg-ions supplier. Core B 124, 69,9 m depth, sponge-microbial boundstone facies, Malm, Geislingen area, eastern Swabian Alb. Sample 68-12, parallel nicols.
- Fig. 3. Skeletal material controls late fracture cement: Late diagenetic sparry calcite cement in a fracture syntaxially overgrew an echinoderm fragment in surrounding rock. Crystallographic orientation of the sparry calcite is determined by the echinoderm fragment, in contrast to that of the earlier bladed cement in the fracture. Core B 124, 46,5 m depth, lithoclastic bioclastic packstone facies, Malm, Geislingen area, eastern Swabian Alb. Sample 46-3; fig. 3a: parallel nicols; fig. 3b: crossed nicols.
- Fig. 4. Primary facies determines intensity and path of dissolution: More of the micritic matrix is dissolved than of sponges (S) and crusts (C). Additionally, the stylolites are related to the surfaces of the biogenic components (arrows). Core B 124, 88,2 m depth, sponge-microbial boundstone facies, Malm, Geislingen area, eastern Swabian Alb. Sample 88-1, polished specimen.



Distribution of sponges: Sponges are mostly represented by lithistid demosponges. They are accompanied by hexactinellids in the deeper or more distal parts of the depositional environment and calcareous sponges in shallower, higher energy environments. Sponges are accompanied by automicritic aphanitic crusts or consist of encrusting foraminifera in the more distal or deeper water environment. Peloidal crusts dominated in shallower waters under sediment starvation. Sponges are generally colonised by dense clusters of serpulids and bryozoans, independent of their stratigraphical position.

Growth of sponges first started in the Sauzei Zone. They appear directly over the hiatus of the Sowerbyi or lowermost Sauzei Beds. The widest distribution of in situ sponges occurs in the lower portions of the Humphriesianum Zone where sponges have been documented in the entire Demanda area. These sponges are linked to automicritic hardgrounds and like these became frequently reworked; thus they never developed larger biogenic structures. With the beginning of the Niortense/Garantiana Zones sponge growth seemed to be partly inhibited by terrestrial input. Sponges were toppled, often corroded, iron-stained, and poorly preserved. However, sponges even colonised the platform margin during periods when sedimentation of, probably allochthonous, oolitic limestones was interrupted by brief intervals of more stable conditions. In the Garantiana-Parkinsoni Zones and the massive carbonate limestones of the upper Parkinsoni Zone sponges mostly built biostromal meadows. Locally, their thicknesses increase to several metres, and sponges are tightly connected to peloidal microbial crusts and peloidal

cementation. But at the same time they became increasingly restricted to localised areas of the western and southern Demanda. In the uppermost sections of the Parkinsoni Zone they became rare and have only a patchy distribution. They were substituted by tuberolitic packstones, or more rarely oolitic grainstones, indicative of a shallow, high energy environment. In the eastern Demanda, sponge facies was completely replaced by these sediments and even seem to have been largely missing in its central part.

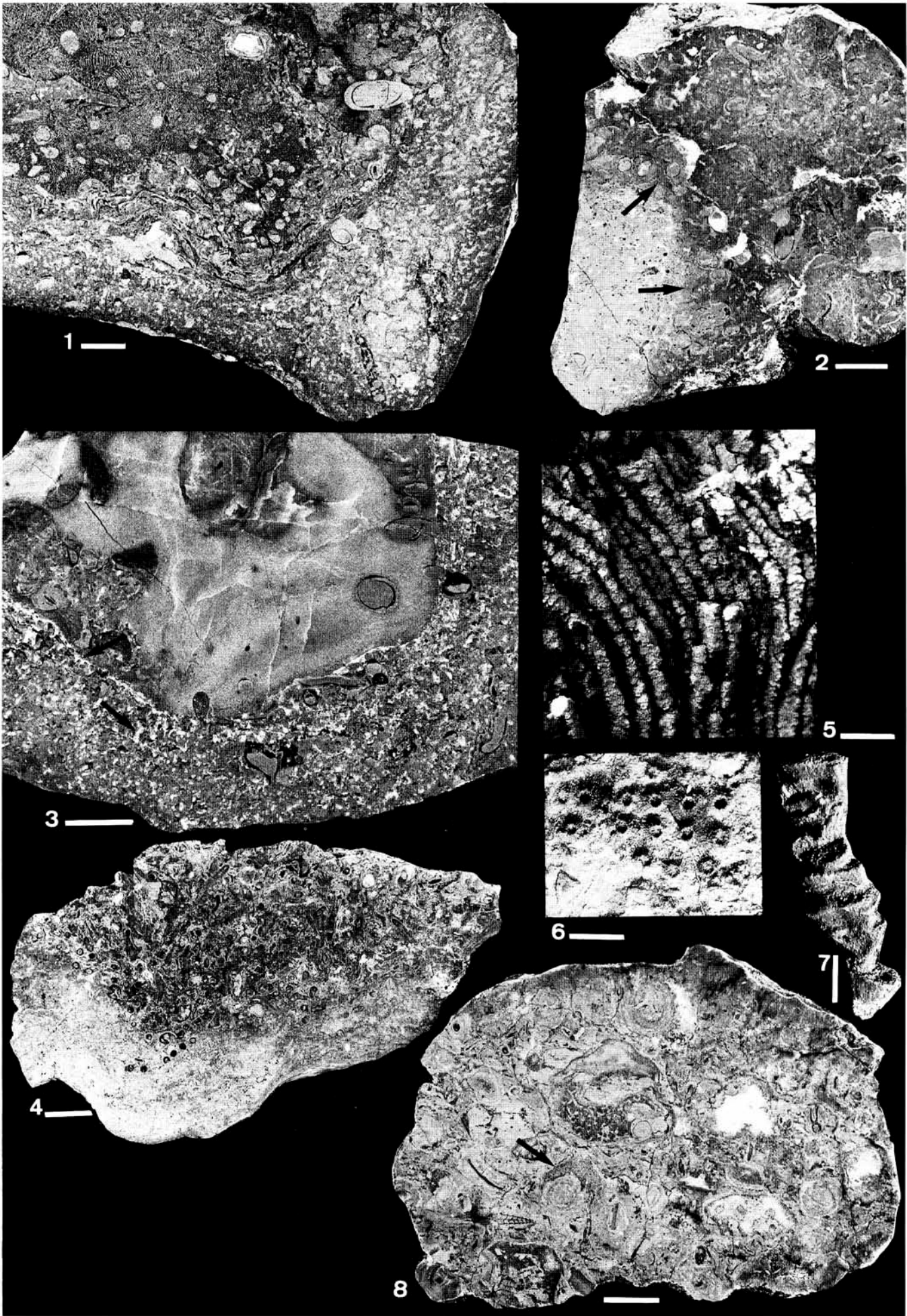
In the adjacent Celtiberian Basin, to the south, similar spongiolite development occurred penecontemporaneously. In contrast with the Demanda area, the more frequent occurrence of bioherms in addition to the dominant biostromal facies, and the dominance of dictyid rather than lychniskid sponges (FRIEBE 1991), indicate a generally deeper setting (cf. section 5.2).

Site of sponge preservation: The cyclic development of facies during the Mid and Late Bajocian of the Sierra de la Demanda indicates several external factors controlling sponge growth and sponge preservation:

1. Sponges are closely linked to environments of sediment starvation and thus are preferentially found in connection with automicritic deposits which exhibit hardground characteristics.
2. They vanish or are not recorded in higher energy environments.
3. They reconquered a suitable habitat very quickly. During generally unstable conditions, such phases were very short-lived.

Plate 3 Shallow-water coral and microbialite facies from the Upper Jurassic of Iberia (bars indicate 1 cm, except in Fig. 5: 2 cm)(Nose/Schmid)

- Fig. 1. Detail from coral-stromatoporoid-chaetetid-microbial crust reef: downward facing microbial crusts grew on massive thamnasterioid *Synastrea multicincta* (Koby, 1904). Common participation of *Tubiphytes* (white dots); Jabaloyas, Celtiberian Basin, Spain.
- Fig. 2. Two generations of shallow-water microbial crusts. First crust generation (dark crust to the right) exhibits a peloidal thrombolitic fabric; the younger lighter crust (lower left corner) is rich in *Tubiphytes* (white dots) and is characterised by a dense to clotted fabric. The boundary (indicated by arrows) is heavily bored by lithophagid bivalves, indicating interruption of crust development. Arroyo Cerezo, Celtiberian Basin, Spain.
- Fig. 3. Detail from coral-stromatoporoid-chaetetid-microbial crust reef: thrombolitic crusts, rich in *Tubiphytes* (white dots) grew on the lower surface of a stromatoporoid demosponge (?*Dehornella*) which is intensively bored by lithophagid bivalves. The orientation of *Tubiphytes* encrusting the demosponge clearly demonstrates the downward growth of microbial crusts (arrows) forming downward facing hemispheroids; Jabaloyas, Celtiberian Basin, Spain.
- Fig. 4. Detail from coral-microbial crust reef: microbial crusts growing on the bottom side of *Stylosmilia michelini* MILNE-EDWARDS & HAIME, 1848, forming downward facing hemispheroids; Monte Céu, Lusitanian Basin, Portugal.
- Fig. 5. Branched *Ovalastrea plicata* Koby, 1904, an important element of thrombolitic and marly reef facies forming large colonies up to a height of two metres; Patameira, Lusitanian Basin, Portugal.
- Fig. 6. *Stylinia decipiens* ÉTALLON, 1864, on the surface of a thrombolitic limestone bed; C. da Lapa, Lusitanian Basin, Portugal.
- Fig. 7. *Trocharea* cf. *gregoryi* (Koby, 1904), this patellate coral is restricted to siliceous sponge-bearing coral thrombolites in outer ramp settings. The specimens often represent stacked individuals exhibiting a tree-like morphology; C. da Lapa, Lusitanian Basin, Portugal.
- Fig. 8. Detail from coral-chaetetid-mud reef: mud-rich reef type with corals (e.g. *Dermoseris*) growing on secondary hard substrates, such as oncoids (arrow); Terriente, Celtiberian Basin, Spain.



4. Sponge record and preservation are best in environments with peloidal cementation.

Sponge-hosting automicritic sediments and crusts

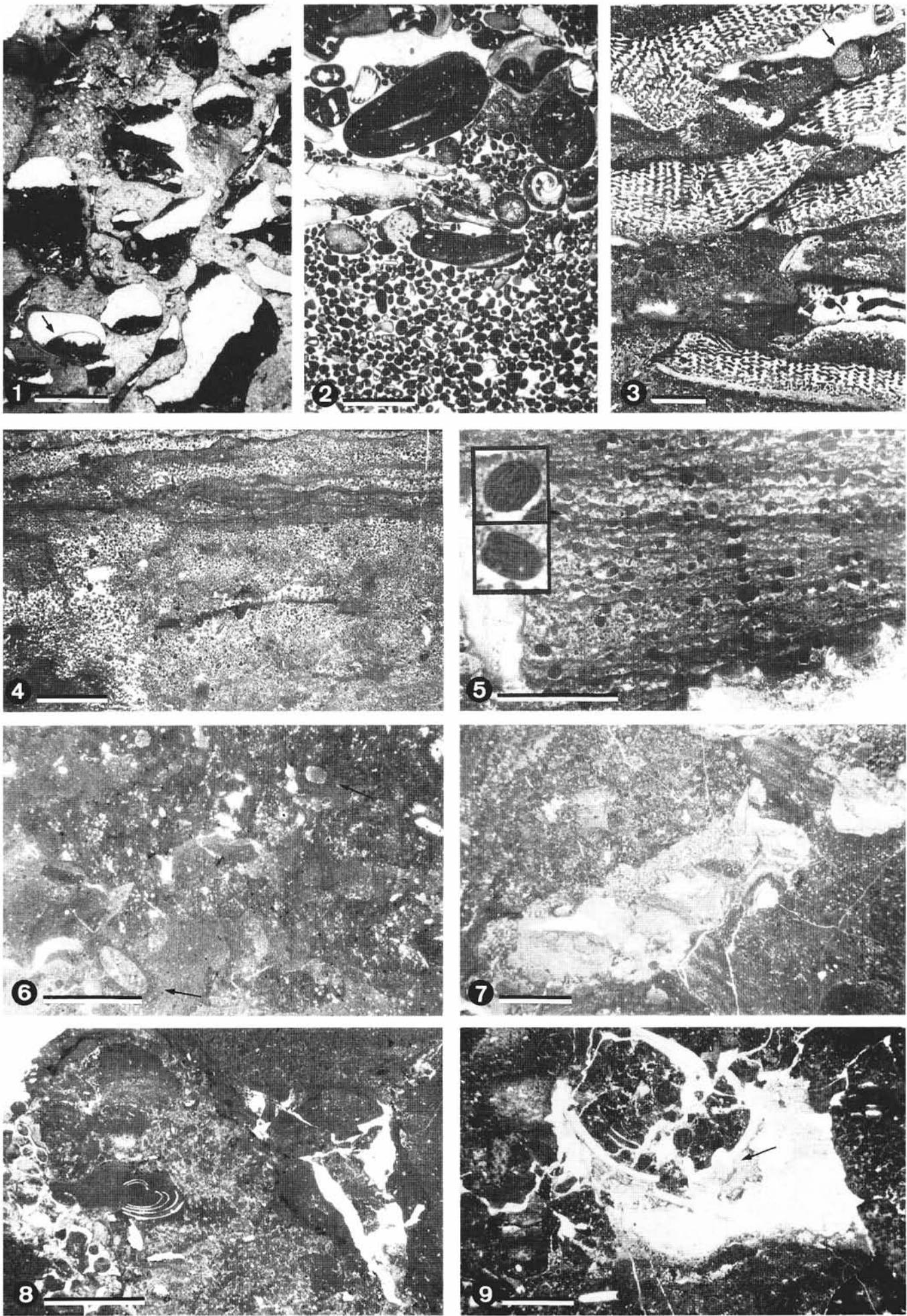
Characteristics and origin of automicritic sediments (Fig. 11, Pl.1/7): Siliceous sponges with a rigid skeleton (lithistid demosponges, dictyid and lychniskid hexactinellids) probably contribute only a minor portion to the entire sponge fauna within the Bajocian sponge limestones of the Sierra de la Demanda. Most of them were "soft sponges" with only isolated spicules in their tissues. High abundance of isolated sponge spicules, which often still occur in clusters, always appear in micritic limestone darker than other, e.g. bioclastic, micrites. This co-occurrence of dark micrites and soft sponges is considered as diagnostic of automicritic sediments in the Demanda area, whose origin is considered to be related to the decay of 'soft sponge' tissues. Lithistids and many of the hexactinellid taxa were hardly, or to a much lesser degree, affected by degradation processes and thus only pretend to be the main contributors to sponge limestone development.

Very high contents of sulphur (in the form of finely disseminated pyrite; oral comm. V. Thiel, Hamburg) suggest that degradation of the organic matter, and thus development of automicritic sediments, took place in an environment of negative redox potential, possibly under a sedimentary cover. This allomicritic cover probably represents periods of elevated allochthonous input and/or a shift of the redox boundary farther into the sediment. Rich benthic fauna and abundant *Zoophycos* burrows suggest a well oxygenated soft bottom substrate. *Zoophycos* burrows are restricted to the very uppermost parts of the automicrite surface (Fig. 11), which either points to dysoxic or anoxic conditions that were not suitable for *Zoophycos* burrowing or to a hard substrate.

Development of automicritic crust: Along with automicrite development, due to degradation of sponge organic matter pore space developed. Subsequent mechanical and/or chemical widening by circulating pore waters (see also WALLACE 1987) resulted in the development of a three-dimensional cavity system, which also cuts across original

Plate 4 Coral, siliceous sponge and microbialite facies from the Oxfordian of Central Dobrogea (Romania) (Herrmann)

- Fig. 1. Strongly bored coral colony fragment from high-energy setting. Internal sediments on the bottom and on the roof of the cavities are due to turning over of the clast during cementation. Borings originate predominately from lithophagid bivalves (arrow indicates preserved shell).
Facies: Coral patch reef belt (2B); location: Sitorman quarry, zone E; length of bar is 5 mm
- Fig. 2. Temporarily increased water energy is documented by coarse, poorly sorted layers, with material from reef and back reef areas, which are intercalated within bioclastic/intraclastic grainstones.
Facies: Coral patch reef belt (2B); location: Piatra quarry; length of bar is 5 mm
- Fig. 3. Thin laminoid fungiid corals (*Microsolena*) with associated *Neuropora* sp. (arrow) and a large amount of sponge spicules are typical constituents of biostromes in the mid-ramp position.
Facies: Microsolenid biostromes (3D); location: Piatra quarry; length of bar is 5 mm
- Fig. 4. Coarse peloidal/detritic microbialite (crust type 1). Spar-cemented, more loosely packed layers reflect an increased input of allochthonous material, such as coated grains, small bioclasts and lithoclasts. Pure peloid and ooid bearing horizons are thought to have formed in situ. This crust type was not colonized by other organisms.
Facies: Microsolenid biostromes (3D); location: Piatra quarry; length of bar is 5 mm
- Fig. 5. Microbialite incorporating numerous faecal pellets (*Favreina* sp.) which dominate the detrital portion of this crust. This type of crust occurs in cavities inside the microsolenid biostromes. Closeup: two *Favreina* pellets with diameters of ca. 0.3 mm.
Facies: Microsolenid biostromes (3D); location: Piatra quarry; length of bar is 5 mm
- Fig. 6. *Terebella* sp. (arrows) colonising very dense thrombolitic microbialites.
Facies: Buildups formed by thrombolitic crusts and siliceous sponges (4E); location: Valea Cekirgea, western Central Dobrogea; length of bar is 2.5 mm
- Fig. 7. A sponge skeleton is almost entirely substituted by cements. After early cementation and calcification the skeleton was repeatedly bored. Disintegration of the skeletons usually started from the underside. Cavities were subsequently cemented by peloidal microbialites and blocky calcite. The surrounding sediment is a dense peloidal microbialite.
Facies: Microbialite/siliceous sponge reef (4C); location: Cheia; length of bar is 5 mm
- Fig. 8. Dense peloidal crusts developed on the upper surface of a siliceous sponge, whereas various forms of serpulids grew on its lower surface. After calcification, the sponge skeleton was attacked by boring bivalves. Abandoned borings were later filled by laminated microbialites, which grew under dysphotic conditions.
Facies: Microbialite/siliceous sponge reef (4C); location: Cheia; length of bar is 5 mm
- Fig. 9. Inside rigid buildups open cavern systems existed. A lithophage bivalve (arrow) bores into the roof of such a cavity which was supported by a terebratulid brachiopod shell.
Facies: Microbialite/siliceous sponge reef (4C); location: Cheia; length of bar is 5 mm



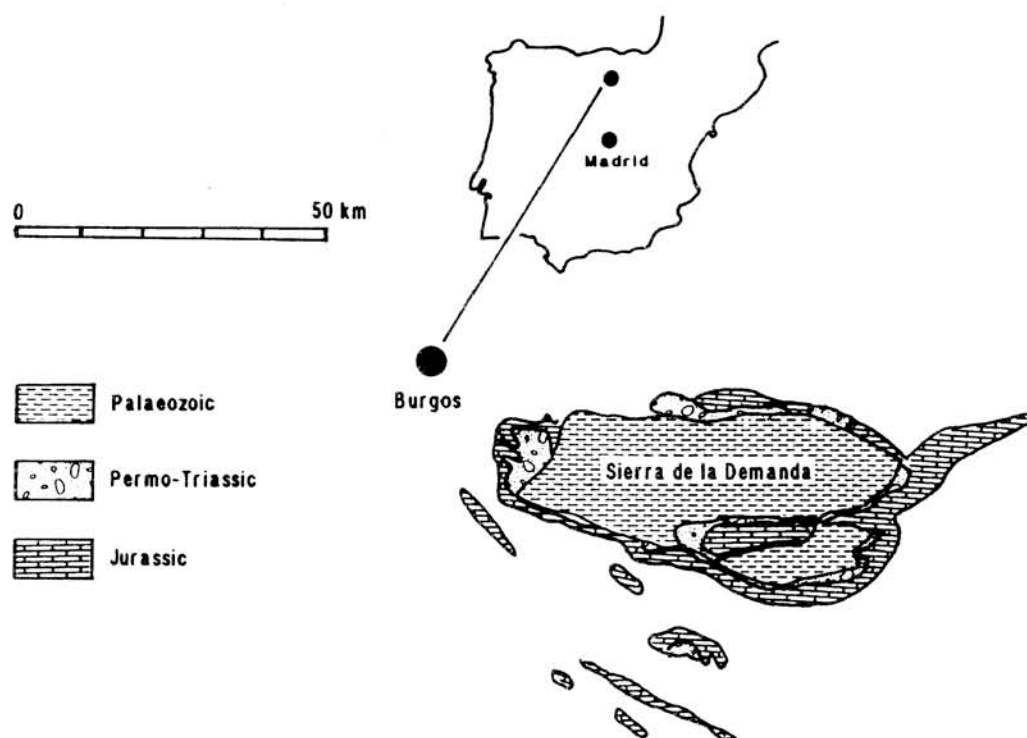


Fig. 10. Location of the Demanda study area.

bedding surfaces. Crusts developed within this cavernous system. Three generations of pore space development and infill can be distinguished (Fig. 11).

In an early stage pore cavities were confined to the immediate sponge area. Always smooth bottoms of the pore cavities hint at still restricted rates of pore water circulation (cf. WALLACE 1987). The concentration of dissolved organic matter and/or ions in the pore solution must have been high. Such increased alkalinities resulted in the precipitation of dense, cryptocrystalline, partly laminated crusts, possibly mediated by microbial films. At this first stage crusts were still in close connection with the underlying sponges. As the cavities widened and an interconnecting cavernous system developed, cavity walls became more rugged and angular in shape, crosscutting the original bedding surfaces. A second generation of crusts with a peloidal fabric developed. The last stage of development is represented by microcrystalline calcitic silt, resembling vadose silt. This silt must have initially filled up the entire remaining pore space, since thin linings along the vertical cavity walls are still preserved. Only later was it replaced by blocky calcite, giving the entire cavity system a stromatolite-like fabric.

3.2.2 Upper Jurassic sponge reefs of Iberia (Krautter)

The recently described Upper Jurassic siliceous sponge fauna of Portugal is known from both the Lusitanian and the Algarve Basin (LEINFELDER et al. 1993a). Reefs characterised by the occurrence of siliceous sponges form intercalations within large-scale basinal to terrestrial shallowing-upward successions. Their vertical position in the succession is controlled primarily by bathymetry. However, their

general occurrence and their composition also depends on low sedimentation rate and rate of oxygenation. Five sponge facies types are established: (a) siliceous sponge meadows, (b) siliceous sponge mud mounds, (c) siliceous sponge-bearing thrombolites, (d) siliceous sponge-coral thrombolites and (e) mixed coral-siliceous sponge debris facies. The siliceous sponge fauna consist of 'Lithistida', Tetracrinellida, Dictyida and Lychniscida.

In Spain, the Oxfordian sponge facies (Formación Calizas con Esponjas de Yátova, GOMEZ & GOY 1979) ranges stratigraphically from the Cordatum Zone to the Planula Zone. Upper and lower boundaries of this entirely spongiolitic formation are heterochronous. Sponge growth started within the Cordatum-Transversarium interval and ended within the Bimammatum-Planula zones (Fig. 12). The widest geographic extension of the Oxfordian sponge facies occurred during the Bifurcatus and Bimammatum Zones.

The palaeogeographic situation indicates a flat, low-angle to level-bottom carbonate platform of great lateral extension situated to the south of the Ebroia high and to the east of the Hercynian Iberian Massive (Fig. 13). Towards south and east, the area was open to the deep pelagic Betic sea as a part of the western Tethys ocean.

The Yátova formation reaches a maximum thickness of up to 40 metres, with an average of 10 to 15 metres. Interestingly, the greatest thickness of the spongiolitic formation coincides with the shortest time of development (Fig. 12). Unusually high thicknesses are always combined with thick and pervasive growth of microbial crust. Automicritic microbial crusts only developed under very reduced to zero allochthonous sedimentation rates. In these areas, conditions for microbial activity were very favour-

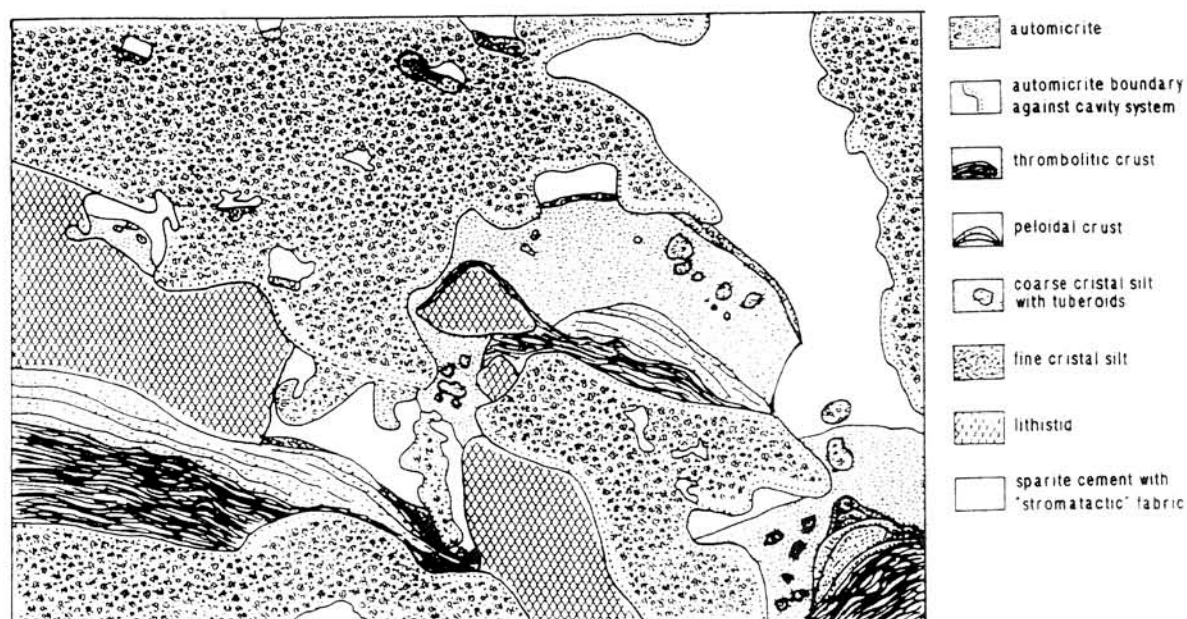


Fig. 11. Relationship between automicrite and cavity system with crusts and crystal silt infill. For further explanation see text. Width of sketch is 3 cm.

able for autochthonous production of crusts and automicritic sediments, probably due to the lack of contamination by allochthonous sediments). Automicritic production exceeded the allochthonous sedimentation rate in other parts of the basin. This shows that a great thickness of Celtiberian sponge limestones from the Oxfordian does not reflect high background sedimentation rate but rather high microbially productivity of automicrites (see section 5.1, 5.4).

The Yátova Formation is composed of bedded spongiolitic limestones and marls which represent stacked siliceous sponge meadows and biostromes (Pl. 1/6) with very great lateral continuity. Small biohermal structures are rare and known only from a few localities.

In general, the bedded limestones and marls are 10 to 50 cm thick, but at the base of nearly all sections a 2 metre thick massive carbonate bed occurs, implying uniform sedimentological and palaeogeographical settings in the Celtiberian and Prebetic Basin. Generally, 'tuberolitic' wackestones are common besides the prevailing faunal wackestones and packstones. Sponges are very abundant, and mostly even occur in rock-forming quantities. The following dictyid taxa are very common: *Stauroderma* sp., *Stauroderma lochense*, *Stauroderma* cf. *explanatum*, *Tremadictyon* sp., *Tremadictyon reticulatum*, *Craticularia* sp., *Craticularia paradoxa*, *Craticularia parallela*, *Thyroidium* sp., *Verrucocoelia verrucosa*, *Verrucocoelia gregaria*, *Porospongia marginata*, *Amphiblestrum* sp.. Lychiscida are less abundant. The following taxa belong to this group: *Pachyteichisma* sp., *Trochobolus* sp., *Trochobolus dentatus*, *Discophyma foraminosa*, *Discophyma* sp., *Placotelia* sp. The lyssakid sponge *Stauractinella jurassica* is very rare as are lithistid demosponges: e.g. *Hyalotragos pezizoides*, *Hyalotragos* sp., *Cnemidiastrum* sp., *Platychonia* sp. (cf. Pl. 1/2-4).

Besides the sponges, a great variety of ammonites (see GÓMEZ 1979, GÓMEZ & GOY 1979, MELÉNDEZ 1989, GEYER

1965), belemnites, echinoderms, and terebratulid as well as rhynchonellid brachiopods are common. Bivalves and gastropods are less abundant. Spicules, lagenid and protoglobigerinid foraminifera dominate the microorganisms. Lituolid and miliolid foraminifera as well as bryozoans and ostracodes are less frequent.

The sponge biostromes are strongly dominated by plate- or dish-shaped sponges (Pl. 1/2, 3). Other morphotypes, e.g. branched, vase- and tube-shaped specimen, are much less common. Up to now, no major differences in the composition of the Celtiberian and Prebetic sponge faunas or between different localities of each region have been noted. The sponges are colonised by serpulids, bryozoans, rare thecideid brachiopods and sessile foraminifers and sometimes even by ostrean bivalves. In the bedded facies distinct microbial crusts are negligible or absent, except for the zone of maximum thickness mentioned above.

Up to now, only five locations with Oxfordian sponge bioherms have been found in the Oxfordian sedimentary basin of Eastern Spain, demonstrating their general rarity. Three of them developed within the Bifurcatus Zone, the other two are slightly older and younger, respectively. The bioherms consist mainly of microbial crusts. Micritic mud and dictyid sponges are even rarer than in the bedded biostromal facies. In general the sponge bioherms reach diameters between 1 and 5 m and are up to 8 m in height. The composition of organisms is comparable to the biostromal facies, but abundances are lower. Calcareous crusts from mounds often show peloidal fabrics typical of microbial origin (see section 5.1): peloids are of comparable size and form small clots or sometimes are arranged in a string-like fashion.

Hardgrounds developed at the top of each ammonite zone and show that the sedimentation was interrupted several times. These hardgrounds show considerable enrichments of Fe-oxides, Fe-Mn-crusts and a high con-

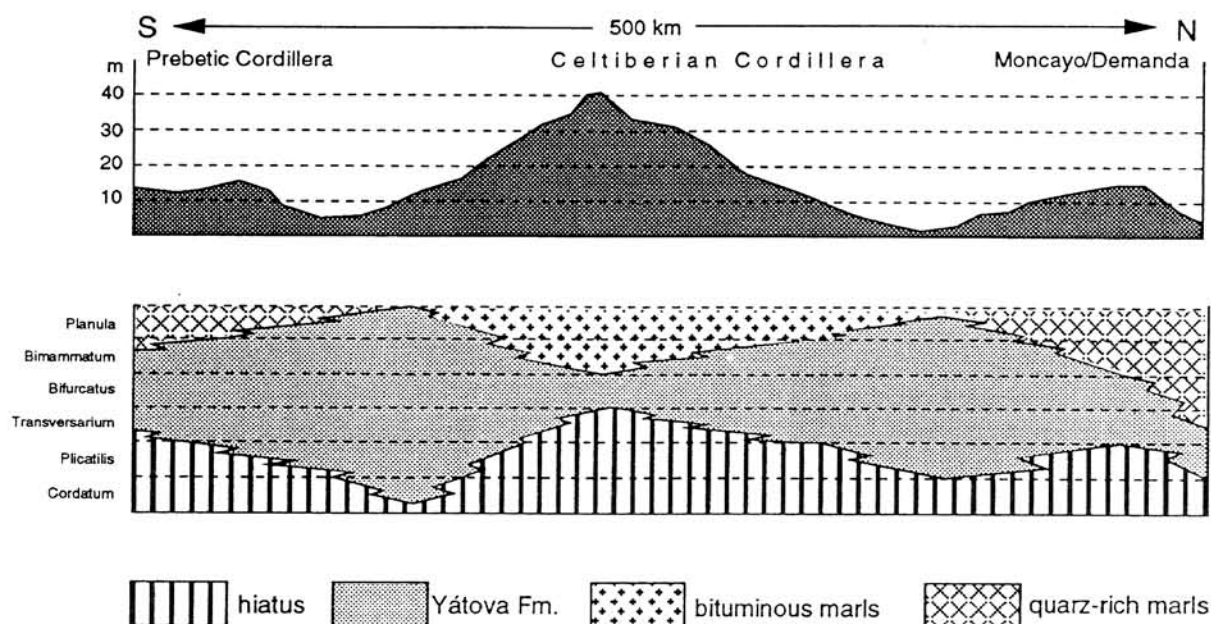


Fig. 12. Thickness and stratigraphic range of the spongiolitic Oxfordian Yátova Formation, Eastern Spain.

centration of sessile and nektonic organisms. Ammonites and crinoids are very common. Furthermore, these hardgrounds are characterised by borings of algae or fungi and, sometimes, of lithophagid bivalves. The hardgrounds are interpreted to be the result of discrete high-order sea level rises within Oxfordian time, although detailed sequence stratigraphic interpretation has not yet been done.

3.2.3 Upper Jurassic coral reefs of Iberia (Nose)

Coral facies are particularly well developed in the Upper Jurassic of Iberia, where they occur along the northern Tethyan shelf (Celtiberian Basin: CB; Eastern Algarve Basin: ALB) and the marginal basins of the young North Atlantic ocean (Lusitanian Basin, especially Arruda Subbasin: AB) (cf. Fig. 1).

Coral facies or coral reefs thrived in a variety of settings and shelf configurations such as on mixed carbonate-siliciclastic homoclinal and steepened ramp systems (CB, ALB, AB), on intrabasinal tectonic or halokinetic uplifts (ALB, AB) and within siliciclastic fan deltas (AB) (cf. ELLIS et al. 1990, LEINFELDER 1986, 1992, 1993a, 1994, WERNER 1986). Although coral facies exhibit a partly independent development in each basin, comparative analysis based on semiquantitative palaeoecology and sedimentology of reefs as well as of sequential analysis and palaeogeographic interpretation of reef-bearing successions allowed separation of reef types and their related environmental factors. These types can be partly recognised in other Upper Jurassic reefal settings, thereby facilitating environmental analysis (Fig. 14).

Coral-stromatoporoid-chaetetid debris reefs are widespread in the Iberian examples. The morphology ranges from low relief biostromes (CB) to large reef bodies up to 150 metres in height with great lateral extension (ALB).

Reef building organisms are mainly corals (e.g. *Thamnasteria*, *Fungiastrea*, *Psammogyra*, *Actinastrea*, *Amphiastrea*, *Microsolena*), chaetetids (e.g. *Chaetetes*, *Ptychochaetetes*) and *stromatoporoids* (*Burgundia*, *Dehornella*, *Actinostromaria*). Besides the normal medium to high diversity composition, low diversity associations locally appear in strongly wave-agitated, high stress environments (*Actinastrea* association, AB). Metazoans occur in boundstone patches but are more frequently fragmented and incorporated as clasts in the moderate to high energy debris facies. The prevailing fabric is grain-supported with variable grain size and lime mud content, although mud-supported fabric is frequent at some localities (ALB, CB). Microbial crusts are rare. They only form irregular coatings on the components. Locally, the coral-debris reef facies is strongly influenced by fine to coarse grained siliciclastics (CB).

This debris-rich reef type represents the most frequent Upper Jurassic coral reef facies (CREVELLO & HARRIS 1984, SCOTT 1988, LEINFELDER 1993a), which is interpreted by LEINFELDER (1993a) as reflecting the lack of the effectively binding organisms, namely the coralline algae of modern high-energy reefs.

Coral-stromatoporoid-chaetetid microbial crust reefs (Pl. 3/1, 3) are widespread in the three Iberian basins. They occur in slightly deeper settings under very low sedimentation rates, the paramount factor for extensive development of microbial crusts (see section 5.4).

The reefs exhibit a variable morphology including small biostromes, large cup-shaped patch reefs and laterally extended reef bodies up to tens of metres in height. The fauna consists of low to high diversity coral associations (*Thamnasteria-Microsolena* ass., CB; *Microsolena-Trocharea* ass., AB; *Microsolena-lithistid* sponge ass., ALB). The dominant taxa are *Microsolena*, *Thamnasteria*, *Fungiastrea*, *Ovalastrea*, *Dimorphastrea* and *Dermoseris*.

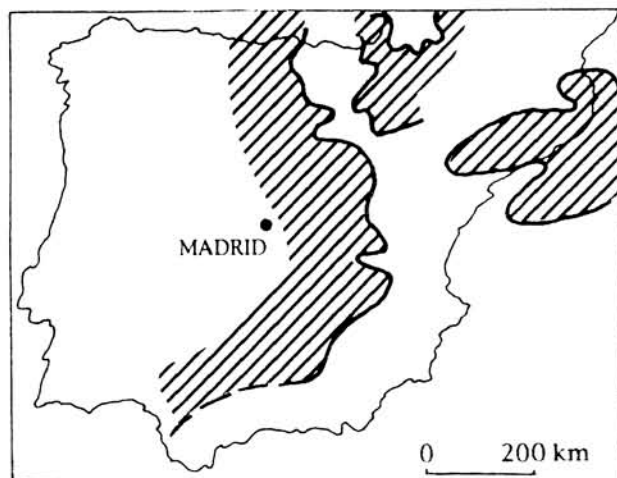


Fig. 13. Palaeogeography of the Oxfordian in Spain (after BENKE 1981). Bold line: presumed coast line; cross-hatched: positive subaerial areas. Western Iberia is not considered.

Siliceous sponges (mainly 'lithistid' demosponges), chaetetids and stromatoporoids often occur as well, though in much lower abundance. Peloidal, mostly thrombolitic, microbial crusts grew extensively within these reefs.

Coral-chaetetid-stromatoporoid-mudreefs (Pl. 3/8) occur in the Celtiberian Basin and to a minor extent in the Arruda Subbasin. In the Celtiberian localities the reefs are composed of mud-rich, oncoid-bearing boundstones/floatstones. They represent low-relief stacked reef patches which laterally interfinger with oncoid-bearing debris facies. Microbial crusts are rare. The fauna is dominated by massive to hemispheroid corals and chaetetids (e.g. *Fungiastrea*, *Comoseris*, *Thamnasteria*, *Ptychochaetetes*). Comparable mud-rich reef patches in the Arruda Subbasin consist predominantly of ramose corals (*Microsolena*, *Convexastrea*) and stromatoporoids (?*Actinostromaria*). The reefs pass laterally into bioclastic wackestones which sporadically contain intercalated storm beds.

This reef type could be also termed coral mudmound. Reefs of this type occur in moderate energy, mid-ramp settings and often pass vertically into high-energy reef debris facies. These coral-chaetetid-stromatoporoid muddy mounds indicate a catch-up phase in reef growth.

Marly coral-stromatoporoid meadows are a common reef type in the Arruda Subbasin and to minor extent also occur in the Celtiberian Basin. Low diversity coral associations with dominance of one or two species characterise the meadows in the Arruda Subbasin (*Microsolena* ass., *Ovalastrea-Enallhelia* ass., *Calamophylloipsis* ass.). These reefs grew in protected and/or deeper ramp situations (shallow outer ramp or lagoonal settings). The dominance of ramose, phaceloid and dendroid growth forms can be interpreted as an adaptive reaction towards high sedimentation rates. This assumption is supported by the low frequency of encrusting organisms. In the Celtiberian Basin the meadows exhibit a higher diversity fauna and, locally, large amounts of detrital quartz grains and allochthonous shallow water components (e.g. ooids).

Common encrustation and the dominance of massive and platy growth forms indicate low sedimentation rates with only sporadically high sediment supply.

The above coral reef types occur in all three Iberian basins. However, regional differences in structural or sedimentary conditions gave rise to additional, local reef types. They comprise the following types:

Coral-microbial crust-debris reefs occur at the margins of isolated platforms developing on intrabasinal structural uplifts (AB, e.g. Ota limestone, LEINFELDER 1992, 1994). As in the coral-stromatoporoid-chaetetid-debris reefs, a high content of reefal debris is indicative of a high energy setting. In contrast to the pure debris reefs, the intensive participation of microbial crusts causes the stabilisation and binding of debris. This particular situation reflects an equilibrated sediment balance at the margins of structural highs maintained by gravitational export of debris along steep escarpment margins (LEINFELDER 1992, 1993a).

Marly coral-microbial crust reefs are characterised by a high marl content but also contain a large amount of microbial crusts. The low relief biostromes and bioherms consist mostly of high diversity coral associations (*Ovalastrea-Calamophylloipsis* ass., *Thamnasteria-Ovalastrea* ass., *Convexastrea-Dendrohelia* ass.) (Pl. 3/5). Marly coral-rich intervals are mostly dominated by branched corals and grew under slightly elevated allochthonous sedimentation. They alternate with microbial crust-rich layers, reflecting a cessation of sedimentation. Obviously, only small amounts of terrigenous clay inhibited the extensive development of microbial crusts, favouring the growth of the better adapted coral fauna (LEINFELDER et al. 1993b). These reefs grew in mid-ramp positions marginal to channels bypassing terrigenous sediment and ooids.

3.2.4 Upper Jurassic thrombolite reefs of Iberia (Schmid)

Thrombolitic crusts are common in siliceous sponge facies as well as in coral facies, where they may even become dominant, resulting in the development of coral microbialites and siliceous sponge microbialites, most of which exhibit a thrombolitic fabric (LEINFELDER et al. 1993a). This section deals with more or less pure thrombolites, which are microbial reefs without participation of large reef metazoans, whereas various encrusting microorganisms are present in nearly every type of microbial crust (see section 5.2).

Three morphological types can be distinguished: thrombolite biostromes, thrombolite cups and thrombolite bioherms; the latter may pass laterally into thin biostromes. Thrombolite biostromes are widespread in the Upper Jurassic of Spain and Portugal, and so are thrombolite bioherms, ranging in thickness from one to 30 m at Rocha/Algarve (cf. LEINFELDER et al. 1993a,b). Thrombolite cups - morphologically similar to the Recent Shark Bay stromatolites of Australia - are restricted to only one locality: Cotovio/Algarve (cf. LEINFELDER et al. 1993b: Pl. 38/6, 7).

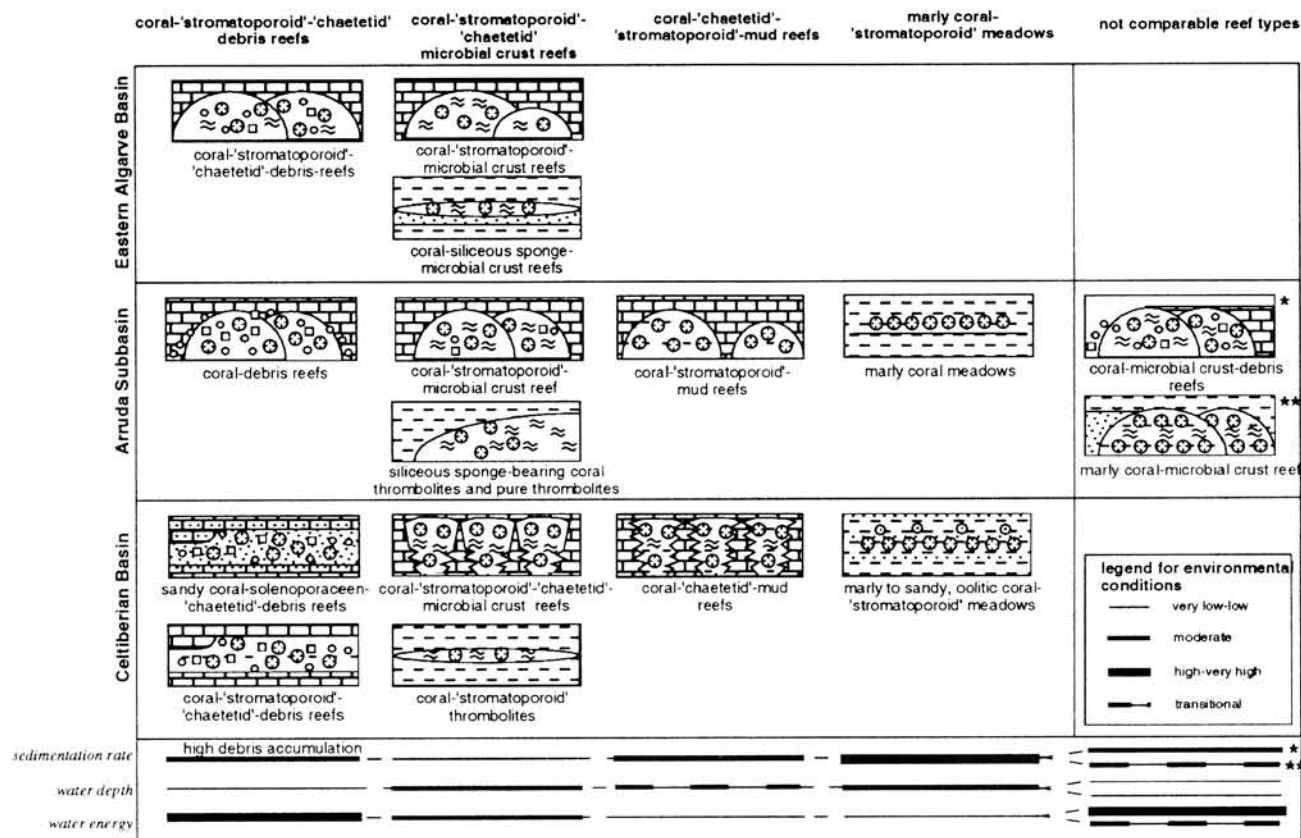


Fig. 14. Coral reef types from the Upper Jurassic of Iberia. Four coral reef groups can be subdivided into 16 reef subtypes which include 18 coral associations.

Thrombolitic buildups may also be distinguished according to their *associated bathymetric facies*, as they occur in certain levels of shallowing upward successions (see section 5.2). Pure thrombolites are most widespread in ammonite-bearing deep to moderately shallow slope marls of both the Algarve and the Lusitanian Basin, where they are restricted to distinct levels. Thrombolite biostromes also occur in similar facies in the Celtiberian Basin. In one case (Trancoso/Lusitanian Basin), pure thrombolites pass laterally into a coral bioherm.

The outline of the crusts is commonly irregular, often forming distinct outward (including upward) protrusions and knobs. A particular crust type is represented by *downward facing nodular hemispheroids*, typically occurring at the base of metazoan-bearing thrombolite reefs (Pl. 3/1, 3). A coral or sponge specimen is nearly always present in the upper part of these hemispheroids, which may consist of thrombolitic crust to a maximum extent of 90 %. The growth of these crusts was directed radially downward and sideward, starting at the surface of the metazoan. In a second stage - after the death of the metazoan - the crusts continued growing on the upper side. This hemispheroidal crust development enabled the reef to build ledges sidwards, which in some cases were attacked by boring bivalves from below or encrusted by thecideidid brachiopods, serpulids, oysters and bryozoans. Such reefs are frequent only in Iberia, but rarely also occur elsewhere (e.g. south-western France; unpublished results; cf. HANTZPERGUE 1991).

Transitions between thrombolitic, stromatolitic and aphanitic fabrics are occurring, but thrombolites - which are characterised by peloidal crusts with a clotted macroscopic fabric - are clearly dominant (see section 5.1). Stromatolites are rare and play only a minor role in the formation of crusts.

3.3 Upper Jurassic reefal environments from Eastern Romania (Herrmann)

Upper Jurassic reefal buildups are extensively developed in the Dobrogea region of southeastern Romania. Reefs were studied in Central Dobrogea which is the middle of three northwest-trending, fault-bounded, structural zones (Fig. 15). The weakly folded Middle and Upper Jurassic sediments directly overlie Precambrian basement (BARBULESCU 1971a,b, 1972, 1974; DRAGANESCU 1976).

Facies Zonation of the Central Dobrogea Carbonate Ramp

Interpretation and correlation of lithological sections from Lower to Upper Oxfordian limestones in Central Dobrogea suggest that they were deposited on a gently sloping wave-agitated W to SW inclined ramp which exhibited facies zonation. From E to W, i.e. towards the open sea, a lagoonal belt is followed by a coral patch reef belt, a bioclastic - oolitic sand belt, and a spongiolitic belt (Figs. 16, 17). The sediments described here comprise an interval from the Lower Oxfordian (Cordatum Zone) to the Upper Oxfordian (Bimammatum Zone) (BARBULESCU 1976, 1979).

The *lagoonal belt* is rich in structureless to laminated microbial crusts, which occasionally exhibit prism cracks and comprise bioclasts and dark lithoclasts (Type 1A, Fig. 16). Crusts are accompanied by oncoidal wackestones with *Bacinella-Lithocodium* oncoids measuring 2 mm to 2 cm in diameter (1B). *Cladocoropsis* dominated floatstones (1C) are transitional to the coral patch reef belt. The stromatoporoid *Cladocoropsis* is accompanied by microbial and algal-type forms, such as *Bacinella*, *Lithocodium*, *Thaumatoporella*, 'cayeuxiids' (*Bacinella*-association').

Up to one metre high patches of high diversity coral framestones (2A) are characteristic of the *coral patch reef belt*, although debris piles representing reworked patch reefs are more common (2B). The small patch reefs were constructed by massive domal and phaceloid coral colonies. Secondary framebuilders were *Solenopora* sp. and *Lithocodium/Bacinella*. Boring bivalves frequently attacked the coral colonies (Pl. 4/1). Distinct microbial crusts were not observed. Debris pile sediments are dominated by reefal clasts. Coral colonies are mostly broken into large fragments which were rounded by water movement (Pl. 4/2). Large megalodontid bivalves and nerineid gastropods are common locally. Bioclasts were frequently overgrown and attached to each other by *Bacinella* and *Lithocodium*.

Bioclastic and oolitic sands occupy the broad *sand belt* on the carbonate ramp. They were deposited between the high energy setting of the coral patch reef belt and the low-energy siliceous sponge/microbial crust dominated distal ramp area. This transitional position is reflected by changes in sedimentary and faunal composition from moderately to poorly sorted bioclastic and intraclastic grainstones/rudstones (3A), to oolitic sands (3B), and eventually to fine grained bioclastic packstones (3C). In these packstone areas, coral reef banks grew which were constructed almost exclusively by thin laminoid *Microsolena* (3D) (Pl. 4/3). In contrast to the high diversity coral limestones, green algae and the '*Bacinella*-association' are lacking, and molluscs are rare. These features indicate a deeper environment.

Tuberolitic limestones (4A) form the transition from the bioclastic sands (3C) to the *spongiolitic belt*. Fragments of siliceous sponges which are overgrown by brown coloured dense microbial crusts in association with serpulids and sessile foraminifera are typical clasts in this part of the ramp. Adjacent are sponge meadows (4B) in which microbialite/siliceous sponge reefs (4C) are interspersed. Sediments following seawards are monotonous hemipelagic wackestones (4D) in which small thrombolitic siliceous sponge bearing buildups (4E) are intercalated. The two different types of sponge reefs (4C and 4E) are described below.

Types of sponge buildups

Interspersed in biostromal limestones are massive unbedded bodies of *microbialite-siliceous sponge reefs* (4C) which range from 5 up to 30m in height. The shape of these reefs is quite variable. The most eye-catching variety are atoll-like structures with a height of up to 30 m and diameters from 15 to 30 m. The interior of these ring-structures is filled with well bedded bioclastic debris.

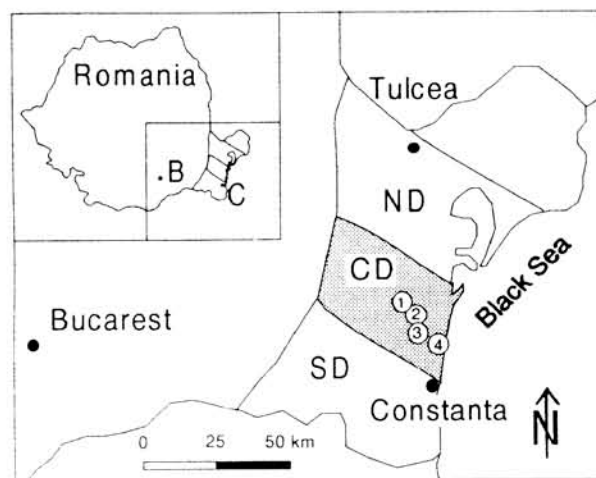


Fig. 15. Location of study area in Romania. B: Bucarest, C: Constanta, ND: North Dobrogea, CD: Central Dobrogea, SD: South Dobrogea. Location of sections shown in Fig. 17: 1: Cheia/Casian, 2: Valea Gura Dobrogei, 3: Sitorman quarry, zone C and zone E, 4: Piatra.

Other bioherms represent incomplete rings ('horse-shoes'), as well as wall-like or globular bodies. In contrast to the biostromes, the portion of dominantly 'lithistid' sponges is much lower, and microbial crusts, or their disintegration products, prevail. The spaces between the crust-constructed framework are filled with sparsitically cemented reefal clasts or with a bioclastic wackestone to packstone. Crusts are intensely populated by micro-encrusters (serpulids, foraminifera, bryozoa) and affected by boring organisms (Pl. 4/7-9). In many cases, an original boundstone character is poorly recognisable because of synsedimentary and early postsedimentary bioerosion during nondeposition under hardground conditions. Reef debris accumulated in a packstone to rudstone texture, including many pockets filled with grainstones. Particles were bound by microbial crusts.

Within the biostromal zone the crust-sponge bioherms were places of preferential growth of microbial crusts. The factors controlling this local dominance are at the moment still unclear. Most likely is a differentiated morphology of the substratum, where crusts grew best on slight elevations (see also section 5.1).

Buildups bearing thrombolitic crusts and siliceous sponges (4E) are represented by small lens-shaped or globular structures (height 0.5 to a few meters), which are embedded in a monotonous series of well bedded hemipelagic wackestones. In contrast to the above described buildup type where 'lithistids' dominated, mainly hexactinellids participated in the thrombolitic buildups. Generally sponges were less common in this bioherm type (Pl. 4/6). The microbialites are dominated by fine peloidal to micritic crusts with a macroscopically clotted, thrombolitic fabric. The crusts grew on the sponges or within the surrounding mud. Microencrusters, particularly abundant *Terebella* sp., *Tubiphytes* sp., serpulids and foraminifera, are frequent.

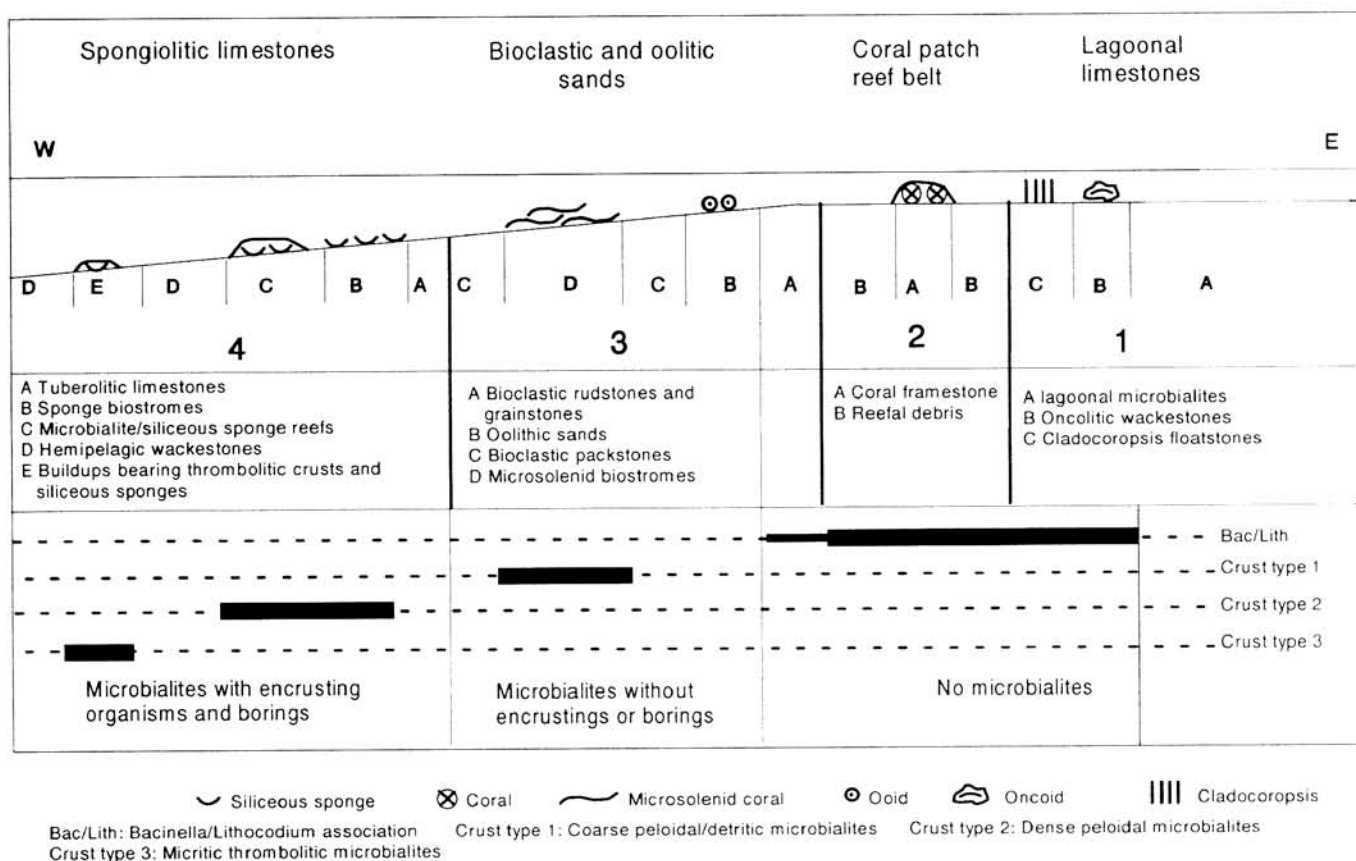


Fig. 16. Facies distribution and occurrence of different crust types on the Central Dobrogea carbonate ramp during the Mid-Oxfordian. The development of different reef types as well as different types of carbonate crusts was controlled by bathymetry and sedimentation rate.

Types of microbial crusts and their distribution (Figs. 16, 17; Pl. 4)

The widespread occurrence of microbialites in different settings allows detection of differences in shape and texture which are thought to be environmentally controlled. Three main types of crusts can be distinguished in the Central Dobrogea ramp setting.

Coarse-grained peloidal/detritic crusts (crust type 1; Pl. 4/4,5) are characterised by microscopic irregular lamination which results from a rhythmic alternation of micritic rinds and thicker loosely packed laminae. The dominant part of the laminae exhibits a peloidal and oolitic grainstone fabric as well as detrital material like fecal pellets (*Favreina* sp.), foraminifera, ostracode shells, small lithoclasts or, rarely, sponge spicules. Surfaces are not colonised, and no borings were observed. A possible explanation is that calcification took place under microbial mats below the surface, so that no hard substratum was available for encrusters. Another possibility might be some sort of chemical surface defense that prevented larvae from settling down. These crusts grew within the sand belt where the input of bioclasts and lithoclasts from more proximal ramp areas is still noticeable. Crusts occur on top of the microsolenid corals or in small cavities within the coral boundstone (4B,C,E).

Dense peloidal crusts (crust type 2; Pl. 4/8) mostly exhibit a macroscopically well laminated (stromatolitic) fabric, but may also show only indistinct, irregular lamina-

tion. Crusts form domal, columnar or pillar-type constructions with relief of up to 5 cm as well as subplanar constructions. It is assumed that the microrelief of the substrate strongly controlled the growth form. Overgrowth by serpulids, foraminifera, bryozoa and sponges on top of the crust surfaces points to rapid calcification at the surface. Lamination is produced by rhythmic alternations of spar-cemented peloidal intervals with dense micritic layers. These microbialites occur in the sponge belt and are typical for sponge biostromes and for microbialite/siliceous sponge reefs of all shapes (3D).

Micritic thrombolitic crusts (crust type 3, Pl. 4/6) exhibit a macroscopically clotted fabric with outward or upward protrusions and knobs. A dense fabric with very irregular or no lamination is observed under the microscope. Micro-encrusters like serpulids, foraminifera, *Tubiphytes* sp. and *Terebella* sp. always participate. Nevertheless, the variety of microencrusters is conspicuously small (dominating *Terebella* sp.). This impoverishment of the fauna possibly indicates temporarily reduced bottom water oxygenation (compare discussion in LEINFELDER 1993a) at this relatively deep position. These crusts are restricted to the deepest and most seaward buildup-type (4E) in the westernmost part of Central Dobrogea.

The Oxfordian Central Dobrogea carbonate platform displays a typical ramp setting which, after an initial short retrogradational phase, developed aggradational to progradational architecture, characteristic of an entire sec-

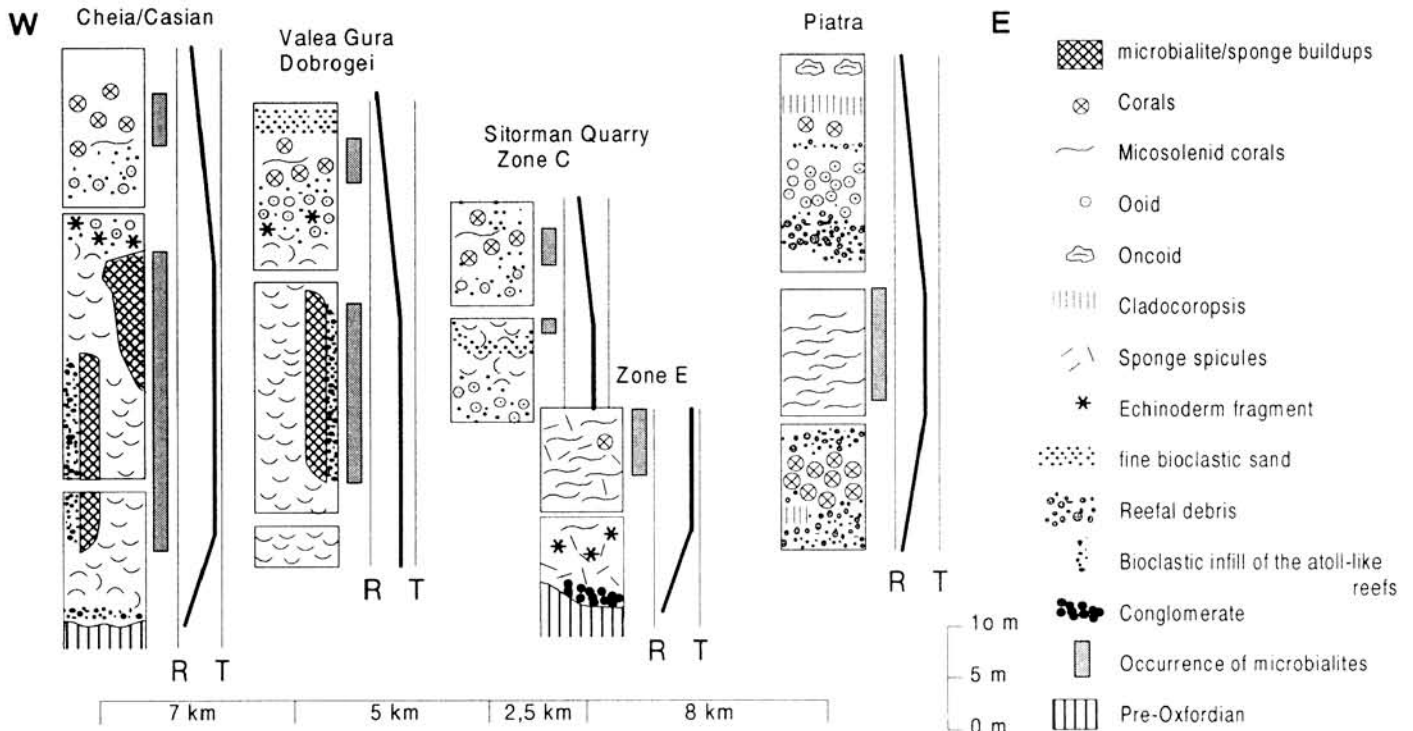


Fig. 17. Simplified stratigraphic columns of the Oxfordian from the eastern and middle part of Central Dobrogea, comprising Lower to Upper Oxfordian strata (BARBULESCU 1976, 1979). An initial short transgressive phase is followed by a period of sea level highstand and, eventually, regression. Microbialite growth preferentially occurred during transgression or high sea level. Curve on the right side of each column indicates relative sea-level changes (for location of sections see Fig. 15).

ond order sea level cycle. The main factors controlling the distribution of the different facies and buildups were bathymetry and sedimentation rate (see sections 5.2 and 5.4), both of which were largely related to the distance from the inner ramp carbonate factory.

4 STRATIGRAPHIC CORRELATION OF JURASSIC REEF FACIES

In order to obtain the results discussed above a considerable part of the existing chronostratigraphic frameworks had to be refined. New ammonite data led to a completely new correlation for the youngest Kimmeridgian to early Tithonian interval of southern Germany, with consequences for palaeogeographic interpretation (section 3.1.3) and correlation of sea level development (section 4.1.2). For the same area, palynostratigraphy and mineralostratigraphy can partly substitute for ammonite stratigraphy in sections where no or insufficient ammonite data are available (e.g. in buildup facies or subsurface sections). Sequence stratigraphy applied to the Middle and Upper Jurassic of Iberia as well as southern Germany helps to elucidate factors responsible for reef development, although many problems with its application remain unsolved.

4.1 Ammonite biostratigraphy of the Upper Kimmeridgian to Tithonian of southern Germany (Schweigert & Zeiss)

The most precise dating of Upper Jurassic reefs of southern Germany can be obtained from ammonite faunas

which are derived from the reef or buildup facies or from interfingering bedded facies. During an attempt to correlate new biostratigraphic data of Western France (HANTZ-PERGUE 1989) with those of southern Germany, it became evident, that the traditional correlations between Swabia and Franconia (e.g. MEYER & SCHMIDT-KALER 1989) had to be improved (SCHWEIGERT 1993a). Upper Kimmeridgian ammonite faunas from Swabia demonstrate that the Subboreal Eudoxus Zone partly overlaps with the Tethyan Beckeri Zone (SCHWEIGERT 1993b) (cf. Fig. 18), a fact which is important for long-distance correlations and the application of sequence stratigraphic concepts. Moreover, biostratigraphic data have been subordinated to an oversimplified lithostratigraphic concept ignoring extensive lateral facies changes. Kimmeridgian strata younger than the Setatum Subzone are present all over Swabia, in contrast to Franconia, where higher parts of the 'Ulmense Subzone' (Fig. 18) are not recorded by ammonites. The closest faunal affinities of the upper part of the Roegling/Geisental formations are given by ammonites from the base of the 'Hangende Bankkalke' Formation. Hence, a stratigraphic or faunistic gap is likely within the Franconian sections, the exact duration of which is still uncertain because the ammonite faunas of this period have not been described in detail. Similar specimens of *Hybonoticeras* cf. *hybonotum* in the Roegling Formation and in the uppermost 'Liegende Bankkalke' Formation and 'Zementmergel' Formation of western Swabia seem to favour the view that these strata are of the same age.

A rich ammonite fauna of latest Kimmeridgian age has been found recently in the topographically elevated sponge

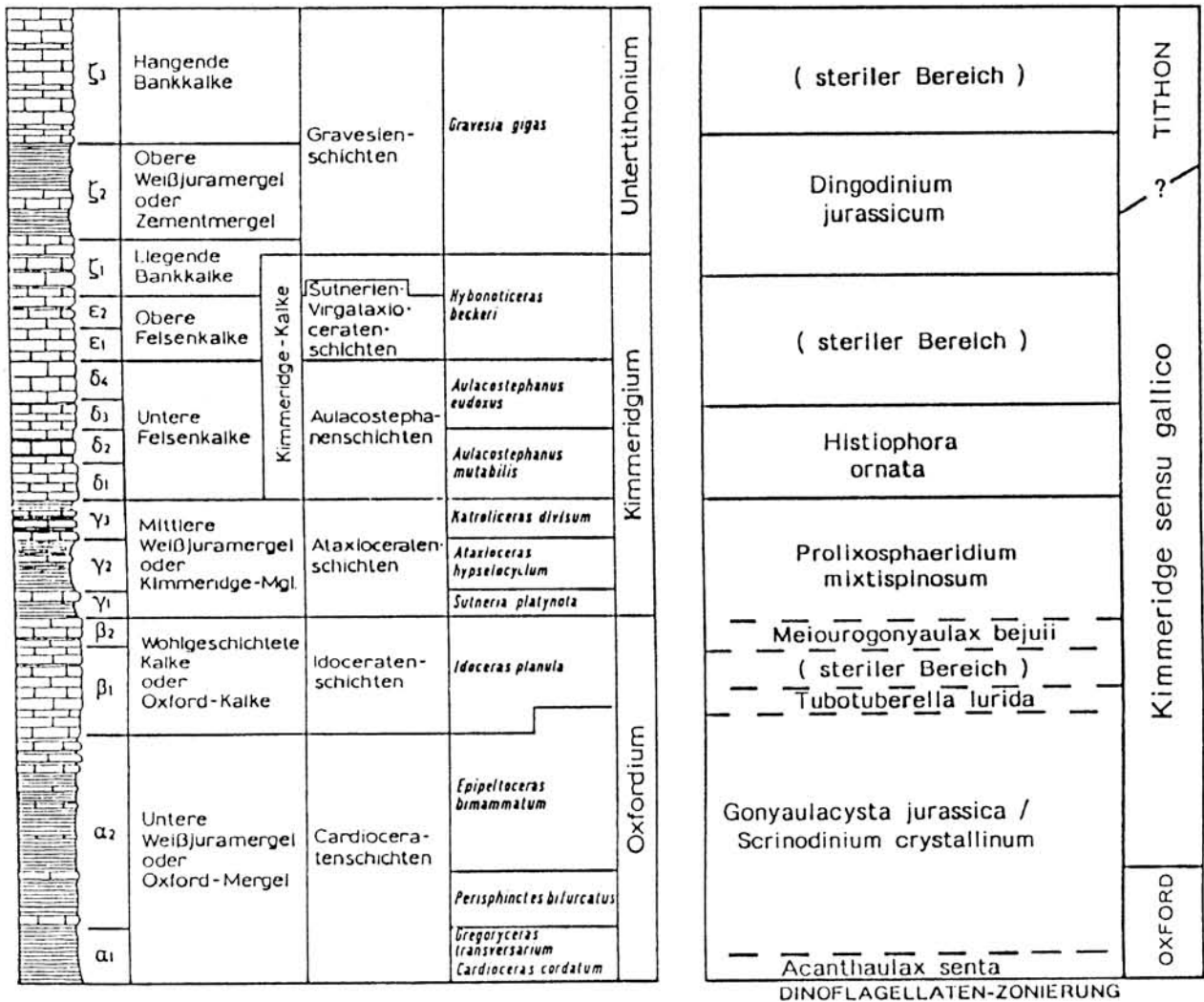


Fig. 19. Subdivision of the Upper Jurassic of 'Schwäbische Alb', southwestern Germany (after GEYER & GWINNER 1991) and dinoflagellate zones according to BRENNER (1988) and DÜRR (1988). Note discrepancy in the position of the Oxfordian/Kimmeridgian according to established use and as based on correlation by dinoflagellate cysts with northwestern Europe.

western Germany results in the use of partially differing ammonite zonation in these two areas. Some problems concerning the detailed correlation between these two zonation are still unsolved and hamper the comparison of the ranges of dinoflagellates observed in southern Germany with those established in northwestern Europe. For this reason, it is often not possible to decide whether discrepancies in the observed ranges with those reported from the standard sections of northwestern Europe are real or are merely caused by difficulties in correlation of the ammonite standard scale.

The ranges of selected dinoflagellate cysts in the Upper Jurassic of southwestern Germany are shown in Fig. 19 adapted from FEIST-BURCKHARDT & WILLE (1992). The zonation of the same area as proposed by DÜRR (1988) and BRENNER (1988) and its correlation with the traditional subdivision of the Swabian Upper Jurassic is given on Fig. 19.

The dinoflagellate cysts of the lower part of the Upper Jurassic have been studied mainly by BRENNER (1988). The Oxfordian (Mariae Zone of the 'Braunjura ζ' to Bimammatum Zone of the 'Weißjura β') can be subdivided into three

dinoflagellate zones which are in rather good agreement with the zonation introduced by WOOLLAM & RIDING (1983). Based on the generally rich and diversified dinoflagellate cyst assemblages, it should be possible to separate the equivalents of the Mariae Zone from those of the Cordatum Zone (= equivalents of the 'Weißjura α₁'). The interval from the Densiplicatum Zone to the Bimammatum Zone ('Weißjura α₂', Impresa-Mergel' to basal part of the 'Weißjura β₁', Wohlgeschichtete Kalke') corresponds to a single dinoflagellate zone. The lower part of the Planula Zone ('Weißjura β₁') again contains a typical dinoflagellate assemblage (BRENNER 1988).

According to DÜRR (1988), the upper part of the 'Weißjura β₁' is devoid of dinoflagellate cysts, which have been destroyed diagenetically. The top of the 'Wohlgeschichtete Kalke' (= 'Weißjura β₂') is attributed to the Meourogonyaulax bejui Zone. The interval from the base of the Platynota Zone to the top of the Divisum Zone, i.e. the entire 'Weißjura γ' (= 'Mittlere Weißjura-Mergel') corresponds to a single dinoflagellate zone. The base of the middle Kimmeridgian (Acanthicum Zone, 'Weißjura δ₁' to approximately δ₂), equivalent to the lower part of the

'Untere Felsenkalke') again contains a rich and diversified dinoflagellate assemblage which can be readily recognised (*Histiophora ornata* Zone of D_{CRR}, 1988). The heterochronous upper limit of this assemblage corresponds to the onset of dolomitisation.

The upper part of the 'Unterer' and the entire 'Oberer Felsenkalk' (approximately 'Weißjura δ_4 to Weißjura ε_2 and/or ζ_1 , an interval roughly corresponding to the Beckeri Zone of ZIEGLER 1987), lacks stratigraphically useful dinoflagellate assemblages and other palynomorphs probably because of the extensive dolomitisation.

The 'Zementmergel' (Weißjura ζ_2 = upper part of Beckeri Zone, see section 4.1) again contains a characteristic dinoflagellate cyst assemblage. (Dingodinium jurasicum Zone of DÜRR, 1988). The lower and upper boundary of this assemblage cannot be defined because it is bracketed by intervals barren in palynomorphs.

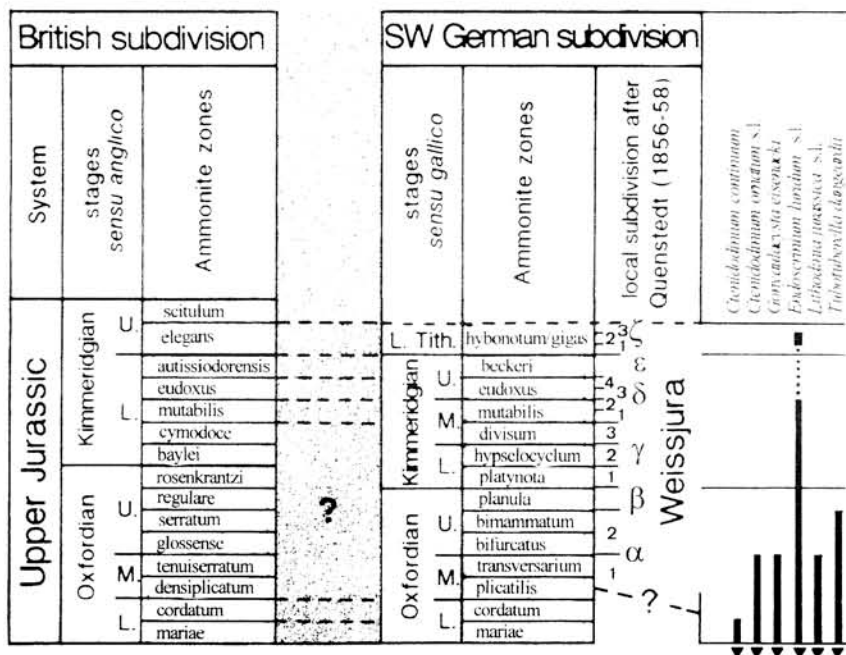
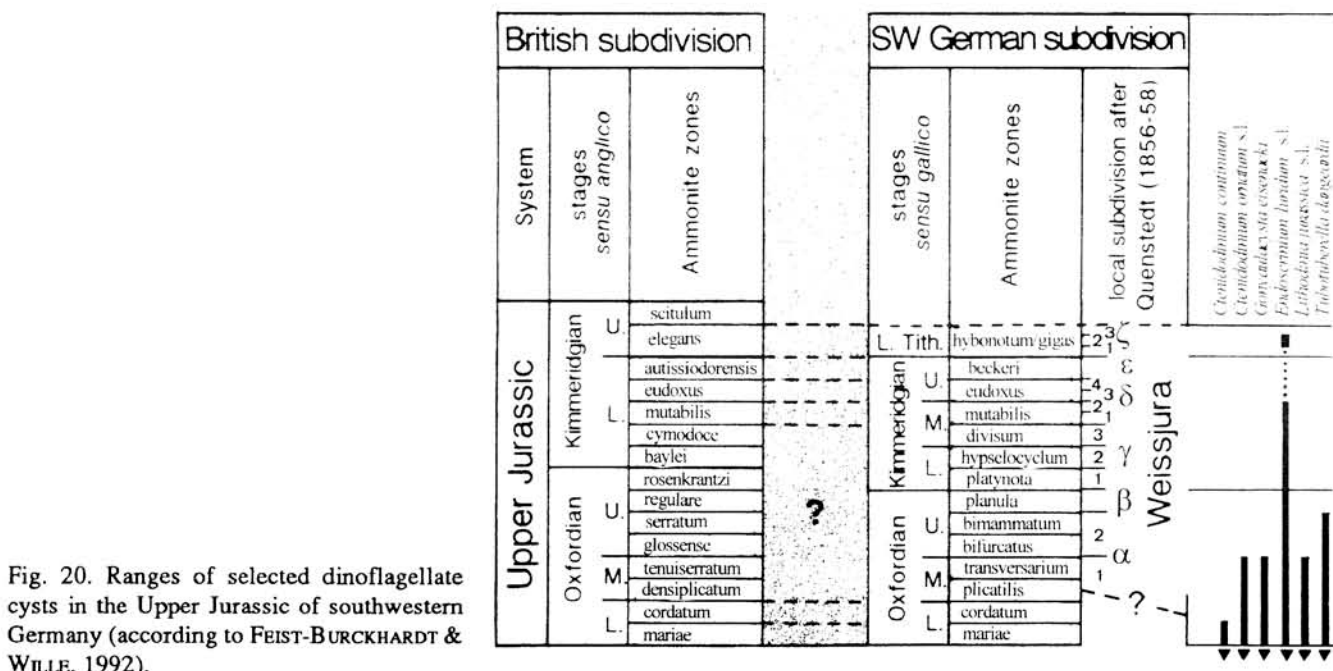
In southwestern Germany, surface samples from beds younger than Weißjura ζ_2 have been unproductive until now. Age-equivalent samples from the 'Oberer Quintnerkalk' (Helvetic facies realm) of the deep well Tettang 1 (sub-surface of the Molasse Basin, LANG 1989) which are roughly age-equivalent to the Weißjura ζ_2 and/or ζ_3 contain a poor assemblage of dinoflagellate cysts.

In the Upper Jurassic of southwestern Germany, the application of dinoflagellate cysts as stratigraphic tools meets several restrictions:

- (1) The record of dinoflagellate cyst assemblages is discontinuous; productive intervals are interrupted by barren ones. In limestones and dolomites with good porosities and permeabilities, palynomorphs are frequently oxidised. Dolomitisation, in part connected with vadose recrystallisation, generally destroys all organic-walled microfossils (see e.g. the discussion of the relation between the degree

- (2) The calibration of stratigraphic subdivisions based on dinoflagellate cysts with the standard ammonite zonation is still rather patchy. In the Upper Jurassic of southwestern Germany, biostratigraphic resolution by ammonites is rather loose as compared with the Lower and Middle Jurassic (ZIEGLER 1987). The traditional 'Quenstedt' subdivision of the Swabian Jurassic in lithostratigraphic units with biostratigraphic connotations has proven its value for field mapping and regional overviews, but its deficiencies become evident whenever higher degrees of stratigraphic resolution are needed.

- (3) Problems of correlating the 'Swabian' ammonite zones with those established in northwestern Europe make it difficult to recognise truly heterochronous first and last occurrences of some stratigraphically significant dinoflagellate cysts. Ages based on the correlation of dinoflagellate zones and assemblages of southwestern Germany with those from northwestern Europe differ considerably from those used traditionally (see Fig. 19).



4.3 Mineralostratigraphy of well-bedded and spongiolitic massive carbonate lithologies of the Swabian Alb (Christmann, Menges & Schweizer)

Samples from both the western and eastern Swabian Alb were analysed for the mineralogy of the insoluble residue, in order to recognise local or regional fluctuations in clay mineralogy, which are interpreted to be of stratigraphic relevance (Fig. 21).

In contrast to the eastern Swabian Alb, development of spongiolitic massive facies of the western Swabian Alb locally commenced in the Early Oxfordian. Both eastern and western Swabian Alb show the localised or extensive development of spongiolites and spongiolite-bearing massive limestones within all Upper Jurassic stages from the Upper Oxfordian upwards. However, in the western Swabian Alb there was no accompanying growth of coral reefs during the latest Kimmeridgian and Tithonian, contrasting with the situation in the eastern Swabian Alb (see section 3.1.3).

If the development of sponge-microbial buildups in the Late Jurassic were controlled by terrigenous input and/or the movement of ocean currents, these conditions should have existed throughout the Upper Jurassic of the Swabian Alb. Therefore, it should be possible to test this assumption through mineralogical characterisation of detritus in samples taken from southern Germany.

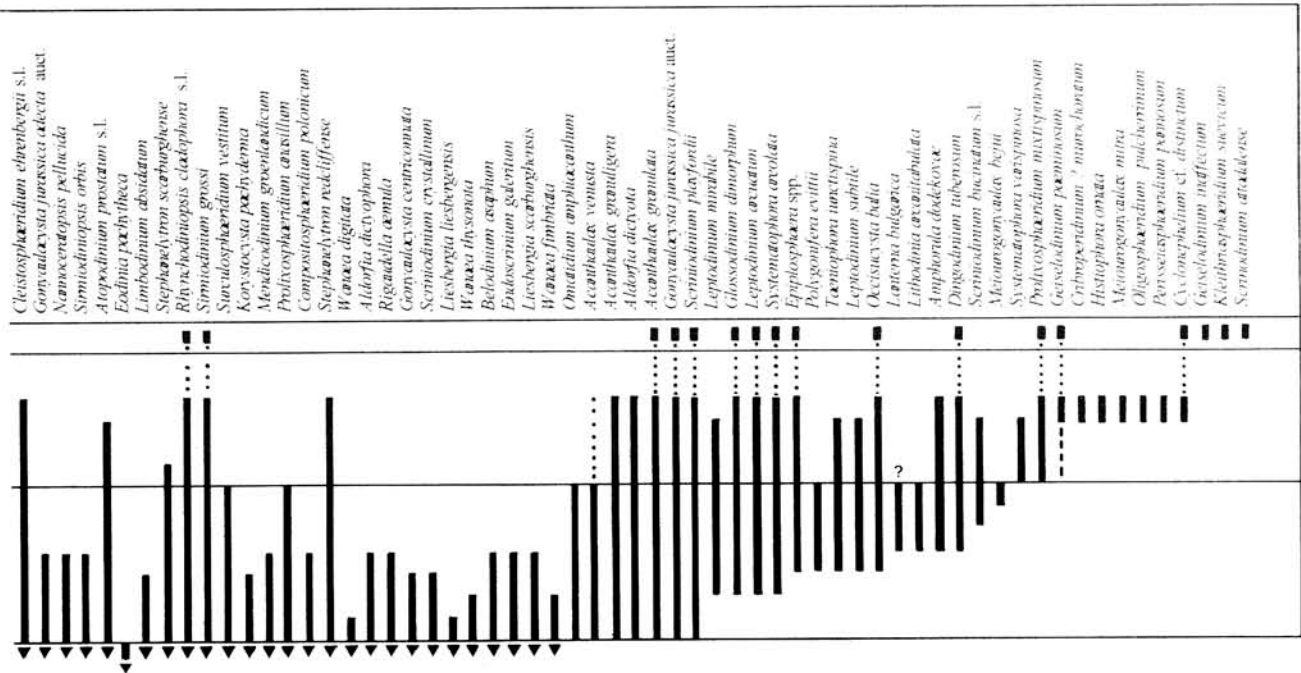
During this study, 950 samples were selected from outcrops in the well-bedded carbonate and the massive lithologies (including sponge-microbial limestones). To recognise and eliminate any weathering effects, an additional 128 samples were taken from cores provided by the Geological Survey of Baden-Württemberg. Samples were also collected from sites where the sponge-microbial carbonates have been transformed to dolomite and whose stratigraphic position could be well constrained.

The carbonate matrix was dissolved in dilute monochloric acetic acid, to avoid chemical alteration of the clay and silt

minerals. The coarse fraction of the insoluble residue was removed and the remaining material was separated into particles > and < 2 µm by using a centrifuge. Control measurements with a laser granulometer showed the silt fraction to contain less than 5% particles which were smaller than 2 µm. Both fractions were analysed by XRD and the clay/silt-ratio was determined by weight. The clay content of the samples from the core profiles was quantified using the quantification program of Siemens 'Diffrac-AT' Software Package. Moreover, a representative number of clay samples of all stages and facies units of the Upper Jurassic were geochemically investigated (Si, Al, Fe, K, Mg, Ca, Na, P, Zn, Zr, Sr, Mn, Ba, Rb and Y), the results of which will be published elsewhere within two theses (CHRISTMANN in press, MENGES, in press.).

Clay fractions: The <2µm fraction is represented by the clay minerals kaolinite, chlorite and an illite/smectite mixed layer mineral. The qualitative and quantitative composition changes remarkably in the stratigraphic column which is in agreement with the results of OPPELT & BAUSCH (1989) from Upper Jurassic samples of the Saulgau GB3 borehole (situated to the southeast of the western Swabian Alb).

Kaolinite: The distribution of kaolinite in the stratigraphic sequence is very heterogenous. Directly above the Middle/Upper Jurassic boundary no kaolinite was detected within the insoluble residue, whereas in the transition to the transversarium beds, the kaolinite content sharply increases. In some sections, the kaolinite disappears abruptly at the boundary between the Lower and Upper Oxfordian, either in the spongiolitic or the well bedded facies, whereas in other profiles it does not. If kaolinite exists in sponge-microbial Upper Oxfordian carbonates, it is restricted to some buildups which are interpreted by us to have been exposed early at the surface, as indicated by birdseye structures and pseudomorphs after gypsum crystals (Koch



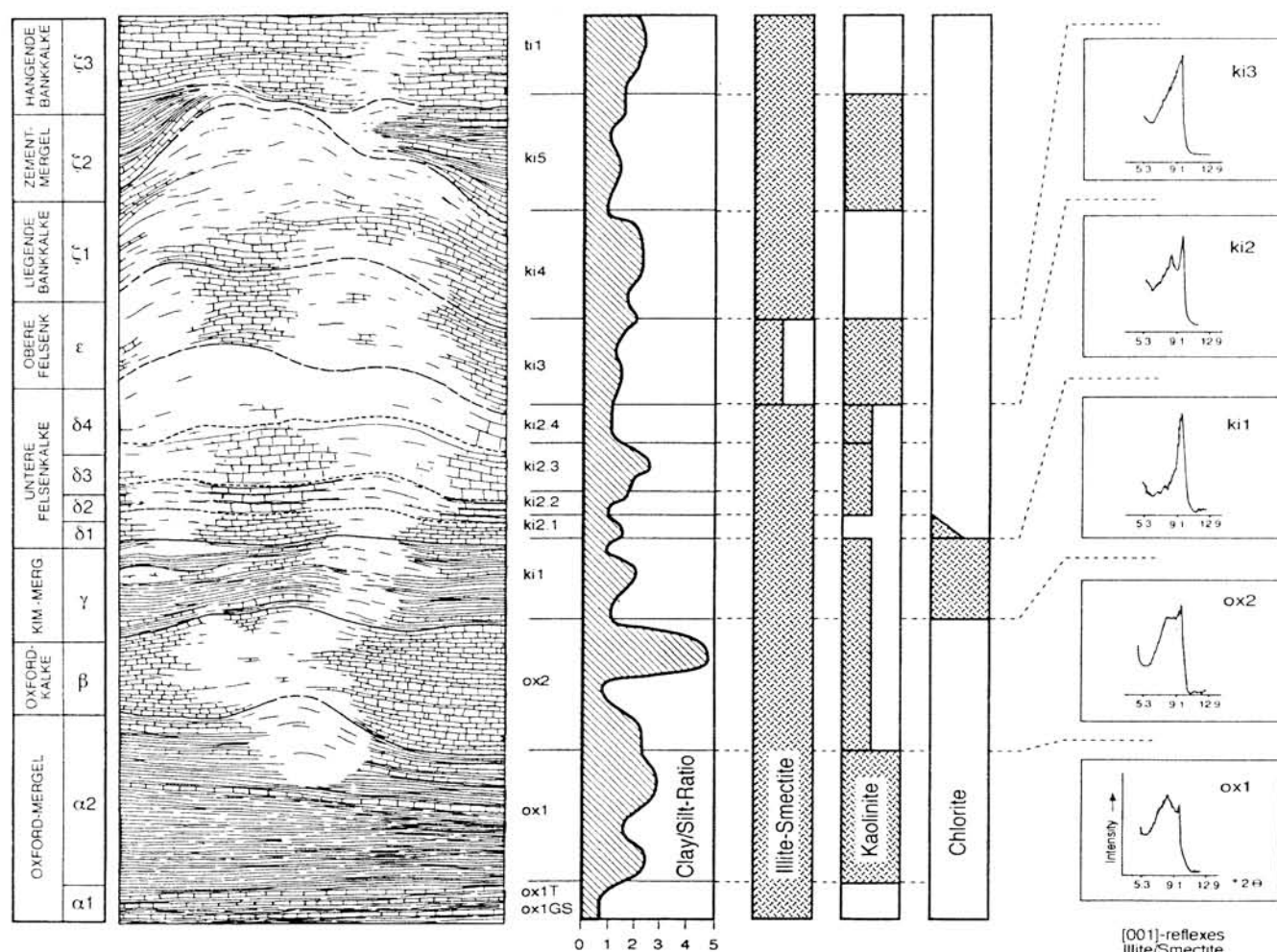


Fig. 21. Distribution of the clay/silt-ratio and the clay minerals within the Malm in the western Swabian Alb.

& SCHWEIZER 1986). In both borehole logs of the Oxfordian stage, kaolinite reaches 10% of the total clay fraction. In contrast to some other sections, kaolinite also appears in the borehole of the Upper Oxfordian.

The content of kaolinite fluctuates in the Lower Kimmeridgian. In the Malm γ kaolinite reappears, to become the dominant clay mineral in the Malm ϵ . In the Malm ζ_1 (Upper Kimmeridgian) kaolinite disappears again, to reappear from the Malm ζ_2 (Uppermost Kimmeridgian) up to the Malm ζ_3 (Hangende Bankkalke, Lowermost Tithonian) (Figs. 21, 22).

Therefore, in some higher units of the Upper Jurassic of the Western Alb it is clear that kaolinite can be used for stratigraphic purposes, whereas in the lower part of the succession it could not be used as an index mineral. Cathodoluminescence investigations show no evidence for an authigenic origin of kaolinite, but in some Malm δ (lower part of Upper Kimmeridgian) profiles there is a negative correlation between the content of kaolinite and feldspar, suggesting a partial detrital origin of kaolinite.

Chlorite: Chlorite forms an excellent stratigraphic index mineral in the Upper Jurassic of the Western Swabian Alb. An increase in chlorite occurs across the boundary from the Oxfordian to the Kimmeridgian. It is followed by the disappearance of this mineral at the beginning of the

Malm δ . Chlorite is only present as an accessory mineral in the Malm γ , constituting no more than 5% of the total clay fraction.

Illite (10 Å-peak): Illite is the most common clay mineral in the Upper Jurassic sediments comprising between 80 and 90% of the clay fraction. It was recorded in all facies varieties throughout the Oxfordian to Tithonian, with the exception of samples from the Malm ϵ (Upper Kimmeridgian), where kaolinite is the dominant clay mineral. The geometry of the 10 Å-peak profile appears to result from a mixture of two phases, illite/smectite and illite/muscovite (STERN et al. 1991). The appearance of the illite/smectite phase is not a consequence of recent weathering because the mixed layers are also found at depth within the core profiles.

Throughout the Upper Jurassic succession, characteristic illite (001)-peak profiles were observed, which enable recognition of separate subunits. This is of particular value for subdivision of the Kimmeridgian, where the different peak geometries can be used for stratigraphic division within the massive sponge-microbial carbonates, which could not be performed by other lithological or biostratigraphical methods alone.

Silt fraction: The content of silt consists mainly of quartz and minor feldspar (plagioclase and/or orthoclase).

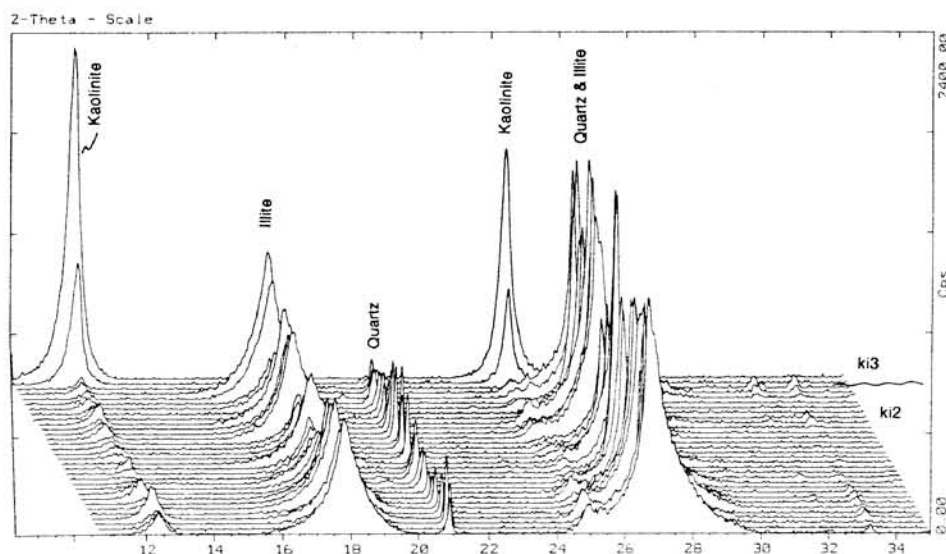


Fig. 22. The dominance of kaolinite clearly onsets at the ki2/ki3 boundary (samples from borehole Ro 7820 B1).

In the Malm δ (lower part of Upper Kimmeridgian), feldspar is restricted to special horizons showing an antagonistic behaviour to that of kaolinite. In the samples of the Malm α (lower part of Upper Oxfordian), pyrite is a common mineral, whereas in the samples of the other stages, pyrite is fairly rare. In seven samples from the Malm ϵ (Upper Kimmeridgian) small amounts of carbonate-fluorapatite were detected.

Clay/silt ratio: In some levels of the investigated sections there seems to be a connection between the development and the spreading of sponge microbial reefs and the input of clay. If the clay mineral input was reduced relative to silt, development of sponge-microbial reefs was more pronounced and covered wider areas. Obviously, an accelerated input of very small particles was a fundamental factor for the partial suppression of growth in such buildups (see section 5.4).

As a conclusion, the qualitative and quantitative distribution of clay minerals in the well-bedded limestones, in the sponge microbial buildups and in the dolomitic carbonates is nearly identical in the different stages of the Upper Jurassic of southern Germany. At certain boundaries there are typical changes in the relative percentage of the clay minerals which can be traced throughout all facies units. On this basis, the ammonite-free massive limestones of sponge-microbial facies and even the dolomites can be divided stratigraphically.

The relationships between clay/silt ratio and enhanced reef development in times of reduced clay-input indicates that a higher input of clay reduced reef growth. Therefore, the amount of clay delivered to the area of deposition appears to have been an important controlling factor of reef genesis (see section 5.4).

4.4 Sequence stratigraphy of Jurassic reef-bearing successions

4.4.1 Sequence stratigraphy of the Middle Jurassic of the NW Iberian Chains (Sierra de la Demanda), Spain (Rehfeld-Kiefer)

Relative changes of sea level appear to have caused the variable progradational pattern of the Mid and Late Bajocian

(Sauzei to Parkinsoni Zone) moderately deep carbonate platform of the Demanda area (see section 3.2.1). Sea level fluctuations are documented by three depositional sequences, each of them related to a more or less complete deepening-shallowing cycle (Fig. 23). A precise biostratigraphic framework of ammonite zones allows reliable lateral correlations over wide areas. This sequence stratigraphical approach is based on eight sections from the western, eastern and southern Demanda. Published data were incorporated as well (esp. WESTERMANN 1955, GERVAIS 1988, FERNANDEZ-LOPEZ et al. 1988). Coastal onlap curves of RIOULT et al. (1991) from the western border of the Anglo-Paris Basin are largely in good accordance with the data from the Demanda and thus suggest a close relationship of subsidence history in both areas. In both cases sea level fluctuations may be not only controlled by eustasy but also by basin tectonics (cf. WESTERMANN 1955). Exact correlation remains somewhat uncertain since stratigraphic resolution on the subzone level is not possible in the Demanda area due to strong faunal mixing (see section 3.2.1). Very good coincidence exists in the lowermost cycle 2.1a (sensu RIOULT et al. 1991) with a distinct sequence boundary above the Sowerbyi or lowermost Sauzei Zone. The second cycle (2.1b) locally cuts down to the base of cycle 2.1a and extends to heavily eroded and reworked iron-stained beds of the Garantiana Zone mixed with ammonites of the Niortense Zone. The latter defines the base of the third cycle. The third depositional sequence (2.2) starts above the Garantiana sequence boundary and reaches to the top of the thick bedded limestones which probably extend into the Lower Bathonian (WILDE 1988).

Possibly, depositional sequence 2.2 comprises two cycles since one or two metres above the Niortense-Garantiana Zones a second faunal mixing suggests partial reworking of the Garantiana beds within the Parkinsoni Zone. This would imply a second, less conspicuous transgressive surface. The lithological succession consists of a thinly bedded marl-limestone alternation which is very poorly exposed in the entire area. With this possible subdivision of the third cycle in mind, the depositional sequences identified in the Demanda area largely correspond to those proposed by RIOULT et al. (1991), but appear to have one additional depositional sequence intercalated between 2.1b and 2.2 (Fig. 23).

Environment of sponge cementation: Sponges occurred in situ during the late transgressive systems tracts and the early highstand systems tracts. From this it may be inferred that environmental parameters within these depositional units provide favourable conditions for sponge preservation, which comprise:

1. Transition from a retrograding to an aggrading carbonate platform. This implies low sedimentation rates but simultaneously gradual increase in carbonate productivity ('catch-up' carbonate platform of SARG 1988).

2. Sediment rich in micrite and pervasive cementation (automicrite) in a succession of hardgrounds.

3. Oligotrophic conditions, increased salinities and low oxygen content (see section 6.2) (SARG 1988).

4. Maintenance of low carbonate accumulation rates over long periods. This is mediated by increased subsidence rate and/or limited growth potential of the organisms involved (BOSSCHER & SCHLAGER 1993).

4.4.2 Sequence stratigraphy of the Upper Jurassic successions - an overview (Leinfelder)

Sequence stratigraphic interpretation of the Lusitanian Basin revealed that sea level changes of third order modify but do not change the style of basin fill of this rift-related basin (LEINFELDER 1993b, 1994, LEINFELDER & WILSON, submitted). Reefs of various types grew in a great variety of settings. Siliceous sponge-bearing coral reefs occurred during transgression and early highstand in a coarse siliciclastic fan fed from the eastern basin margin (Fig. 24). Thrombolites, coral meadows and extensive biostromal to biohermal coral limestones grew on a southwards prograding fine siliciclastic slope system during pauses in progradation caused by sea level rise. Marly coral biostromes grew in an estuarine, siliciclastically influenced environment during sea level rise, which again lowered siliciclastic influx. Isolated, reef rimmed carbonate platforms also had their maximum phases of development during sea level rise and early highstand, but steep tectonic platform margins prevented progradation despite high productivity. Available biostratigraphic data allow a good match with the third-order depositional sequences of PONSOT & VAIL (1991a, b; (VAIL & JAQUIN, pers. comm.), which are thought to be valid at least for Europe, if not globally (Fig. 24).

A comparison with the Upper Jurassic of Algarve shows that condensed sections mostly developed during sea level rise, although some condensed horizons are due to lowstand condensation, probably caused by a breakdown of shallow-water carbonate factories during these episodes (cf. LEINFELDER 1993a). Siliceous sponge bearing thrombolites as well as pure thrombolites frequently developed within condensed transgressive parts of the section.

A framework of second-order sequences of the Spanish Upper Jurassic was developed only recently (AURELL 1990, AURELL & MELENDES 1993) and appears debatable. Most of the condensed or hardground intervals of the Oxfordian probably represent flooding surfaces or maximum flooding events. Amalgamation, however, makes the resolution

of single sequences difficult. Another problem is the separation between transgressive and lowstand condensation. In any case, exhaustive growth of sponge meadows, as well as crust-rich sponge bioherms, is clearly related to such condensed intervals, proving the importance of strongly reduced allochthonous sedimentation for spongiolite development. Kimmeridgian development of coral-bearing to coral-rich thrombolites can be again correlated with the transgressive interval of the Hypselocyclum to Divisum Zone, where thrombolites also developed in the Algarve and the Lusitanian Basin.

Many of the condensed intervals and the reef-bearing transgressive intervals from Iberia can be identified across major parts of the northern Tethys shelf (France, Switzerland) and can be recognised again in southwestern Germany (LEINFELDER 1993a). Development of reef facies, i.e. particularly sponge facies, was more pervasive in southern Germany than in other areas. Sponge facies (i.e. spongiolites or massive limestones hosting spongiolites) not only occurred in single intervals but locally persisted throughout major parts of the Late Jurassic. This is an effect of generally reduced allochthonous sedimentation in comparison with, e.g. Iberia. However, pulses of lateral expansion of sponge facies or massive facies at the expense of the bedded ammonitic facies again is correlatable with transgressive and highstand phases of Portugal and the PONSOT & VAIL (1991a,b) sequences (Fig. 24; cf. LEINFELDER 1993a). This once more proves the importance of reduced background sedimentation even for the development of sponge mudmounds, since a large part of the cryptocrystalline material accumulated in these structures is of authigenic microbial nature (see section 5.1). The maximum lateral development of the biohermal complex at Gosheim, for example, is characterised by a high amount of microbial crusts, i.e., authigenic carbonate. This level is situated close to the Malm α/β boundary, which is correlatable with a transgressive interval in the PONSOT & VAIL sequences.

Exact correlation of lithological sections of the Oxfordian from eastern Romania is hampered by the scarcity of biostratigraphic indicators. However, all sections show one symmetric cycle from a transgressive lower half to an upper regressive part with crust formation preferentially taking place during transgression or early sea level highstand when sedimentation rates were lowered (cf. Fig. 17). This correlatability of sea level states despite different facies development supports the assumed synchronicity of deposition and, hence, the homoclinal ramp model postulated in section 3.3.

5 CONTROLLING FACTORS OF REEF GROWTH

This section will discuss the role of crusts as well as basic environmental factors controlling the formation and style of Jurassic reefs. Since all reefs studied grew under normal salinity conditions, no further discussion of this basic factor is given. It should be, however, emphasised that the low-diversity *Amphiastrea piriformis* coral-asso-

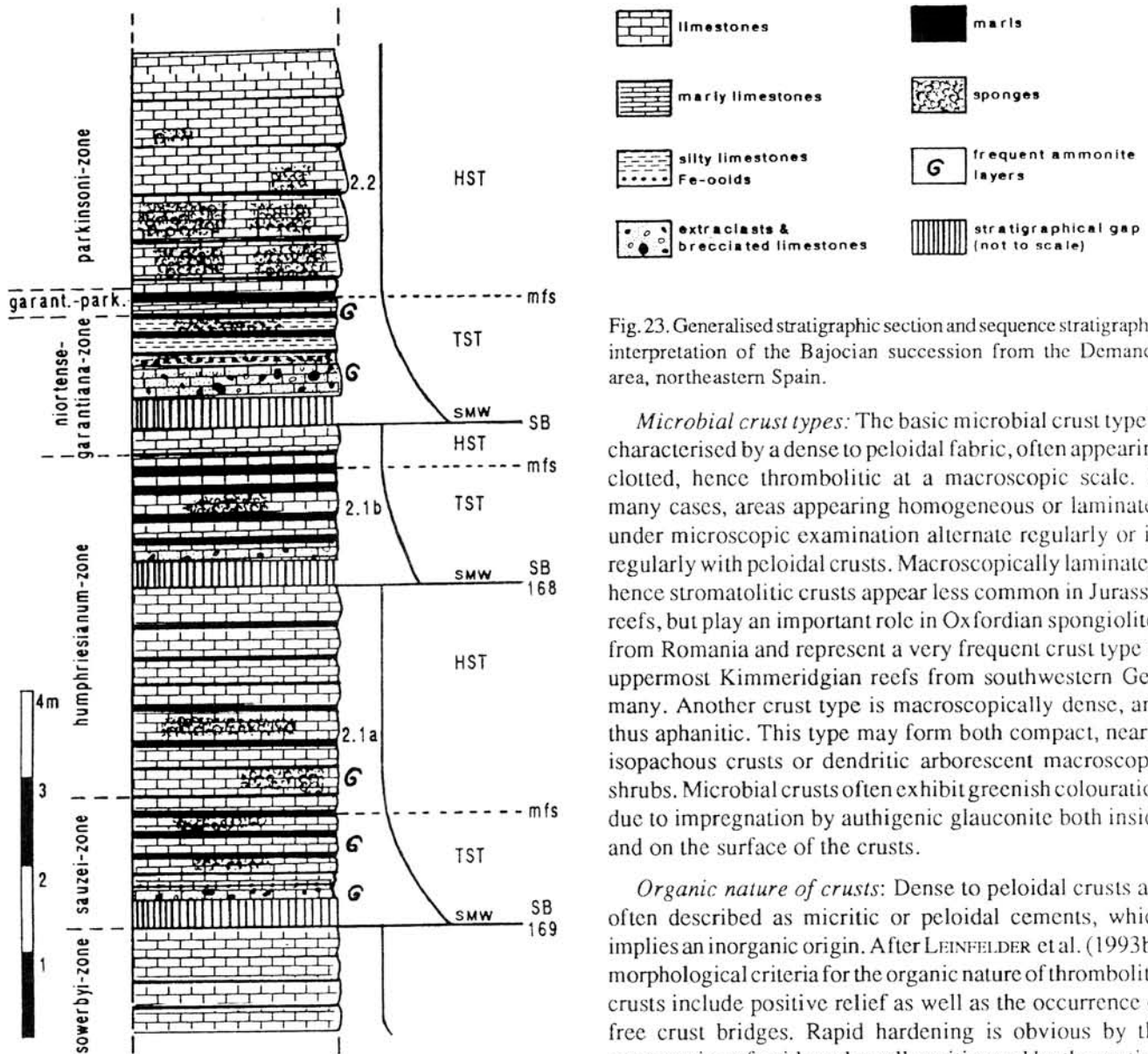


Fig. 23. Generalised stratigraphic section and sequence stratigraphic interpretation of the Bajocian succession from the Demanda area, northeastern Spain.

Microbial crust types: The basic microbial crust type is characterised by a dense to peloidal fabric, often appearing clotted, hence thrombolitic at a macroscopic scale. In many cases, areas appearing homogeneous or laminated under microscopic examination alternate regularly or irregularly with peloidal crusts. Macroscopically laminated, hence stromatolitic crusts appear less common in Jurassic reefs, but play an important role in Oxfordian spongiolites from Romania and represent a very frequent crust type in uppermost Kimmeridgian reefs from southwestern Germany. Another crust type is macroscopically dense, and thus aphanitic. This type may form both compact, nearly isopachous crusts or dendritic arborescent macroscopic shrubs. Microbial crusts often exhibit greenish colouration due to impregnation by authigenic glauconite both inside and on the surface of the crusts.

Organic nature of crusts: Dense to peloidal crusts are often described as micritic or peloidal cements, which implies an inorganic origin. After LEINFELDER et al. (1993b), morphological criteria for the organic nature of thrombolitic crusts include positive relief as well as the occurrence of free crust bridges. Rapid hardening is obvious by the preservation of voids and small cavities and by the participation of other encrusting organisms (cf. Pls. 3 and 4). Moreover, crusts of shallow-water environments often are attacked by boring bivalves. At a microscopic scale, peloids are occasionally arranged in rows, possibly mirroring an originally trichomal arrangement of bacteria or cyanobacteria. In the Iberian examples, the almost exclusive restriction of peloids to crusts and similarity of reefal crusts with fabrics of oncoid cortices also points to their autochthonous microbial formation. Such characteristic fabrics identify microbial crusts as an important and easily detectable form of hard, partly peloidal automicrites. Dense, homogeneous cryptocrystalline crusts (or automicrites) are only identifiable as such if they exhibit a different, darker colouration than embedding micrites and if they form irregular crust morphologies. It can be assumed that other, less easily identifiable automicrites have formed as well, partly by microbial activity.

Responsible organisms: In comparison with modern examples it must be assumed that microbial crusts chiefly were built by microbes, particularly cyanobacteria and heterotrophic bacteria, although they normally include

ciation from Portugal was interpreted as euryhaline by LEINFELDER (1986) and FÜRSICH & WERNER (1986).

5.1 The nature and role of crusts in reef formation (Leinfelder, Schmid)

In many Jurassic reefs from Portugal, Spain, southern Germany and Romania, calcareous microbial crusts are a major constituent. They occur within coral reefs, mixed coral-siliceous sponge reefs and siliceous sponge facies, but also construct thrombolite reefs with or without additional reef metazoans. Upper Jurassic reefal crust types, as well as clues for their microbial origin and role in the formation of reefs, were recently presented by KEUPP et al. (1993) and LEINFELDER et al. (1993b). Comparable modern crusts, analysed by REITNER (1993), occur in dark reef caves of Lizard Island, Australia. Therefore, only a brief overview of reefal crusts is given here and the reader is referred to the cited papers for further information.

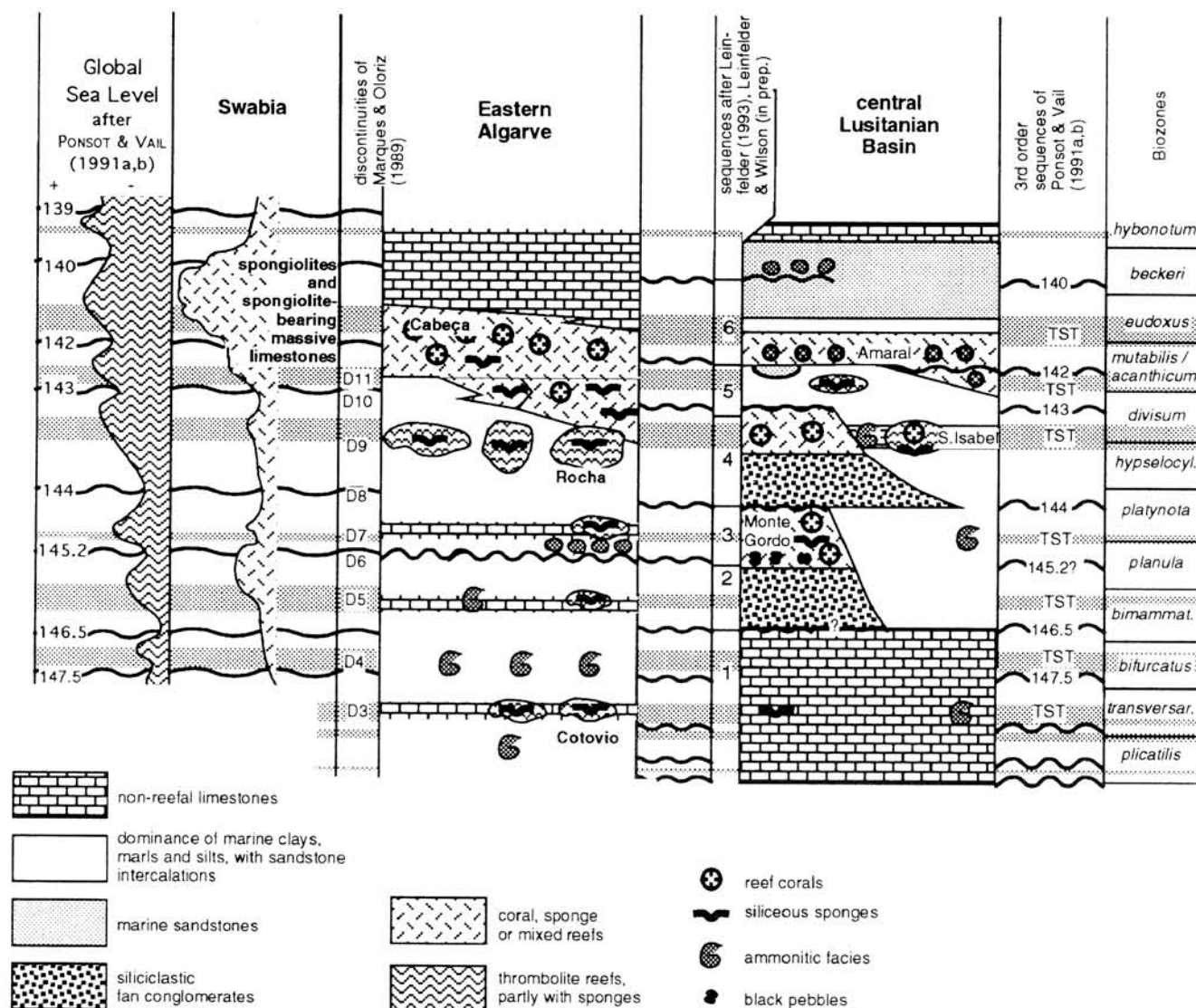


Fig. 24. Sequence stratigraphic correlation of the Oxfordian to Kimmeridgian succession of Portuguese Basins and southwestern Germany with the PONSOT & VAIL (1991a,b) third-order sequences. Reefs developed or expanded during transgressive and early highstand phases. Particularly obvious is the occurrence of thrombolites and siliceous sponge facies within the marl dominated Kimmeridgian upper Hypselocyclum to Divisum Zone in all three areas (from LEINFELDER 1993a, simplified).

other encrusting organisms, such as algae, foraminifera and metazoans. The place of carbonate autoprecipitation is within the extracellular polysaccharide substances of the microbial film or mat community. The process of microbially induced in-situ precipitation of peloids has been produced in the laboratory (CHAFETZ 1986, CHAFETZ & BUCZYNSKI 1992).

HEFTER et al. (1993) were able to detect biomarkers in samples from the Upper Jurassic sponge facies, including dense and thrombotic crusts, sponge-mummies and detrital sediment. Some of the organic compounds identified indicate the presence of distinct groups of organisms. There is evidence of activity of different anaerobic and aerobic bacteria including cyanobacteria (see also B. LANG 1989). In cases of high diagenetic alterations the specificity of this information based only on the hydrocarbon fraction decreases, because the relative compounds distributions become more similar.

Carbon and oxygen stable isotope values from various Upper Jurassic reefal settings mostly range between -1.2 and +2.3 (KEUPP et al. 1993, LEINFELDER et al. 1993b) which clearly excludes a methanogenic seep origin of crusts. These values are not far from a supposed equilibrium with the sea water, which favours the view that precipitation was an inorganic process under organic control, i.e. mediated in an organic matrix provided by the microbes.

Role of crusts in reef formation: Microbial crusts play a paramount role in shaping the morphology of reefs. For example, the difference between siliceous sponge biostromes and biohermal siliceous sponge - microbial crust mudmounds is merely caused by a much higher participation of crusts in the latter. In the same way, Upper Jurassic crust-free high energy coral reefs do not show any preserved organic relief unless microbial crusts participate in their formation, acting as debris-binding organisms. In conclusion,

reef associations with little or no microbial crusts normally did not develop distinct relief. Crusts also are important in contributing remarkable quantities of reef rock. The perfect example for this is the unusual thickness of Upper Jurassic spongiolite development in eastern Spain. There, great thicknesses accumulated during a relatively short time interval only in an area with extensive development of crusts (see section 3.2.2). The abundance of crusts particularly in the basal part of many reefal bioherms shows that crusts also played an important role by rapidly stabilising the formerly soft sea floor and hence helped in the rapid establishment of reef growth. The large amount of supposedly soft mud in some Oxfordian sponge mounds might indicate that uncalcified microbial mats also were important for stabilisation of mudmound material.

5.2 Factors related to bathymetry (Nose, Schmid, Werner)

The bathymetry of Upper Jurassic reefs (e.g. the Upper Jurassic sponge-microbial crust mudmounds of southern Germany, pure microbial crust reefs and various coral-rich reef types of Iberia) is difficult to evaluate due to the almost lack of directly comparable modern examples.

Bathymetric calibration of reefs can be best performed in the Iberian examples: The Upper Jurassic successions of the Arruda Subbasin (Lusitanian Basin) and the Eastern Algarve Basin (Portugal) are rich in reef types of various composition. They exhibit a clear shallowing upwards trend, as proven by the general increase of benthic macrofauna within the slope marls and the general succession from deeper water ammonitic limestones to shallow water platform facies where coral facies is associated with typical shallow-water sediments such as cross-bedded oolitic grainstones or dasycladacean limestones. Additionally, seismic data from the Arruda Subbasin revealed southward dipping clinoforms outlining the transition from inner ramp to outer ramp settings within a prograding slope system.

Therefore, according to Walther's facies law (WALTHER 1893/94), the reefs occurring at different vertical positions within the successions can be attributed to different water depths (cf. LEINFELDER et al. 1993a): coral-dominated reefs are clearly related to the shallowest parts of the successions. They are bathymetrically separated from reef types rich in siliceous sponges occurring deeper in the ramp. Mixed coral-siliceous sponge reef associations are transitional between the two end members. Thrombolitic reefs with dominance of microbial crusts may occur from the deepest settings up to the base of the coral facies. Sometimes thrombolitic patches are even found within coral reef structures. Comparable shallowing upwards successions with siliceous sponge facies in their deeper part, and/or mixed siliceous sponge-coral facies grading into coral facies in their upper part, occur in Eastern Spain (Celtiberian Basin, LEINFELDER 1993a.), Romania (see section 3.3) and, locally, in southwestern Germany (cf. section 3.1.3). They also are known from some basins on the western side of the Northern and Central Atlantic (CREVELLO & HARRIS 1984,

ELLIS et al. 1990), and from Argentina (Neuquén Basin, LEGGARETA 1991). This gross bathymetric interpretation of reef structures and facies derived from the shallowing-upwards successions can be further substantiated and refined by comparative semi-quantitative analysis of reefal and non-reefal faunal associations. Again, the Upper Jurassic successions of Portugal proved to be most suitable for this approach due to their faunal richness and the existence of an independent bathymetric dipstick provided by the above mentioned shallowing-upwards characteristics of successions. The main ecologic trends are discussed in detail by WERNER et al. (1994) and LEINFELDER et al. (1993a, 1993b), and are briefly summarised here (Fig. 25):

Along a bathymetric gradient the diversity and composition of sponge fauna changes drastically. Towards greater depth coralline sponges diminish in number both in individuals and species, whereas siliceous sponges increase. Although hexactinellids (especially lychniscids) do occur in moderate water depth, they clearly outnumber the lithistids in deeper environments. Among the hexactinellids, dictyids rather than lychniscids dominate the deep environments;

Cementing bivalves partially exhibit distinct species replacement. *Praeexogyra pustulosa*, restricted to shallow water, is substituted by *Atreta unguis* and *Plicatula ogerieni* in deeper water. Lithophagid bivalves show a maximum distribution in very shallow water.

Factors such as illumination, hydrostatic pressure, and nutrient supply are related to bathymetry and have effects on the bathymetric distribution of coral taxa (e.g., GEISTER 1983). In the Portuguese examples, distribution of some coral taxa follows bathymetric trends. *Microsolena*, a common fungiid coral, occurring in a broad range of settings and facies types in the Upper Jurassic reefs of Iberia, is nearly absent in high energy, shallow water environments and shows a maximum distribution around the storm wave base in shallow outer ramp settings. *Microsolena* is generally rather common in areas newly colonised by hermatypic corals (cf. BENDUKIDZE 1977, ERRENST 1990). Some coral genera of the Arruda Subbasin (Lusitanian Basin) are restricted to narrow bathymetric intervals, and are diagnostic of shallow outer ramp (*Trocharea*, *Tricycloseris*) or high-energy, upper mid-ramp positions (*Psammogyra*, *Amphiasirea*). Moreover, bathymetric differences are partly also reflected by the distribution of entire coral associations, rather than isolated taxa. For example (Arruda Subbasin), the high diversity *Microsolena-Trocharea* association is related to shallow outer ramp settings, whereas the *Actinastrea* association (e.g. *Actinastrea*, *Psammogyra*) with common lithophagid borings is restricted to strongly wave agitated inner to mid-ramp settings.

Although coral growth forms particularly depend on sedimentation rate (see section 3.2.3), illumination related to bathymetry also influences the morphology of corals. When background sedimentation rates were low, foliate and patellate growth forms characterised deep mid-ramp to outer ramp environments. The enlargement and flattening of the upper surface can be considered as an adaptation to poor illumination (cf. GOREAU & LAND 1974, GRAUS &

MACINTYRE 1976, GEISTER 1983). In the Iberian examples, supposedly ahermatypic corals like *Trochocyathus*, *Stylocyathus* and *Caryophyllia* are part of condensed, fauna-rich layers in the lower part of the prograding slope marls. These non-reef building taxa are indicative of deep-marine outer ramp settings.

Microbial crusts, participating in the formation of nearly all reefal facies types, include various encrusting organisms, which form different micro-encruster associations. The distribution of micro-encruster associations together with diversity trends have proven to be a useful tool for the estimation of bathymetry (LEINFELDER et al. 1993b). The medium-diversity *Bacinella-Lithocodium* association is frequent both in reefal crusts and in large oncoids and is clearly restricted to shallow water settings (see sections 3.1.3, 3.3). A high-diversity micro-encruster association, also containing *Bacinella* and *Lithocodium*, occurs slightly deeper. *Lithocodium*, which is interpreted as an loftusiid encrusting foraminifer, might owe its light-dependance to a relationship with symbiotic algae (unpubl. results). The low-diversity *Girvanella* association, restricted to oncoids, is typical for inner ramp settings with frequent salinity fluctuations. The *Terebella-Tubiphytes* association, most common in peloidal crust fabrics, is of low diversity and occurs from mid-ramp settings down to the deepest reef facies as well as in probably oxygen-controlled reefs. The agglutinating polychaete *Terebella* is the only encruster which never appears in high-energy shallow water. In contrast, *Tubiphytes* alone may also appear in the inner ramp areas and therefore has no bathymetric value.

Oxfordian reefal settings from eastern Romania exhibit similar bathymetric characteristics as in Iberia, as suggested by their position within shallowing-upwards successions (see section 3.3, Fig. 17). However, the Romanian examples additionally provide the direct realisation of the 'Waltherian' rule, because shallowing also is obvious in an eastwards direction. Along this gradient, crust types change, which probably reflects a decrease in sediment influx as a function of distance from the shallow-water carbonate factory.

In the Swabian Alb of southwestern Germany, where bathymetric interpretation is still discussed controversially, the results from Iberian shallowing-upward successions can be tested. With the exception of the coral-bearing isolated localities of latest Kimmeridgian to Tithonian age, the total lack of shallow-water forms in rocks associated with spongiolites is obvious, whereas forms of the *Terebella-Tubiphytes* association appear in great abundance. Additionally, a typical shallow-water form, *Lithocodium aggregatum*, could be detected in the Swabian Alb - significantly in the highest part of the uppermost Kimmeridgian coral reef facies at Arnegg. All this strongly supports the view that the Oxfordian and most of the Kimmeridgian reefs of southwestern Germany have formed in a deep mid-ramp to dominantly outer-ramp setting. Not fully compatible with this trend is an interpretation of the grain-rich massive limestones of the Late Kimmeridgian as autochthonous sand wave environments, possibly supporting the alternative interpretation as debris lobes of

allochthonous material or microbial buildups (see section 3.1.2).

5.3 Environmental factors reflected by morphometry of reef brachiopods (Brugger, Keupp)

Brachiopods are a characteristic element in most of the Jurassic reefs, particularly spongiolites. They represent a rather conservative group of organisms. Often, convergent shell morphologies developed in different taxonomic groups due to strong environmental control (Fig. 26). This fact can be used to interpret distinct morphologic elements of brachiopods, particularly the general shape of the shell and its symmetry of the frontal commissures, width and position of the foramina, sculptures and other features of both, modern (EMIG 1988 1989, POECK et al. 1989, SCHUMANN 1991) and fossil associations (RUDWICK 1974, AGER 1965, FÜRSICH & PALMER 1984). As an additional tool for environmental interpretation diversity assemblages of articulate brachiopods from different Upper Jurassic spongiolite localities of southern Germany were analysed morphometrically. The studied material has been collected mainly from the following localities: (a) Schüpfelberg near Neumarkt/Oberpfalz: marly limestones of the Middle Oxfordian; (b) Laibarös east of Bamberg: spongiolitic marls of the lowermost Kimmeridgian; (c) Engelhardtberg near Ebermannstadt: spongiolitic limestones rich in detritic components of the Upper Kimmeridgian.

Brachiopod faunas of these localities were compared with a quantitatively sampled brachiopod association of the Early Tithonian coral facies of Saal near Kelheim (Franconia) and of the low diversity fauna of Oxfordian normal bedded limestone/marl facies from Schönberg/Swabia. The following results and interpretations of environmental differentiation can be deduced:

(1) In contrast to brachiopods of the coral facies (dominated by the large *Juralina* and similar terebratulids), the spongiolitic associations are generally characterised by a high symmetry of clearly biconvex shells and absence of shell injuries.

(2) The frontal commissures of most brachiopods from spongiolitic facies demonstrate an effective separation of the inhalant/exhalant streams by biplicate and episulcate (*Argovithyris* and similar terebratulids, particularly in limestone) or monoplicate features (*Nucleata nucleata*, *Zittelina gutta*, particularly in marly occurrences). These morphotypes resemble the *Aulacothyris*-association of bedded non-spongiolitic marls. In contrast, the terebratulids of the coral facies (Saal) exhibit more or less rectimarginate frontal commissures.

(3) The rhynchonellid genus *Lacunosella* seems to be restricted to reefal facies. It is characterised by a small foramen located below a long rostrum-like umbo and can be interpreted to have settled on an unstable substrate by a rhizoid stem, comparable to modern counterparts (RICHARDSON 1981). Therefore, associations of marly reefal facies are dominated by *Lacunosella*, while the limestones (spongiolitic and coral facies) are dominated by terebratulid taxa.

In conclusion, the often nearly globular morphology (cf.

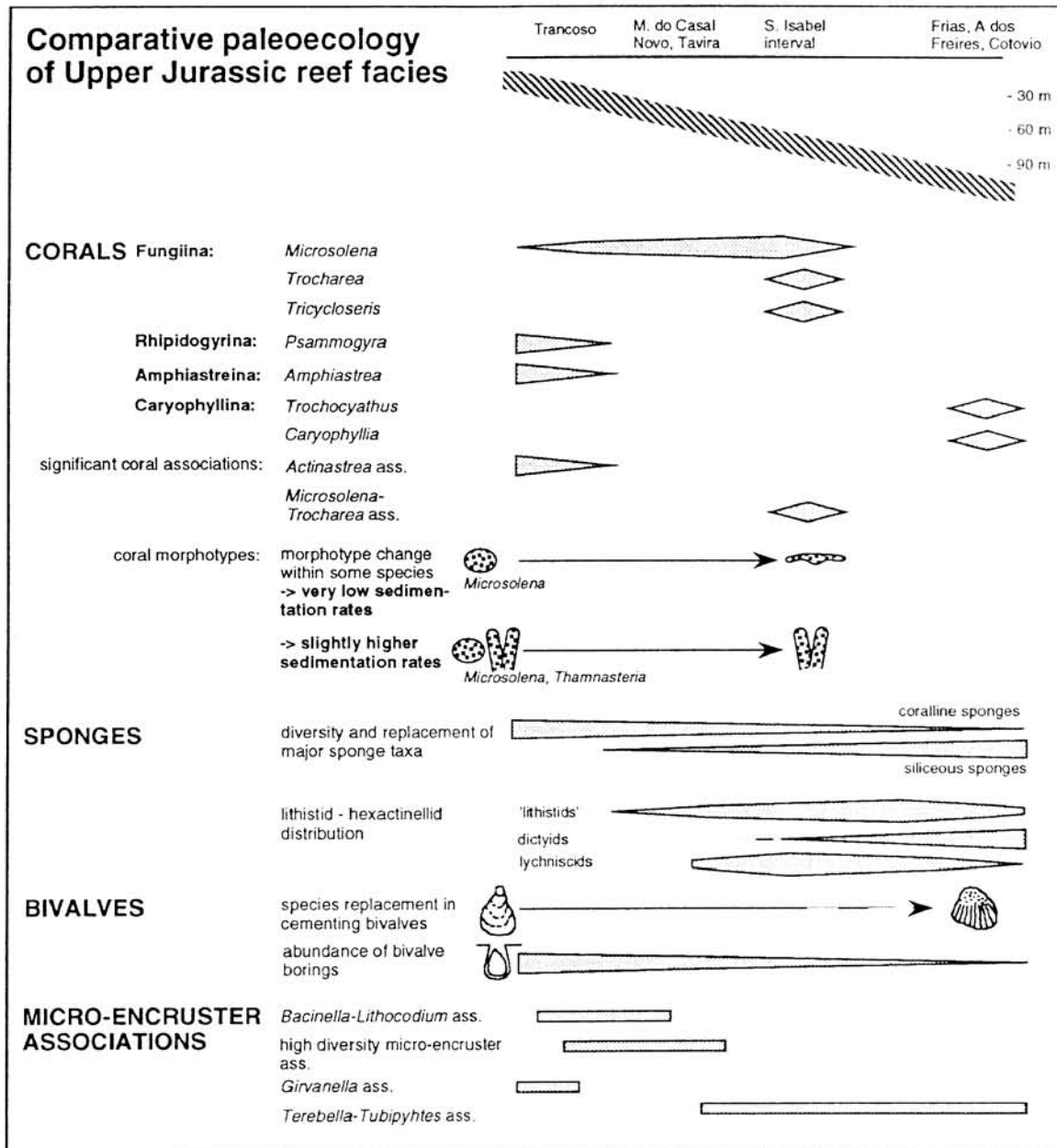


Fig. 25. Bathymetric distribution and comparative palaeoecology of Upper Jurassic metazoans and micro-encruster associations of Iberia. Compiled from LEINFELDER et al. (1993a,b) and WERNER et al. (1994).

McGHEE 1980) of highly symmetric shells and characteristic frontal commissures of spongiolitic brachiopod associations correspond to modern associations of a deeper-water environment below wave base.

The differences between marl and limestone were considered to demonstrate the primary differences of substrate conditions. The terebratulid taxa dominating the spongiolitic limestones corroborate the suggestion of a primary hard substrate (ALMERAS & ELM 1985) of spongiolitic buildups (cf. KEUPP et al. 1993), while the *Lacunosella* dominated spongiolitic marls, particularly of Oxfordian/Lower Kimmeridgian occurrences, prove the originally high portion of mud and more or less soft substrate consistency, in which terebratulid brachiopods and most of the siliceous sponges settled on shells or other small firm secondary hardground 'islands'.

5.4 The influence of sedimentation rate on reef growth and composition

(Krautter, Leinfelder, Nose, Schmid)

The rate of allochthonous (or background) sedimentation is one of the most important factors for the establishment of reefs and the morphology and diversity of reef-building metazoans. Most reefal associations occur in a regime of low to very low background sedimentation rates leading to stable substrates (LEINFELDER 1993a). Low sedimentation rates are directly indicated by the attack of bioeroders (e.g. boring bivalves, the frequent overgrowth by oysters, serpulids, bryozoans, coralline sponges and microbial crusts).

Sequence stratigraphic interpretation indicates that the initiation or the entire growth of coral, siliceous sponge

and microbial reefs occurred during third-order episodes of rising sea level, i.e. during times of regionally or globally lowered allochthonous sedimentation (see section 4.1). A high input of fine siliciclastics as well as allochthonous carbonate mud mostly excluded reef development, although adapted reef fauna partly could withstand a slightly elevated rate of background sedimentation. The growth of reef organisms seems to be particularly hampered by clay-sized terrigenous material (LEINFELDER 1994; see section 4.3). It will be shown that the actual rate of a generally reduced background sedimentation is an important modifier for reef composition, reef fabric and reef morphology.

Corals and sedimentation rate: High diversities of coral faunas are always associated with a high rate of borings and encrustation by cementing macrofauna, micro-encrusters or microbial crusts, indicating very reduced rates of allochthonous sedimentation. Only some adapted coral taxa characterised by a high morphologic variability or phaceloid to ramose, mostly thin-branched growth form (*Microsolena*, *Thamnasteria*, *Ovalastrea*, *Calamophylliopsis*) could grow under elevated background sedimentation to form marly or calcareous low-diversity reefal meadows. Here, corals were not attacked by bioeroders or extensive microbial encrustation, which is an additional criterion for higher sedimentation rates.

Besides physiologic and ontogenetic determinations, sedimentation rate appears to be one of the most important factor controlling the morphology of corals (LEINFELDER 1986, 1994). Observations on the species level show some adaptive trends in several coral taxa. The taxa *Microsolena agariciformis*, *Thamnasteria lobata* and *Thamnasteria moreana*, all occurring over a broad range of settings and facies types, especially reflect the dependence of growth forms on sedimentation rate. *Microsolena agariciformis* occurs in nearly all possible growth forms (foliate, ramose, massive) in the Arruda Subbasin of Portugal, but it is never observed that different growth forms of *Microsolena* co-exist in one reefal association. For example, thin branched ramose forms of *Microsolena* dominate marly coral meadows with no overgrowth by microbial crusts and other organisms, which points to higher sedimentation rates. The phaceloid *Calamophylliopsis* thrived in regimes with a high supply of fine allochthonous material (e.g. *Calamophylliopsis* meadows, cf. WERNER 1986, LEINFELDER 1993a). Corals not only react to higher sedimentation rates by variations of growth forms but also by rejection of fine siliciclastic detritus. Highly integrated corallites, especially meandroid and thamnasterioid types with confluent septae, are able to transport surface sediment to the edges of the colony (HUBBARD & POCKOCK 1972), a feature which can be used for the interpretation of potential adaption of fossil scleractinians as well (cf. LEINFELDER 1986, 1994). Hence, the modifying influence of sedimentation rate on coral faunas is well documented in the reefs studied.

Sponges and sedimentation rate: In general, epibenthic sponges prefer low sedimentation rates. However, some modern demosponges (e.g., *Spherospongia vesparium*)

can withstand an elevated sedimentation rate. According to STORR (1976) they are able to reverse the water current and keep their incurrent canals and pores free from dirt. Such backwashing even enables the sponge to eject detrital material which has already clogged some pores. This process is probably caused by a sudden contraction of the polluted area. Other modern sponges (e.g., *Condrilla nucula*) create secretions which carry detrital particles out of the canal system. A third possibility of some demosponges (*Mycale* sp., *Verongia gigantea*, *Tethya crypta*) to get rid of sediment particles is attributable to amoebocytes. These cells phagocytose particles and transport them from inhalant to exhalant canals (REISWIG 1971).

Up to now it is not known if modern and fossil hexactinellids and 'lithistids' are able to react in a similar way. Due to their rigid architecture, contractional abilities seem very unlikely. Secretional cleaning is, however, possible. As all sponges have amoebocytes, it is likely that the 'amoebocyte capture system' (REISWIG 1971) is also developed.

Most extant hexactinellids live in greater depths, where the grain size of the sediment particles usually is very small. The canals of hexactinellid sponges are large, so infiltration of fine grained sediment particles is not severe, since they probably clean their canal system by means of phagocytosis. 'Lithistid' sponges have a denser skeletal mesh than hexactinellids, so that the mobility of amoebocytes is restricted. If present, the canal system is also much smaller. It seems very probable that sedimentation is a problem for 'lithistid' sponges. For the Jurassic examples, this interpretation is corroborated by the rather frequent occurrence of 'lithistid' specimens within medium diversity coral associations.

Morphological adaptations for elevated sedimentation rates are developed in the calcareous sponge *Eudea clavata*, which is abundant in some Upper Jurassic marly shallow-water coral associations of the Lusitanian Basin (WERNER et al. 1994). *Eudea clavata* was able to close inactive openings during its lifetime with a solid wall. The resulting cortex exhibits small hemispherical pustules and blisters. In most cases, only basal parts of the sponges were affected. Sometimes one complete side of the sponge but never the entire sponge is characterised by this feature. The secondary cortex development is interpreted as protection of basal cells during times of increased sedimentation. A sealing of all pores on one side is diagnostic for toppling of sponges into the marly substrate during their lifetime. Functional deactivation of some pores by sealing was apparently preferable to infiltration of detrital material into the choanoderm of the sponge (KRAUTTER 1994).

As a typical coralline sponge, *Eudea clavata* needed a firm substrate to settle on. On the other hand, the ability to close the pores allowed *Eudea clavata* to withstand an elevated sedimentation rate, at least for a longer period of its lifetime. This contrasts with the majority of members of this sponge group, which need low sedimentation rates and clear water, as they are often associated with hermatypic corals (e.g., BERGQUIST 1978, MÜLLER 1984, VACELET 1988).











Stratigraphy	Localities	Facies				Rhynchonellid/ Terebratulid- Ratio	Most frequent Type of Front- commisure
		Bedded Limestones	Marls	Spongiolites Limestones	Coral Facies		
Lower Tithonian	Saal						
Upper Kimmeridgian	Engelhardt- berg						
	Laibarös						
Oxfordian	Schlüpfel- berg						
	Schönberg						

Fig. 26. The brachiopod assemblages of Upper Jurassic occurrences from southern Germany exhibit significant differences both in taxonomic composition (e.g., rhynchonellid/terebratulid ratio) and in prevailing shell morphologies (e.g., frontal commissures controlled by facies conditions as well as water movements and substrates).

Hence, *Eudea clavata* was adapted to live in a marly, sediment-stressed environment, provided small skeletal debris was available for its attachment.

Only for very few Jurassic siliceous sponges is a relation to soft bottom substrates proven by a nodular ancre-type stem (e.g. *Tremadictyon radicum*, cf. MÜLLER 1991), whereas the large majority is thought to be dependant on firm substrates. This might be generally true, but the *Eudea* example shows, that small secondary substrates such as shell fragments might be sufficient for attachment. Some siliceous sponges might have been able to tolerate occasional phases of allochthonous sedimentation. On the other hand, the growth of huge dish shaped sponges up to two metres in diameter (see section 3.1.1), which are encrusted in-situ by serpulids and other organisms, even on their undersides, shows that in these examples background sedimentation was negligible over an extended period of time.

Microbial crusts and sedimentation rate: Microbial crusts are of diagnostic value for the estimation of sedimentation rate. As suggested both by modern examples (REITNER 1993) and their dominant occurrence in transgressive intervals in the fossil example, microbial crusts have low growth capacities and therefore are very sensitive to supply of fine sediment. Additionally, the fact that the preferred site of crust-rich reefs within fine siliciclastic settings are often slope breaks is also indicative of a decrease in terrigenous input of mud during the growth of the microbialitic reefal limestones.

At a mesoscopic scale, microbial crust morphologies allow estimation of the rate of the remaining allochthonous contamination. Thrombolitic layers or biostromes only developed when allochthonous sedimentation was zero. There are numerous clues for this interpretation (see also section 3.2). As the growth capacity of microbial crusts is

very low, the time involved in the formation of a thrombolitic reef is considerable. Some of these reefs laterally grade into thin thrombolitic biostromes and therefore show no interlocking with the surrounding detrital sediment. All thrombolite reefs were found in correlatable horizons with characteristics of sedimentary starvation (see section 4.1.2). As an example, authigenic glauconite is a common feature not only inside and on top of thrombolitic buildups, but also in the detrital facies lateral to the buildups. The capability of reefal crusts to build ledges sideways, which often were attacked by boring bivalves from the underside (see section 3.2), clearly indicates reduced sedimentation rates. In all other cases, microbial crusts developed columnar to dendritic growth forms as a response to detrital sedimentation, so that allochthonous sediment can be stored in the space between the crust columns or branches. Similar behaviour is known from Tertiary freshwater microbialites (LEINFELDER & HARTKOPF-FRÖDER 1990). These examples show that microbial crusts can withstand very minor background sedimentation. However, the calibration within a sequence stratigraphic framework shows that extensive development of microbial crusts within reefs is one of the best indicators of a complete cessation of background sedimentation during the growth of these reef types.

Reef fabrics and sedimentation rate: The dependance of crust-rich bioherms on background sedimentation rates lower than for similar, though crust-poor biostromes (cf. section 3.2.2), is related to the demands of crusts for very reduced sedimentation rates. Apart from the amount of crusts some other fabric varieties of Jurassic reefs can be interpreted as related to the rate of background sedimentation. Cryptocrystalline carbonate is abundant in most sponge mounds and some coral mounds. Bioturbation fabrics and lack of bioeroders show that a variable part of this material

represents originally soft allochthonous mud rather than hard microbial automicrites. In spite of this, these mounds are again correlatable with transgressive phases, suggesting that background sedimentation was lower than during times of deposition of the underlying and superimposed bedded carbonate muds. It is assumed that phases of slightly elevated allochthonous sedimentation account for the differences with pure automicritic sponge microbialites. LEINFELDER (1992, 1993a) discussed how coral-debris reefs reflect an overproduction of bioclastic sediment which could not be winnowed. Here autochthonous extensive production of carbonate sand rather than allochthonous sedimentation accounts for this frequent reef type.

5.5 Reefs growing under oxygen fluctuations (Leinfelder, Nose, Schmid, Werner)

As described in section 5.4, the major prerequisite for thrombolite reef growth is a very low to zero sedimentation rate. However, this does not explain the different development of thrombolite reefs: Thrombolite reefs may show a diverse participation of reef metazoans (sponges, corals) in many cases, whereas others are completely devoid of such organisms. Moreover, such pure thrombolites without metazoans occur at different water depths. We suggest that general or episodic dysaerobic conditions at the sea floor were an important factor in preventing the growth of organisms of higher systematic range.

This interpretation is supported by the study of Portuguese reef successions from different bathymetric positions (Fig. 27). The Rocha bioherm, positioned in the outer ramp, consists almost entirely of microbial crusts which contain only very few siliceous sponges. Sponges are largely restricted to one intercalated level. This layer is interpreted as having formed during short-term oxygenated conditions (LEINFELDER et al. 1993a). In the so-called Serra Isabel level of the Kimmeridgian of the Lusitanian Basin, small scale transitions from siliceous sponge-bearing thrombolites into coral-rich thrombolitic facies can be observed. At Trancoso (Lusitanian Basin), a pure thrombolite biostrome passes laterally into a coral reef with very few crusts. The last two examples show very rapid changes from microbial crusts to reef metazoan facies, which is explained most credibly with oxygen concentrations shifting from dysaerobic or poikiloaerobic (cf. OSCHMANN 1991) to aerobic.

There are direct criteria to support this interpretation: Thrombolites occur in distinct levels where authigenic glauconite is a common feature not only inside and on top of the thrombolitic crusts but also in the detrital sediment lateral to the thrombolites, indicating phases of low bottom water oxygenation during the formation of the entire level. Clusters of *Aulacomyella*, a thin-shelled pectinacean bivalve with 'flat clam' morphology, also occur in some thrombolite levels. This bivalve is considered a dysaerobic form (KELLY & DOYLE 1991; LEINFELDER et al. 1993a). Framboidal pyrite may also be frequent in some of these

levels. The low-diversity *Terebella-Tubiphytes* association (see section 5.2) is mostly related to deeper water. However, it is also present in shallower mid-ramp thrombolites, lacking reef metazoans. Therefore, this association is thought to have tolerated low oxygen conditions and, in shallow water, is normally outcompeted by associations which cannot withstand oxygen depletion. This is supported by studies carried out in the Black Sea (BAÇESCU 1963), where *Terebellides*, a modern counterpart of *Terebella*, was found to tolerate oxygen contents of only 4-8 % of the oxygen content at the surface.

The occurrence of criteria for dysaerobic conditions in levels characterised by sediment starvation allows these oxygen fluctuations to be attributed to an oscillating rise of dysaerobic waters during sea level rise (LEINFELDER 1993a, see section 6.2).

6 GLOBAL ASPECTS

In this final section, preliminary interpretations of the influence of global factors on the occurrence and composition of Jurassic reefs will be discussed. The great variety of Jurassic reefs is partly explained by the style of shelf morphology, as determined by the development of the Tethys and the breakup of Pangaea, by the general development of eustatic sea level, and by climatic and oceanographic peculiarities. Jurassic evolutionary radiation of reef fauna had only minor importance on the reef pattern of the Mid and Late Jurassic.

6.1 The influence of shelf morphology on reef development (Leinfelder)

When comparing the examples studied, it becomes obvious that siliceous sponge facies only developed extensively in near level bottom deeper mid to outer ramp settings. Spongiolites are thus abundant in the Bajocian, Bathonian and Oxfordian of eastern Spain as well as in the Oxfordian to Lower Tithonian of southern Germany and in the Oxfordian of Romania. They are less frequent where steepened mid-ramp configurations or steep slopes of rimmed shelves prevailed as in the Upper Jurassic of both Portuguese basins and in the Kimmeridgian of eastern Spain. The same holds true in comparison with other examples: the Oxfordian of the French and Swiss Jura chains provided suitable outer and deep mid-ramp settings for the development of spongiolites only in distal areas, but slope steepenings prevented their development in more proximal parts (cf. GYGI 1986). Thrombolite reefs, among other factors (see section 5.5), particularly demand very reduced background sedimentation, which is facilitated when growing on steepened slopes. Consequently, many of them occurred in the Upper Jurassic of southern Portugal and in the Kimmeridgian of the Lusitanian Basin and Eastern Spain, where steepened slopes predominated. In southern Germany, no true thrombolite reefs but only thrombolitic patches within sponge-bearing buildups oc-

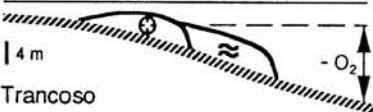

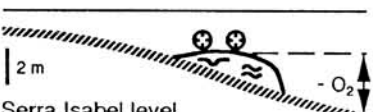


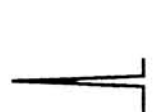
reefs (examples from Portugal)	O ₂ fluctuations through time	ramp position	criteria for O ₂ depletion
 Trancoso		mid ramp	<ul style="list-style-type: none"> * lack of reef metazoans * some glauconite * <i>Terebella</i> - <i>Tubiphytes</i> - association
 Serra Isabel level		shallow outer ramp	<ul style="list-style-type: none"> * lack of corals in shallow water * <i>Aulacommyella</i> common * glauconite fairly common
 Rocha		deeper outer ramp	<ul style="list-style-type: none"> * reef metazoans restricted to one level * glauconite abundant beside and above reef * <i>Terebella</i> - <i>Tubiphytes</i> - association

Fig. 27. Reefs growing under oxygen fluctuations based on examples are from the Upper Jurassic of Portugal. Similar situations occurred in Spain and southern Germany. As the successions of reef building organisms show, oxygen is the dominant factor determining composition of these reefs. Ramp classification after BURCHETTE & WRIGHT (1992).

cur. Fig. 28 shows that these patches grew preferably on the margins of the buildups, hence at local slope steepenings, which were not related to the structure of the shelf.

Coral reefs grew in a wider range of structural settings, provided they were situated in shallow water. They grew on inner and mid-ramps, where they mostly represent coral-debris reefs in a high-energy environment or coral meadows, biostromes and local bioherms in more protected settings. Unlike modern coral reefs, they even conquered proximal ramp settings contaminated by siliciclastics during times of reduced terrigenous influx. They also developed widely on platform margins, where they may be rich in microbial crusts, if export of reefal debris was facilitated by steep slopes (LEINFELDER 1992, 1994). In lagoonal areas of rimmed shelves, low-diversity patch reefs developed occasionally. The Arnegg example (section 3.1.3) shows moreover that coral reefs developed on isolated elevations arising from mid-ramp settings, whose development was, though, not structurally related but rather due to pervasive growth of a sponge-bearing buildup.

The absence or penecontemporaneous occurrence and spacing of coral and siliceous sponge reefs, the frequency of mixed coral-siliceous sponge reefs and their spacing relative to pure siliceous sponge facies and pure coral facies, as well as the occurrence or absence of thrombolitic reefs appear to be a suitable tool for interpreting the existence or absence of slope steepenings.

The differences in abundance and style of Jurassic reefs between the northern and southern Tethys margin clearly reflect general differences in the structural style of both margins. The European northern Tethyan shelf was a

tectonically very inactive continental margin, with a passive regional subsidence pattern. Contrastingly, the southern margin of the Tethys was tectonically much more active, being segmented into small crustal blocks, parts of which were split off from the Gondwana continent as terranes (cf. ZIEGLER 1988). Steep margins and partly rapid vertical tectonic movements were responsible for the general scarcity of reefs, which were dominated by coral-reefs (LEINFELDER in press). The Lusitanian Basin, on the other hand, is a typical example of basin development on the North Atlantic margin, and hence is characteristic of the breakup of Pangaea in this region. The marginal basins were tectonically active, particularly during the Late Jurassic, being characterised by reactivated Hercynian structures causing intensive vertical and lateral movements of small blocks (LEINFELDER & WILSON 1989). The structural type is partly comparable with the southern Tethys margin, although the Lusitanian Basin exhibits block faulting on a much smaller scale and in a setting dominated by siliciclastics. Both features caused intensive facies differentiation and the dominance of a great variety of reef types, many of which were adapted to thrive in settings contaminated by terrigenous material (LEINFELDER 1994).

6.2 Late Jurassic circulation pattern, sea level change, and climatic feedbacks (Leinfelder)

Sea water temperature: Siliceous sponges today live both in temperate to cold and tropical waters and their fossil distribution should not be taken as a temperature indicator. On the other hand, fossil scleractinian reef corals, as today, appear to be restricted to shallow warm

water, which is corroborated by their frequent association with green algae and oolites. Therefore, the distribution of Jurassic corals seems to reflect warm surface waters. Most Jurassic coral reefs occurred in low palaeolatitudes (southern part of the North Atlantic realm, along the margins of the European-North-African part of the Tethys, Crimea, Caucasus, Karakorum, Madagascar, East Africa, Middle and Far East; for additional references on Jurassic coral reefs see BEAUVAIS 1973, 1977, 1984, TALENT 1988, FLÜGEL & FLÜGEL-KÄHLER 1992 and LEINFELDER 1993a).

The occurrence of some Jurassic reefs at apparent high palaeolatitudes mostly can be explained by their position on exotic terranes (e.g. Lower Jurassic reef from north-western Canada: POULTON 1988; Upper Jurassic reefs from the Siberian Sakhalin Islands: KRASNOW & SAVITSKY 1973). Some Upper Jurassic high latitudinal reef occurrences do, however, not permit such an explanation. This is true for reefs or coral associations, or relics of them, discovered in northern Scotland and Greenland (BEAUVAIS 1977, 1984) as well as in southern Argentina (RAMOS 1978, LEGGARETA 1991). Whereas the character of high-latitudinal coral associations from the northern hemisphere is unclear, the south Argentinian reefs are better studied, although palaeocological analyses are lacking. Well developed coral reefs occur together with oolites and are associated with mixed coral-siliceous sponge reefs and pure siliceous sponge reefs of deeper settings (LEGGARETA 1991).

This unusual occurrence of high-latitudinal Upper Jurassic coral reefs was interpreted by LEINFELDER (1993a) as reflecting a wider global distribution of warmer surface waters than today, caused by a more equilibrated, 'greenhouse'-type Late Jurassic global climate. This contradicts the global palaeoclimatological models of MOORE and coworkers (MOORE et al. (1992a,b, ROSS et al. 1992) who calculated very cold high latitude regions characterised by sea ice. In contrast, VALDES & SELLWOOD (1992) modelled a much more equilibrated climate with fairly warm temperatures even in high latitudes, supporting qualitative considerations, e.g. by HALLAM (1985, 1993) as well as the distribution of Upper Jurassic reefs. In addition, ammonoid faunas of this epoch show a lot of mixing and exchange from different biogeographic provinces (e.g. ENAY 1972, ENAY & MANGOLD 1982), and new finds indicate that provincialism was much less developed than previously thought (cf. ZEISS 1971, SCHWEIGERT 1993a,b, SCHWEIGERT 1994). Good possibilities of faunal exchange existed, due to extensive seaway connections and weak climatic differences. It must be assumed that the equilibrated, maritime Late Jurassic climate over most areas of the globe was due to the high sea level, which strongly buffered temperature differences (LEINFELDER 1993a; cf. LEINFELDER & SEYFRIED 1993).

Sea level effects on oceanographic circulation, and oxygen concentration: The distribution of reefs also helps reconstruction of oceanographic conditions. Jurassic coral reefs, as those of today, are interpreted as reflecting rather oligotrophic, fully oxygenated environments, although the occurrence of coral meadows in very proximal settings

strongly contaminated by siliciclastics might indicate that some or all Jurassic corals were more tolerant to slightly elevated nutrient values than modern corals. Evaluation of nutrient/oxygen dependance of Jurassic siliceous sponge facies is not unequivocal. The success of some modern siliceous sponge associations seems to be due to settings characterised by a nutrient input higher than in adjacent areas (cf. HENRICH et al. 1992). Modern soft sponges often occupy nutrient-rich waters which may be depleted in oxygen (SARA & VACELET 1973, KÜHLMANN 1988, SCHUHMACHER 1991). They even occur in the strongly dysaerobic environments of the Black sea (BAÇESCO 1963). On the other hand, the majority of modern siliceous sponges seems to occur in very oligotrophic settings (REITNER, pers. comm.).

Possibly, a few Jurassic siliceous sponges, particularly larger specimens occurring isolated within thrombolites, were adapted to elevated nutrient and/or reduced oxygen levels whereas the majority seems to reflect fairly oligotrophic situations. Pure thrombolitic reefs are interpreted here as reflecting occasional oxygen depletion (see section 5.5) which appears related to elevated nutrient input, thermostratification of oceans or shelf seas, or both. It was shown before that metazoans which can be found together as additional elements within some thrombolites lived during times of improved oxygen conditions (LEINFELDER et al. 1993b). This means that thrombolites of moderate depths which are completely devoid of larger metazoans indicate extended phases of oxygen depletion, whereas thrombolites with some macrofauna as well as alternations of pure thrombolites and reefal macrofauna associations are indicative of fluctuating oxygen levels.

It seems that deep-water thrombolites (ELMI et al. 1988, JANSÁ et al. 1988) were also related to episodes of general or oscillating oxygen depletion, which is plausible by their proximity to black shale occurrences in the bordering seas of the Atlantic rift. The general Jurassic sea-level rise with its peak in the terminal Kimmeridgian not only equalised the temperatures on the Earth by the thermal buffer capacities of the wide sea cover, but during the Late Jurassic probably led to frequent thermostratification as a result of such climatic leveling which strongly reduced atmospheric and oceanic circulation. This is indicated by the widespread occurrence of deeper water black shales and bituminous facies both in the north Tethyan and North Atlantic realm, but particularly by the frequent occurrence of thrombolites of moderate water depths in the western part of the European northern Tethys shelf. Black shales and bituminous facies occurred particularly on the eastern Atlantic margin and its adjacent epicontinental seas (cf. compilation by ZIEGLER 1988: Pl. 26-30; see also BROWN 1984, OSCHMANN 1988), in the Helvetic zone of the northern margin of the Tethys (SCHNEIDER 1962, SELG & WAGENPLAST 1990, GEYER & GWINNER 1991) and possibly in the northern Penninic Basin. A possible circulation pattern for the Late Jurassic is shown in Fig. 29. A supposedly weak Tethyan water circulation was chiefly driven by evaporation, aerating equatorial regions (southern Tethys).

homoclinal ramps

coral biostromes and patch reefs

coral-debris reefs, with
framestone patches

siliceous sponge meadows and bioherms

steepened ramps

coral biostromes and patch reefs

coral-debris reefs, with
framestone patches

crust-rich
mixed coral-
sponge reefs,
thrombolites

rimmed shelves

coral biostromes and patch reefs

crust-rich
coral-debris reefs

siliceous sponge facies, rarely
thrombolites

crust-rich
mixed coral-
sponge reefs,
thrombolites

Fig. 28. Jurassic reef types related to different shelf configurations. Siliceous sponge biostromal and biohermal facies thrived pervasively on very flat, homoclinal ramps. Coral-debris sands are indicative of inner ramp and shelf depositional margin situations, whereas crust-rich coral-debris reefs rimmed platforms with steep bypass margins (partly after CREVELLO & HARRIS 1984).

Oxygen was rapidly consumed due to the warm water temperature and the partial thermostratification. Facilitated by a low-intensity trade wind belt, a weak upwelling system, which possibly did not affect deeper waters, brought up dysaerobic waters onto the northwestern Tethys shelf (cf. LEINFELDER 1993a, LEINFELDER in press).

The possible influence of enhanced alkalinity: As shown above, the widespread occurrence of black shales in the Upper Jurassic testifies to the existence of anaerobic oceanic basins. The sulphate reduction governing the remineralisation of sinking organic matter in anaerobic basin (present day example: the Black Sea), produces increased alkalinity in order to keep the charge balance of the consumed sulphate ion. Part of this alkalinity escapes the basin due to upwelling and can cause supersaturation events in adjacent shallow seas. Such systems have been termed 'alkalinity pumps' (KEMPE 1990). In the seawater-filled and stratified crater lake of Satonda/Indonesia, an alkalinity pump is presently operating, leading - compared to average seawater - to an enhanced alkalinity, pH and CaCO_3 -supersaturation in its aerated surface layer. Under these conditions most marine biomineralisers are excluded and reefs composed of in situ calcifying coccoidal cyanobacteria (microbialites) and red algae have developed (KEMPE & KAZMIERCZAK 1990a,b, 1993, KAZMIERCZAK & KEMPE 1990b). Other modern examples are also characterised by high CaCO_3 -supersaturations, high pH and by

moderate to very high alkalinities as for example in Lake Van/Turkey (KEMPE et al. 1991)

The example of Satonda and the existence of coeval anaerobic basins suggest that the microbialites of the Upper Jurassic may be partly caused by supersaturation events triggered by alkalinity plumes escaping from down-current deeper basins in the Tethys or Proto-Atlantic. Temporal variation in the amount of alkalinity advected or changes of current patterns and shelf-water residence time may, in this scenario, be the cause for the temporally and spatially limited presence of other biomineralisers in the Upper Jurassic reef facies. Other examples of microbialites from different periods of the history of the Earth could be explained similarly, illustrating that the 'alkalinity pump' could be a fundamental process governing amount and type of Phanerozoic carbonate deposition (KEMPE & KAZMIERCZAK 1994)

However, increased alkalinity alone probably cannot explain the majority of the thrombolite occurrences. The occasional occurrence of higher metazoans even within pure thrombolite reefs, the frequent association of pure thrombolites with crust-rich metazoan reefs and the isolated rather than laterally extensive occurrence of microbialites stand against such interpretation. Together with the available criteria for oxygen depletion (section 5.5), this suggests that fluctuations in bottom-water oxygenation, probably accompanied by a certain increase in

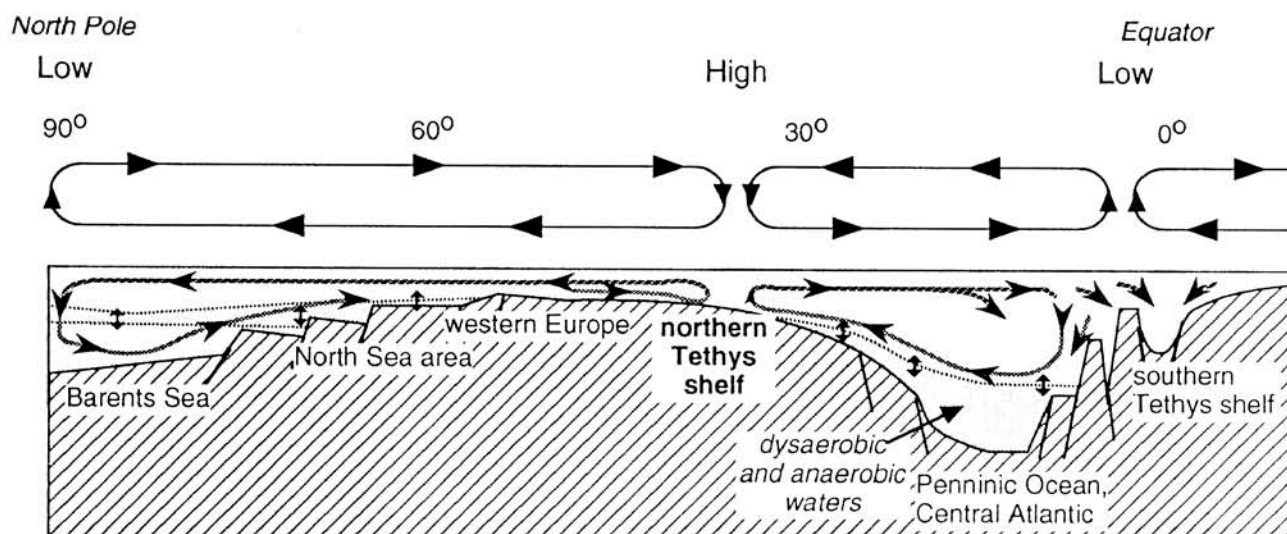


Fig. 29. Possible circulation pattern in the Tethyan and North Atlantic realm during the Oxfordian and Kimmeridgian. It can be assumed that, due to the equilibrated climate, ocean circulation was sluggish and partly driven by evaporation, and oceans and shelf seas were partly stratified. The cross-section shows a hydrospheric - atmospheric circulation for a Late Jurassic summer (circulation partly modified after OSCHMANN 1988, 1990; from LEINFELDER 1993a).

alkalinity, were the major control mechanism for pure thrombolites, at least for the Iberian examples.

Hierarchy of sea level effects: The controlling role of sea level rise on the distribution and composition of Jurassic reefs covered various fields and temporal hierarchies. The general Jurassic first and second order sea level rise was responsible for increasing carbonate dominance and, therefore, the creation of suitable settings. It also buffered climatic and oceanographic circulation, as shown above. Third-order sea level rises were particularly important for reef growth, by reducing the rate of allochthonous sedimentation allowing appearance or lateral expansion of reef facies (section 4.1.2), but also by partly enhancing climatic buffering, resulting in partial oxygen depletion and, hence, development of pure thrombolitic reefs in fairly shallow water (Fig. 30). Feedbacks between sea level rise and climate might, however, also result in a more humid climate during late transgression, by providing larger areas for cloud formation. As a result terrigenous influx might be even higher during late transgression and early highstand in such cases. Climatic modification of sequence stratigraphic concepts should be kept in mind when establishing systems tracts based on the presence or absence of terrigenous material (LEINFELDER 1993a). At a higher order, sea level oscillations are thought to be also partly responsible for repetitive successions of dysaerobic and aerated reef facies, as frequently observed in the Upper Jurassic reefs of Iberia (sections 3.2.3, 5.5).

6.3 Reef expansion during the Jurassic: evolution versus habitat availability (Leinfelder)

A comparison of the distribution pattern of Middle and Upper Jurassic reefs provides another important clue to the factors controlling reef growth. Both coral and siliceous

sponge reef facies dramatically expanded in the course of the Jurassic period. This trend might reflect evolutionary radiation or increasing availability of environments suitable for reef growth, or both.

Evolutionary effects (Fig. 31): The Jurassic was a time when major reef organisms, particularly scleractinian corals, stromatoporoids, coralline sponges, siliceous sponges and microbes were generally available, with the corals and siliceous sponges representing the dominant reef macrobiota. Scleractinian corals, possibly being derived from non-calcifying 'sea anemones' rather than survivors of rugose corals (cf. STANLEY 1988), only slowly developed during the Triassic, but rapidly expanded during the Norian. After the setback for corals at the base of the Jurassic, corals rapidly diversified during the Early and, particularly, Mid Jurassic (STANLEY 1981, 1988, BEAUVAIS 1984). Corals from the earliest Jurassic are relics of the Late Triassic fauna and are mostly considered as ahermatypic (e.g. BEAUVAIS 1984, 1985), although some biohermal reefs are known (e.g. France, ELMI 1987, American Cordillera, POULTON 1988). Biohermal coral reefs became more frequent from the Pliensbachian onwards, but even in Toarcian reefs faunal diversities were not very high which is partially related to the reduced availability of coral taxa.

Middle Jurassic coral reefs are mainly of Bajocian/Bathonian age, although a number of Callovian occurrences are known (cf. BEAUVAIS 1984). Despite the fact that Middle Jurassic coral reefs were not as widespread as Upper Jurassic coral associations, coral taxa availability during the Mid Jurassic was already almost as high as during the Late Jurassic. According to BEAUVAIS (1984), only 59 genera of corals are known from the Early Jurassic, whereas 92 genera are known from the Mid Jurassic, reaching 128 genera during the Late Jurassic. It is obvious that the much greater expansion of coral reefs during the Late Jurassic was only to a certain part due to a higher

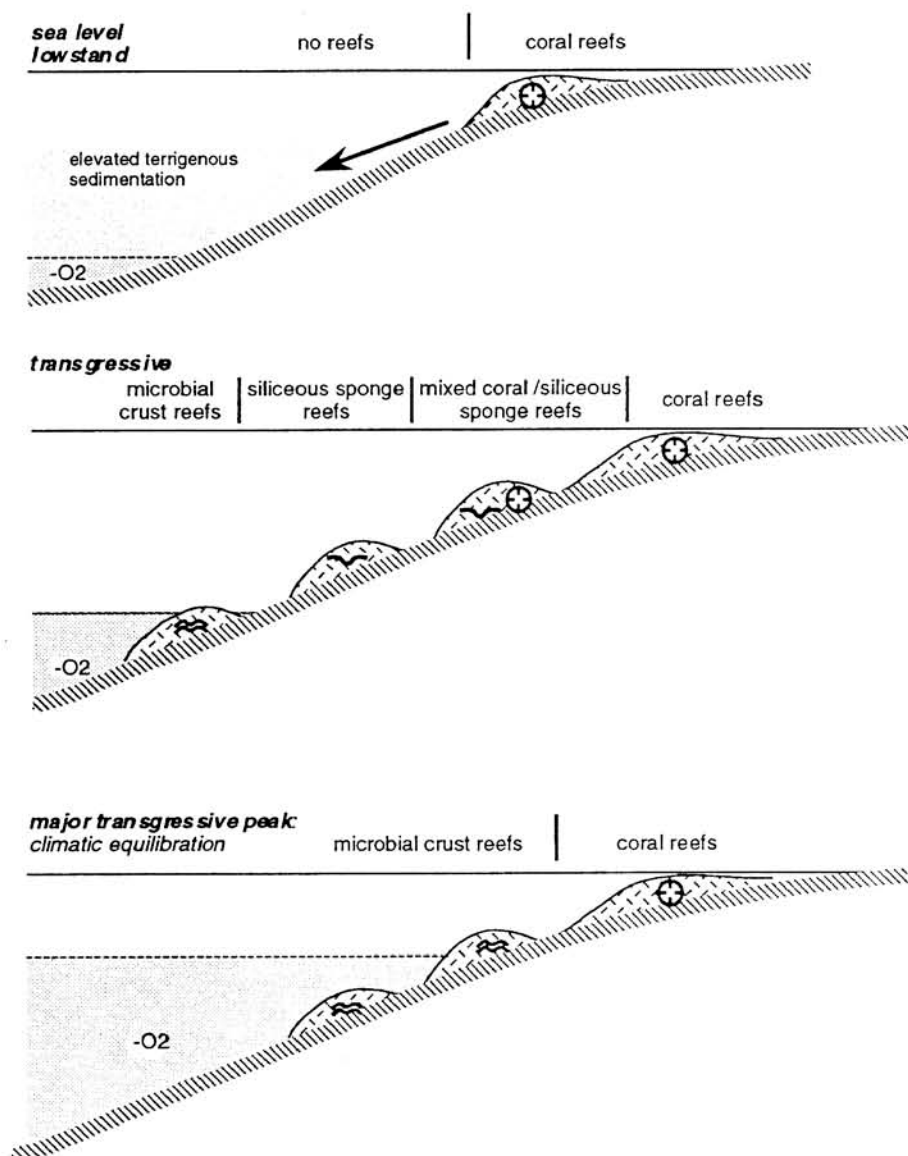


Fig. 30. Model for the distribution of Iberian Upper Jurassic reefs in relation to sea level change. During periods of low sea levels (top) only coral reefs could grow in wave-washed settings. In deeper water, high sedimentation rate prevented reef growth. The predominantly terrigenous, allochthonous sedimentation was reduced during sea level rises (middle), to give way to bathymetrically separated different compositional reef types. Extreme transgressive peaks (bottom) could cause additional climatic equalisation, leading to reduced water circulation and a rise of dysaerobic waters. Pure microbial reefs could grow over a broad bathymetric range (simplified after LEINFELDER 1993a and LEINFELDER et al. 1993a).

degree of evolutionary development of Upper Jurassic corals. Most major coral groups already existed during the late part of the Early Jurassic.

Less is known about the evolutionary radiation of siliceous sponges. They are very conservative organisms which apparently did not change much in their functional adaptations since the Palaeozoic. In the Jurassic, reefal facies with preserved siliceous sponges occurred since the Sinemurian and, particularly, Pliensbachian. Siliceous sponge facies was more widespread during the Mid Jurassic, particularly during the late Bajocian and early Bathonian, and rapidly spread regionally during the Late Jurassic. The available data indicate that many dominant taxa existed during the entire Jurassic or at least since the Mid Jurassic. Only the lychniscids first appeared during the Bajocian (PISERA 1993) to become particularly widespread during the Late Jurassic (MEHL & REISWIG 1993). Apart from this exception, it seems that the expansion of siliceous sponge facies through time again is only to a certain degree caused by evolutionary radiation. However, this conclusion is hampered by the fact that for the majority of occurrences of Jurassic siliceous sponge facies no detailed taxonomic

determinations exist so far. In any case, the available taxa of siliceous sponges had the potential to form siliceous sponge reefs at any time during the Jurassic.

Changes in habitat availability (Fig. 31): Some Lower Jurassic siliceous sponge reefs as well as coral reefs are known from the southern Tethys shelf (e.g. BECCARELLI-BAUCK 1988, HAUPTMANN 1990, PARK 1983, SCHMIDT & SCHWEIGERT 1991, TURNSEK et al. 1975), where both steep-walled, shallow-water platforms as well as low-angle depositional slopes were still available, due to incomplete drowning of Triassic carbonate-dominated shallow-water environments (cf. ZIEGLER 1988). With very few exceptions (ELMI 1987) similar reefs did not develop on the northern Tethyan margin despite the existence of a suitable bathymetric range, because terrigenous influence was too elevated. During the Mid Jurassic, particularly during the Bajocian/Bathonian interval, shallow-water ramps developed in many areas due to the rising sea level. Consequently, associated shallow-water coral reefs occurred particularly in Portugal (ROCHA 1976) and the Paris Basin (GEISTER & LATHUILIERE 1991, also for further references), northern Switzerland (cf. GENSER 1966, GONZALES, pers.

comm.) and also in Romania (DRAGANESCU & BEAUVAIS 1986). In southern Germany, siliciclastic influx from the Vindelician massif prevented reef growth. Reef corals were nevertheless available as is shown by some isolated occurrences (cf. GEYER & GWINNER 1984).

Whereas during the Late Jurassic reef growth mostly ceased on the southern Tethys shelf due to tectonic slope steepening and accelerated drowning, coral, siliceous sponge and, to a lesser extent, thrombolite reefs developed widely in the shelf seas of the northern Tethys margin. This was mostly an effect of the accelerated retrogradation of terrigenous material, effects which were particularly pronounced during the Oxfordian, where reefs developed on carbonate-dominated homoclinal to steepened ramps. In Europe, siliceous sponge facies, of deeper mid to outer ramp position, developed in a continuous belt from Romania to southern Portugal. Coral reefs occupied the same regions in inner ramp settings (for additional reef references see KEUPP et al. 1990 and LEINFELDER 1993a). Despite the continuing rise in global sea level until the end of the Kimmeridgian, reef development ceased during the Kimmeridgian in most areas. This was largely caused by a revival of terrigenous sedimentation, an event which is roughly correlatable across the northern Tethyan shelf and which seems to reflect regional accentuation of hinterland exposure (LEINFELDER 1993a). Only in southern Germany was contamination by siliciclastics reduced and thus could be tolerated. As a consequence, both siliceous sponge reefs and coral reefs continued growing.

The distribution of Jurassic reefs is mainly governed by habitat availability. The ramp-style of shelf structuration was a prerequisite for the extensive development of siliceous sponge facies, but it was only after a general eustatic sea level rise which provided carbonate-dominated settings with low background sedimentation that reefs could spread regionally during the Late Jurassic. Effects of evolutionary radiation were minor, but it appears plausible that the increase of taxa during the Late Jurassic reflects feedbacks between increasing habitat availability and phylogenetic diversification, particularly among scleractinian corals.

7 CONCLUSIONS AND PERSPECTIVES

(Leinfelder)

7.1 Conclusions

* Middle and Upper Jurassic reefs were studied from settings along the northern Tethyan shelf (Romania, southern Germany, Eastern Spain, southern Portugal) and the Atlantic margin Lusitanian Basin (central Portugal). Most of them grew on ramps, ranging from near level-bottom to homoclinal to steepened types. In the Lusitanian basin isolated, steeply bordered platforms with reef rims or inner platform reefs existed as well. Reefs comprise three basic compositional types, namely coral reefs, siliceous sponge reefs and microbial reefs. Siliceous sponge reefs grew in mid to outer ramp settings at least 50 to 60 metres deep, whereas pure Jurassic coral reefs, as today's, occupied fairly shallow water. Mixed coral-siliceous sponge reefs

grew in a broad transitional zone. Microbial reefs were largely independent of bathymetry, growing from the deepest reefal settings below the sponge reef zone up into the coral facies.

* Upper Jurassic siliceous sponge reefs of southern Germany mostly occur as biohermal, micritic sponge-microbial crust mounds. Mounds show internal facial and faunal differentiation. They frequently are small but may cluster to form large buildups. In southern Germany huge massive buildups developed during the Late Kimmeridgian and Tithonian, and previously were frequently regarded as sponge reefs or sponge-algal reefs. The internal composition of these buildups is, however, strongly differentiated. The major part of the buildups is composed of fine, dominantly peloidal packstones and grainstones which are stabilised by thin laminae of microbial crusts. This facies also contains intraclasts and coated grains in variable, sometimes large, proportions. Micritic siliceous sponge-microbial mounds of fairly small dimensions occur particularly at the flanks of these grain-rich buildups. This great facies variety had a strong influence on the style of diagenesis which proved to be largely controlled by sediment composition and fabric. Examples are selective dolomitisation of buildups, exclusion of crusts from primary dolomitisation, affinity of pyritisation for distinct microstructures of hard parts, and selective silicification of certain organisms in the presence of siliceous sponges. Time-slice interpretations within massive, ammonite-lacking facies could be partly improved by palynostratigraphy and mineralostratigraphy. Easily identifiable dinoflagellate assemblages exist in the uppermost Oxfordian, and middle and uppermost Kimmeridgian. Mineralostratigraphic subdivision is based on variable proportions of kaolinite, chlorite and illite as well as on the composition of silt fractions and clay/silt ratio in the insoluble residue. Both methods partially allow chronostratigraphic correlation of even recrystallised or dolomitised buildups. Improvement of the ammonite biostratigraphic frame shows that already during the terminal Kimmeridgian and simultaneous with the formation of the spongiolite-hosting, grain-dominated massive buildups, coral reefs of variable dimensions and cross-bedded bioclastic oolitic sands developed in shallow areas. This is evidence of the development of enormous relief due to buildup formation on the ramp which had been nearly flat at the beginning of the Late Jurassic.

* Oxfordian siliceous sponge facies from Romania is largely comparable with southern Germany, whereas the Iberian examples differ markedly. In the Bajocian and Oxfordian of eastern Spain, sponge facies is largely dominated by laterally extensive siliceous sponge biostromes of fairly uniform faunistic composition. In Portugal, sponge facies is not very widespread, but nevertheless shows the greatest variety of types, including micritic mounds, meadows as well as thrombolitic and mixed coral-siliceous sponge varieties. At the present state of study, siliceous sponge associations appear fairly uniform. No major differences in sponge composition are obvious within the Oxfordian

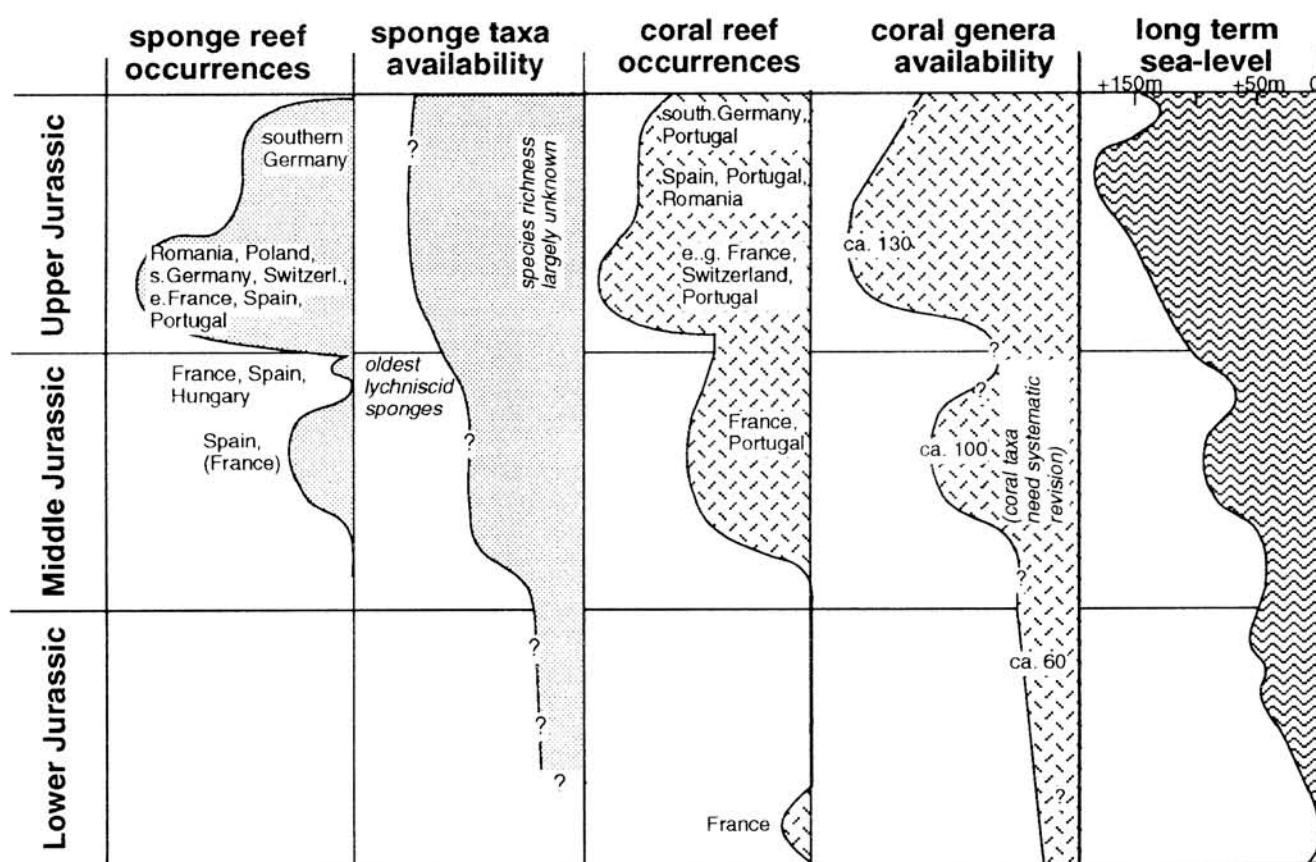


Fig. 31. Distribution of Jurassic coral and siliceous sponge facies on the northern Tethys shelf. The comparison of reef occurrences with habitat availability, evolution of reef biota, and sea level change shows that the expanse of reefs largely reflects increasing habitat availability in the course of sea level rise. Compiled from various sources.

sponge facies of Spain despite their enormous lateral extension. Sponge taxa, determined from the Oxfordian of Germany, Spain and Portugal, are largely identical, pointing to the conservative nature of sponge associations. The favourite sites for development of reefal sponge facies were mid to outer ramp settings on near level-bottom homoclinal ramps, although these may show a rugged morphology due to sponge reef and grain-buildup development.

* Upper Jurassic coral reefs of Iberia show a great variety in fabric types and coral associations. Four groups of coral reef types, including 16 subtypes and 18 coral associations could be identified in the Iberian Basins. This differentiation perfectly reflects general and local variations in environmental parameters, such as background sedimentation rate, terrigenous influx, water depth, bottom morphology and steepness of platform margins, making coral reefs a powerful tool in palaeoenvironmental and palaeogeographic reconstruction.

* Microbial crusts participated in reef formation to a variable, mostly large, degree. Microbial control is indicated by crust morphology, fabric, organic biomarkers and similarity with modern counterparts. Crusts are dominated by thrombolitic peloidal crusts, but stromatolitic, dense to peloidal as well as unstructured, cryptocrystalline crusts occur as well. Despite the lack of crust morphologies,

darkened micrites with abundant isolated sponge spicules may represent another type of automicrites. Such automicrites are considered to be related to the decay of organic matter, particularly of 'soft sponges', resulting in an anoxic, high pH environment. The Bajocian example of Spain shows that such automicrites may have grown under partial sediment cover. Many biohermal reefs from Iberia show a very large participation of crusts, resulting in metazoan-thrombolite reefs or pure thrombolite reefs. The latter grew independent of water depth but occur in horizons with dysaerobic features, such as dysaerobic epibenthic bivalves, *Chondrites* horizons, abundance of authigenic glauconite, and framboidal pyrite. This suggests that macrofauna was excluded by general or episodic oxygen depletion in bottom waters. Possibly, enhanced alkalinity additionally facilitated rapid calcification of microbial mats.

* Bathymetric separation between coral and siliceous sponge facies can be substantiated by the relative position of reefs within shallowing-upwards successions and by bathymetric faunal gradients. Faunal analysis allows bathymetric interpretation to be refined not only between but also within siliceous sponge and coral reef facies. Particularly useful for independent bathymetric interpretation are cementing bivalves and microencruster associations. Within the siliceous sponge facies, dominance of dictyid sponges characterises outer ramp settings, whereas

a dominance of lithistid demosponges together with lychniscid sponges reflects mid-ramp settings and may be transitional with coral facies.

* Low background sedimentation rates are a prerequisite for the formation of reefs. This is substantiated by the high incrustation rate of reef fauna, with incrusters often also occurring on the undersides of macro-organisms. The frequent restriction of Iberian reefs to horizons showing enrichments of glauconite, sedimentary condensation of nectonic fauna, as well as incipient or pervasive hardground formation is also indicative of reduced sedimentation or sedimentary hiatuses. In a sequence stratigraphic context, coral, siliceous sponge and microbial reefs particularly grew during transgressive and early highstand phases which were responsible for the reduction in allochthonous sedimentation. In southern Germany, expansion phases in the development of spongiolites and spongiolite-hosting massive buildups also match transgressive phases, indicating that micritic mounds as well as grain-dominated buildups not only accumulated allochthonous material but particularly were highly auto-productive. Possibly, sponge preservation is biased by sea-level fluctuations of higher order. Preservation rate was enhanced during flooding events due to more rapid cementation, whereas elevated allochthonous sedimentation might have inhibited preservation rather than growth of sponges. Adaption of sponges to increased sedimentation rates could be detected in the coralline sponge *Eudea*, which can close its lower inhalant pores. Among corals, taxa with fairly good adaptations towards slightly elevated sedimentation existed which could form low-diversity meadows even under allochthonous sedimentation. Brachiopods from reefal settings particularly reflect bottom consistency and water energy and hence also are useful for indirectly identifying sedimentation rate and water depth. Brachiopods from Upper Jurassic sponge facies of southern Germany indicate that hardened substrates, either as primary or secondary hardgrounds, were widely available even within micritic mounds, but rare soft bottom dwellers occurred as well. This may reflect the above assumption of a large participation of early hardened automicrites occurring together with soft muds within many of these mounds. In general, detailed ecological analysis, including interpretation of functional morphology and comparison of faunal associations at the species and generic level, allows a refined interpretation of bathymetry, background sedimentation rate and substrate characteristics.

* When comparing reef abundance of the Lower, Middle and Upper Jurassic, reefs were much more widespread during the final epoch of the period than during the earlier ones. During the Early Jurassic this was partly an effect of restricted availability of taxa, at least in the coral facies, whereas the much wider occurrence of both sponge and coral reefs during the Late Jurassic relative to the Mid Jurassic is interpreted as an effect of increasing habitat availability provided by the general Jurassic sea level rise. This gave way to the development of large mid to outer ramp systems as a prerequisite for sponge reef growth, and

to a carbonate dominated realm well into the shallow water. Whenever environmental conditions were favourable for reef growth, well developed coral reefs and siliceous sponge reefs already occurred during the Mid Jurassic. This shows that evolutionary radiation was no prerequisite for the pervasive development of reef facies during the Late Jurassic, but rather was the result of increasing habitat availability.

* The global distribution of coral reefs shows some autochthonous reef occurrences in astonishingly high palaeolatitudes (e.g. southern Argentina). This indicates a very equilibrated, 'greenhouse'-type Late Jurassic climate, which is thought to be largely related to the buffering capacities of the wide sea cover. The widespread occurrence of Upper Jurassic black shales as well as the distribution of pure thrombolites suggests that climatic equilibration caused a reduction of water circulation and, therefore, partial oxygen depletion. Relation of thrombolite development and most of the black shales to transgressive intervals shows that slackening of circulation was particularly the result of intra-Upper Jurassic sea level rises. The occurrence of dysaerobic pure thrombolites in fairly shallow water suggests that climatic equilibration could be very pronounced, allowing dysaerobic waters to occasionally rise to fairly shallow water.

7.2 Perspectives

This paper presents interim results of continuing research activities. Many of these results were completely unexpected when starting the project. This is particularly true for the partial oxygen control of reefs, the importance of microbial crusts and automicrites in reef formation, the facies architecture of Upper Kimmeridgian massive buildups from Germany, the frequent dependance or enhancement of reef development on transgressive phases and the reflectance of global climate by reef type distribution. In this context, many questions still remain to be answered, and interpretation of Jurassic reefs will demand a better comparison with reefs of other times of Earth history as well as with modern ones. Among the remaining targets are:

* *The origin of grain-dominated buildups hosting spongiolites.* To the present date, the origin of the grains within this important Upper Jurassic buildup type is unclear. Coated grains within this facies are petrographically almost identical with shallow-water ooids. The partial grainstone character also could be interpreted as very shallow origin. Against this stands the occurrence of micritic siliceous sponge - microbial crust lenses at the flanks of these buildups. It remains to be proven, whether the carbonate grains represent autochthonous shallow-water particles, allochthonous material, autochthonous microbial precipitates, or a combination of all. Which were the conditions responsible for spongiolite development within this setting?

* *The exact mechanism of formation of crusts and microbial automicrites.* Automicrite formation is described by us from siliceous sponge biostromes. On the other hand,

microbial crusts, as one type of authigenic carbonates, are more important in bioherms than in biostromes, even being responsible for the formation of mounds. Which factors enhanced the growth of crusts, eventually resulting in mound formation? Which factors determined whether a flat ramp developed crust-poor sponge biostromes or crust-rich bioherms? Besides crusts, abundant cryptocrystalline, micritic carbonates occur in sponge mounds. Criteria will have to be developed to identify allochthonous mud, primarily soft automicrites, and early hardened automicrites.

** Establishment and comparison of faunal associations at a regional scale.* Palaeoecological analysis turned out to be one of the most important tools in deciphering control mechanisms. Coral associations will have to be compared across the Tethyan shelves to show possible similarities and differences. It will not be until many more localities of siliceous sponge facies are palaeoecologically analysed, that environmental differences in sponge reef facies will become apparent. In order to better assess the influence of evolution on reef distribution and reef composition, taxonomic revision of both corals and sponge faunas would be a prerequisite.

** The influence of temporal climatic variations,* most of which seem related to sea-level change. Such changes appear to be important in determining reef composition and reef distribution. Temporal variations in composition of clay minerals probably could also be interpreted in terms of climatic variation, an aspect which remains to be studied.

** Jurassic reefs from high palaeolatitudes,* which presently are only insufficiently known, will have to be directly compared with the studied examples, to reveal similarities and differences.

** Comparison with other reefs from Earth history.* Differentiation of Jurassic reefs in many different compositional reef types appears to be an effect of the generally high sea level of the Jurassic as well as the sedimentological and climatic effects of intra-Jurassic sea level rise. Differentiation of reefs in many different fabric types in part reflects differences in the structure of the shelf. This concept should be tested by integrating more reef studies from the early and mid epoch of the Jurassic, and by comparing with similar general settings from other times of Earth history, such as the Ordovician to Devonian or the Cretaceous. These periods of Earth history appear in part comparable with the Jurassic examples in a way that (1) sponges and corals were available as reef builders, (2) modern coralline algae were not existing or not dominant, (3) different compositional reef types as well as micrite-dominated mounds occurred, (4) many widely flooded, carbonate dominated, passive continental margins were available, (5) sea level was generally high and mostly rising, and (6) a 'greenhouse'-type climate is reflected by the frequent occurrence of black shales.

** Modern counterparts.* Jurassic coral reefs find partially actualistic counterparts in modern coral reefs, al-

though encrusting organisms are dominated today by coralline algae rather than microbial crusts. No direct modern counterparts apparently exist for Jurassic sponge bioherms. This certainly is due to the low sea level of today, resulting in a scarcity of suitable mid to outer ramp settings of shelves. However, reef caves of modern shallow reefs are partially comparable to Jurassic sponge settings, since despite the shallow position of the reef caves both corals and coralline algae are excluded by the lack of illumination, making these caves laboratories for studying interrelations of microbial crusts and sponge growth. The apparent general uniformity of Jurassic sponge associations and the very low rate of evolutionary radiation suggests that relic, moderately deep associations of lithistid demosponges, as occurring on the lower Barbados shelf or in the deeper parts of the Australian Coral Sea (pers. comm. Reitner), may prove to be close analogues to some of the Jurassic sponge faunas.

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