

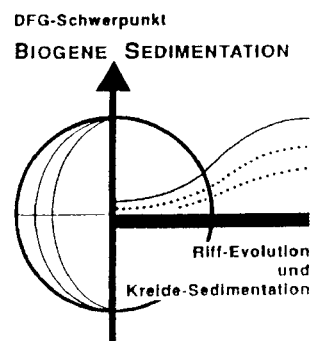
FACIES	31	1-56	Pl. 1-4	31 Figs.	--	ERLANGEN 1994
---------------	-----------	-------------	----------------	-----------------	-----------	----------------------

Research Report 'Evolution of Reefs'

The Origin of Jurassic Reefs: Current Research Developments and Results

Reinhold R. **Leinfelder**, Manfred **Krautter**, Ralf **Laternser**, Martin **Nose**,
Dieter U. **Schmid**, Günter **Schweigert**, Stuttgart
Winfried **Werner**, München
Helmut **Keupp**, Hartmut **Brugger**, Regina **Herrmann**, Ursula **Rehfeld-Kiefer**,
Johannes H. **Schroeder**, Carsten **Reinhold**, Berlin
Roman **Koch**, Arnold **Zeiss**, Erlangen
Volker **Schweizer**, Heinrich **Christmann**, Götz **Menges**, Heidelberg
and Hanspeter **Luterbacher**, Tübingen
(edited and coordinated by Reinhold R. **Leinfelder**)

KEYWORDS: CORAL REEFS – SILICEOUS SPONGE REEFS – MICROBIAL REEFS
– MASSIVE LIMESTONES – SEDIMENTOLOGY – AUTOMICRITES
– MICROBIAL CRUSTS – PALAEOECOLOGY – DIAGENESIS –
SEQUENCE STRATIGRAPHY – AMMONITE STRATIGRAPHY –
PALYNOSTRATIGRAPHY – MINERALOSTRATIGRAPHY – SEDI-
MENTATION RATE – BATHYMETRY – OXYGENATION – EVOLU-
TION – SHELF STYLE – PALAEOGEOGRAPHY – PALAEOCLIMATE
– PALAEOCIRCULATION – SOUTHERN GERMANY – PORTUGAL
– SPAIN – ROMANIA – MIDDLE JURASSIC – UPPER JURASSIC



CONTENTS

- | | |
|--|---|
| <p>1 Introduction</p> <p>2 Overview of Jurassic reef organisms and reef types</p> <p>3 Reef case studies</p> <p>3.1 Upper Jurassic reefs from southwestern Germany</p> <p>3.1.1 Upper Oxfordian sponge reefs from the western Swabian Alb</p> <p>3.1.2 Oxfordian and Kimmeridgian spongiolitic reefal environments from the Geislingen area, eastern Swabian Alb.
The spatial distribution of spongiolites in the Eybtl area.
Investigation of cores in the Geislingen area</p> <p>3.1.3 Swabian coral facies from the terminal Kimmeridgian</p> | <p>3.2 Iberian Jurassic reefs</p> <p>3.2.1 Middle Jurassic spongiolite and automicrite development from the NW-Iberian Chains (Sierra de la Demanda, Spain)</p> <p>3.2.2 Upper Jurassic sponge reefs of Iberia</p> <p>3.2.3 Upper Jurassic coral reefs of Iberia</p> <p>3.2.4 Upper Jurassic thrombolite reefs of Iberia</p> <p>3.3 Upper Jurassic reefal environments from Eastern Romania</p> <p>4 Stratigraphic correlation of Jurassic reef facies</p> <p>4.1 Ammonite biostratigraphy of the Upper Kimmeridgian to Tithonian of southern Germany</p> <p>4.2 Remarks on the subdivision of the Upper Jurassic of southern Germany by dinoflagellates</p> <p>4.3 Mineralostratigraphy of well-bedded and spongiolitic massive carbonate lithologies of the Swabian Alb</p> |
|--|---|

Addresses: Prof. Dr. R.R. Leinfelder, Dr. M. Krautter, Dipl.-Geols. R. Laternser, M. Nose, D.U. Schmid, G. Schweigert, Institut für Geologie und Paläontologie der Universität, Herdweg 51, D-70174 Stuttgart, Fax ++49/711/1211341

Dr. W. Werner, Bayerische Staatssammlung für Paläontologie und historische Geologie, Richard-Wagner-Str. 10, D-80333 München, Fax ++49/89/5203-286

Prof. Dr. H. Keupp, Dr. U. Rehfeld-Kiefer, Dipl.-Geols. H. Brugger, R. Herrmann, Institut für Paläontologie der Freien Universität, Malteserstr. 74-100, D, D-12249 Berlin, Fax ++49/30/7762070

Prof. Dr. J.H. Schroeder, Dipl.-Geol. C. Reinhold, Institut für Geologie und Paläontologie der Technischen Universität, Ernst-Reuter-Platz 1, D-10587 Berlin, Fax ++49/30/31421107

Profs. Dres. R. Koch, A. Zeiss, Institut für Paläontologie der Universität, Loewenichstr. 28, D-91054 Erlangen, Fax ++49/9131/852690

Prof. Dr. V. Schweizer, Dipl.-Geols. H. Christmann, G. Menges, Geologisch-Paläontologisches Institut der Universität, Im Neuenheimer Feld 234, D-69120 Heidelberg, Fax ++49/6221/565503

Prof. Dr. H.P. Luterbacher, Institut und Museum für Geologie und Paläontologie der Universität, Sigwartstr. 10, D-72076 Tübingen, Fax ++49/7071/296990

- 4.4 Sequence stratigraphy of Jurassic reef-bearing successions
 - 4.1.1 Sequence stratigraphy of the Middle Jurassic of the NW Iberian Chains (Sierra de la Demanda), Spain
 - 4.1.2 Sequence stratigraphy of Upper Jurassic successions - an overview
- 5 Controlling factors of reef growth
 - 5.1 The nature and role of microbial crusts in reef formation
 - 5.2 Factors related to bathymetry
 - 5.3 Environmental factors reflected by morphometry of reef brachiopods
 - 5.4 The influence of sedimentation rate on reef growth and composition
 - 5.5 Reefs growing under oxygen fluctuations
- 6 Global aspects
 - 6.1 The influence of shelf structuration on reef development
 - 6.2 Late Jurassic circulation pattern, sea level change, and climatic feedbacks
 - 6.3 Reef expansion during the Jurassic
- 7 Conclusions and perspectives

References

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 thrombotic 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 thrombotic 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

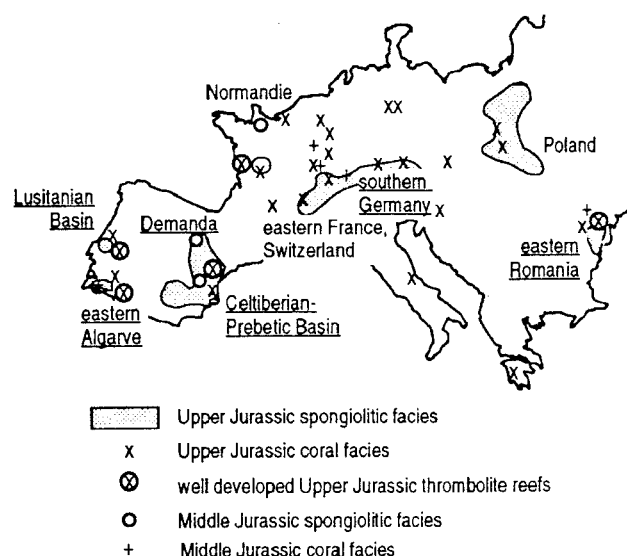


Fig. 1. The distribution of European Jurassic reefs. Underlined locations were studied in detail.

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.

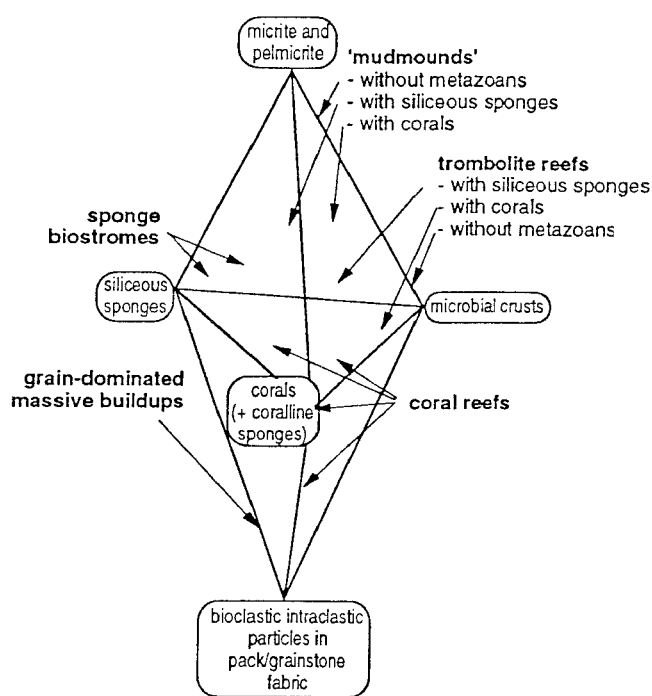


Fig. 2. Compositional types of Jurassic reefs and buildup types. The end members coral reefs, siliceous sponge reefs, microbialite reefs, mudmounds and bioclastic sand shoals frequently form transitional types. Arrows indicate the most common types (partly after LEINFELDER 1993a).

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

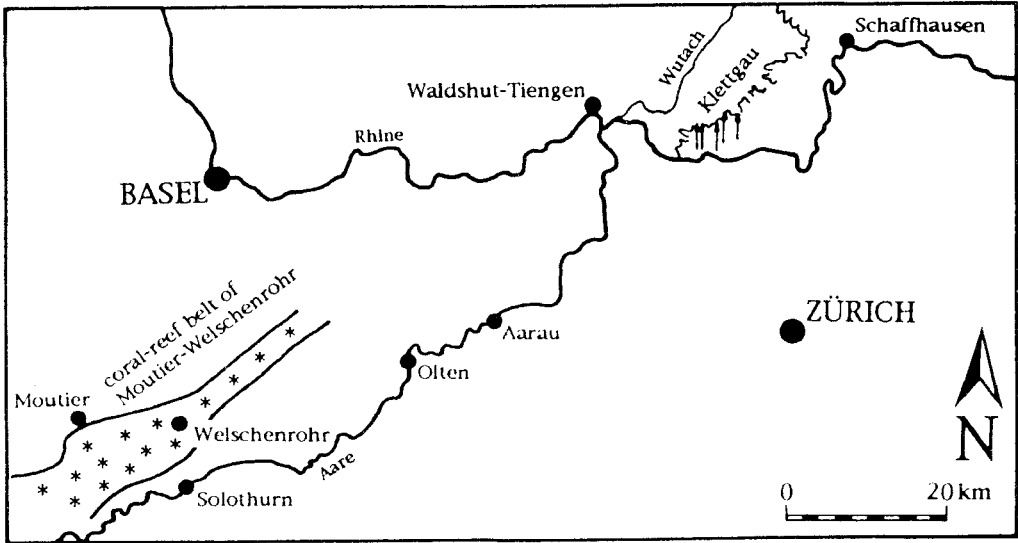


Fig. 3. Position of Oxfordian Klettgau sponge mounds and the Oxfordian coral reef belt of Moutier-Welschenrohr (Switzerland) (after GYGI 1969 and MÜLLER et al 1984).

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*. *Chonellopsis 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-*

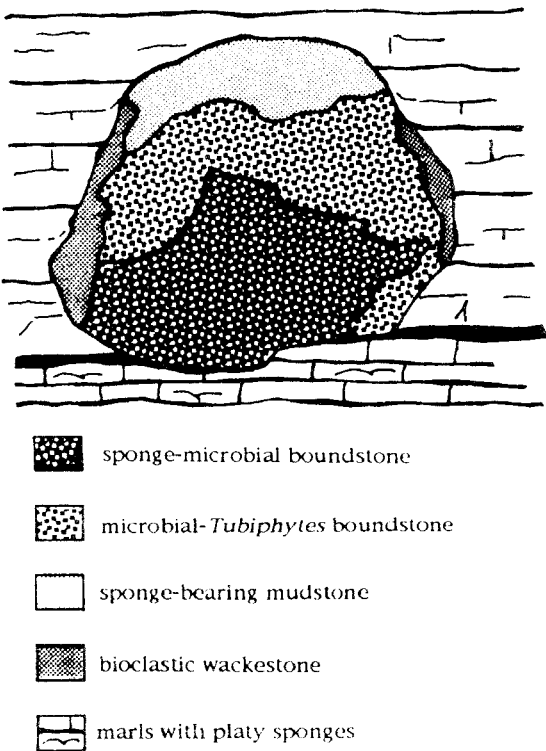


Fig. 4. Idealised section across a typical siliceous sponge - microbial mudmound of the Hornbuck Formation, Klettgau (Baden-Württemberg, Germany).

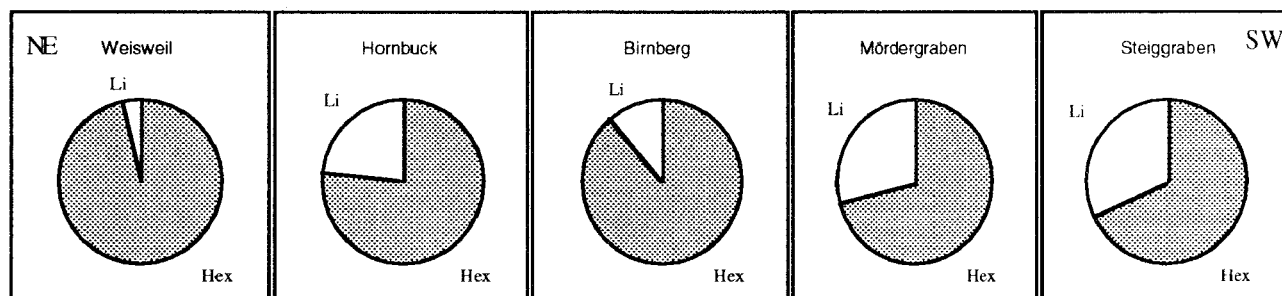


Fig. 5. The hexactinellid/lithistid-ratio from NW to SE in some outcrops of the Hornbuck Formation, Klettgau (Baden-Württemberg, Germany). Note that lithistid abundance increases relative to hexactinellids towards west, i.e. towards the shallower water.

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. Lothen).

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

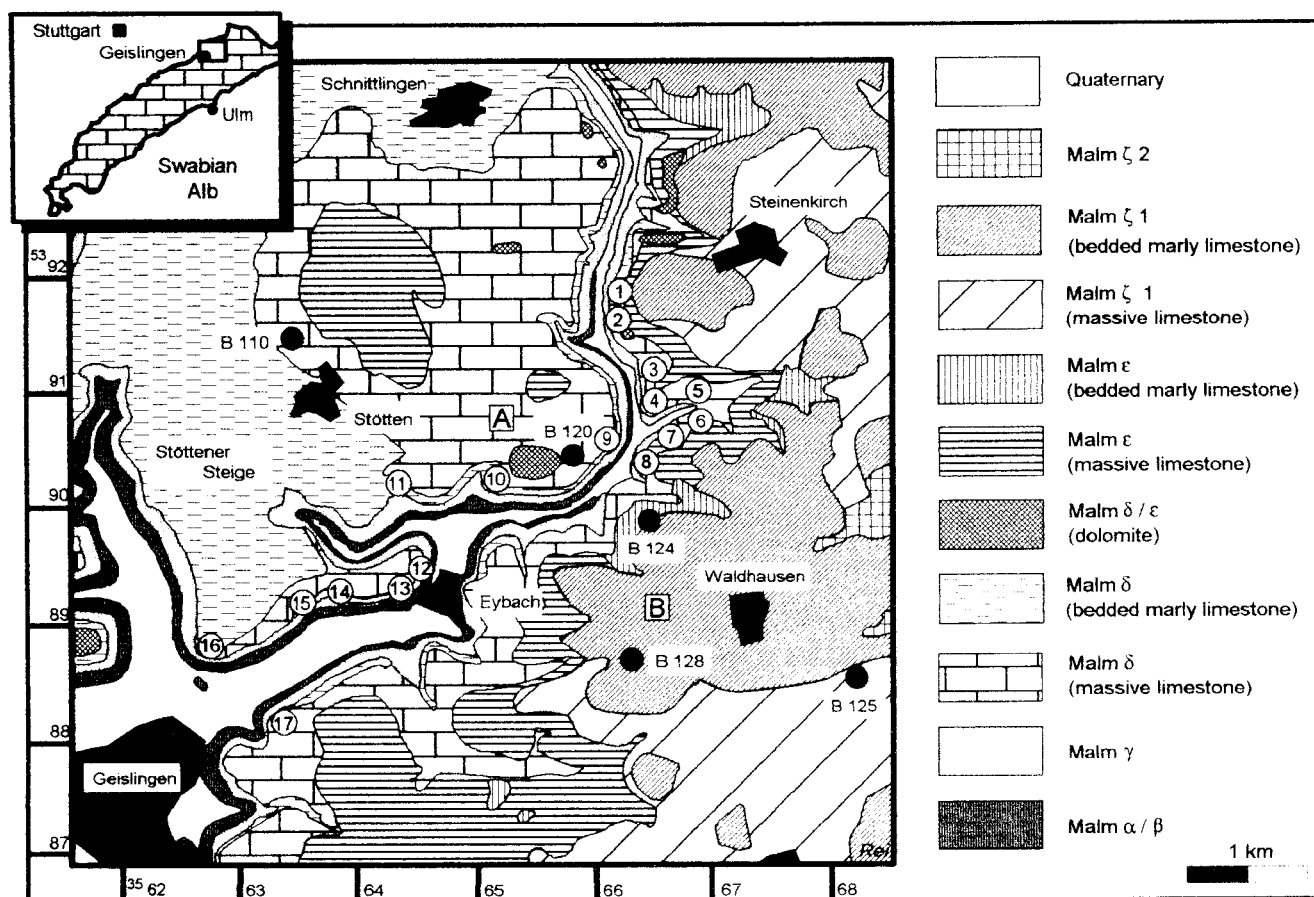


Fig. 6. Geological sketch map of the Upper Jurassic at the Geislingen - Eybatal area showing the locations of the investigated cores and major outcrops of massive limestones forming crags along the flanks of the Eybatal valley near Geislingen: 1.- Öhrnadel, 2.- Sphinx, 3.- Schulterfels, 4.- Gabelfels, 5.- Eisliger 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

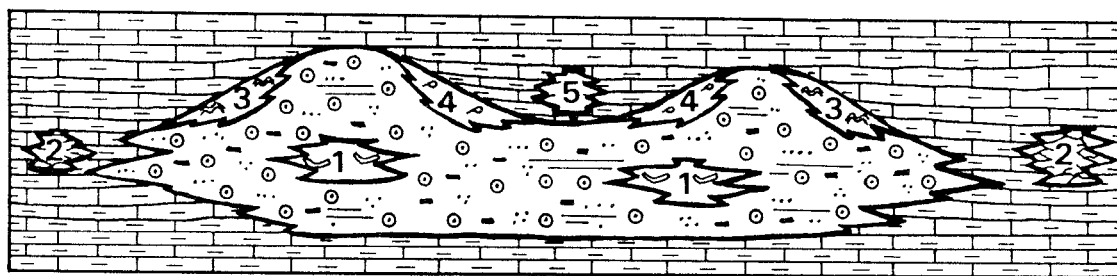


Fig. 7. Model of facies architecture of grain-dominated massive limestones for the lower part of Upper Kimmeridgian of the eastern EybtaI area. The model is thought to be valid for major parts of the Malm $\delta - \zeta 1$ of southern Germany, where not developed in mud-dominated 'basinal' facies. Spongiolite 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 EybtaI (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	.....	.....	.....	=====	.....	.....	.....	m
bladed calcite	.....	.....	.....	.....	=====	.....	.....	m
peloidal cement	.....	.....	=====	=====	=====	.....	.....	m
pyritization	=====	=====	=====	=====	.....	.....	.....	m/b
chert nodules	.....	.....	.....	.....	.....	.....	=====	m?
aragonite leaching	-----	-----	-----	-----	-----	-----	-----	b
calcification of sponges	.....	.....	.....	.....	-----	.....	.....	b
syntaxial rims	.....	-----	-----	-----	-----	.....	.....	b
scalenohedral cem.	.....	.....	.....	=====	.....	.....	.....	b
fracture I (partly syngedimentary)	.....	-----	-----	-----	-----	.....	=====	b
neomorphism of micritic matrix	.....	.....	.....	=====	=====	.....	.....	b
sparry calcite	-----	-----	=====	=====	=====	-----	-----	b
vug formation	-----	-----	-----	=====	-----	-----	-----	b
dolomite replacement in the matrix and along stylolites	-----	.....	-----	=====	-----	.....	-----	b
(Fe)-dolomite cem.	.....	.....	-----	=====	.....	.....	.....	b
saddle dolomite	.....	.....	-----	=====	.....	.....	.....	b
vertical stylolites	-----	=====	=====	=====	=====	-----	-----	b
horizontal stylolites	-----	-----	-----	-----	-----	-----	-----	b
fracture II	-----	-----	-----	-----	-----	-----	-----	b
fracture III	.....	-----	-----	-----	-----	-----	-----	b
dedolomite	-----	.....	-----	=====	-----	.....	.....	mp
sparry Fe-calcite	.....	-----	-----	=====	=====	.....	.....	mp
helectite	.....	-----	-----	-----	-----	.....	.....	mv
silicification	.....	-----	=====	-----	-----	.....	-----	mp
quartz cement	.....	.....	.....	.....	-----	.....	-----	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 southwestern 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 southwest (cf. SCHWEIZER-KLEMP 1982, SCHWEIGERT 1993a).

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

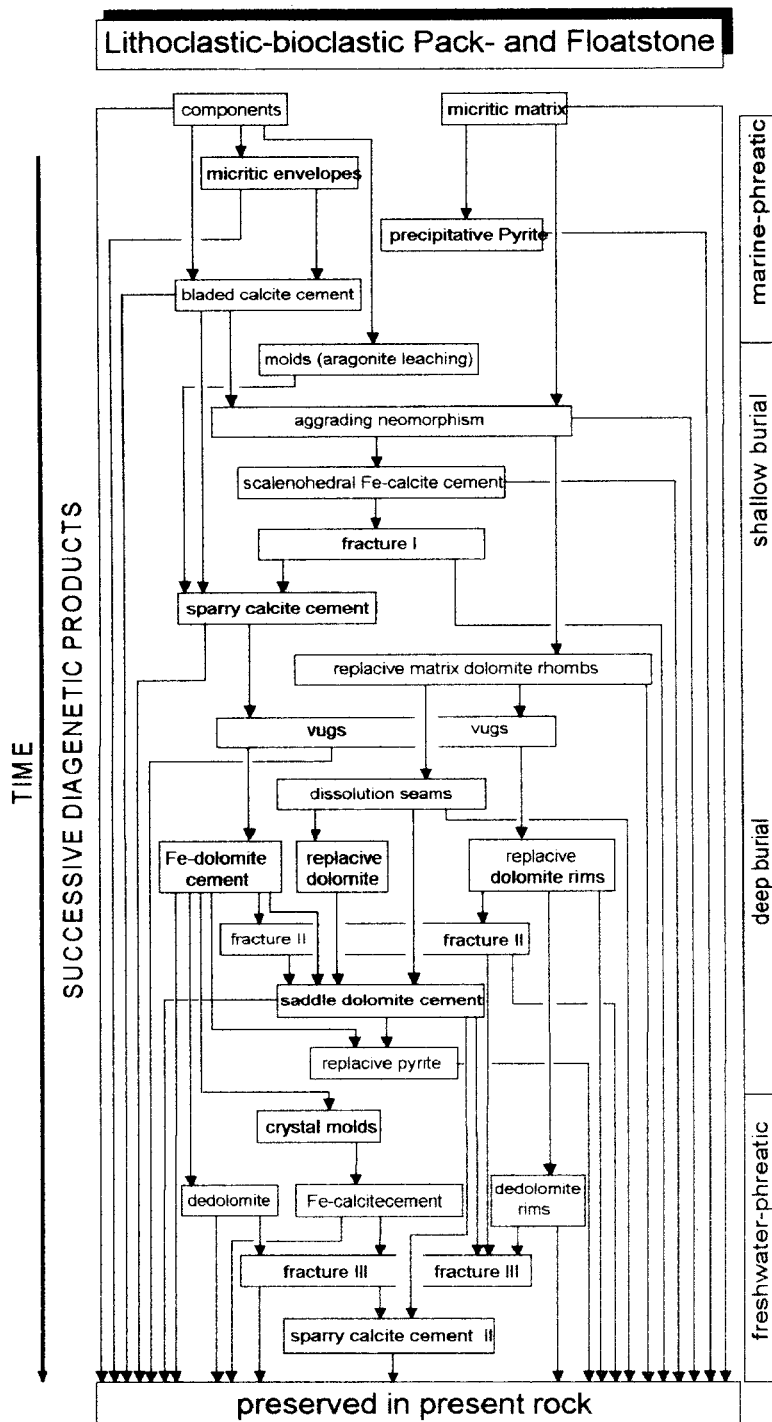


Fig. 9. Example for a facies controlled diagenetic sequence: Preliminary petrogenetogram of the lithoclastic-bioclastic pack- and floatstone facies showing the successive diagenetic development observed in the present rock. The connecting lines indicate the diagenetic sequences; diagenetic products of 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 *Eurysolenopora 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. Brenztaltrümmeroolith') (REIFF 1958, SCHLÜSSNER 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

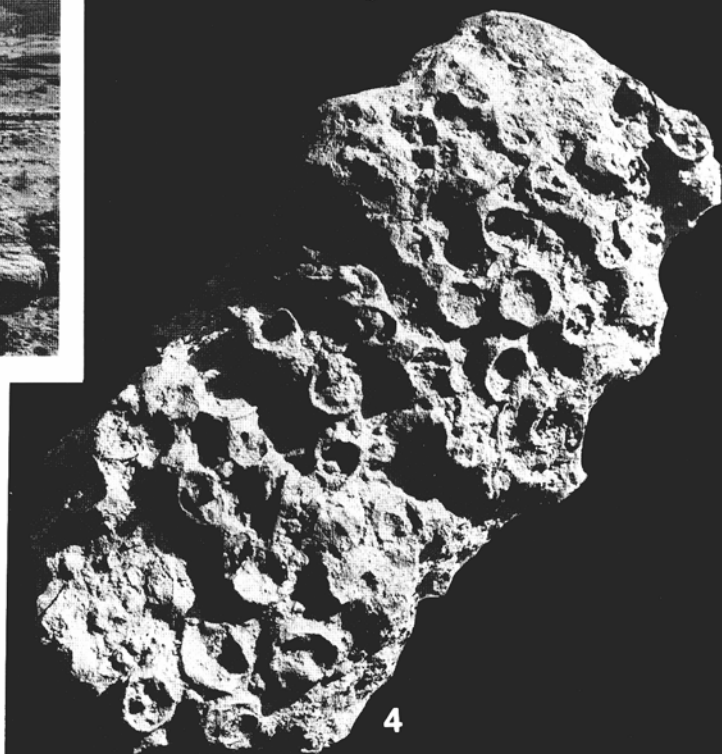
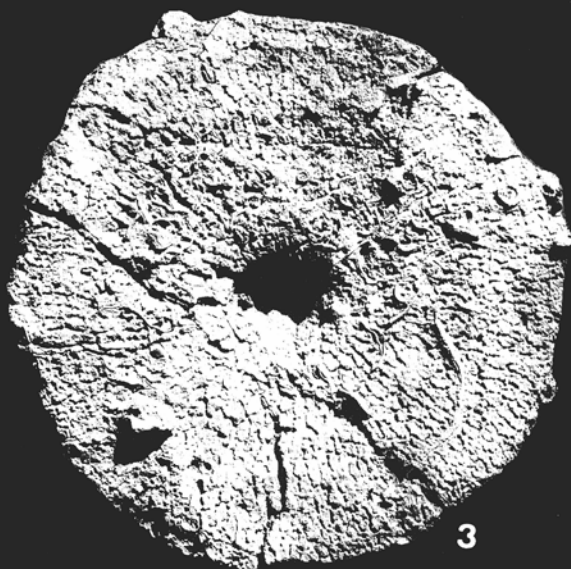
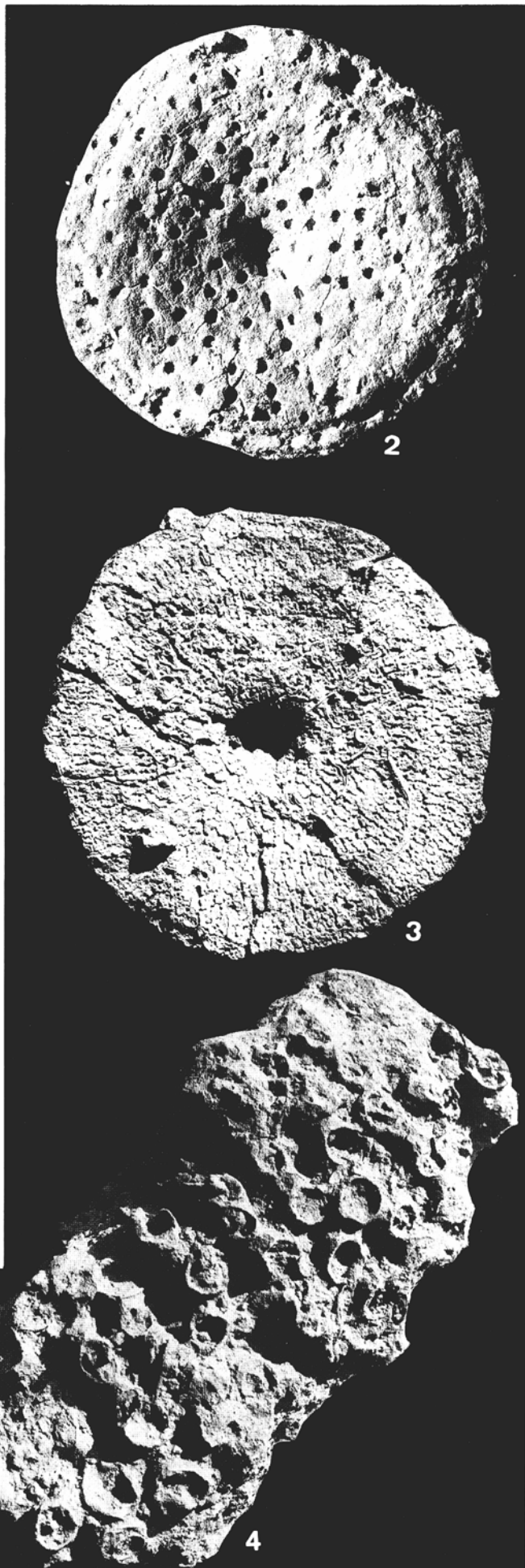
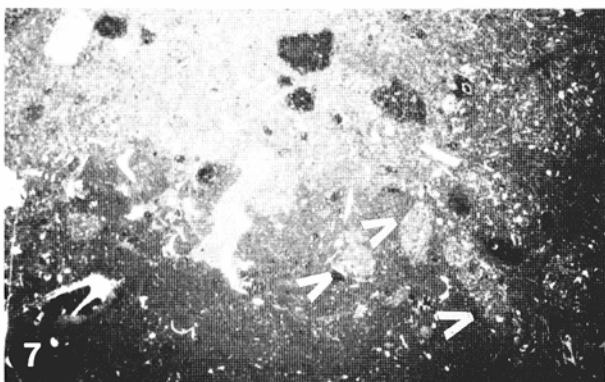
Middle Jurassic strata of Mid and Late Bajocian age are characterised by the widespread development of siliceous sponge facies. Their stratigraphic distribution ranges from the Sauzei to the Parkinsoni Zone.

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.

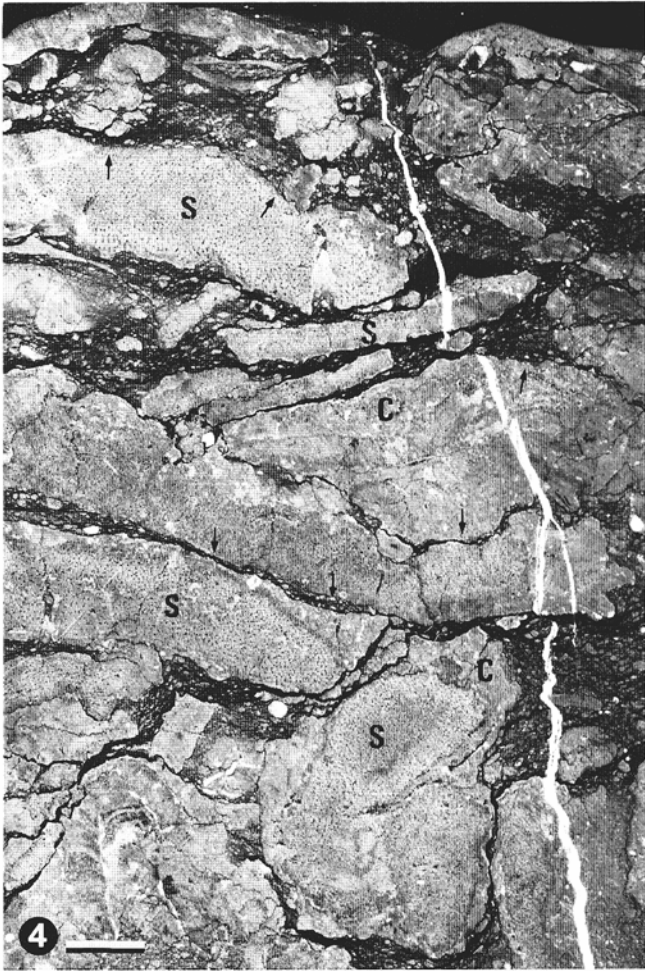
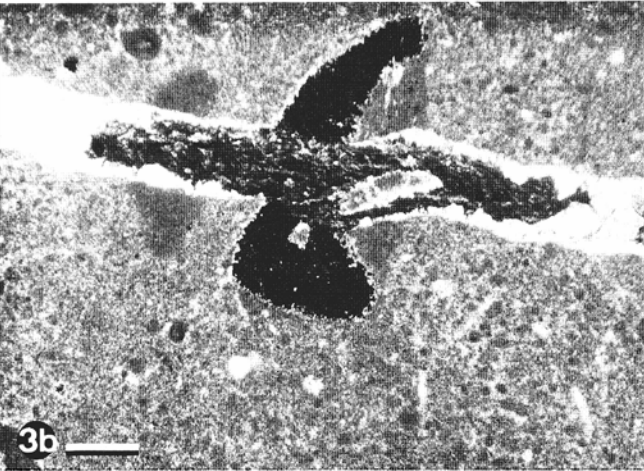
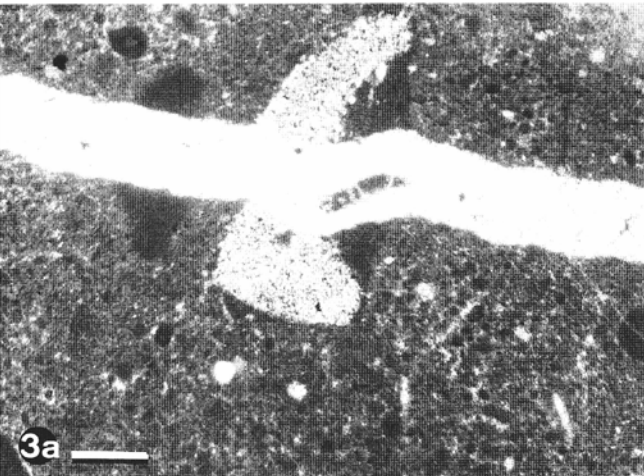
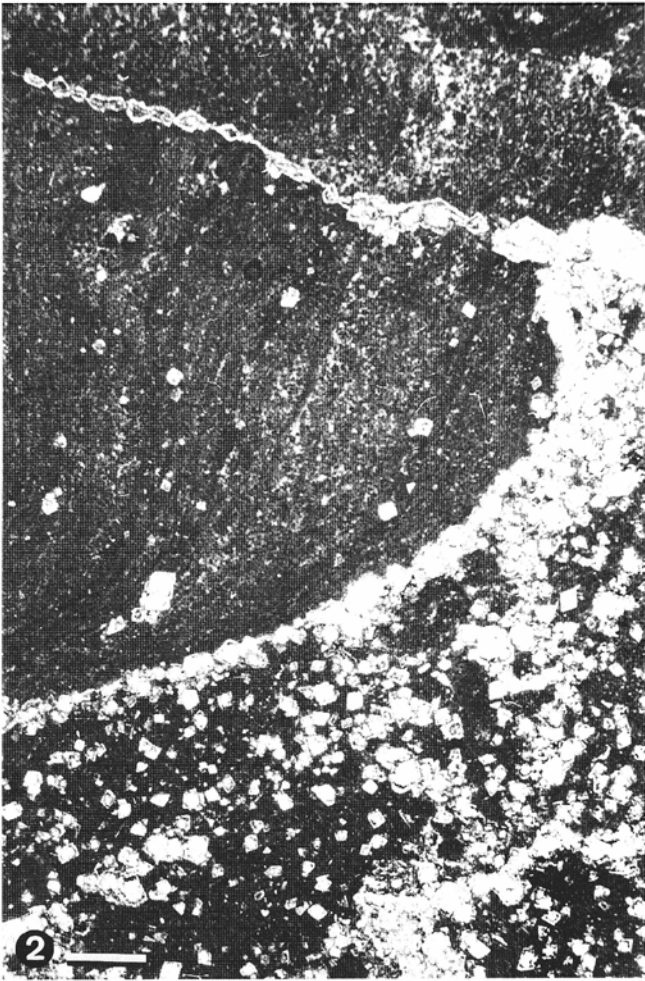
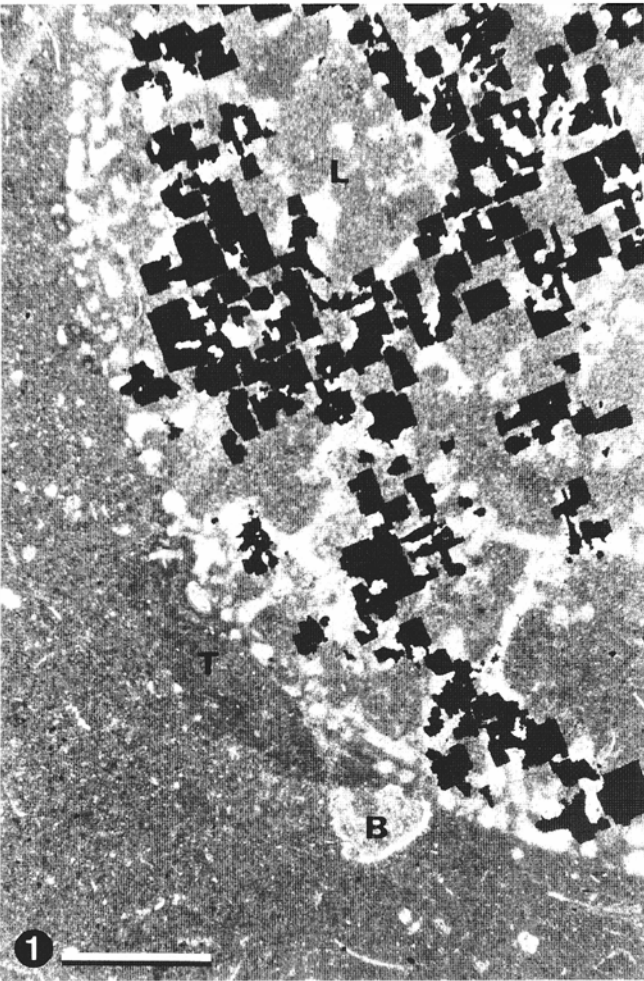
The upper beds of the Humphriesianum Zone and the base of the Upper Bajocian (biostratigraphically mixed Niortense-Garantiana Zone) suggest a short-term development of a second deepening/shallowing cycle. Sedimentation starts with moderately thick bioclastic limestone beds (still belonging to the Humphriesianum 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 *Bullopora 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:

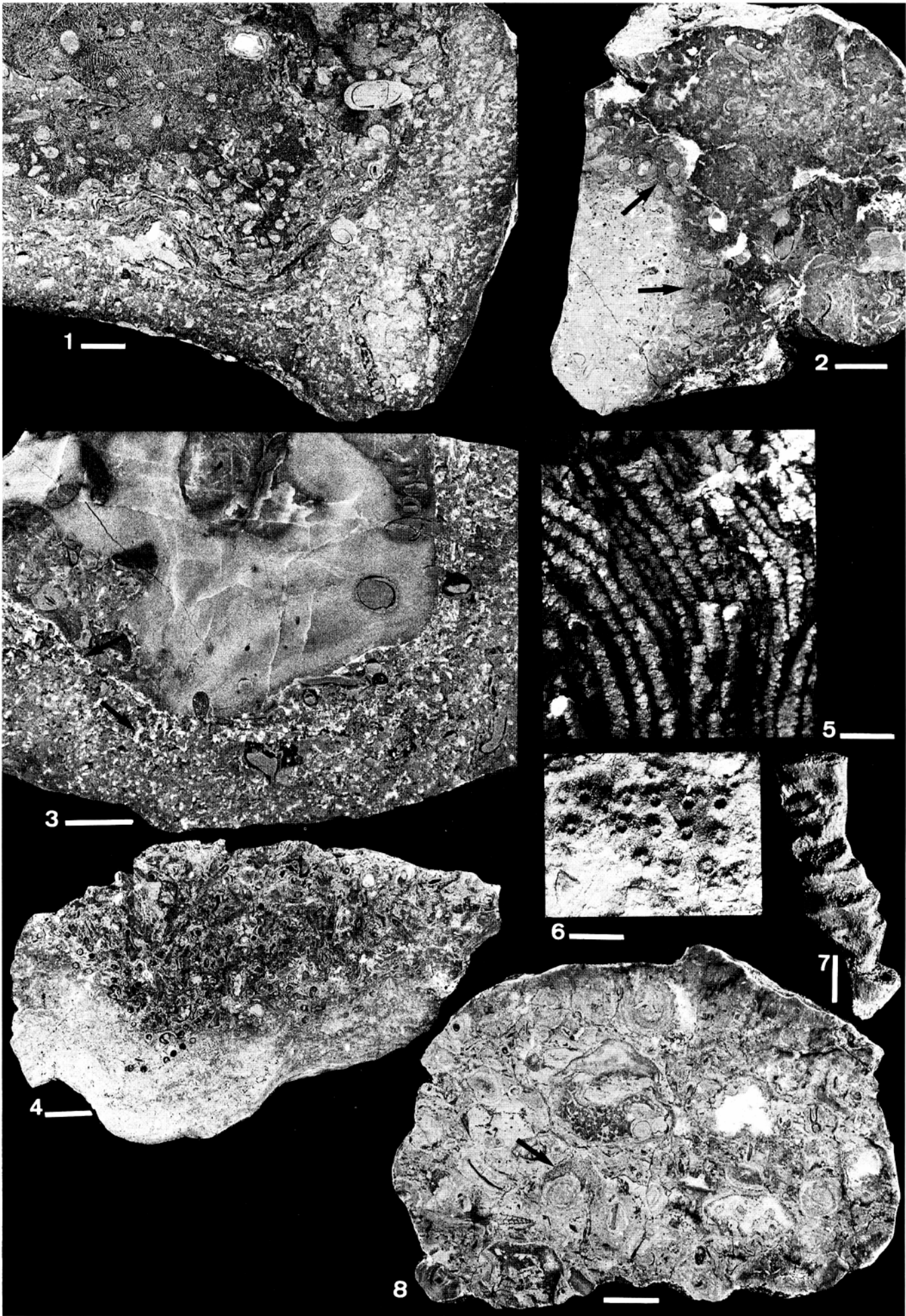
1. Sponges are closely linked to environments of sediment starvation and thus are preferentially found in connection with automicritic deposits which exhibit hardground characteristics.

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

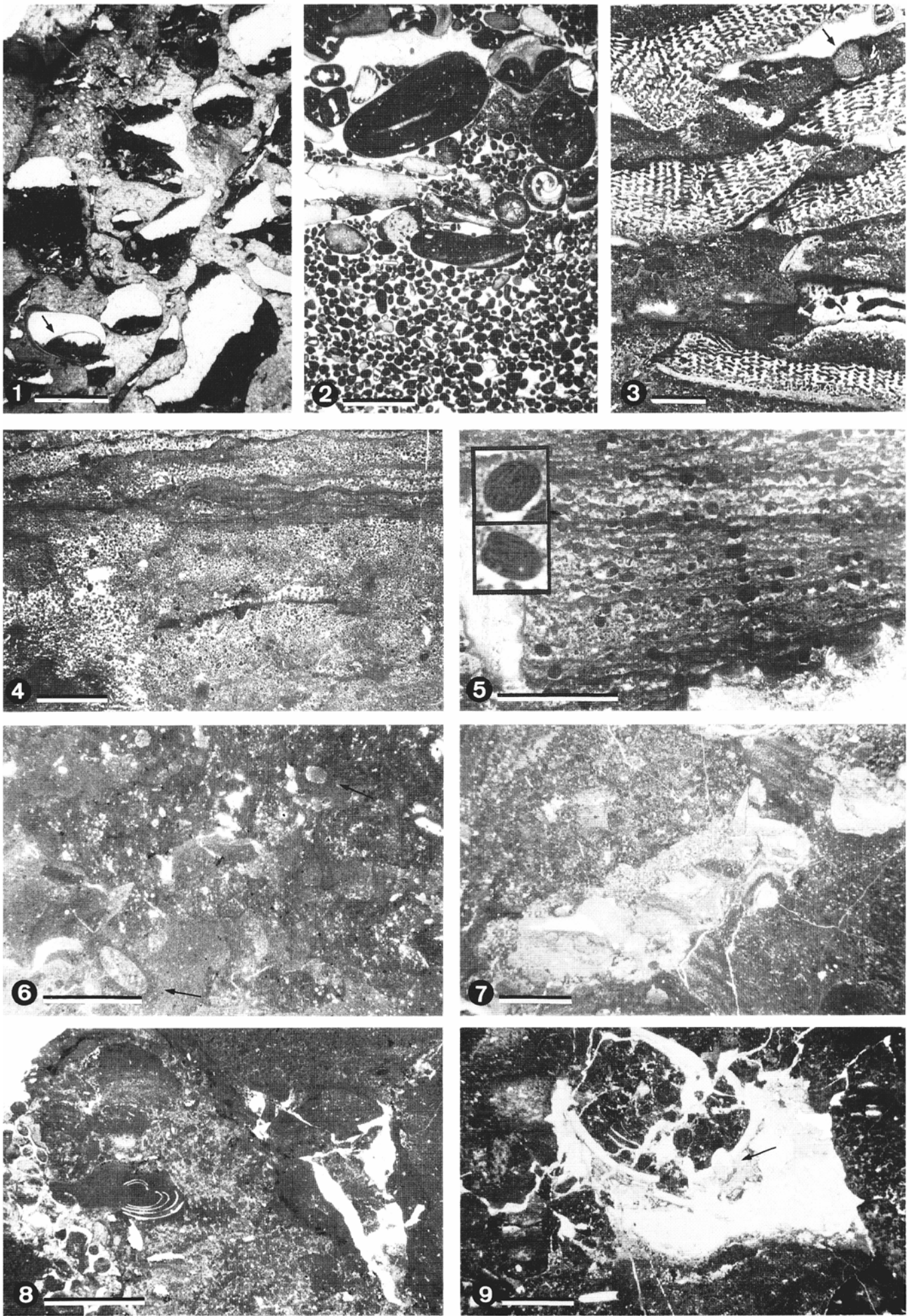
Characteristics and origin of automicritic sediments (Fig. 11, Pl.1/7): Siliceous sponges with a rigid skeleton (lithistid demosponges, dictyid and lychniskid hexactinellids) probably contribute only a minor portion to the entire sponge fauna within the Bajocian sponge limestones of the Sierra de la 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 biolastic/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 Cekirgeaua, 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



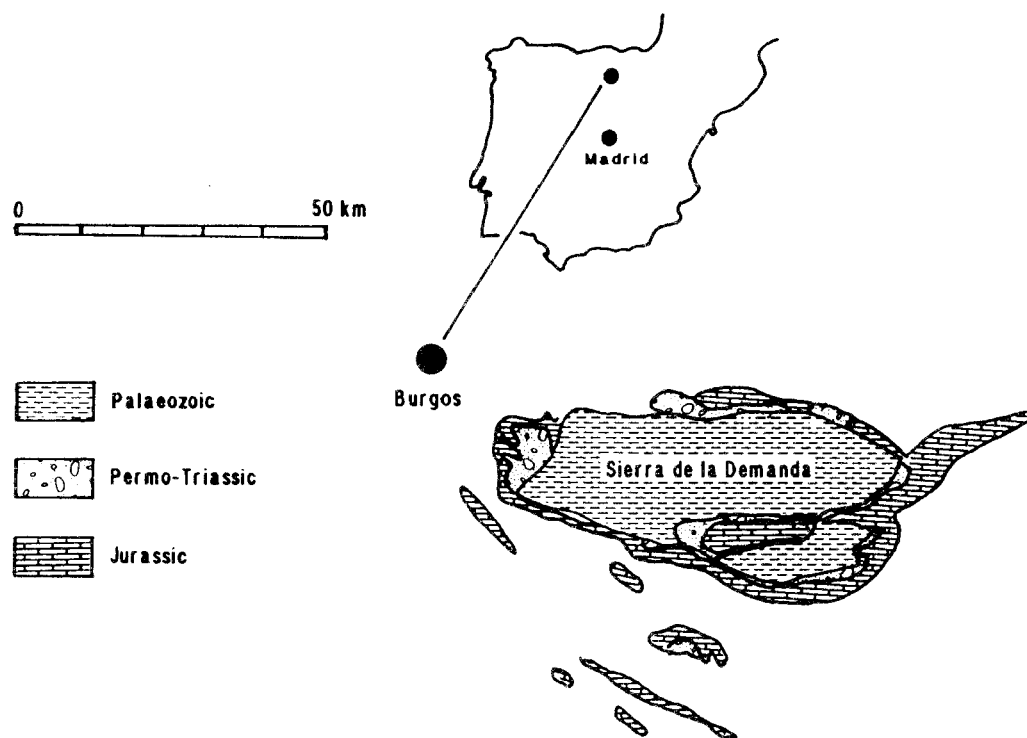


Fig. 10. Location of the Demanda study area.

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-

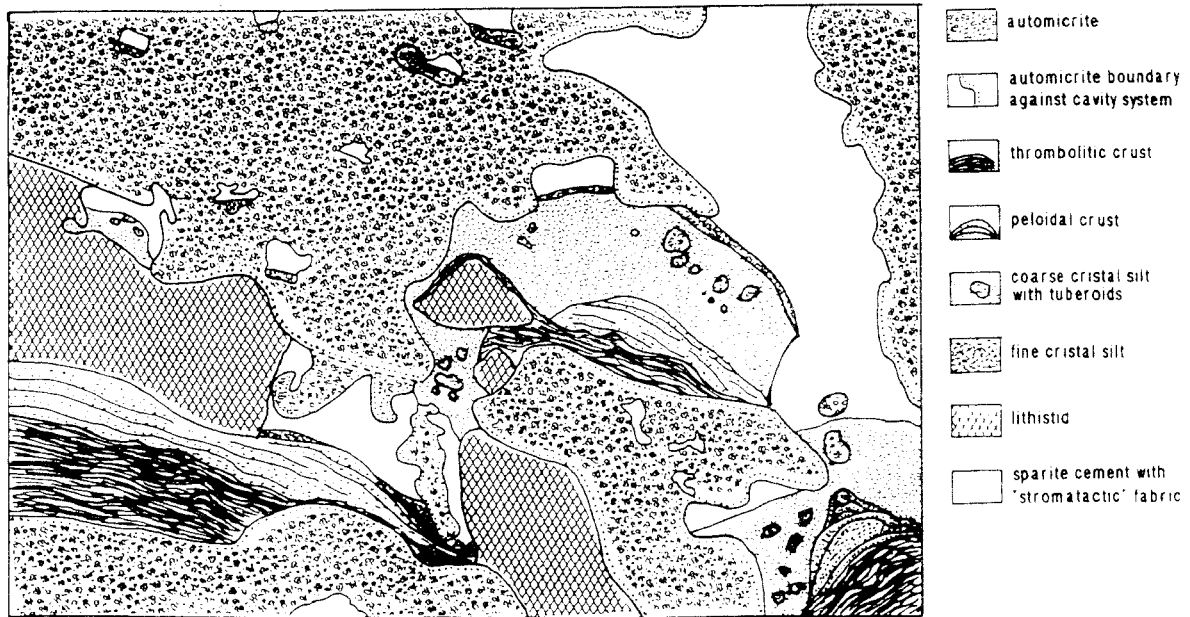


Fig. 11. Relationship between automicrite and cavity system with crusts and crystal silt infill. For further explanation see text. Width of sketch is 3 cm.

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 microbial 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-

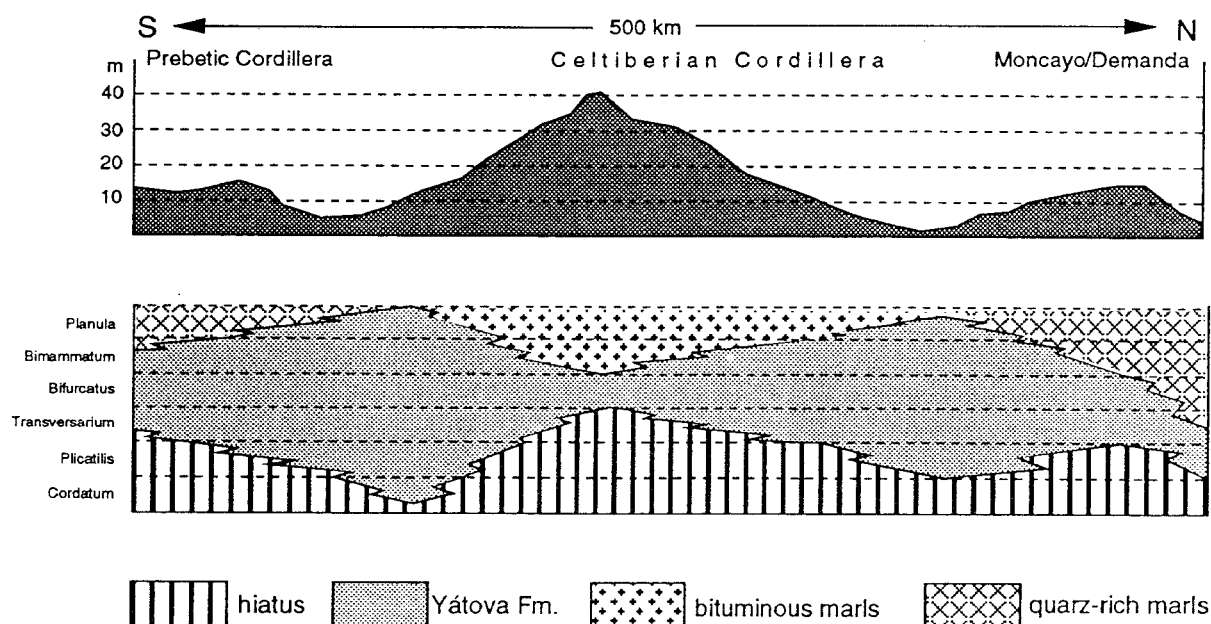


Fig. 12. Thickness and stratigraphic range of the spongiolitic Oxfordian Yátova Formation, Eastern Spain.

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*.

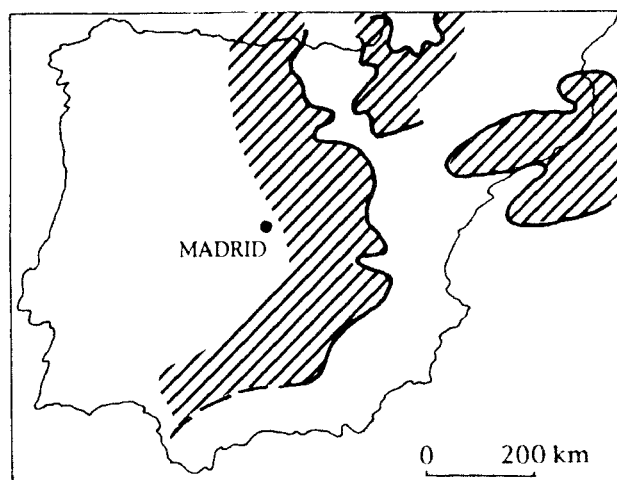


Fig. 13. Palaeogeography of the Oxfordian in Spain (after BENKE 1981). Bold line: presumed coast line; cross-hatched: positive subaerial areas. Western Iberia is not considered.

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-Enallhelina* ass., *Calamophylloids* 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-Calamophylloids* ass., *Thamnasteria-Ovalastrea* ass., *Convexastrea-Dendrohelina* 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).

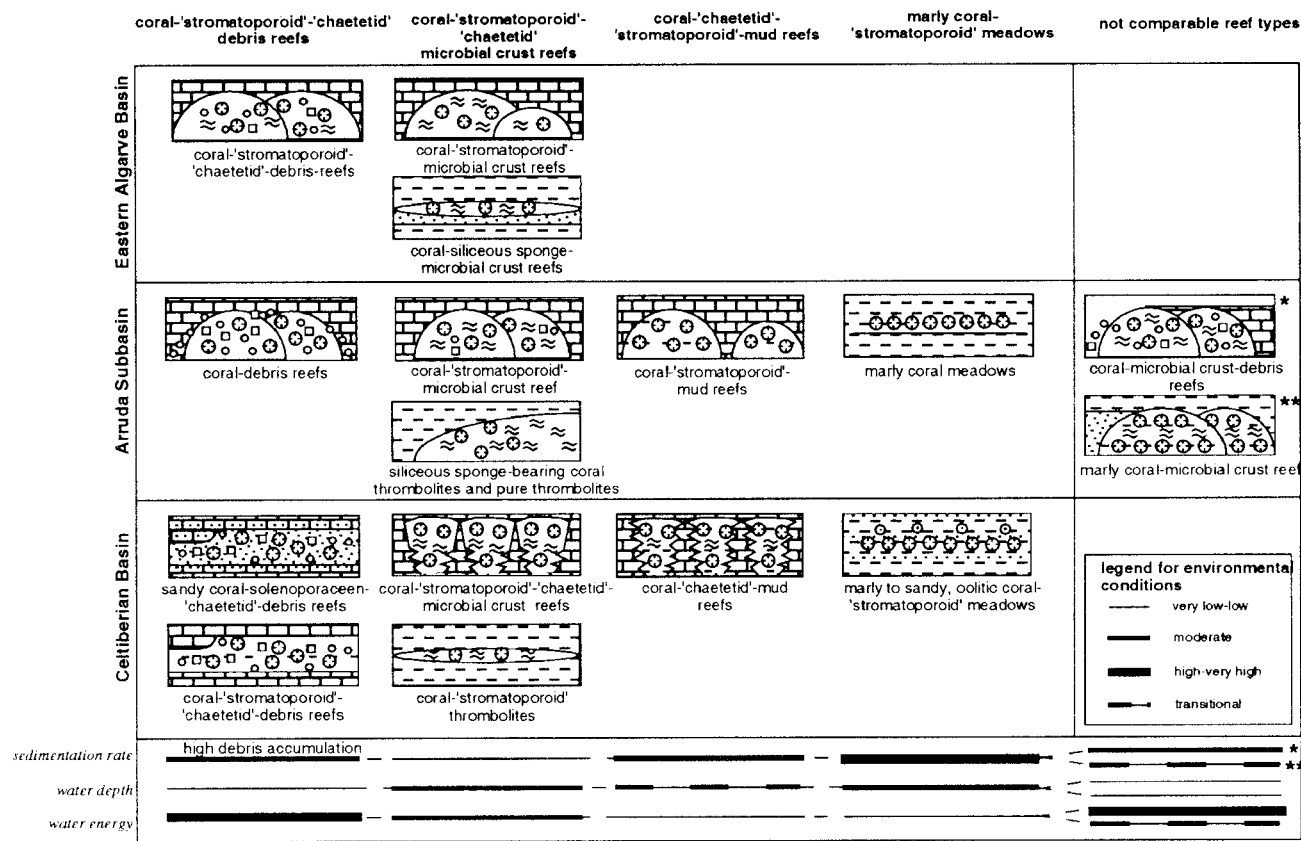


Fig. 14. Coral reef types from the Upper Jurassic of Iberia. Four coral reef groups can be subdivided into 16 reef subtypes which include 18 coral associations.

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.

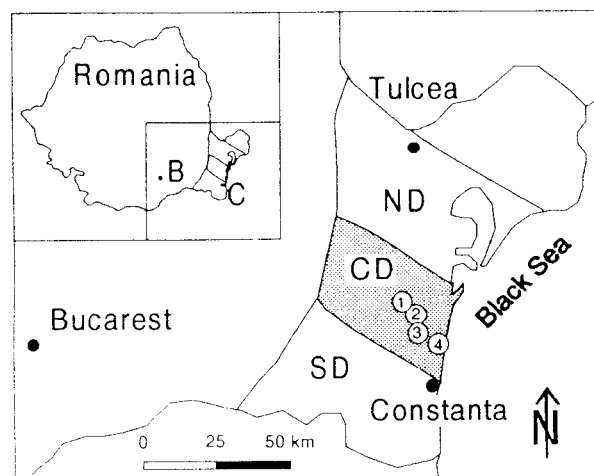


Fig. 15. Location of study area in Romania. B: Bucarest, C: Constanta, ND: North Dobrogea, CD: Central Dobrogea, SD: South Dobrogea. Location of sections shown in Fig. 17: 1: Cheia/Casian, 2: Valea Gura Dobrogei, 3: Sitorman quarry, zone C and zone E, 4: Piatra.

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., *Tabiphytes* sp., serpulids and foraminifera, are frequent.

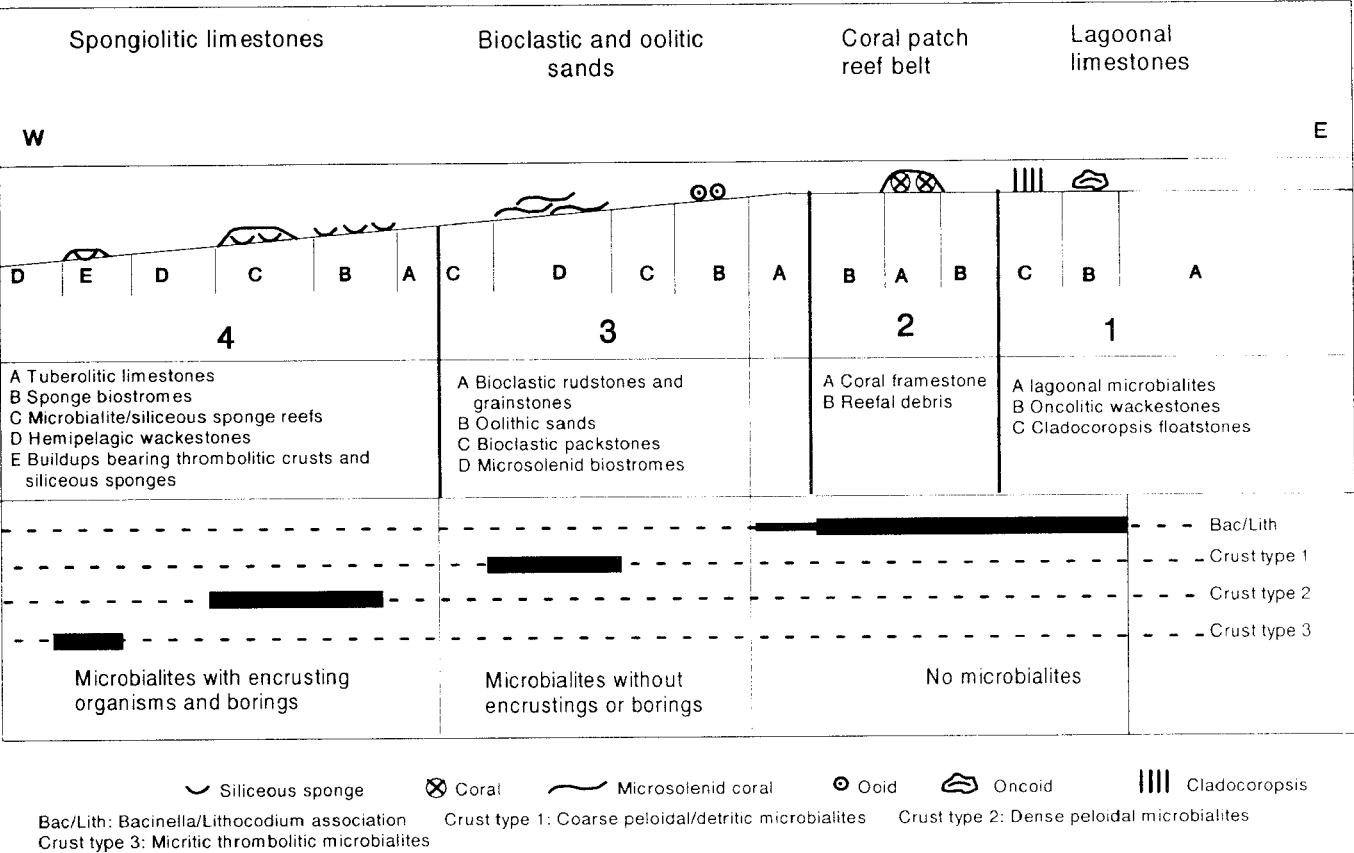


Fig. 16. Facies distribution and occurrence of different crust types on the Central Dobrogea carbonate ramp during the Mid-Oxfordian. The development of different reef types as well as different types of carbonate crusts was controlled by bathymetry and sedimentation rate.

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-