Mud Mounds:
A Polygenetic Spectrum of Fine-grained Carbonate Buildups

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DFG-Schwerpunkt
BIOGENE SEDIMENTATION

**Riff-Evolution
und
Kreide-Sedimentation**

KEYWORDS: MUD MOUNDS – SPONGES – AUTOMICRITES – ORGANOMICRITES – STROMATACTIS - PELOIDS – THROMBOLITES – MICROBIAL COMMUNITIES – BENTHIC COMMUNITIES – BIOFILMS – MICROBIALITES – MACROMOLECULES – REEF EVOLUTION – DEVONIAN – CARBONIFEROUS – PERMIAN – TRIASSIC – CRETACEOUS – HOLOCENE

CONTENTS

SUMMARY

This research report contains nine case studies (part II to X) dealing with Palaeozoic and Mesozoic mud mounds, microbial reefs, and modern zones of active micrite production, and two parts (I and XI) summarizing the major questions and results. The formation of different types of *in situ* formed micrites (automicrites) in close association with siliceous sponges is documented in Devonian, Carboniferous, Triassic, Jurassic and Cretaceous mounds and suggests a common origin with a modern facies found within reef caves. Processes

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involved in the formation of autochthonous micrites comprise: (i) calcifying mucus enriched in Asp and Glu, this type presumably is linked to the formation of stromatolites, thrombolites and massive fabrics; (ii) protein-rich substances within confined spaces (e.g. microcavities) result in peloidal pockets, peloidal coatings and peloidal stromatolites, and (iii) decay of sponge soft tissues, presumably enriched with symbiotic bacteria, lead to the micropeloidal preservation of parts of former sponge bodies. As a consequence, there is strong evidence that the primary production of micrite in place represents the initial cause for buildup development. The mode of precipitation corresponds to biologically-induced, matrix-mediated mineralization which results in high-Mg-calcites, isotopically balanced with inorganic cements or equilibrium skeletal carbonates, respectively. If distinct automicritic fabrics are absent, the source or origin of micrite remains questionable. However, the co-occurring identifiable components are inadequate, by quantity and physiology, to explain the enhanced accumulation of fine-grained calcium carbonate. The stromatolite reefs from the Permian Zechstein Basin are regarded as reminiscent of ancestral (Precambrian) reef facies, considered the precursor of automicrite/sponge buildups. Automicrite/sponge buildups represent the basic Phanerozoic reef type. Analogous facies are still present within modern cryptic reef habitats, where the biocalcifying carbonate factory is restricted in space.

Part I
MUD MOUNDS: RECOGNIZING A POLYGENETIC SPECTRUM OF FINE-GRAINED CARBONATE BUILDUPS
J. Reitner and F. Neuweiler

The implementation of the Priority Programm of the 'Deutsche Forschungsgemeinschaft' (DFG) 'Controlling Factors of Biogenic Sedimentation: Reef Evolution and Cretaceous Sedimentation' in 1990 led to the establishment of a group of scientists to work on the topic of mud mounds and microbial mounds. This 'mud mound-group' has concerned itself with the study of fine-grained (mostly micritic) carbonate buildups including case studies ranging from the Lower Devonian to the Recent, with localities from N-Africa, N-Europe and modern environments with active micrite production, e.g. reef caves of the Great Barrier Reef, Australia (Fig. 1). We have held several meetings to introduce our individual case studies and to concentrate on the key questions of mud mound genesis. Besides the annual meetings in Neustadt a.d.W., we had discussions in Hamburg 1992, organized by G. HILLMER and J. SCHOLZ (cf. FACIES vol. 29: 'Microbial Carbonates'), in Göttingen 1993 (D. MEISCHNER) and most recently in Berlin (J. REITNER and F. NEUWEILER).

The main topics of our discussions were: i) paleoecology and environmental settings, ii) microbial textures, iii) the role of sponges, iv) lithification processes, v) types of cavities and their time of formation, vi) stable isotope geochemistry, vii) micrite genesis related to the diagenesis of organic matter, viii) micrite genesis via diffuse organic matter and associated organic macromolecules, and viiii) the distinction between allomicrite, parautochthonous micrite and automicrite, respectively (micrite budgets).

In summer 1993, CLAUDE MONTY (Nantes) convened a meeting in Paris in order to define the main aims of IGCP 344 'Correlation of microbial buildups'. The meeting postulated that the main effort should be related to the microbial processes by which sediments are precipitated, accumulated and lithified (cf. Stromatolite Newsletter 1993). Studies of mud mounds should focus on: (i) the interaction between microbial processes, sea-water and macro-organisms, (ii) the environmental setting and possible nutrient sources, and (iii) the role of microbial organisms in the processes of cementation, dissolution, cavity formation and neomorphism during mud mound diagenesis. A compilation of Phanerozoic mud mounds will be published soon (MONTY et al. 1995).

The German group is aware of the fact, that we use the term 'mud mound' in a very broad, descriptive manner for a fine-grained carbonate buildup at the macroscopic scale. The evaluation of the origin of micrites involved in the formation of mud mounds is crucial in determining their polygenetic history and forms the basis of a refined genetic classification of ancient fine-textured carbonate buildups, e.g. biodetrital feedback mechanisms *vs* different kinds of *in situ* production.

As far as we know, the original use of the term 'mud mound' referred to biodetrital carbonate bodies in areas like the Florida Bay. Their origin is related to the baffling of currents by marine grasses (e.g. *Thalassia* sp.) and a surplus of carbonate production by numerous epibiontic organisms (GINSBURG & LOWENSTAM 1958; LAND 1970). Other modern occurrences of lime mud bodies are characterized by purely hydrodynamic accumulation near zones of enforced mud production induced by *Penicillus* sp. and mechanical skeletal breakdown (STOCKMAN et al. 1967). Genetically, all these bodies are clearly related to the bank category of buildups, lacking a 3-dimensional framework, i.e. the ability of the involved organisms for active vertical (skeletal) growth or non-skeletal accretion, respectively.

In contrast to the above-mentioned processes, MONTY (1976) postulated that many ancient mud mounds represent 'a megadevelopment of cryptalgal textures' with a significant amount of organically-induced peloids. The term 'cryptalgal texture' (AITKEN 1967) has been largely replaced by 'microbial texture', stressing the predominant role of the involved procaryotic organisms (bacteria). Commonly, siliceous sponges are the main associated faunal element, considered as a biostrategic consortium between microbes and sponges (MONTY 1984). This consortium presumably originated during the Late Proterozoic (cf. STEINER et al. 1993) and is regarded as an ultraconservative life strategy which marks the onset of metazoan-bearing carbonate buildups in Earth's history (cf. ROWLAND & GANGLOFF 1988 for summary). Until recently, no modern counterparts of bioherms consisting of microbial carbonates and sponges have been known. However, there are examples in deeper

Phanerozoic Mud Mounds and Mud Mound Facies (sensu lato)

reference points	time	this compilation

reference points

Otway margin, S. Australia;
Boreen & James (1993)

foreslope, Red Sea;
Brachert & Dullo (1991)

Automicrite-bearing debrite;
Reitner & Keupp (1991)

Turonian microbial mounds
from Tunesia;
Camoin & Maurin (1988)

Chemosynthetic mounds
from the Canadian Arctic;
Beauchamp & Savard (1992)

Sponge mounds from China;
Wendt et al. (1989), Wu (1989)

Waulsortian Banks
Less & Miller (1994)

Red Stromatactis-Mounds from
Belgium and Quebec (Appalachan)
Bourque & Boulvain (1993)

Stromatactis-Mud Mounds from
southern Nevada;
Ross et al. (1975)

Thrombolite Bioherms from
central Australia;
Kennard & James (1986)

Mud mounds from
Flinders Ranges (Australia);
James & Gravestock (1990)

Archaeocyath/microbial mounds
from the Siberian platform;
Rowland & Gangloff (1988)

time: TERT · CRET · JUR · TRI · PER · CARB · DEV · SIL · ORD · CAM

this compilation

① Automicrite production
within modern reef caves
(Lizard Island, Great Barrier Reef; Australia)

comparative study by Reitner & Neuweiler

② Microbialite reefs
at marginal platform areas
(Soba Reef Area; N. Spain)

③ Mid-ramp sponge/microbial crust reefs
from southern Germany
by Leinfelder & Keupp

④ Cryptic automicrites of
Cipit-blocs from northern Italy
by Neuweiler & Reitner

Stromatolite Reefs within an evaporite basin
of southeastern Germany
by Paul

⑤

⑥ shallow marine algal/microbial mounds
and diagenetic mounds from N. Spain
by Hensen, Dingle & Schäfer

Deeper shelf sponge/microbialite mounds
from NW. Ireland
by Warnke & Meischner

⑦

Mud Mound of Rübeland
in the Harz Mountains (Germany)
by Weller

⑧

Shallow to deeper ramp reef mounds
⑨ and mud mounds from Morocco (Anti-Atlas)
by Kaufmann

Deeper water Stromatactis-Mounds
⑩ from France
by Flajs, Hüssner & Vigener
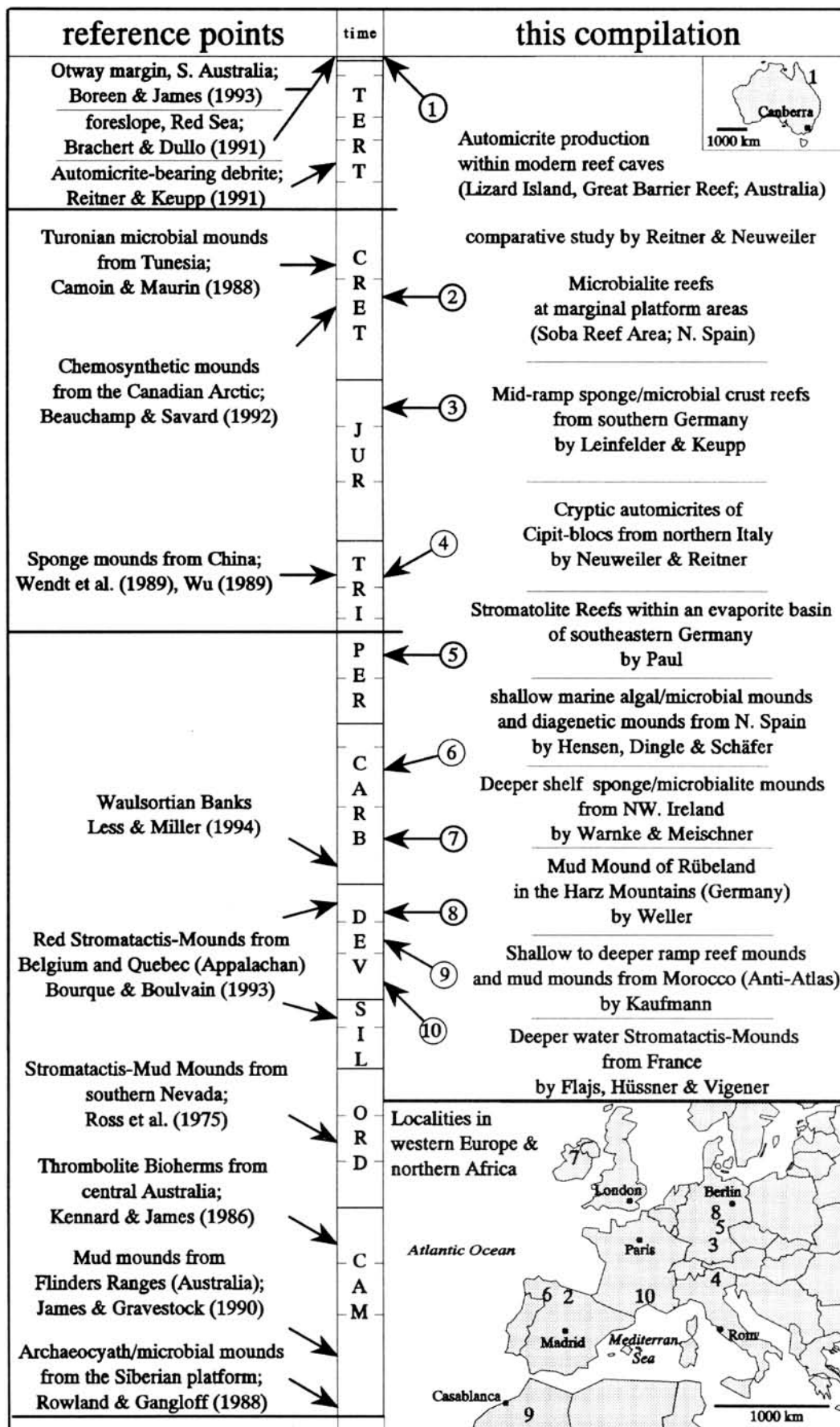
Localities in western Europe & northern Africa

Fig. 1. Stratigraphic distribution and general settings of compiled case studies. Subdivision according to the geological time table (HAQ & VAN EYSINGA 1987)

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shelf areas, like those of the Otway Margin, southeastern Australia (BOREEN & JAMES 1993), and the deeper forereef slopes in the Red Sea of Sudan (BRACHERT & DULLO 1991) (Fig. 1).

Several authors have proposed a practicable terminology for fossil carbonate buildups, dominated by mud (incl. micrite). JAMES (1984) used the ratio of skeletal metazoan remains relative to mud as the criterion to distinguish between mud mounds, reef mounds and reefs. Similarly, RIDING (1990) used the relative amount of skeletons to separate reefs (framework reefs) from carbonate mounds, which seems, at least in part, contradictory to his own earlier statement that 'micrite mounds may in some cases be organic reefs'. These proposals suggest a continuous spectrum of buildups where the relative amount of mud increases with increasing depth of formation, correspondingly from wave-resistant to quiet-water bioherms. But how can wave resistance be assessed below wave base?

In agreement with the IGCP 344, we use the term mud mound in a descriptive mode for every carbonate buildup consisting of more than 50 % of mud and/or peloidal mud, where mud represents microscopically unidentifiable components, usually < 16 μm (cf. STOCKMAN et al. 1967). In a strict sense the term mud infers a primarily soft, muddy substrate; but this is not necessarily the case for every carbonate body labeled mud mound. We stress the point, that genetic and environmental interpretations may be misleading without an evaluation of the origins and relative amounts of micrites involved. Particularly, in situ production of micrite excludes any conclusion with respect to the hydrodynamic environment, because this fraction never was held in suspension.

This compilation of case studies provides an opportunity to confirm the polygenetic origin of mud mounds and to discuss specific groups with a similar origin. Some authors have nearly completed their work, whereas others are presenting preliminary results.

The case studies are arranged in stratigraphic order beginning with a comparative study of fossil and modern automicrites by REITNER & NEUWEILER. Their petrographic and analytical results suggest, at least in part, a common organically mediated origin of micrites and peloidal micrites of Lower Cretaceous mud mounds of northern Spain and those observed within cryptic habitats of modern reefs from eastern Australia (Great Barrier Reef). - cf. Part II.

The second contribution by LEINFELDER & KEUPP introduces the strong relationships of the widely-known European Upper Jurassic micritic siliceous sponge facies with respect to microbial mud mounds. The paper provides different aspects of micrite accumulation and a summary of controlling environmental mechanisms. - cf. Part III.

The Mesozoic examples are completed by NEUWEILER & REITNER with a short note concerning excellently preserved automicrites from cryptic environments in the Upper Triassic (Cipit-boulders; Cassian Formation). They used fluorescence-microscopy to demonstrate various aspects of automicrite characteristics. - cf. Part IV.

Paleozoic mud mounds/microbial buildups are illustrated with 6 case studies of Permian, Carboniferous and Devonian age. Stromatolite reefs from the German Zechstein Basin are described by PAUL. He stresses the importance of considering relative sea-level changes and excursions of salinity in understanding the relative production of microbial and macroskeletal fabrics. - cf. Part V.

HENSEN, DINGLE & SCHÄFER present several indicators for distinguishing between primary mounds and diagenetic mounds exemplified by the Upper Carboniferous of the Cantabrian Mountains (northern Spain). They demonstrate the inadequacy of the preserved skeletal algae (dasyclad Donezella and rhodophyte Petschoria) to produce, baffle and bind large amounts of mud. - cf. Part VI.

The origin and depositional environment of Lower Carboniferous mud mounds from Ireland are discussed by WARNKE & MEISCHNER. They conclude that the diagenesis of sponge soft tissue led to the formation of a rigid microcrystalline frame and early stromatactoid cavities. - cf. Part VII.

The Upper Devonian mud mound of Harz area (Germany) consisting of stromatactis-bearing micrites, stromatolites and zebra limestones is discussed by WELLER in the context of microbial activities and tectonic setting. - cf. Part VIII.

Middle Devonian mud mounds and reef mounds from Morocco are the subjects of the paper by KAUFMANN. He describes the variability of these buildups ranging from neritic to pelagic environmental settings. - cf. Part IX.

The case studies are completed by Lower Devonian stromatactis mud mounds from France presented by FLAJS, HÜSSNER & VIGENER. They consider the large stromatactis structures to be cavities formed by the decay of microbial mats and summarize their subsequent diagenetic history. The pronounced internal rhythmicity of facies is discussed in the light of high frequency sea-level changes. - cf. Part X.

The epilogue tries to summarize our major results and evaluates the principal modes of mud mound genesis. It sets out the major aims with regard to furthering our understanding of ancient fine-grained carbonate buildups and includes the conceptual framework for future research. - cf. Part XI.

Part II
MODERN AND FOSSIL AUTOMICRITES:
IMPLICATIONS FOR MUD MOUND GENESIS
J. Reitner, F. Neuweiler and P. Gautret

Significant automicrite production is taking place within modern reef caves of Lizard Island (Great Barrier Reef) and it is considered to have been crucial in the development of Albian (Lower Cretaceous) mud mounds situated on the outer platform margins of the Vasco-Cantabrian Basin (N. Spain). Two principal types of automicrites are distinguished: i) accretionary automicrites exhibiting a distinct growthform, and ii) container automicrites occurring within closed and semi-closed microenvironments.

Accretionary automicrites form via reactive organic matter dominated by glucidic and proteic compounds (organomicrites). Macromolecules of soluble matrices contain large amounts of acidic amino acids (32 mole % Asp and Glu) and specific monosugars which are important in calci-

sponge tissues and found specific sterols and typical bacterial remains.

Soba Reef area: The diagenesis of sponge soft tissue acts as a second process of the *in situ* production of micrite within mud mounds (NEUWEILER & REITNER 1993a, b). Pl. 5 shows various geological endproducts found within lithistid and non-lithistid demosponges and within hexactinellids. Distinct aggregates of minipeloids exist, resembling calcified bacteria (Pl. 5/1); especially when compared to the stained bacteria of Pl. 2/3 and entirely preserved individuals of *Aka* embedded in peloidal flakes (Pl. 5/2). Because *Aka* only excavates calcareous substrates and it is found within a lithistid demosponge, the entire fabric of Pl. 5/2 suggests a very early, perhaps *synvivo* diagenesis of the involved sponge. In addition, fairly intact bioclasts of demosponges found within tempestite beds support this timing of the onset of sponge petrogenesis (cf. Pl. 1/8).

The automicritic nature is well expressed by autochthonous sponge skeletons representing a 'carbonate island' surrounded by marls and limy marls of the basin depositional environment (Pl. 5/3-5). This is apparent from the embryonic stages of automicritic buildup developments, which first appear like erratic carbonate boulders but reveal an autochthonous fauna mainly consisting of hexactinellid sponges, platy corals and bryozoans (Pl. 5/5).

An external rim of dense automicrite provides an excellent preservation of lithistid demosponges, including the outer dermal layer (NEUWEILER 1993; Pl. 5/6). This particular preservation was detected within the reef caves of Lizard Island (cf. Pl. 2/7-8). Currently, we don't know whether these automicritic rims originate from the sponge soft tissue and related symbionts, or from external biofilms and imported organic matter. Growth of accretionary automicrites upon a lithistid demosponge normally occupies the outer area of the sponge skeleton (NEUWEILER 1993: plate 44, fig. 1) and is well separated from internal peloidal organomicrites, exhibiting incomplete calcification, collapse structures, and sometimes early stromatactoid cavities.

A succession of 'reactive' non-lithistid demosponges in association with thin thrombolites results in a cauliflower-like structure (Pl. 5/7-8). However, these combinations of accretionary organomicrite and container organomicrite are restricted to well-protected areas of cavities and therefore do not participate in active vertical growth of Albian mud mounds.

3.2 Allomicrites

Lizard Island: In contrast to automicrites the allochthonous micrite or allomicrite is enriched in aragonite and exhibits lighter carbon isotope values ($\delta^{13}C$ +1 ‰). The allochems reveal a fluorescence behaviour completely different and much more variable than that seen in the automicrites. The soluble organic matter differs also from all previous studied matrices. The soluble organic matter is composed of 90 % glucidic material and 10 % proteic ones only. This is characterized by the lowest amounts of acidic amino acids (Asp + Glu: 15 mole %), while the basic ones dominate (Lys+Arg+His: 19 mole %). The high amount of

Lys is combined with the presence of ornithine due to decaying matter. Relatively large amounts of the bacterial diaminopimelic acid is also detected. Allochem components are reworked material, products of bioerosion, and disintegrated biodetritus.

Soba Reef area: Relatively pure sedimentary micrite mostly exhibiting a geopetal fabric is found within coarse tempestite beds (Pl. 1/8). Their co-occurrence with heavily bored rudist debris suggests of intense bioerosion. This is in agreement with stable isotope analyses ($\delta^{13}C$ vs PDB), which give comparable values for allomicrite and embedded calcitic parts of rudist valves ($\delta^{13}C$ +2.5 ‰) clearly separated from the mean values for the automicrites with $\delta^{13}C$ +3.5 ‰) (NEUWEILER 1993). The small amount of intracrystalline organic compounds of allomicrites was not suitable for chromatography.

4 GEOCHEMICAL ASPECTS

Stable oxygen and carbon isotopes exhibit the same character in all studied specimens of automicrites/microbialites. The Mg-calcitic automicrites were precipitated in equilibrium with the ambient sea water and exhibit mean values of $\delta^{13}C$ +3.5 and $\delta^{18}O$ -1 ‰. This is typical for a non-enzymatic fractionation and the CO_2 source is from DIC. Most of the biologically controlled carbonates are in disequilibrium due to enzymatic fractionation (e.g. via carbonic anhydrase), as exemplified by the coralgal facies.

Large amounts of P and S were detected within calcifying mucus substances using EDX. Possible sources for the S are Ca-binding sulphate groups of polysaccharids and glycoproteins, and sulphur containing amino acids methionine and cysteine. Phosphor is related to lysing cells and therefore often enriched in decaying sponges. Si is related to sponge spicules and some radiolarians and clay minerals. Fe (as goethite) and Mn-oxids are common in Fe/Mn-microbial biofilms often with traces of Mo.

Part III
UPPER JURASSIC MUD MOUNDS: ALLOCHTHONOUS SEDIMENTATION *VERSUS* AUTOCHTHONOUS CARBONATE PRODUCTION
R. R. Leinfelder and H. Keupp

1 INTRODUCTION

If mud mounds are defined as buildups dominated by cryptocrystalline ('micritic') or peloidal carbonates, where the macrofauna does not form an obvious framework, a large number of Upper Jurassic reefs and massive buildups falls into this category. Mud mound characteristics are most common within siliceous sponge facies, but may occur also as a rare type of coral reef. Cryptocrystalline to peloidal crusts of microbial origin can dominate to form microbial crust reefs (LEINFELDER et al. 1993b). They represent true framestone reefs and are not considered mud mounds in the strict sense here, both because of the apparent crust-type
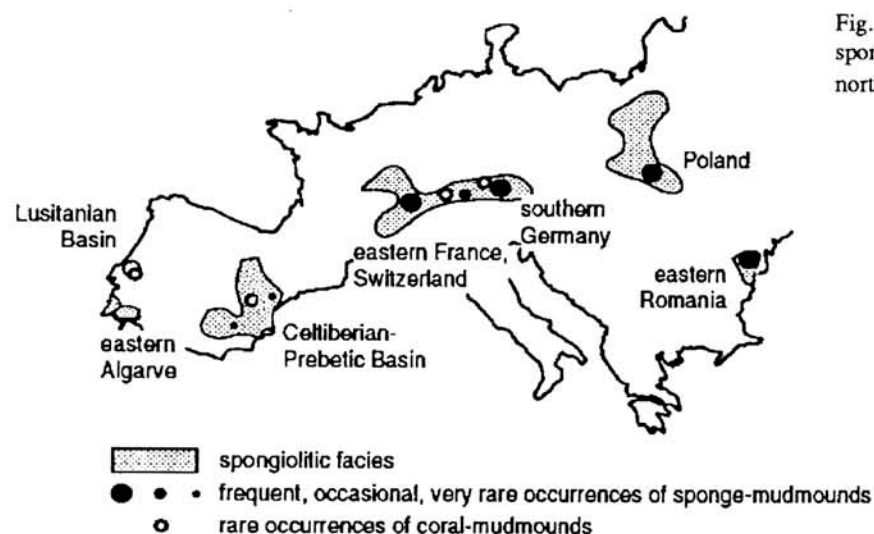
Fig. 2. Occurrences of Upper Jurassic siliceous sponge facies and mud mounds on the European northern Tethys shelf.

spongiolitic facies
● ● · frequent, occasional, very rare occurrences of sponge-mudmounds
○ rare occurrences of coral-mudmounds

nature of the carbonate and because the entire mound material obviously was hardened already at the time of formation. However, their mode of formation is of importance for understanding growth mechanisms of mud mounds as a whole. Additionally, non-correlatable lagoonal shallowing upward sequences up to 10 m thick were compared with Florida Bay type mud bank successions by LEINFELDER (1994).

Upper Jurassic mud mounds are here regarded of special significance for the general understanding of mud mounds, because most, though not all, exhibit sponge faunas as well as distinct, calcified microbial mats, i.e. distinct calcareous crusts. The co-occurrences of sponges and calcified microbial films or mats, are considered as crucial for mound formation by some authors (cf. REITNER 1993, REITNER & NEUWEILER, this set of contributions). Consequently, their participation in mound formation is often assumed, though not always obvious, for many other mud mounds from the Earth's history.

This contribution results from a comparative analysis of the entire range of Jurassic reef types presented elsewhere in greater detail (LEINFELDER 1993, LEINFELDER et al. 1994), to which the reader is referred for a more complete interpretation of factors controlling occurrence and characteristics of Jurassic reefs. In the present study we emphasize factors thought to be of particular importance for the growth of Jurassic mud mounds, namely microbial activity and the relative importance of allochthonous *versus* autochthonous generation of mound 'micrites'.

2 GEOLOGICAL FRAMEWORK
2.1 Location, structural unit, general environment, and age

Most Upper Jurassic siliceous sponge-microbial crust mud mounds occur in southern Germany, where they form part of limestone-dominated ammonitic limestone-marl successions, deposited on a very wide, initially near level-bottom, mid-ramp setting. Major episodes of mound formation were the Late Oxfordian and the Late Kimmeridgian. The dominance of fine terrigenous deposits resulted in a

setback of mound development during the Early Kimmeridgian (cf. GWINNER 1976, BRACHERT 1992). To a lesser extent, similar mounds occur within the Middle to Upper Oxfordian siliceous sponge facies of Romania, Poland, Switzerland, France, Spain and Portugal. Isolated coral-bearing to coral rich mud mounds have been located in southern Germany, Switzerland, eastern Spain and central Portugal. In Iberia they occur within shallowing-upwards succession at the base of widespread biohermal to biostromal coral reef facies (MEYER 1977, LEINFELDER et al. 1994). Most are of Kimmeridgian age. Except for central Portugal, all mud mounds formed within the peri-/epicontinental seas bordering the northern Tethyan margin (Fig. 2).

2.2 Size, geometry, architecture and dimensions of mounds

Both small (0.5-5.0 m in height) and large (> 50 meters) mud mounds occur in southern Germany and show a discrete zonation of facies (WIRSING 1988, SCHORR & KOCH 1985, BRACHERT 1992, KEUPP et al. 1993, LEINFELDER 1993, LEINFELDER et al. 1994). Commonly, basal crust-rich facies is followed upwards by more micritic types and/or by layers of intraclastic to peloidal packstones. Other examples show a general increase of crust at the expense of siliceous sponges. More frequently, crust facies has a patchy, unpredictable distribution. Other mounds are composed of crust and sponge containing micrite and/or pelmicrite. Late Kimmeridgian mud mounds diminish in number, in favour of buildups rich in allochthonous and autochthonous silt and sand-sized particles (KOCH in LEINFELDER et al. 1994). Small micrite-dominated mounds occur at the flanks of these grain-rich buildups. Larger mud mounds tend to develop on top of pre-existing ones, so that in certain areas, formation of micritic and peloidal mounds appears to occur across several ammonite zones or even stages, but they represent stacked and amalgamated mounds rather than one single mound only.

Oxfordian sponge mud mounds which occur within the biostromal siliceous sponge facies of Switherland and Spain, only a few meters thick developed extensively in homoclinal

Small high-relief sponge-crust buildups
Pronounced relief development only with a high abundance of crusts.
Diagnostic are: crusts of buildup bored laterally, cavities occupied by coelobites, onlap termination with bedded sediments
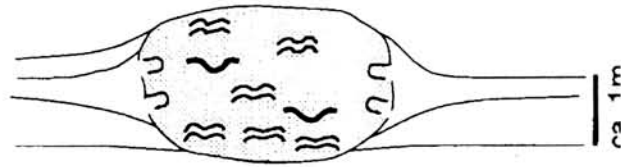
Large sponge-mudmounds with high primary relief
Diagnostic are: gravitational debris aprons, occasional slump scars, updomed bedded intercalations, formation of intermound basins, coral reef growth localised on top of mudmounds
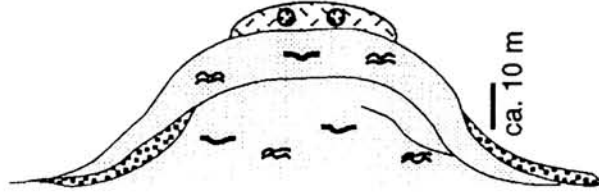
Low-relief sponge buildups, often small, occasionally large structures.
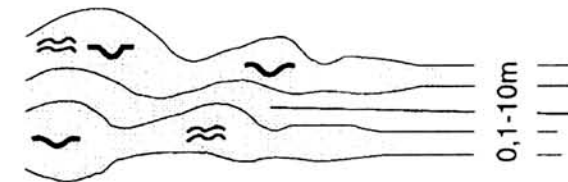Diagnostic are: lateral transitions with bedded sediments, subhorizontally bedded intramound areas

Fig. 3. Upper Jurassic spongiolitic mud mound geometries and internal composition. Mounds include both stratigraphic buildups representing stacked low-relief muddy biostromes as well as small and large ecologic buildups which developed a distinct primary relief.

to near level bottom midramp to outer ramp settings. In eastern Spain most sponge mud mounds occur within a narrow stratigraphic range (LEINFELDER et al. 1994). The same is true for southeastern Portugal, the few examples of where siliceous sponge mud mounds up to 6 meters thick occur in one single level which otherwise is dominated by the occurrence of thrombolitic microbial crust reefs one meter up to 30 meters thick (LEINFELDER et al. 1993a). Coral-bearing mud mounds do not exceed a couple of meters in height.

The microbial crust facies of biostromal and biohermal spongiolitic buildups contains a variable amount of mm to cm-sized cavities, particularly of the stromatactis-type. Some can be interpreted as shelter pores, whereas the majority of cavities appears to be related to internal erosion and reworking (cf. WALLACE 1987, KOTT 1989, MATYSKIEWICZ 1993). The high content of isolated sponge spicules within the spongiolites and the fairly frequent nearly complete preservation of non-rigid demospongia and hexactinellids by automicritic envelopes (GAILLARD 1972, DRESNAY et al. 1978, cf. REHFELD in LEINFELDER et al. 1994) suggests that the formation of many cavities results from the decomposition of organic material and the coeval precipitation of auto-micrites. Such processes are assumed for analogous examples of many Paleozoic mud mounds as well (see this set of contributions).

External geometries are very variable and often irregular, although an inverted cone to convex-upward hemi-spheroidal shape predominates. In some cases, the width of a mound appears narrower than its height, although this might be a two-dimensional outcrop effect of an originally elongated shape. The lateral margins are often oversteepened by compactional differences between massive mound and

the surrounding bedded limestone marl succession. The occurrence of debris aprons, coelobitic faunal dwellers in open mound cavities, onlap contacts to surrounding bedded sediments and topography-reflecting intercalation of marly horizons proves the development of a pronounced positive relief in many examples, whereas subhorizontal marl layers or indistinct limestone beds are indicative of stacking of low-relief biostromal bodies to form a stratigraphic buildup (*sensu* DUNHAM 1970, HECKEL 1974; cf. GAILLARD 1983: fig. 120) (Fig. 3). Rarely, small biohermal lenses cluster and amalgamate to form larger mound bodies (LEINFELDER 1993).

3 FORMATION AND PRESERVATION OF MUD MOUNDS
3.1 Bathymetric range

Based on the establishment of bathymetric faunal and floral gradients by comparative palaeoecology and sedimentological analysis, the coral facies is bathymetrically separated from siliceous sponge facies, with a broad overlap zone characterised by mixed coral-siliceous sponge facies (LEINFELDER et al. 1993a, LEINFELDER et al. 1994). Consequently siliceous sponge-bearing mud mounds should occur at depths generally deeper than 50 to 60 meters and mud mounds with corals from below fair-weather wave base to depths of about 30 to 40 meters (cf. GYGI & PERSOZ 1986, LEINFELDER et al. 1993a). Particle-rich muddy mounds with mixed coral-siliceous sponge fauna occasionally occur below coral reef facies. Within the siliceous sponge bearing mounds, the sponges of the Oxfordian examples are largely dominated by hexactinellid ('dictyid') sponges, whereas during the Kimmeridgian, lithistid Demospongiae were prevailing, which reflects a general shallowing (KEUPP et al.

Criteria - Explanation

- no boring organisms occur in most aphanitic material, *these are mostly attacked microbial crusts or macrofaunal hardparts, but only rarely early lithified aphanitic surfaces.*

- debris aprons normally are devoid of clasts with aphanitic fabric *but rather are composed of fragments of microbial crusts or sponge mummies ('tuberoids')*
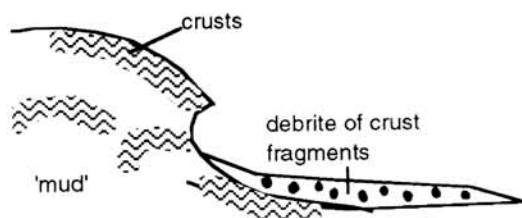
- bioturbation fabrics occur, although discrete burrows or endo-benthos are rare. *Oxygen depletion within mound sediments or early diagenetic hardening might restrict abundance of burrowing fauna*

- no petrographic differences between ammonite-bearing, aphanitic, bedded limestones and aphanitic parts of mounds. *Aphanitic parts of mounds are sometimes vaguely bedded, pointing to allochthonous sedimentation*

Fig. 4. Criteria for identification of primarily soft mud within Upper Jurassic mud mounds.

1990, LEINFELDER et al. 1993a, WERNER et al. 1994). However, even within single small mounds the concentration of siliceous sponge groups may vary, which is evidence that their distribution is not governed by bathymetry alone (LEINFELDER et al. 1994). Mud mounds without accompanying macrofauna are associated with sponge bearing mud mounds and, hence, apparently grew at similar water depths.

### 3.2 Organisms, burrows and borings

The organisms occurring in Jurassic reefs, including mud mounds, are discussed in more detail in LEINFELDER et al. (1994). The sponge-bearing mud mounds contain brachiopods, cementing bivalves, serpulids, bryozoans, gastropods, echinoids, glochoceratid ammonoids, belemnites, certain taxa of coralline sponges (particularly *Neuropora*) and small solitary corals besides the lithistid, lychniscosan and hexactinosan sponges. Faunal abundances are variable, but are mostly low. Rarely, siliceous sponges are dense enough to influence the style and structure of the mound. In some cases, siliceous sponges occur dominantly at the margins of the mounds. The coral mud mounds from Iberia are dominated by a community of meandroid corals (LEINFELDER et al. 1994). *Chondrites* burrows occur in some Oxfordian examples of siliceous sponge mounds. Distinct vertical burrows are rare but do occur in some examples. More common is a mottled fabric which appears related to bioturbation of soft muds. Borings in siliceous sponge mounds, mostly by the excavating sponge trace *Aka*, in coral-bearing mounds by *Cliona* and by lithophage bivalves (REITNER & KEUPP 1991), show that borers attacked calcar-

eous crusts or other macrofauna but very rarely affected homogeneous micritic parts. This indicates selective early lithification.

3.3 Composition and fabrics of mound sediments and calcareous crusts

Upper Jurassic mud mounds are composed predominantly of cryptocrystalline to peloidal carbonate. This is even true for larger mounds which developed a distinct positive relief. Although in some examples mound flanks may be secondarily oversteepened due to differential compaction, it appears that not only low-relief but also, particularly during the Late Kimmeridgian, also high-relief buildups existed. This raises questions as to the consistency and stabilization of the mound material. We will present evidence which indicates that:
* Upper Jurassic spongiolitic mud mounds were composed both of initially indurated carbonate (early lithified microbial automicrites, including microbial crusts) as well as of primary soft carbonate muds.
* primary soft carbonate muds represent both allochthonous material (allomicrites) and in place deposits.
* both calcified and uncalcified microbial mats and biofilms as well as organic matter from the interstitial water were important for stabilization of primary soft muds, although the influence of inorganic early diagenetic cementation is difficult to decipher.

Hardened automicrites (including microbial crusts) are easy to detect when they show features typical of calcified microbial crusts (cf. NEUWEILER 1993, LEINFELDER et al. 1993b). Such features include laminoid to irregular overgrowth of secondary substrates (e.g. sponges), macroscopic thrombolitic or, more rarely in Jurassic mud mounds, laminated stromatolitic fabrics. Analysis of Middle Jurassic spongiolitic biostromes (N-Spain: LEINFELDER et al. 1994) indicate partial subsurface formation of thrombolitic and peloidal carbonate crusts, precipitated under mostly anaerobic conditions within the sediment and cavities. Similar conclusions were drawn from Cretaceous buildups by NEUWEILER & REITNER (1993a), who related the origin of peloidal automicrites to subsurfaces processes, whereas dense, cryptocrystalline automicrites are considered to have grown on the surface, similar to modern examples in coral reef caves. This is in partial contrast with the examples from Iberia, where most peloidal crusts of thrombolitic buildups are intensively colonized by micro-encrusters (SCHMID in LEINFELDER et al. 1994). This suggests that automicrite fabrics are a fraction of process of numerous factors, thus similar fabrics may be caused by different processes.

Dense hardened automicrites (cryptobacterial crusts *sensu* RIDING 1991b) may be recognized macroscopically by their darker coloration, together with a crust-like appearance and partial reworking into irregular clasts (commonly known as

Interpretation - *Explanation*

* Crusts are important for constructing and stabilising mudmounds. *It is the amount of crusts, not of sponges, which is higher in sponge mudmounds than in sponge biostromes*
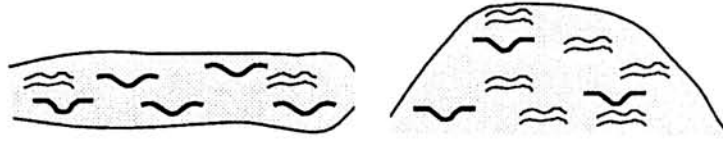
* Possibly more biofilms and microbial mats became calcified as crusts than during many other times of earth history. *No convincing explanation to date. Possibly generally elevated sea water alkalinity during the Late Jurassic? Distinct microbial associations without calcification inhibitors, producing high pH-EPS?*

* Calcification of mats mostly represents true calcification (of EPS) rather than trapping of particles. *Crust exhibit distinct calcification fabrics. Carbonate crust bioherms often occur within clay-rich successions*
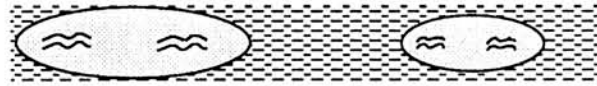
* Widespread occurrence of uncalcified biofilms and microbial mats is probable:
- *occasional occurrence of mudmounds or parts of them without crusts*
- *epifauna is not restricted to crusts only*
- *occasional transitions from soft mud to crusts*
- *domal grain fabrics, often without obvious crusts*
- *aphanitic texture of Jurassic supratidal LF-limestones does not differ from aphanitic muds*

Fig. 5. The importance of microbial crusts in the construction and stabilization of Upper Jurassic spongiolitic mud mounds.

'tuberoids' in Upper Jurassic sponge mud mounds, cf. FRITZ 1958). Clotted peloidal micrites, with peloids partly arranged in laminae are typical of microbial crusts, although dense cryptic fabrics occur as well. Sponge 'mummies' exhibit similar fabrics, indicating that sponge preservation is related to microbial activity. Borings by bivalves and sponges and the presence of microencrusters prove the early hardening of the crusts, but alone do not allow recognition of automicrites, since they also develop on hardgrounds, where primarily soft mud becomes microbially and diagenetically hardened at the sea floor. No new carbonate is produced except in interstitial pores. Problems exist particularly with non-crustose cryptocrystalline micrites. An automicritic origin may only be substantiated by geochemical analyses (cf. NEUWEILER 1993), if at all. It is assumed that hardened automicrites represent completely calcified microbial mats or stacked microbial films. The place of autoprecipitation of carbonate was probably the extracellulary polymeric substance (EPS), as examination of modern counterparts by REITNER (1993), has revealed. Different calcification textures are thought to be related to differences in microbial film characteristics, such as thickness, chemical composition, water content, microbial association, external microenvironment, internal pH and available time.
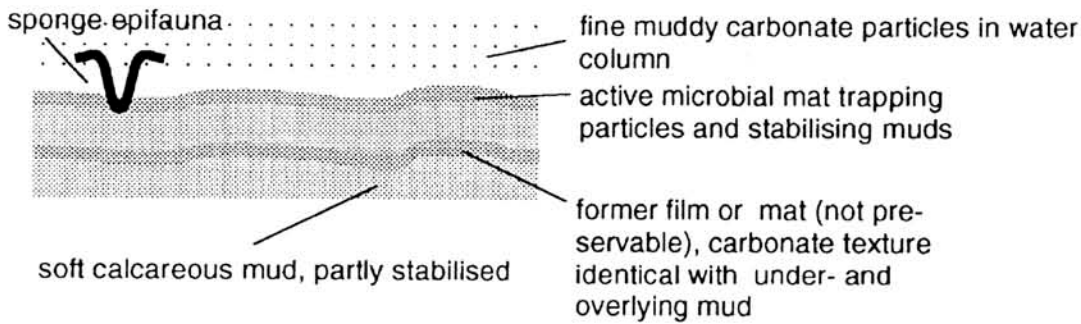
Some authors (e.g. RIDING 1991a), have suggested that microbial mats trap allochthonous material rather than autoprecipitate carbonate, and hence would be preserved by trapped allomicritic particles. If this was generally true for the Upper Jurassic examples, automicrite formation could

be ruled out. However, in both Upper Jurassic mud mounds as well as Jurassic reefs as a whole, the existence of microbial bioherms exclusively composed of microbial crusts within clayey and marly successions clearly corroborates the interpretation of calcareous crusts as automicrites. This does not exclude the possibility that Jurassic microbial films trapped particles. However, whenever the fabric of crusts is clearly different to the fabric of the over- and underlying micritic sediments, autoprecipitation of the crust carbonate is apparent.

Soft carbonate muds (allomicrites and soft in-place micrites): Particularly in the Oxfordian mud mounds of southern Germany, as well as in the Iberian mounds, a large part of the micritic material involved in mound formation must have been soft. This is indicated by the following observations: Bioturbation fabrics and rare burrows are present; gravitational debris apron composed exclusively of microbial clasts ('tuberoids'), indicates that soft mud was winnowed and redistributed; and indistinct slump features occur at the margin of the mounds (Fig. 4). The more clay-rich Oxfordian and early Kimmeridgian spongiolites contain a large number of the presumed soft-bottom dwelling brachiopod *Lacunosella* (BRUGGER & KEUPP in LEINFELDER et al. 1994). Also known from these sediments is *Tremadictyon radicatum*, the only dictyid poriferan species with root knots, which indicates adaptation to soft substrates (MÜLLER 1991).

On the other hand, some of these mounds were either

low rate of background sedimentation
microbial mat traps available allochthonous particle

sponge·epifauna · · · · · · · · · · · · · · · — fine muddy carbonate particles in water
column

— active microbial mat trapping
particles and stabilising muds

soft calcareous mud, partly stabilised

former film or mat (not pre-
servable), carbonate texture
identical with under- and
overlying mud

no allochthonous background sedimentation
microbial mat precipitates carbonate within extracellularly polymeric
substance --> clear textural difference between former mat and mud

sponge epifauna

— hardly allochthonous particles
in water column

active microbial mat with
stabilising effect
precipitation within EPS leads to
calcareous crust with distinct texture

older microbial calcareous crust
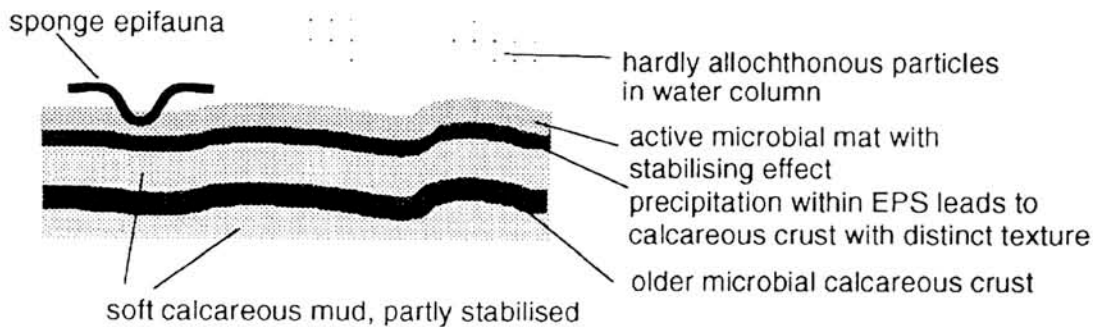
soft calcareous mud, partly stabilised

Fig. 6. Preservation of biofilms and microbial mats in Upper Jurassic mud mounds, in relation to allochthonous sedimentation.

initially indurated or hardened very early, which can be interpreted from the low accumulation rates involved. This is evidenced by decimeter to meter-scaled biohermal blocks which were transported within slumps or debris flows. It appears that induration of soft muds in the Late Kimmeridgian mounds was more rapid than in the earlier ones. This may have been related to the shallower water, a high amount of peloidal packstone to grainstone fabrics with an elevated primary porosity, and, possibly, a denser concentration of microbial mats.

To some extent, the primary soft pure to peloidal carbonate muds must represent soft in-place material. This is obvious for small mud and crust-rich mounds which developed within clayey to marly successions (Fig. 5). NEUWEILER & REITNER (1993) restrict the term automicrites to early lithified microbialites. Therefore, accumulation of crypto-crystalline to peloidal, soft *in situ* carbonate is termed here 'in-place carbonate muds'. Soft in-place muds have a variety of origins. Among the possible sources are: the products of borings made by microbes, algae, fungi or higher organisms attacking the calcified microbial crusts; the excrements of carbonate crunchers and abraders; the loose skeletal elements of soft body organisms such as gorgoniaceans; car-

bonate precipitation in flocculated biofilms; or destruction of incompletely calcified EPS material of microbial films or mats by altered microchemistry or by feeding organisms. Therefore, in-place muds appear to be derived from a mixture of destructive and productive in-place processes.

Allomicrites must be, however, important in the formation of larger mounds. Large mounds only exist within limestone dominated successions, indicating that a substantial part of the allochthonous material of the bedded facies, was accumulated in the mud mounds. The carbonate muds are thought to be derived mainly from the carbonate factories of the shallower waters. Coccoliths are very rare within the successions which is interpreted as a primary feature rather than diagenetic disguise (see BRACHERT 1992).

The role of microbial mats: Calcified microbial films or mats, i.e. automicritic microbial crusts, play an important role in the formation of mud mounds. The fact that they are more common in sponge-bearing mounds than in associated sponge biostromes clearly proves their importance in the formation of high-relief buildups (Fig. 4) (LEINFELDER et al. 1994). They directly and indirectly contribute to the growth of the buildup, by producing carbonate as well as by stabilizing soft sediments.

4. **elevated allochthonous sedimentation**
mudmound becomes buried by bedded muddy sediments

3. **cessation of allochthonous sedimentation** (cf. 1)
revival of formation of automicrites and in-place soft muds;
occasional gravitational collapse leads to 'tuberolitic' debris sheets

2. **low rate of allochthonous sedimentation**
(horizontal or vertical transport)
trapping of mud and partial stabilisation by sticky microbial films and mats;
upbuilding of mound;
lack of distinct calcification pattern prevents recognition of position of former mats and films

1. **cessation of allochthonous sedimentation**
Initiation of mounds growth on initial hardground; allomicrites and in-place muds

dominance of allochthonous soft mud

dominance of in-place soft muds and indurated automicrites without crust features

crust-type automicrites (calcified biofilms and microbial mats)

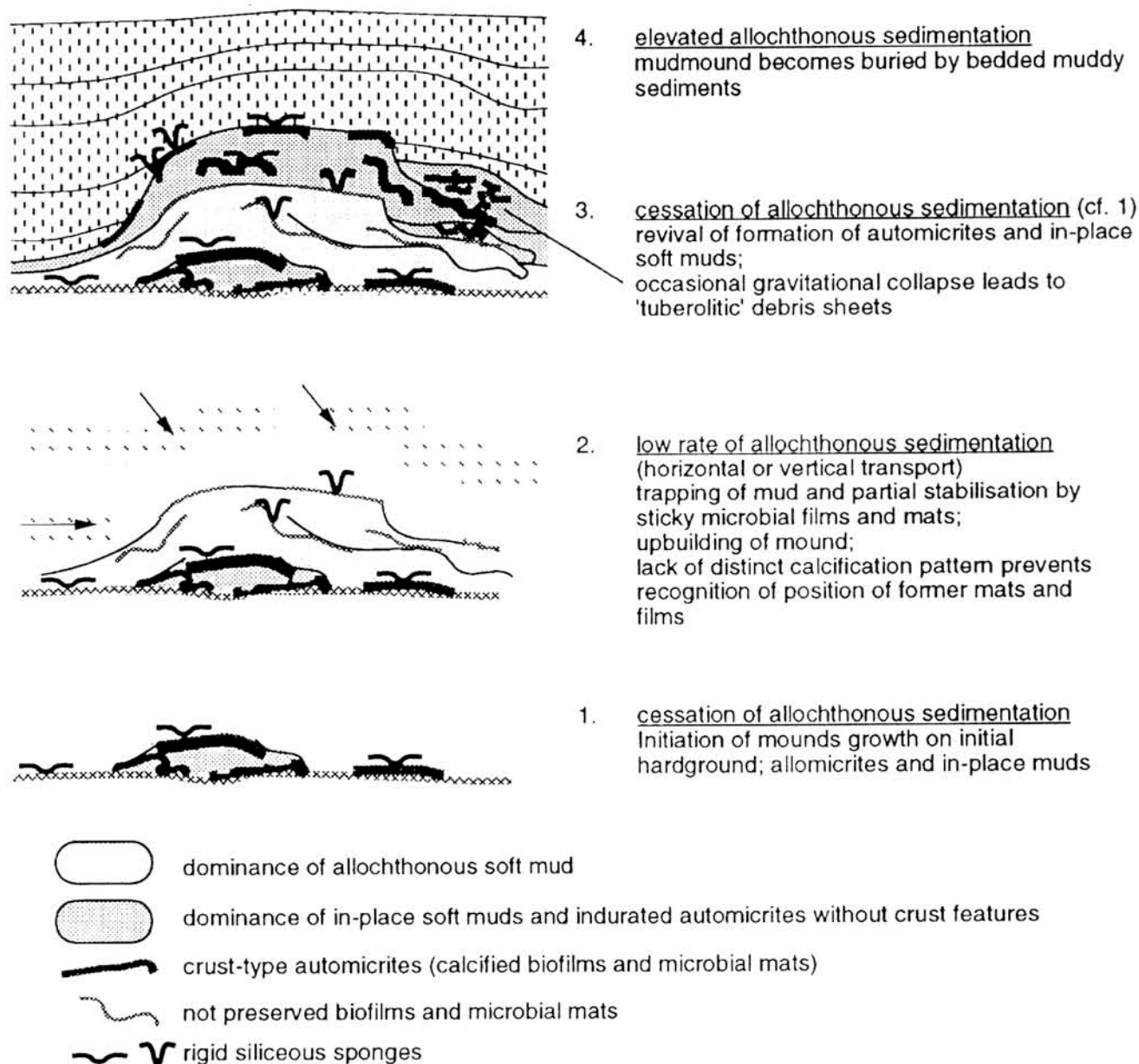not preserved biofilms and microbial mats

rigid siliceous sponges

Fig. 7. Formation of spongiolitic mud mounds by microbial automicrites, in-place muds and allochthonous mud. It is assumed that large Upper Jurassic mud mounds required occasional pulses of allomicritic sedimentation in a transgressive third-order regime characterised by generally reduced rates of background sedimentation. The series is theoretical and cannot be observed in the field. It is assumed that in most Jurassic mud mounds automicritic production, in-place sedimentation and allomicritic deposition was variable and changed in a high-frequency order.

However, although the abundance of crusts is often high, it does not appear high enough to be responsible for the stabilization of large mounds which show features indicative of large amounts of soft material. Crusts never form entire horizons and are very rare in some mounds. This suggests that uncalcified microbial films or mats also played an important role in mound stabilization. Another hint for such interpretation is that epibenthic fauna is not only restricted to microbial crusts, but occurs within the supposed soft muds, indicating that they were partly stabilized. Also, gradual transitions from muddy micrites to indistinct micritic crusts exist. These crusts are only identifiable by a slightly different weathering behavior, but otherwise represent the same macroscopic and microscopic fabric as the surround-ing micrites. Moreover, in the Upper Kimmeridgian mounds, fabrics composed of a large amount of allochthonous grains (see KOCH in LEINFELDER et al. 1994) form domal structures which only rarely are transected by thin microbial crusts. It must be assumed that uncalcified mats helped in the stabilization of these domes.

Obviously, the widespread autoprecipitation of carbonate in the EPS of microbial mats or films, which results in the typical crust-diagnostic features, could be inhibited. A likely explanation is that allochthonous sedimentation was slightly elevated in these cases, whereas the crust bioherms of Iberia are always related to horizons of complete sediment starvation (LEINFELDER et al. 1993b), giving time for autoprecip-itation of carbonate within mats (provided other factors, e.g.
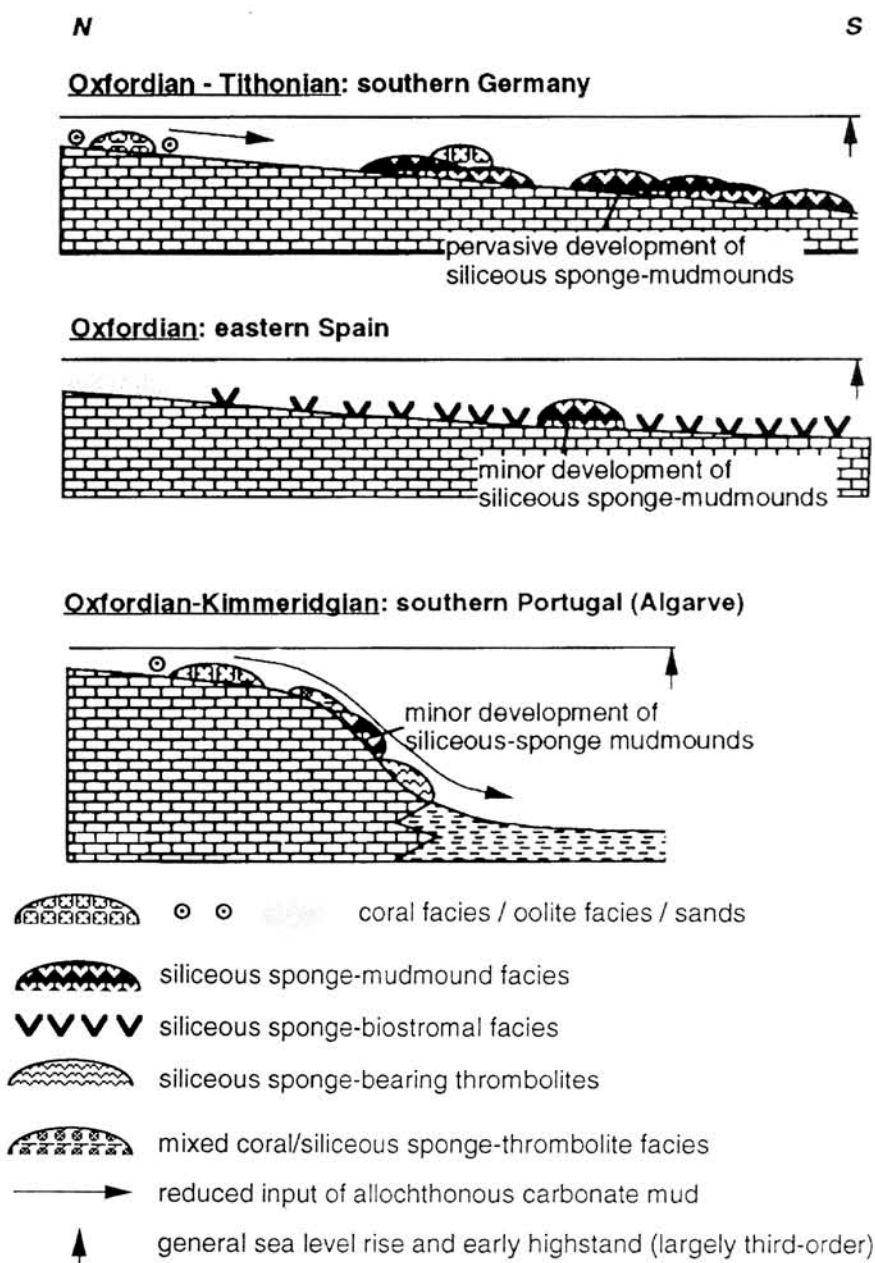
N   S

Oxfordian - Tithonian: southern Germany

pervasive development of
siliceous sponge-mudmounds

Oxfordian: eastern Spain

minor development of
siliceous sponge-mudmounds

Oxfordian-Kimmeridgian: southern Portugal (Algarve)

minor development of
siliceous-sponge mudmounds

 ⊙ ⊙   coral facies / oolite facies / sands

   siliceous sponge-mudmound facies

V V V V   siliceous sponge-biostromal facies

   siliceous sponge-bearing thrombolites

   mixed coral/siliceous sponge-thrombolite facies

⟶   reduced input of allochthonous carbonate mud

↑   general sea level rise and early highstand (largely third-order)

Fig. 8. Dependance of mud mound formation on shelf configuration. Very gently inclined homoclinal mid-ramp configuration together with a moderate rate of allochthonous sedimentation is favourable since imported mud can be redistributed and swept towards the mounds, whereas in steepened ramp settings allochthonous mud is largely bypassed towards distal areas. Note that in the Celtiberian example mud mounds formed very rarely despite a nearly flat homoclinal ramp configuration. The generally low thicknesses and the high proportion of automicrites in this example suggests that allochthonous mud sedimentation was too low rather than too high for mud mound formation. Generalized configurations of the northern Tethys shelf modified from LEINFELDER (1993a).

slightly elevated alkalinity of sea water, were favorable as well). The sticky mats will have trapped allochthonous fine particles, which resulted in a general sedimentary fabric identical to simple muds (Fig. 6). The existence of microbial mats which did not become calcified but rather trapped particles is easily verified in intertidal to supratidal laminoid fenestral limestones ('loferites'), which are widespread in the Upper Jurassic (e.g. FÜRSICH & SCHMIDT-KITTLER 1980, LEINFELDER 1994). Here the former existence of subhorizontal mats is only detectable by the preservation of fenestrae which is related to the rapid cementation in this shallow environment. The sediment itself is normally a homogeneous micrite and shows no differences from other micritic carbonates, e.g. lagoonal limestones.

Whenever a mat was completely clogged by allochthonous sediment, the EPS could not fulfil its tasks as a protective host substrate and nutrient reservoir for the microbial associations, and a new biofilm had to be developed on the top of the new surface. The stickiness of the former films,

and possibly, a more rapid cementation (though without crust-diagnostic features) helped to stabilize the mounds. Theoretically, there should be a positive correlation between the richness of microbial crusts and the amount of non-crust type automicrites. Thus muds which contain few microbial crusts (but do incorporate non-calcified microbial mats or films) should be largely allomicrites, although this remains to be proven by data in the future.

Fig. 7 shows a conceptual model of the formation of Upper Jurassic mud mounds in relation to the variable amount of automicrites, allomicrites and crusts.

4 CONTROLLING FACTORS

Many of the factors controlling Upper Jurassic mud mounds are of general importance in controlling the composition and distribution of Jurassic reefs as a whole. These factors were discussed in LEINFELDER 1993, KEUPP et al. 1993, LEINFELDER et al. 1994. The distribution and growth

patterns of reefs, including mud mounds, clearly indicate that they are related to phases of reduced allochthonous sedimentation. They are particularly related to phases of rising sea level (transgression and early highstand). As for mud mounds, phases of slightly elevated (but not high) allochthonous carbonate sedimentation helps in the building of mounds which were stabilized by microbial mats trapping allomicrites, whereas a very reduced background sedimentation results in the formation of crust-rich, largely automicritic mounds (Fig. 7), provided other, partly unknown, preconditions for the formation of crusts existed. Among the possible causes are slightly increased alkalinity or other chemical sea water characteristics, and the low to moderate abundance of grazing organisms. Upper Jurassic mud mounds may have occurred at all water depths below fair weather wave base, but were most abundant in mid-ramp to the upper part of outer homoclinal ramp settings. In distally steepened ramp settings, mud mounds frequencies diminish in favor of pure microbial crust reefs. This is explained by the longer resistence time of allochthonous material in homoclinal ramps, where it can be swept towards mounds with sticky surfaces by weak, irregular contour currents. Allochthonous material was easily bypassed towards distal settings in distally steepened ramps, and thus had the opportunity to contribute to the accumulation of mud mounds. However, if no shallow-water carbonate factory existed in homoclinal ramps, as may be assumed for the Iberian example, the rate of allochthonous carbonate sedimentation will fall to zero. This may have prevented accumulation of allomicrites and suggests that automicrite production alone rarely accounts for mud mound formation (Fig. 8). The Middle and Upper Jurassic Iberian ramp is largely dominated by sponge biostromes rich in automicrites, whereas mound structures are very rare (cf. KRAUTTER in LEINFELDER et al. 1994, REHFELD-KIEFER in LEINFELDER et al. 1994).

The partial to complete disappearance of reefal macrofauna in many of the Jurassic microbial crust reefs, even in those formed in fairly shallow water, is explained by fluctuations in bottom water oxygenation as a result of sea level - circulation feedback by LEINFELDER (1993) and LEINFELDER et al. (1993a,b). This interpretation is based on the occurrence of dysaerobic elements. The reduction of macrofauna in some but not all Upper Jurassic mud mounds is more difficult to assess. If mud mounds grew under high background sedimentation rates, the softness of the substrate and clogging of filtering apparatuses would have prevented macrofauna from growing. However, the abundance of crusts and encrusting microorganisms as well as the possible correlation of mud mound development with third order transgressive phases shows that background sedimentation was generally low, though somtimes fluctuating. Influx of allomicritic material is thought to have occurred during storms and sea level falls of fourth and higher order. The sometimes exclusive occurrence of elements indicating dysaerobic conditions (e.g. *Terebella, Chondrites*, authigenic glauconite, disperse and framboidal pyrite) and thick irregular levels of pure thrombolitic crusts suggests that oxygen depletion also struck some mud mounds. Similar conclu-

sions based on enrichment of high nutrient dependent organisms below and above small mounds were drawn by BRACHERT (1992) who suggested that the demise of mounds was related to enhanced oxygen depletion. However, the moderate diversity of the fauna in most Upper Jurassic mud mounds shows that oxygen depletion was rare.

5 CONCLUSIONS

*Many Upper Jurassic buildups are mud mounds. They are dominated by cryptocrystalline material, a variable amount of which represents primary soft mud. Macrofauna occurs in variable quantities but did not form a rigid framework. Most mounds are siliceous sponge - microbial crust mud mounds, but coral mud mounds occur occasionally.

* Hard automicrites, most of which are of the crust-type, were important in the formation of mud mounds, by contributing to the mound material and stabilizing soft areas. In comparison with modern counterparts (cf. REITNER 1993) their microfabrics suggest that they represent precipitates within the extraculary polymeric substance of organic films or mats largely produced by microbial activity. The formation of some automicrites appears to have been related to the decay of organic material in interstitial waters.

* Bioturbation, the existence of gravitational debrites composed of crust-fragment and other features indicate the existence of soft mud which includes both allomicrites and mud produced in-place within the mound by a combination of biodestruction and bioproduction. Soft in-place mud must be assumed for bioturbated, micritic, crust-rich carbonate mud mounds developing within clay-dominated successions. Soft mud, both in-place and allochthonous, is thought to represent a major constituent of Oxfordian mounds but may have become less abundant towards the Late Kimmeridgian.

* Low abundance of calcareous crusts in some mounds or parts of mounds, together with features indicating soft mud suggest that uncalcified microbial films and mats also played a major role in stabilizing soft sediment areas as well as trapping allomicrites. Early cementation of soft mud is obvious in transported mud mound blocks, and may have commenced within microbial mats. Comparison with supratidal Jurassic loferites suggests that mats which trapped particles do not show a distinct precipitation fabric although they may have hardened very early. This is in contrast with the microbial crusts which formed under zero background sedimentation and show distinct features which make them discernible from the overlying and underlying micritic sediments.

* Upper Jurassic mud mounds largely developed during third-order TST and early HST, when allochthonous sedimentation was strongly reduced. It is assumed that allochthonous material was imported during storms or high-frequency regressions, and swept towards the sticky surfaces of the mounds by contour currents. Phases of very reduced or zero sedimentation allowed for the development of microbial crust and other automicrites and facilitated early diagenetic hardening at the sea floor.

* Some Upper Jurassic mud mounds grew directly below

fair weather wave base (coral mounds), although the majority of them grew in homoclinal to near level-bottom mid to upper outer ramp settings. The latter characteristically contain siliceous sponges in very variable quantities. Rare phases of oxygen depletion occasionally prevented the growth of macroorganisms.

* Future research on Jurassic mud mounds will have to focus on clearer identification of automicrites *versus* allomicrites and on the detection of features indicative of primary hard *versus* soft material as well as the detection of early diagenetic hardening.

Part IV
EPIFLUORESCENCE-MICROSCOPY OF SELECTED AUTOMICRITES FROM LOWER CARNIAN CIPIT-BOULDERS OF THE CASSIAN FORMATION (SEELAND ALPE, DOLOMITES)

F. Neuweiler and J. Reitner

1 INTRODUCTION

The Carnian 'Cipit-boulders' of the Central Dolomites are well-known to sedimentologists and paleontologists because of the exceptionally high quality of preservation. The sediments of the Cassian Formation (Middle to Upper Triassic) represent various depositional environments ranging from a backreef area, rimmed carbonate platform, slope

and distal basinal subenvironments (FÜRSICH & WENDT 1976). 'Cipit boulders' (RICHTHOFEN 1860) are typical for large parts of the basin and reach sizes of up to several hundred cubic meters (FÜRSICH & WENDT 1977). Their origin is most probably related to an accumulation of boulders and blocks along the active platform margin and episodic basinward displacement by gravity mass movements (olisthostromes). Paleontological work on the Cassian formation has focused on taxonomy, paleoecology and paleobiology (CUIF 1974; FÜRSICH & WENDT 1977; KEUPP et al. 1989; MÜLLER-WILLE & REITNER 1993) Sedimentological work has been concerned with facies, reef types, and paleogeography (FÜRSICH & WENDT 1976; WENDT & FÜRSICH 1980; WENDT 1982), sequence stratigraphy (BOSELLINI 1984) and detailed analyses of diagenetic pathways (SCHERER 1977) combined with the depositional history (RUSSO et al. 1991).

Many of the Cipit boulders contain accretionary organomicrites analogous to those described as dense micritic/fenestral microbialites from Lower Cretaceous mud mounds (NEUWEILER 1993). These organic structures have been described as 'algal crusts', e.g. FÜRSICH & WENDT (1977), RUSSO et al. (1991) or as 'encrusting thrombolitic associations of bacteria' by KEUPP et al. (1989). Meanwhile an organic film mediated mineralization is suggested for such structures, independent of light and linked with sites and episodes of extremely reduced sediment supply (REITNER 1993; NEUWEILER 1993). CUIF et al. (1990) and MÜLLER-WILLE & REITNER (1993) used fluorescence microscopy to detect the relative amounts of organic residues in order to study the

Plate 6   Lower Carnian automicrites (organomicrites) from the Cassian Formation, Seeland Alpe (Dolomites). Fluorescence microscopy with incident light; high performance wide-bandpass filter BP 450-490 nm/LP 520 (blue, no. 487709).

Fig. 1.   Organomicrite/sponge boundstone mainly consists of the thalamid coralline sponge *Cryptocoelia* (S), thrombolitic (t), and massive (m) automicritic fabrics. Note bioclastic packstone deposits at upper right corner of the hand specimen. Polished slab; scale bar = 5 cm.

Fig. 2.   Thin section of organomicrite/sponge boundstone: The basal parts consist of cauliflower-like structures generated by non-lithistid demosponges which grade into thrombolites with distinct stromatolitic microfabric (t). This stage is followed by inreasing sediment supply resulting in massive automicrites (m), clearly separated from pure allochem deposition (lighter areas). Note irregular surfaces of massive automicrites and their geometric control related to precursor thrombolites. + for orientation in Fig. 3. Thrombolite is 4 mm thick.

Fig. 3.   Detail of Fig. 2. Bright fluorescence of thrombolite considered the main locus of enclosed organic substances (e.g. aromates). Internal variation of fluorescence illustrates the primary rhythmicity of accretion. Note the episodic occurrence of microfenestral intervals. Distinct fluorescence halo (arrows) are present within sediments enriched in allochems. This fabrics suggests both, that automicrite still formed within interstitial pore space and that the benthic microbial system provided the source of reactive organic matter (acidic organic macromolecules?). Allochems correspond to organomicritic intraclasts, micritic intraclast (micritization of bioclasts) and angular bioclasts. Scale bar = 400 μm.

Fig. 4.   Organomicrite with incorporated allochems within interpillar pockets (p) and at outer marginal sites (arrows). After allochem deposition the automicrite was produced within the interstitial pores. Scale bar = 100 μm.

Fig. 5.   *Cryptocoelia* (s) and massive organomicrites (m) form a boundstone texture resulting in larger sedimentary pockets (p). x for orientation in Figs. 6 and 7; width of figure = 17 mm.

Fig. 6.   Detail of fig. 5 with fluorescence halo (arrow) and complete automicritic bridges across former sedimentary pockets; scale bar = 400 μm.

Fig. 7.   Detail of fig. 6, illustrating the common bright fluorescence of organomicrites and horizontal chamber layers of *Cryptocoelia*. Note the microgranular microstructure of *Cryptocoelia* chamber layers; scale bar = 100 μm.

Note: References are given for the entire Reitner & Neuweiler (coord.)-article.

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ACKNOWLEDGEMENTS

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