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A Modern-Type Kimmeridgian Reef (Ota Limestone, Portugal): Implications for Jurassic Reef Models

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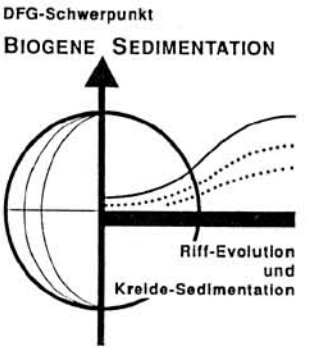

KEYWORDS: CORAL REEFS – MICROBIAL CRUSTS – SEDIMENT BALANCE – PALAEO-OCEANOGRAPHY – REEF MODELS – PORTUGAL – UPPER JURASSIC (KIMMERIDGIAN)

SUMMARY

Upper Jurassic reefs rich in microbial crusts generally appear in deeper (sponge - 'algal' crust reefs) or in very shallow but protected settings (coral or coral-coralline sponge meadows with 'algal' crusts). Upper Jurassic high-energy reefs (coral reefs and coral-stromatoporoid reefs) normally lack major participation of microbial crusts but rather represent huge bioclastic piles with only minor framestone patches preserved.

An exception to this rule is represented by the high-energy, coral-'algal' Ota Reef from the Kimmeridgian of the Lusitanian Basin (Portugal). The narrow Ota Reef tract rims a small intra-basinal carbonate platform exhibiting perfect facies zonation (from W to E: Reef tract, back reef sands, peritidal belt, low-energy shallow lagoon). The reef is dominated by massive corals (*Thamnasteria, Microsolena, Stylina*). Complete preservation of coral framework is rare: like other Upper Jurassic high-energy reefs, the Ota Reef is very rich in debris; however, this debris is largely stabilized by algal and microbial crusts, what contrasts the other examples and gives the Ota Reef the appearance of a typical modern high-energy coral-melobesioid algal reef. Further similarities to modern reefs are the likely existence of a spur-and-groove system, the perfect sheltering of inner platform areas and the occurrence of small islands, as indicated by local blackenings and early vadose and karstic features.

The exceptional character of the Ota Reef is thought to be due to the establishment of an equilibrated sediment balance. In a modern high-energy reef, physical and biological genereration of debris is compensated by
(1) stabilization of loose debris by binding organisms, chiefly melobesioid algae,
(2) accelerated coral-growth in order to keep pace with sedimentation, and
(3) export of surplus material into back reef and fore reef areas through wave action.

Since during the Late Jurassic, fast growing corals were rare and only less effective microbial binders were available, sediment balance could normally not be achieved in a comparable high-energy setting. This resulted in the increasing loss of stable bottom due to sedimentation and eventual suffocation of reef patches. However, in the Ota example the existence of a steep by-pass margin accounted for equilibrated sediment balance:
(1) along the steep margin additional gravitational export was possible;
(2) the steepness of the margin kept the reef tract narrow, so that it could be well winnowed by a longshore current system along the east side of the basin;
(3) the remaining loose debris could, to a large extent, be stabilized by the available algal-like and microbial binders (thrombolitic-peloidal crusts, *Bacinella, Lithocodium, Thaumatoporella, Tubiphytes*).

1 INTRODUCTION

Modern coral reefs commonly grow in shallow-water, high-energy settings. Barrier or wall reef complexes, for example, are characteristic high-energy buildups common in the Carribbean and Pacific realm (e.g. GEISTER 1975, 1983, MARSHALL & DAVIES 1982, HAMELIN-VIVIEN & LABOUTE 1986). Modern and subrecent reef core deposits of such high-energy complexes include only a moderate percentage of framestones with reef organisms in growth position. These are in turn encased in both coarse and fine-grained bioclastic debris. Both framestones and debris material are heavily encrusted and stabilized by sediment binders, notably coralline meliobesioid red algae. Where the top part of the reef wall is exposed to an

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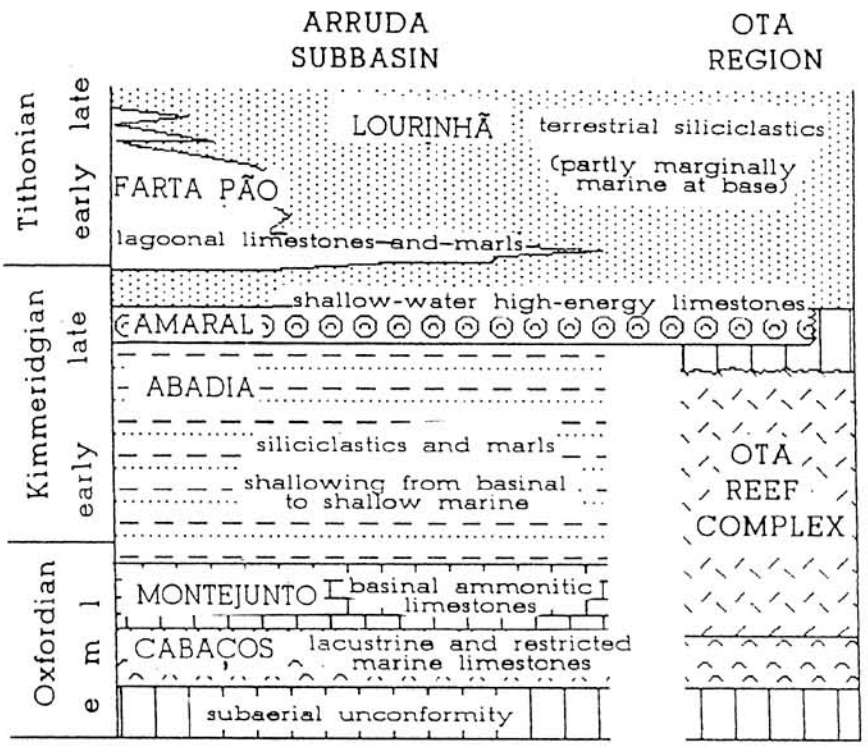


Fig. 1. Simplified lithostratigraphic framework for the Upper Jurassic succession of the Lusitanian Basin of Portugal. Shown is the standard succession of the Arruda Subbasin in the centre and the Ota Region at the eastern margin of the Lusitanian Basin. The age for the lower part of the Ota Limestone is speculative.

open oceanic high-energy wave breaker zone, an algal ridge composed solely of coralline algae typically develops (e.g. GEISTER 1983).

Hence, many modern high-energy reefs lack large areas of unstabilized debris material. Loose material is baffled within coral thickets or between framestone pillars where it subsequently becomes stabilized and hardened by sediment binders prior to inorganic cementation. Hurricane-produced debris may also become rapidly stabilized by encrusting organisms (HAMELIN-VIVIEN & LABOUTE 1986, ZANKL & SCHWABE pers.comm.). Commonly, canyon-like submarine valleys cross-cut the fore reef and outer reef wall. This leads to the typical spur-and-groove system which characterizes many modern high-energy reefs (SNEH & FRIEDMAN 1980, SHINN et al. 1981, SHINN 1988, JAMES 1984b). Grooves are the only sites within the outer reef tract and the upper fore reef where loose, unstabilized debris may accumulate at a larger scale. In some examples grooves occur in the back reef zone as well (GEISTER 1983).

Generally, high-energy reefs from the Late Jurassic differ from modern ones not only by their taxonomic composition but also by their sediment architecture and, partly, by their basinal setting. CREVELLO & HARRIS (1984) established reef models for the Upper Jurassic, which were later reinforced and slightly modified by SCOTT (1988). According to these authors, Upper Jurassic reefs growing along high-energy platform margins are composed of only minor amounts of reef framework patches embedded within huge, unstabilized bioclastic piles (coral reef types 2b, c and 3 of CREVELLO & HARRIS 1984). A frequently cited Upper Jurassic high-energy barrier reef is described from Yugoslavia by TURNSEK et al. (1981). Although mainly based on qualitative thin-section studies, a somewhat higher degree of binding seems to be achieved in this case by the widespread occurrence of encrusting stromatoporoids. To some extent a similar role may be played by specialized sponges in modern reefs (WULFF 1984). Except for the rear parts of Upper Jurassic stromatoporoid-rich reefs encrusting 'algae' are, however, largely absent and unstabilized debris also piles up to large proportions (cf. STROHMENGER 1988; Stromatoporoid-coral-algal reefs of SCOTT 1988). The shallow-water reefs of the Upper Jurassic Plassenkalk (Austria) are somewhat exceptional in that larger patches of debris material became stabilized by encrusting algal-type forms, particularly *Bacinella* (STEIGER & WURM 1980). Many other upper Jurassic reefal structures are well stabilized by micritic crusts, which according to many authors appear to represent encrusting 'algae' or rather microbes, possibly of cyanobacterial or bacterial origin (e.g. GAILLARD 1983, LANG 1989, KEUPP et al. 1990). The models of CREVELLO & HARRIS (1984) and SCOTT (1988) place such crust-rich structures in the deeper offshore waters of ramp settings (sponge-algal reefs) or in deeper parts of protected lagoonal settings (sponge-coral-algal reefs). These models are mainly based on reef occurrences from North America and Central Europe, and actually apply to most reef structures observed within the Upper Jurassic of the Lusitanian Basin of Portugal. There, coral reefs or coral meadows rich in microbial crusts and occasionally sponge-bearing generally characterize deeper or protected settings, whereas high-energy coral reefs represent bioclastic piles with only subordinate amounts of reef framework (LEINFELDER 1989, ELLIS et al. 1990). However, an important exception to this rule and hence to the mentioned models is represented by the Ota Coral Reef which exhibits both high-energy features and a very large amount of reef core material stabilized by algal-type and microbial crusts.

2 GEOLOGICAL SETTING OF THE OTA REEF COMPLEX

The following review on the development of the Lusitanian Basin is mainly based on WILSON (1979), LEINFELDER (1987a), LEINFELDER & WILSON (1989) and WILSON et al. (1989). The Lusitanian Basin which houses the Upper Jurassic Ota Reef Complex is an ocean marginal basin that owes its existence and development to the opening phases of the

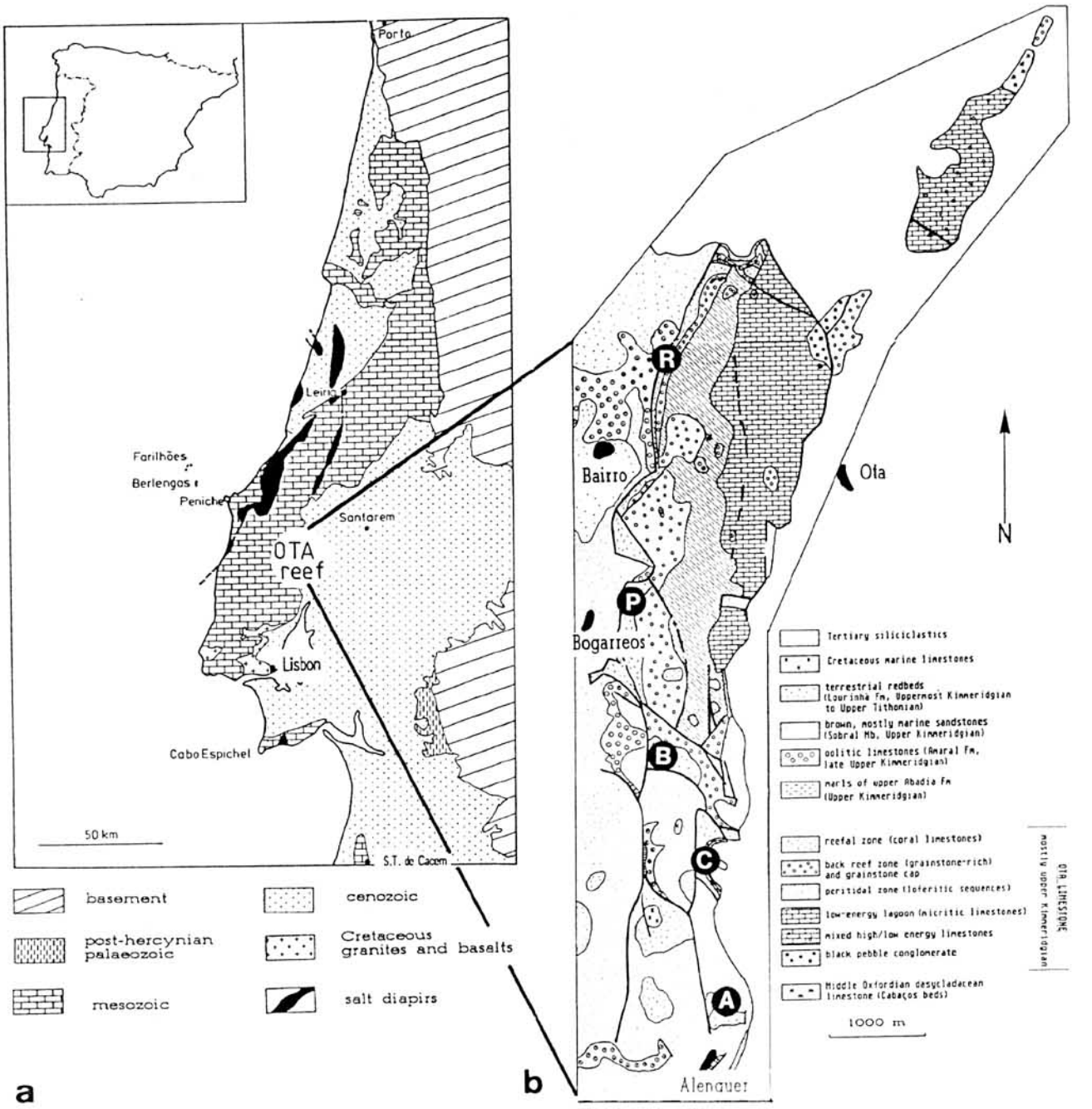


Fig. 2. Geological map of the central Lusitanian Basin (a), and geological/facies map of the Ota area. (b)Location of Ota reef zone sections (b): A = Alenquer, C = Casal Vale Junco, B = Bairro 1, P = Pedreiras Santa (windmill), R = S Rio Ota.

North Atlantic ocean. After Late Triassic and earliest Liassic red bed and evaporite sedimentation of the initial rift phase, gulf phase carbonates and marls developed during the rest of the Early and the Middle Jurassic. This phase culminated in the widespread development of Bajocian to Callovian shallow-water carbonate platforms, mostly of the ramp-type. The Upper Jurassic and Lower Cretaceous development mirrors the rejuvenance of rifting, heralding the onset of sea floor spreading in the Tagus abyssal plain of the eastern North Atlantic. After a tectonically induced regional Lower Oxfordian subaerial unconformity and Middle Oxfordian mixed salinity sediments, intense differentiation into deep-water and shallow-water marine carbonates commenced at the base of the Upper Oxfordian. From the uppermost Oxfordian onwards, intensified rifting caused uplift and subaerial exposure of basement blocks along the eastern and western basin margin, resulting in major input of terrigeneous sediments into the basin. During the rest of the Late Jurassic epoch carbonates were, nevertheless, produced on uplifted blocks or in variously controlled carbonate-siliciclastic depositional systems (LEINFELDER 1987a, 1989; in prep., ELLIS et al. 1990). The Ota Reef Complex developed over an uplifted basement horst close to the eastern basin margin, more precisely on the eastern flank of the Arruda pull-apart subbasin (LEINFELDER & WILSON 1989). Although correlation with ammonite zones is not possible, a 'late' Kimmeridgian age of the complex is indicated by the combination of a microfossil assemblage of diagnostic dasycladaceans

(*Clypeina jurassica, Campbelliella striata*) and foraminifers (*Labyrinthina mirabilis, Alveosepta jaccardi*) together with structural relationships (LEINFELDER et al. 1988). Hence, the Ota Complex appears to be coeval with the siliciclastic Abadia formation, the latter of which represents a prograding slope-basin system (LEINFELDER & WILSON 1989). During the Tithonian, Cretaceous and Tertiary the basin was subsequently filled up with siliciclastics, so that only small marine areas of shallow, partly lime-dominated lagoons remained (Fig. 1).

3 FACIES DEVELOPMENT, COMMUNITIES AND ARCHITECTURE OF THE OTA REEF COMPLEX

The Ota Reef Complex presently forms a 10 km long, up to 2 km wide horst structure which is partly draped by late Upper Jurassic and Tertiary sediments. Fig. 2 shows the well developed facies zonation, in W-E direction, of a narrow reef belt, followed by grainstone-rich backreef sediments, and by peritidal and lagoonal low-energy carbonates. A narrow exposure of grainstones along the northeastern border of the structure may indicate the position of the former eastern margin of the Ota Complex. Some additional grainstone patches are preserved on topographic highs throughout all facies zones of the Ota limestone. They represent relics of a grainstone cap which witnesses the decline of the complex due to structural uplift. Complex karstic features developed both prior and posterior to the formation of the grainstone cap (LEINFELDER 1989; in prep.).

Deeply incised valleys and partly huge quarries point to a minimum thickness of the Ota Limestone in the order of 160 metres. These outcrops also allow vertical examination of sections over long distances and reveal the aggradational structure of the complex, with narrow facies belts remaining in a stable position throughout the entire succession. Internal lithological correlation of profiles is rendered possible by means of two prominent black pebble horizons, one of which, in the reef zone, is sometimes substituted by a blackened horizon with karstic solution features (LEINFELDER 1987b).

3.1 The reef belt

Coral richness enables easy tracing of the reef belt in the field. In the northern part of the Ota, however, coral patches and boundstone areas are less common than further south. This is, at least partly, a primary feature, since a lesser protection of the interior platform in this area is obvious (see below). However, whether and to which extent downfaulting of parts of the reef core to the west, or backstepping palaeoerosion during platform development or after platform uplift also account for this phenomenon cannot be discriminated, since fore-reef slope and adjacent basinal sediments are downfaulted and deeply covered by younger sediments.

3.2 Reef facies types

The reef zone is characterized by a set of distinct facies types which can be subdivided into boundstones, commonly transitional with micritic floatstones to rud/packstones, and into sparitic rud/grainstones.

Boundstones comprise a set of different subfacies most of which are characterized by a high amount of microbial crusts (Fig. 3).

Coral bafflestones (reef subfacies 1): Bafflestones are mainly composed of phaceloid, rarely ramose corals and form isolated structures up to 3 metres high and 5 metres across (Pl. 4/3). Corals are commonly coated with thin microbial crusts. The sediment fill between coral branches is dominated by bioclastic intraclastic packstones.

Microbial-coral bind/framestones and bind/bafflestones (reef subfacies 2a, 2b): Subfacies 2a is very widespread within the Ota Reef (Pl. 5/1, 3). It consists of, partly stacked, clusters of massive and branching corals, which are often marginally fragmented and partly or completely tumbled. The interstitial sediment is composed of reef debris, among which clasts of nerineid gastropods and echinoids are very common. Most important are mostly spongiostromate to pelleted, microbial crusts which overgrow massive and branching corals forming domal to pillar-shaped structures but also stabilize debris, hence giving the sediment a flaser appearance. Crust fragments overgrown by subsequent microbial layers evidence frequent reworking of these stabilizing organic crusts. Centimetre to decimetre-sized pockets of winnowed sediment represent areas where loose deposits escaped stabilization by microbes. Microbial crusts commonly preserve and build up primary submarine relief. Early stabilization and hardening of most boundstone sediment

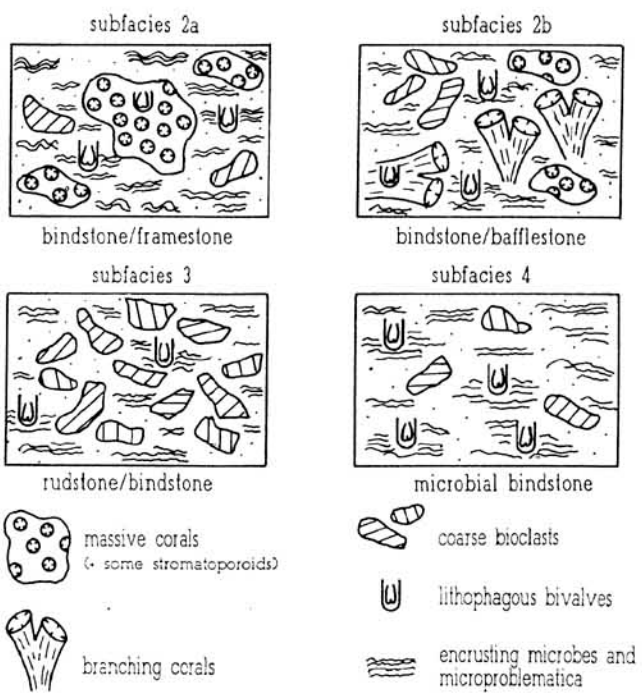


Fig. 3. Schematic sketches of the principal boundstone fabrics from the Ota reefal zone. A high content of encrusting, microbial and algal-like organisms is a characteristic feature of all types (see also Fig. 5)

areas is obvious by the frequent attack of lithophagous bivalves. Bivalve borings are particulary helpful for recognizing early hardening of the substrate in areas where microbial structures are less distinct due to preservational loss of structures. Bind/framestone and bind/bafflestone patches may attain sizes of seven metres across and more, and are normally embedded in microbially stabilized bioclastic sediments (cf. Fig. 6).

Reef debris bindstones and rud/bindstones (reef subfacies 3): This subfacies is transitional with subfacies 2 and differs from the latter by the substitution of larger coral clusters by coarse coral debris. Again the bioclastic, partly oncolitic sediment is intensively stabilized and hardened by microbial crusts, exhibiting winnowed pockets and large areas without obvious microbial structures, yet bored by bivalves (Pl. 4/1). This kind of substrate was the preferred dwelling site of an up to 20 cm large megalodontid bivalve and a nerineid gastropod (*Cryptoplocus*) with similar dimensions (Pl. 4/2).

Microbial bindstones (reef subfacies 4): Pure microbial bindstones are frequent within the reef and form lenses up to 60 centimetres high and several metres wide. They commonly have an irregular laminoid fenestral appearance due to the meshlike growth of the problematic algal or microbial form *Bacinella* which dominates in most of the bindstones (Pl. 5/5, 6/4). Lithophagous bivalves again attack the crusts frequently (Pl. 5/4).

Micritic sediments (reef subfacies 5): Bioclastic sediments containing varying amounts of lime mud are not uncommon in the Ota Reef. Packstones and micritic rudstones are more frequent than wacke/floatstones (Pl. 6/2, 5). Particles represent reefal debris, oncoids, intraclasts and peloids. Peloidal areas are sometimes laminated. The micritic fabric, to a large part, seems to represent poorly preserved microbial crusts, rather than hardened lime mud. This is suggested by the overall lack of in-situ burrowing bivalves, by the inhomogeneous distribution of particles and by flaser-like fabrics. The occasional occurrence of substrate-boring bivalves supports this interpretation.

Sparitic sediments (reef subfacies 6-8): Reef subfacies 6 consists of moderately sorted, well rounded bioclastic intraclastic grainstones (Pl. 6/5). Dominant are, mostly reefal clasts (corals, stromatoporoids, benthic mollusks, large foraminifera and thick dasycladaceans) as well as intraclasts, peloids, oncoids and microbial clasts. Some bioclasts rather represent lithoskels.

Moderately to bimodally sorted, well rounded foraminiferal grainstones represent reef subfacies 7 (Pl. 5/2). Particle composition is similar to above, yet dominated by mass occurrences of conical, up to 5 mm large benthic foraminifers (see below).

Reef subfacies 8 comprises very poorly sorted, very coarse coral intraclast rudstones (Pl. 6/1). Particles reach sizes up to 10 centimetres, are often angular or lobed and are deposited in a chaotic fashion. Elongated components may be imbricated. The indistinct, lobed outline of microbial clasts and intraclasts indicates incomplete hardening at the time of reworking.

3.3 Reef associations

Although preservation of the initially mostly aragonitic reef organisms is fairly poor, several reef associations, which are thought to represent diagnostic parts of former reef communities, were discriminated in a qualitative manner. These reef associations can be mostly related to distinct reef subfacies types.

(a) *Calamophylliopsis/Stylosmilia-Tubiphytes* association: This association is of subordinate frequency in the Ota Reef, as are the related bafflestones (reef subfacies 1). Corals are dominated by phaceloid bushes, amongst which *Calamophylliopsis* (Pl. 4/3) and *Stylosmilia* dominate. Further, partly dendroid or fasciculate taxa comprise *Dermosmilia* and *Thecosmilia*. Ramose forms, such as *Stylina* (*Convexastrea*) *sexradiata* and *Pseudocoenia* are occasionally frequent. Fragments of coralline sponges (cf. *Corynella*) occur occasionally. Corals are coated with microbial crusts and, typically *Tubiphytes morronensis* which is occasionally abundant, so that the facies grades into bind/bafflestones (reef subfacies 2a). *Tubiphytes* has been explained as a symbiotic or commensalic association of a nodophthalmiid foraminifer and cyanobacterial microbes (FLÜGEL 1979; Pl. 2/6). *Tubiphytes* was apparently very hard and brittle, since the form is occasionally enriched in debris deposits composed of angular clasts.

(b) Highly diverse thamnastroid plocoid coral - microbial crust association: Corals frequently build framestones or are broken into cm-sized fragments. Hence, related facies types encompass coral bind/framestones (reef subfacies 2a) as well as coral debris rud/bindstones and bindstones (reef subfacies 3). Most members of this faunal community can also be found in the micritic and sparitic debris types (subfacies 5-8). Characteristic are predominantly nodular colonies of plocoid (e.g. *Stylina*, *Ovalastrea*, cf. *Heliocoenia*), thamnasterioid (e.g. *Fungiastrea*, *Microsolena*, *Latusastea*), maeandroid (*Psammogyra*) and flabellate corals (*Rhipidogyra*). Ramose corals of the above types and some coralline sponges (*Actinostromaria*, *Dehornella*, cf. *Corynella*, *Ptychochaetetes*, cf. *Bauneia*) are rare. Sediment binders comprise microbes and microproblematic forms such as *Tubiphytes*, *Thaumatoporella*, *Lithocodium*, *Bacinella* as well as encrusting and coelobitic foraminifers, and bryozoans.

(c) *Bacinella irregularis* association: The microproblematicum *Bacinella irregularis* is composed of a mesh structure possibly formed by cyanobacteria (SCHÄFER & SENOWBARI-DARYAN 1983, MAURIN et al. 1985), although an ancestral red algal character may also be discussed (LEINFELDER 1986). *Bacinella* is a common crust builder in the highly diverse coral association, where it co-occurs with encrusters, such as *Thaumatoporella* (Pl. 6/6), *Tubiphytes* and *Lithocodium*. However, bindstone lenses within the reef (reef subfacies 4) often are almost exclusively composed of *Bacinella* (Pl. 6/4). The *Bacinella* meshwork is coarsest in pure *Bacinella*

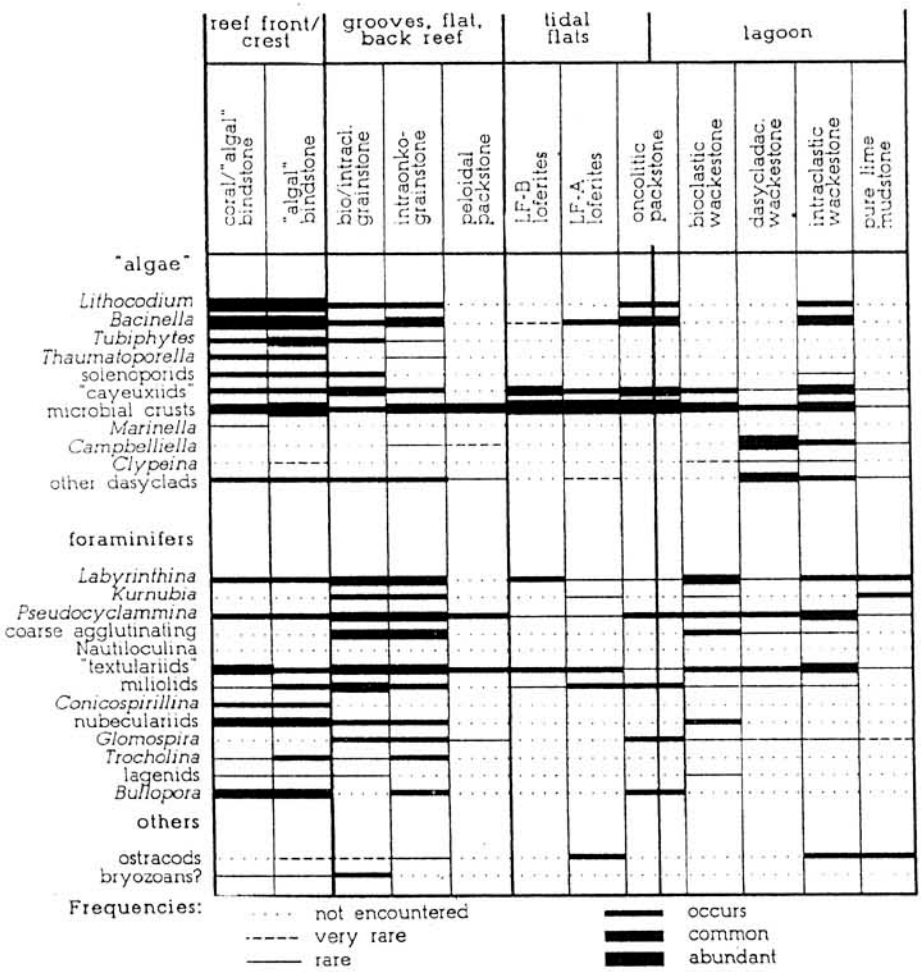


Fig. 4. Distribution of the principal microorganisms within the facies belts of the Ota Reef Complex

bindstones, possibly indicating optimum growth conditions. Crusts are frequently bored by lithophagous bivalves and truncated by abrasion, indicating their original hard, brittle character.

(d) Microbial association: Large areas within the reef zone are frequently occupied by pure microbial-peloidal crusts with only rare additional elements. Crusts are comparable with those described from Upper Jurassic microbial-sponge reefs of the northern Tethys shelf (e.g. WAGENPLAST 1972, GAILLARD 1983, BRACHERT 1986, LANG 1989). They often form steep to overhanging microrelief (of cm-, rarely dm-scale) which may be laterally bored by lithophagous bivalves (Pl. 5/4). Additional elements are serpulids, encrusting and coelobitic foraminifers (e.g. *Koskinobullina socialis, Bullopora* aff. *laevis, B. tuberculata, Placopsilina,* nubeculariids), bryozoans and other microproblematica. These organisms occur in the *Bacinella* bindstones ond other bindstone types as well. Some of them are also frequent in the crusts of Upper Jurassic sponge reefs of southern Germany (e.g. BRACHERT 1986).

(e) Mollusk-dominated association: coral-debris rud/bindstones and bindstones are commonly characterized by the large nerineid gastropod *Cryptoplocus* and a large megalodontid bivalve (Pl. 4/2). Further nerineids and ampullinid gastropods are common. Corals are mostly fractured into large fragments. A common, unfractured form in this setting is the flabelloid coral *Rhipidogyra*. The microfossil assemblage is highly diverse, indicating high niche diversity.

(f) Labyrinthic foraminiferal association: Sorted grainstone areas within the Ota Reef were frequently inhabited by the elongate to conical lituolid foraminifer aff. *Spiraloconulus* n.sp. (RAMALHO in prep.), commonly occurring in enormous quantities (see LEINFELDER et al. 1988: Pl. 2/10). Foraminiferal shape might indicate that the form had an infaunal or semi-infaunal life habit (cf. HAYNES 1981), occupying interstitial pores of the sandy substrate, which was partly stabilized by sea grass-type algal vegetation. Another common foraminifer is *Labyrinthina mirabilis* exhibiting a similar shape.

3.4 The interior platform area

The narrow belt of the **backreef zone** shows intense facies variation. Frequent are, mostly well sorted, bioclastic intraclastic grainstones and rudstones rich in foraminifers, dasycladaceans, nerineid gastropods and coral debris. Oncoids are sometimes abundant resulting in bimodal sorting. Frequently, the sediments display fine lamination, low-angle stratification, or bidirectional cross-bedding. In more protected subsettings, lagoonal peloid grainstones, grapestone-rich pack/grainstones, as well as cortoid oncoid wackestones and packstones occur. Some layers exhibit keystone vugs and laminoid fenestral fabrics. Early submarine fibrous cements are common as are vadose gravitational and phreatic dogtooth cements. Sediments of the backreef zone are frequently piled up in thin, stacked shallowing upward cycles. However, cycles of neighbouring sections cannot be correlated between adjacent sections. Therefore, an autocyclic development, comparable to the island model of JAMES (1984a) and PRATT & JAMES (1986) is most likely (LEINFELDER 1991).

Adjacent to the backreef belt lies the 100 to 1000 metres broad **peritidal zone**. This zone is characterized by bi- or tripartite peritidal cycles. A bipartite cycle consists of a basal burrowed mudstone to wackestone package 20 to 200 centimetres thick, sometimes containing giant oncoids as

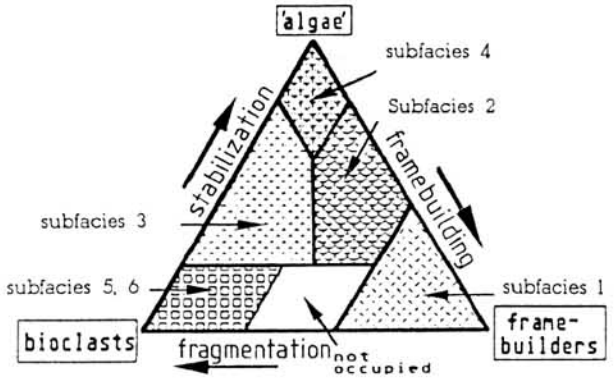


Fig. 5. The facies triangle of the Ota Reef. The occurring facies types are transitional between coral boundstones, 'algal' bindstones and bioclastic debris. For description of reef subfacies see Fig. 3 and text. Note unoccupied field, showing the absence of coral framework patches within loose bioclastic material which are common in other Upper Jurassic high-energy reefs.

lag deposit at its bottom. Gastropods, miliolid and agglutinated foraminifers occur (Fig. 4), whereas coral debris is restricted to a few layers only. Irregular birdseyes increase towards the top of the package. This set is overlain by a centimetre to decimetre thin horizon of laminoid fenestral micritic limestone ('loferite'). These cycles, which again do not correlate laterally, are of autocyclic origin, consistent with the tidal channel migration model of SHINN et al. (1969) and SHINN (1983a,b). A tripartite cycle is composed of an up to 300 centimetre thick basal wacke/packstone layer rich in bioclasts, microorganisms and oncoids, overlain by an up to 100 cm thick package of oncoid intraclast grainstones commonly exhibiting cross-bedding and narrow channel structures. Keystone vugs increase upwards. Laminoid fenestral oncoid intraclast grainstones represent the top of the cycle. The stacked tripartite cycles are thought to be created by an autocyclic progradation-cementation mechanism. A similar model for modern analogues was established by STRASSER & DAVAUD (1986).

The **lagoonal zone** covers a broad area to the east of the tidal zone and is entirely dominated by lagoonal lime mudstones and wackestones with some lituolid and miliolid foraminifers as well as dasycladaceans (e.g. *Clypeina jurassica*, *Campbelliella striata*; Fig. 4). Stenohaline organisms such as regular echinoids and corals in local bafflestones are present, yet fossil diversity and density is generally low, with the exception of the horizons rich in dasycladaceans. This general paucity may be due to lack of nutrients caused by missing water exchange (cf. ENOS 1983) or, rather, to a muddy, thixotropic hostile substrate. Dasycladacean mass occurrences and intercalations of thin layers of inter-/supratidal laminoid fenestral limestones as well as mudcrack horizons document the very shallow character of the lagoon.

Sporadically, shallowing upward sets with a minimum thickness of 6 metres occur within the lagoonal zone. These sets are composed of basal oncolitic packstones, grading

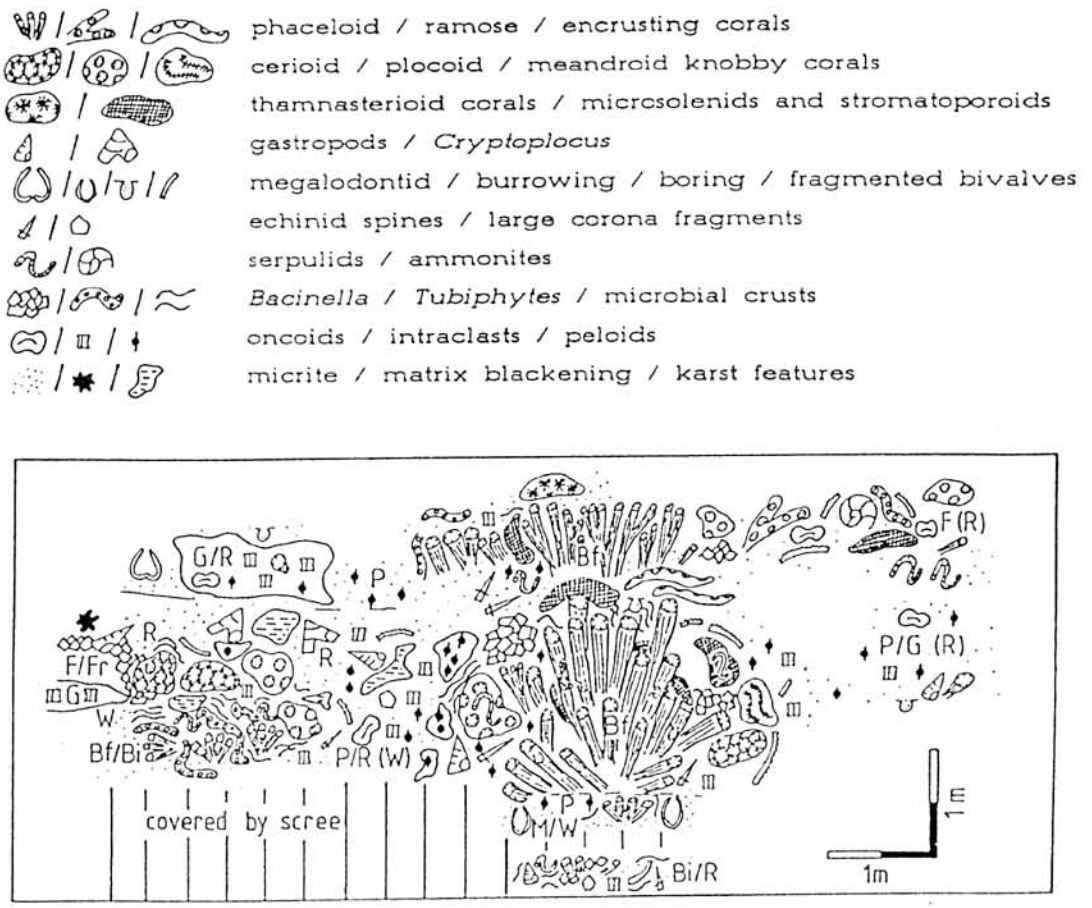


Fig. 6. Example for rapid facies transition in the reefal zone of the Ota Limestone. Facies sketch based on field and sample examinations. Outcrop is 15 metres to the north of section shown in Fig. 7e. Letters refer to DUNHAM and EMBRY & KLOVAN fabric types.

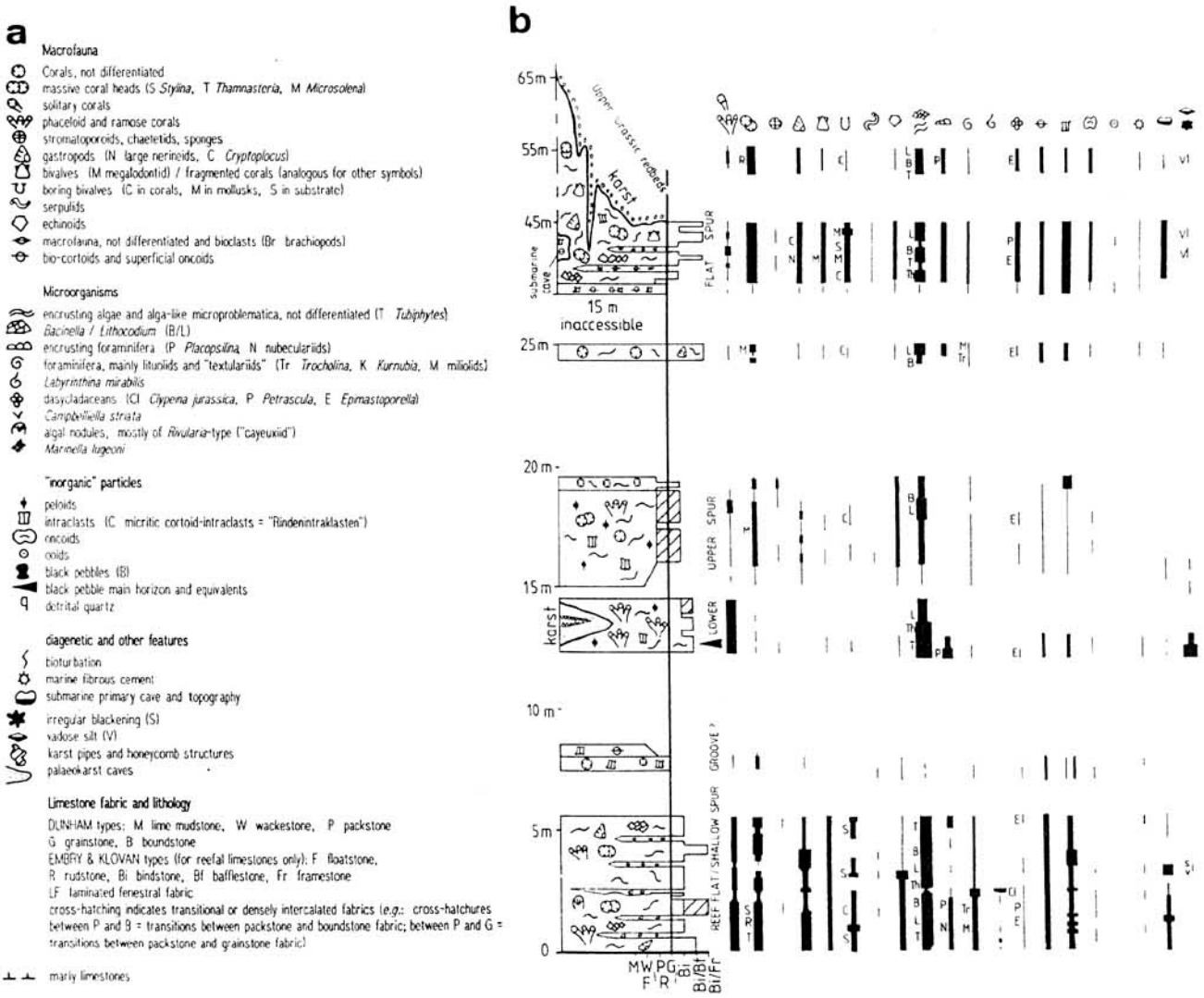


Fig. 7. Sections from the reef zone of the Ota Limestone (for location see Fig. 2)
a)legend for all lithological sections. Horizontal arrow at section columns indicates correlation level between sections
b) Alenquer section (southern part of reef zone)
c) Section Bairro I (southern part of the reef zone)
d) Section Casal da Vale de Junco (southern part of reef zone)
e) Section Pedreiras de Santa (windmill) (middle part of the reef zone)
f) Section south of Rio Ota (northern part of the reef zone)

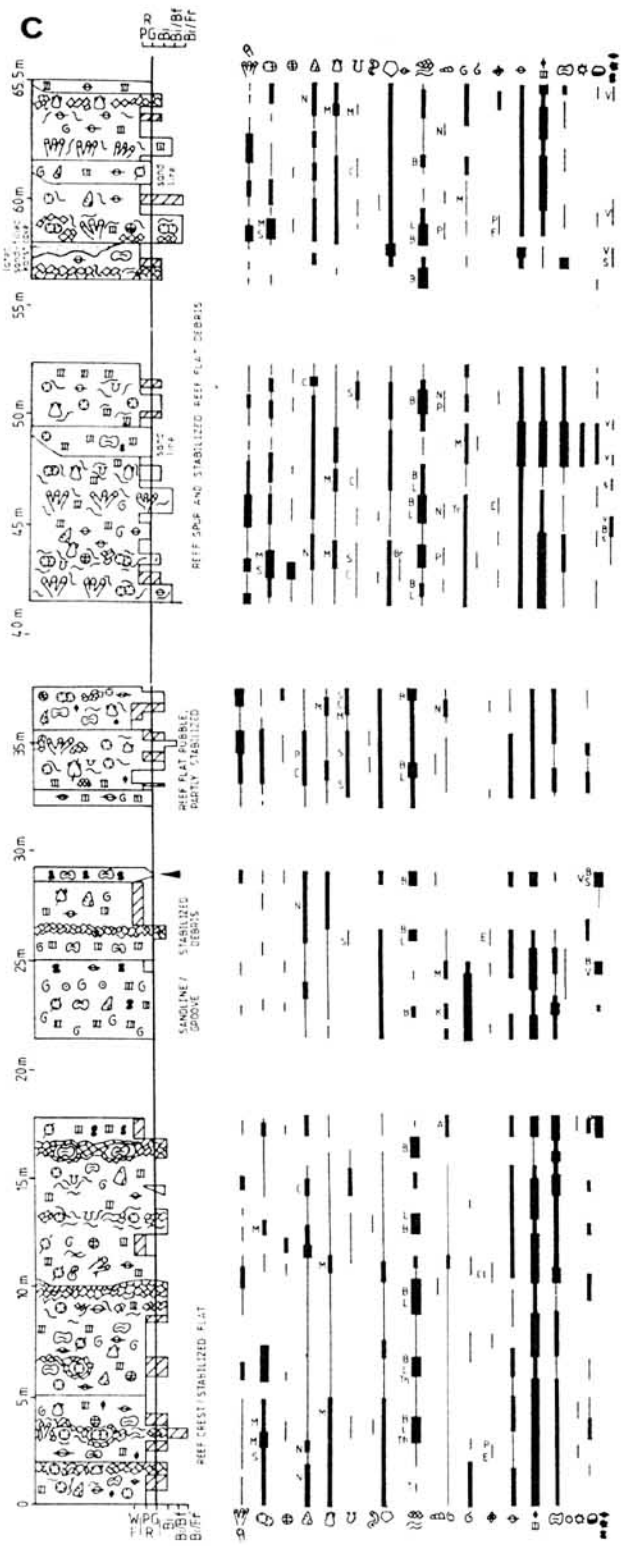
into burrowed lime mud/wackestones with small black pebbles in the upper part and with some isolated dasycladacean and gastropod wacke/packstone horizons. A complete cycle shows upwards increasing features of early meteoric or mixed water diagenesis, such as microspar formation and early solution pipes, and is terminated by either a fenestral or a mudcrack horizon containing vadose cements. The top horizon as well as the mentioned diagenetic features are not laterally persistent. Blackenings, desiccation and early meteoric features developed due to localized island formation. These cycles are thought to represent isolated mud ridges similar to modern Florida Bay (cf. ENOS & PERKINS 1977; LEINFELDER 1989, 1991).

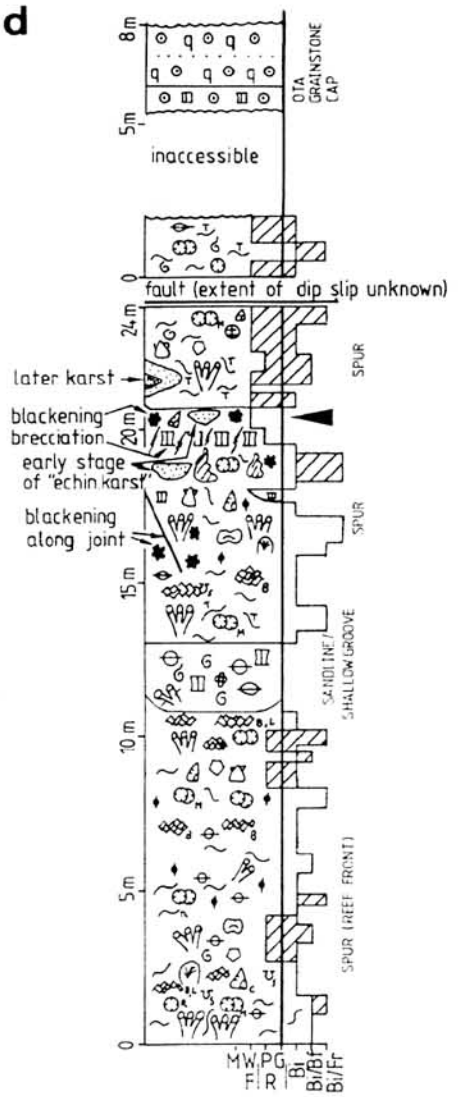
4 THE HIGH-ENERGY CHARACTER OF THE OTA REEF

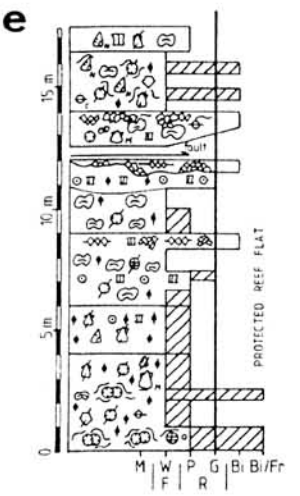
Criteria for placing the microbial crust-rich Ota Reef into a highly wave-agitated setting arise likewise from the faunal, facial and diagenetic characteristics of the reef deposits, from the sediment geometry of the reef tract, from the facies development of the inner platform, and from the geographic setting of the Ota Reef Complex within the Lusitanian Basin.

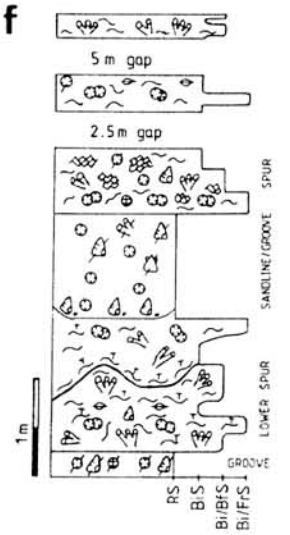
4.1 Clues from faunal and facies development of the reef

The scarcity of major bafflestone structures is a first hint for a high-energy setting. Mesozoic branched phaceloid corals generally occur in protected settings. '*Thecosmilia*', the common phaceloid bafflestone coral from the Late Tethyan Triassic was taken as a partial exception, but Late Triassic '*Thecosmilia* reefs' become increasingly reconsidered as coral meadows growing along slope steepenings in fairly quiet waters (EHSES & LEINFELDER 1988, STANTON & FLÜGEL 1989). The thin-branched phaceloic coral bushes of the Ota Reef seem to have grown in local protected or deeper settings. On the other hand, thick branched ramose corals as *Stylina sexradiata* may, like modern-day branched acroporid









corals, already have had the task of baffling fairly agitated water in order to ensure a better distribution of nutrients and plankton around branches. No studies exist whether and to which extent these corals took, like extant *Acropora* with its high regeneration ability, occasional fragmentation into account.

The Ota Reef is, however, clearly dominated by wave-resistant, massive, nodular to hemispherical to crustose coral heads, which are frequently fragmented. Fragmentation might though, to a certain amount, be due to biological erosion, since from Late Jurassic times onwards bioeroders became increasingly abundant (STENECK 1985) and is hence per se not diagnostic for elevated water energy.

The fairly widespread occurrence of micritic sediment does not contradict a high-energy setting. In modern high-energy reefs, lime mud infiltrates the highly porous reef

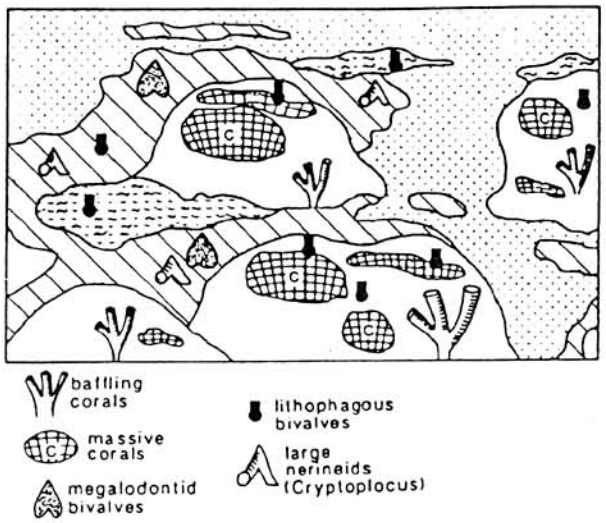


Fig. 8. Summary diagram illustrating the interfingering of facies types in the southern part of the reef zone, as apparent by the non-correlatability of reef sections and outcrop-scale facies transitions (compare Figs. 6, 7). Individual units consist of lense- and channel-like bodies and point to the existence of a spur-and-groove and sandline system. White: coral-rich boundstones; cross-hatched: stabilized debris; wave signature: 'algal' bindstones; dotted: unstabilized grainstone/packstone facies. A scale bar is not given, as the variations shown may occur across widths ranging from one to tens of metres.

framework during the perennially occurring few weeks of doldrum calms, an interval where waters normally agitated throughout the year are completely tranquil. The fine-grained infiltrate settles down to open pores and cannot be completely winnowed during subsequent phases of agitated water (SHINN 1988). Additionally, in the Ota Reef, many apparently micritic areas seem to represent sediments bound by microbes or cemented by micritic cements, as early hardening is obvious by frequent attack of boring bivalves.

Particularly diagnostic for the high-energy character of the reef is the occurrence of winnowed and reworked debris areas. While coarse unsorted rudstones with imbrication fabrics can be interpreted as storm layers, comparable with modern reef flat sediments, grainstones occur in small to large pockets or channels and are comparable with sandlines and grooves of modern spur-and-groove-reefs. Although major grooves are not visible in exposed quarry walls, their existence is likely from the arrangement of reef facies. The typical geometric feature of the Ota Reef is a small-scale facies transition. Reef sediments of the Ota can be described as varying mixtures between the three end members 'autochthonous to parautochthonous reef builders', 'reef binders' and 'bioclastic debris' (Fig. 5). The only field not occupied in this triangle comprises the type '(para-)autochthonous reef builders within loose bioclastic debris', which is the dominant sediment type for other Upper Jurassic high-energy reefs. Fig. 6 gives an example for the small-scale lateral and vertical facies transitions realized in the Ota Reef.

No gradual transitions from sparitic debris sediments into other reef subfacies exist. Facies boundaries of grainstones and sparitic rudstones are sharp, independent of whether the sparitic sediment represents a small void filling, a narrow pocket, a major channel or groove, or a sheet-like sediment layer. As Fig. 6 indicates, sediment types cannot be correlated from one section to the other. An exception is a widespread blackened or black pebble rich horizont which crosscuts all facies belts and serves as a good lithological correlation level between individual sections (LEINFELDER 1987b). Lithological sections may or may not be intensely differentiated vertically. For instance, Section Alenquer (Fig. 7b) from the southeasternmost outcrop of the Ota Complex is dominated by boundstones, with only subordinate amounts of grainstones. In the middle to upper part, this section apparently represents a major reef spur. In its top part, metre-sized grainstone-filled pockets can be interpreted as small grooves (sandlines sensu GEISTER 1975). The margin of these erosive structures is well cemented. The Vale Junco Section, further north (Fig. 7d), displays a similar boundstone-dominated development, whereas the closeby (further northward) Bairro I Section (Fig. 7c) contains frequent grainstone intercalations, which, though, are not laterally continuous. Short sections from the middle and very north of the reef tract are displayed in Fig. 7e and 7f respectively, again illustrating the intense small-scale facies variations.

From this facies distribution the idealized facies geometry given in Fig. 8 can be deduced. However, outcrop conditions do not allow to follow channels or grooves over larger distances, so that interpretation is based on two-dimensional field studies. Framestone-rich patches are encased by debris-rich microbially cemented bindstones. Between and behind such boundstone patches or pillows, debris sediments accumulated which are less intensely or less obviously stabilized by microbes. These were the favorite dwelling sites for the large bivalves and gastropods. In such more

Plate 4 Boundstone facies from the Upper Jurassic Ota Reef of Portugal

Fig. 1. Coral debris rud/bindstone (reef subfacies 3). Frequent borings by lithophagous bivalves (small arrows) and by polychaetes (upper arrow) are indicative of early hardening of the sediment by microbial crusts. Large arrow: *Tubiphytes*. Polished slab. x 0.9

Fig. 2. Mollusk/coral-debris rud/bindstone (reef subfacies 3). Megalodontid bivalve at base. Centre: corals and gastrops; top: frequent lithophagous bivalves, partly boring in pre-existing boreholes. Note primary small caverns as an additional criteria for early stabilization of sediment. Polished slab. x 1.4

Fig. 3. *Calamophylliopsis* bafflestone (reef subfacies 1), partly leached. Polished slab. x 0.9

Fig. 4. Massive *Stylina* head, completely bioeroded in upper part (possibly by boring sponges). Polished slab. x 1.4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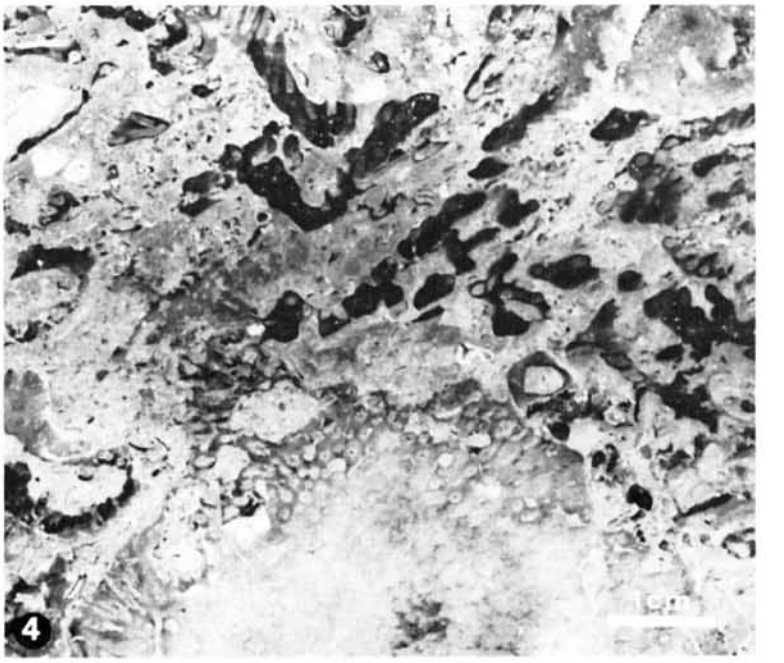
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protected settings as well as in deeper parts of the reef front, local coral bafflestones with or without *Tubiphytes* encrustation developed. Pure microbial bindstones apparently coated fore-reef slopes or spur slopes too steep for settlement of additional reef organisms, whereas *Bacinella* bindstones developed in shallowest subtidal to intertidal position along the crest of spurs, as do modern-day coralline melobesioid algae. Possibly, they were protected by small islands (see below). The frequent occurrence of *Bacinella irregularis* in loferitic sediments and giant oncoids from the adjacent tidal belt gives further evidence for the very shallow character of the microproblematicum. Coarse sparitic rudstones represent storm deposited reef flats developing behind the largest spurs.

4.2 Clues from early reef diagenesis

The early hardening of Ota Reef boundstones was obviously performed by microbes and algal-like organisms. However, dense micritic and peloidal crusts may at least partly represent inorganic early submarine cements (e.g. Ginsburg et al. 1971, Mazullo & Cys 1979, Macintyre 1985, Friedman 1985, Lighty 1985). Early submarine cementation is more obvious in grainstone sediments which frequently exhibit relic structures of former fibrous cements (Pl. 7/5). Due to high water exchange, sediment grooves should be the favorite place for intense early cementation. Vadose dripstone and meniscus cements (Pl. 7/6) occur in some grainstones and coarse sparitic rudstones, indicating that reef flat rubble locally accumulated to form small sand cays and cobble islands. Crystal silt is particularly common in some *Bacinella* bindstones and may give a further criterion for the shallow dwelling position of the problematic micro-organism. DTA-analysis suggests that subaerial blackening of sediment and particles within the reef is mostly derived from microbial matter (Leinfelder 1987b). Whereas one major horizon (including subhorizons) is related to a main phase of intraformational uplift of the entire Ota Complex, other blackenings are of local importance and cannot be correlated. The latter seem to be related to local island formation, which may be both due to autocyclic mechanisms and localized uplifts along the tectonic outer margin of the Ota Complex.

The same applies to the origin of some of the early karstic features common within the Ota Reef. Whereas many karst phenomena of the Ota Complex developed after the final uplift of the platform (Leinfelder 1989), one widespread karst feature is clearly intraformational yet not related to a single correlatable event. The intraformational character is evident (1) from the occurrence of up to metre-sized filled karst pockets also in the deeper part of the Ota sequence, (2) from the gradual lateral development of the laminated karstic fill out of neighbouring sediments and (3) from the selective enrichment of calcitic echinoid and crinoid skeletons (Pl. 7/1,2). Echinoderm fragments are heavily leached and recrystallized. The resulting sediment is laminated, consisting mostly of silt-sized calcitic laminae with intercalated coarser layers, where echinoderm fragments are better preserved (Pl. 7/3, 4). The material clearly represents a leaching relic. Leaching occurred before aragonitic hardparts were diagenetically altered to calcite. This 'echinoderm karst fill' often displays a dark grey colour, contrasting the white appearance of the host rock. Colouring is either due to enrichment of the nowadays very low, not measurable amounts of organic matter from the reefal host sediment or due to infiltration of organic matter thriving in small dolines on localized islands. Sometimes coral moulds are filled with blackened sediment. This early karstification seems to result from small mixed-water or freshwater lenses which developed underneath local islands. Enrichment of echinoderm fragments relative to other elements could be experimentally demonstrated by Walter (1985). Selective dissolution of aragonite is also a common feature of the diagenetic mixed-water zone (Purser & Schroeder 1986). Both by the occurrence of localized subaerial blackenings and early karst features, the very shallow character of the Ota Reef is

Plate 5 Boundstone and grainstone facies from the Upper Jurassic Ota Reef of Portugal

Fig.1. Microbial-coral bind/framestone (reef subfacies 2a). Partly fragmented coral colonies (mostly cf. *Fungiastrea*) within bioclast-rich microbial crusts. Light spots and streaks represent *Tubiphytes*. Polished slab. x 1.4

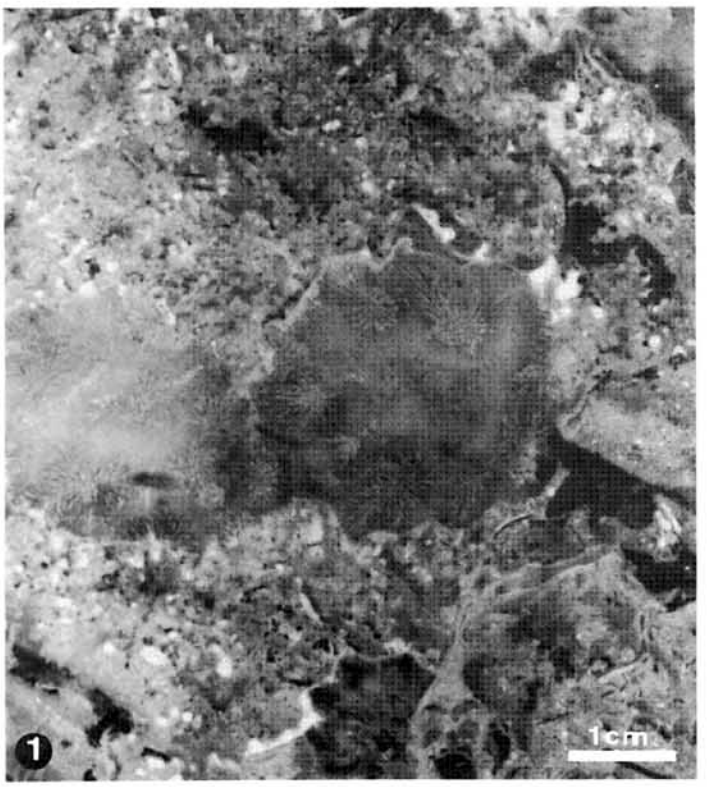
Fig. 2. Poorly sorted bioclastic intraclastic grainstone rich in the foraminifer *Labyrinthina mirabilis* (reef subfacies 7). Common facies in inter-reef and back reef environments of the Ota reef. Thin-section. x 7

Fig. 3. Microbial-coral bind/framestone rich in stylinid (s), fungiid (c: *Calamophylliopsis*, f: cf. *Fungiastrea*) and *Rhipidogyra* (r) (reef subfacies 2a). Grainstones occur in small grooves and cavities within the bindstone areas (reef subfacies 6). Note irregular truncation surfaces within the bindstone (e.g. arrows). Polished slab. x 1.4

Fig. 4. A lithophagous bivalve attacks a small submarine cliff composed of microbial crust facies. The abraded relief later became encrusted by microbes and serpulids. Arrow points to geopetal structure. Thin-section. x 3

Fig. 5. Microbial fenestral bindstone (reef subfacies 4) rich in *Tubiphytes* (light streaks). Such *Tubiphytes*-rich microbialites are interpreted as sediments of lower reef front or protected parts of central reef settings. Polished slab. x 1

Fig. 6. *Tubiphytes morronensis*, possibly a symbiosis between a nodophthalmiid foraminifer (sparitic centre) and a microbe or alga. The brittle character of the problematic form is obvious by fragmentation into clasts. Thin-section. x 8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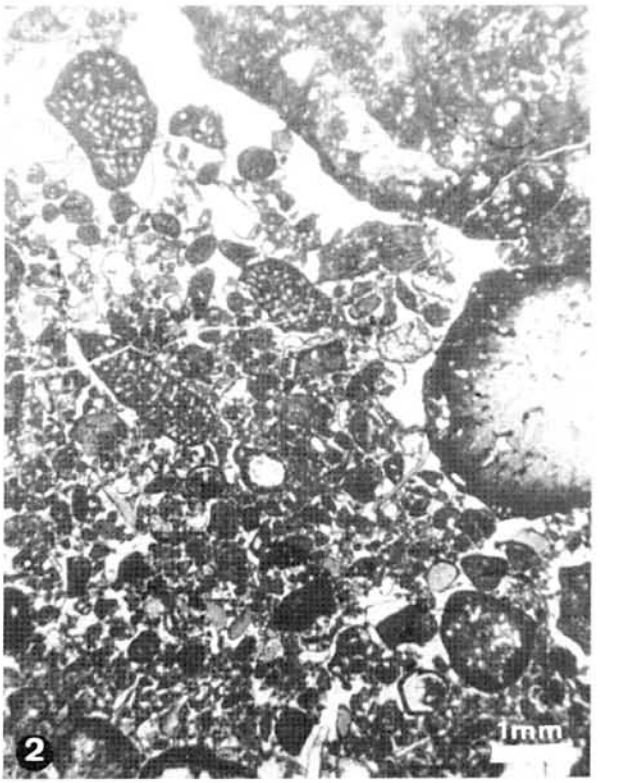
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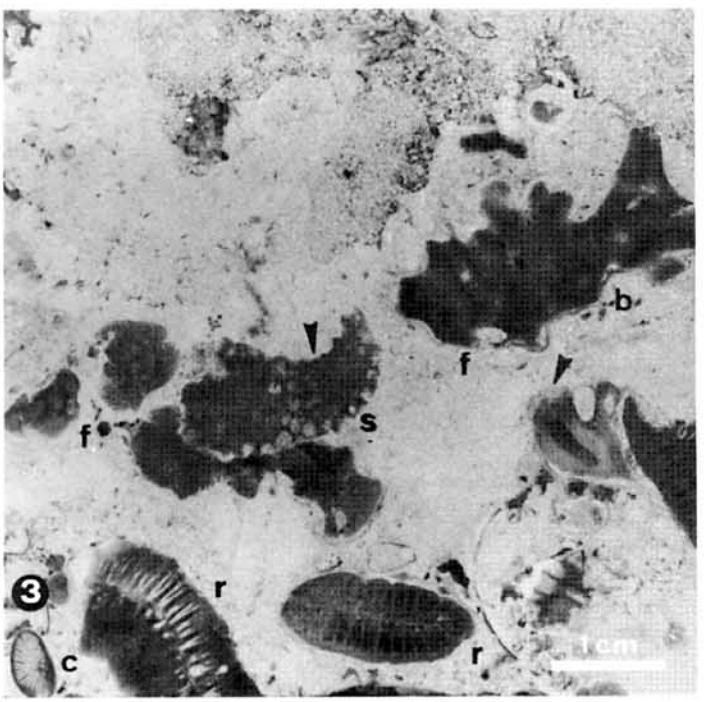
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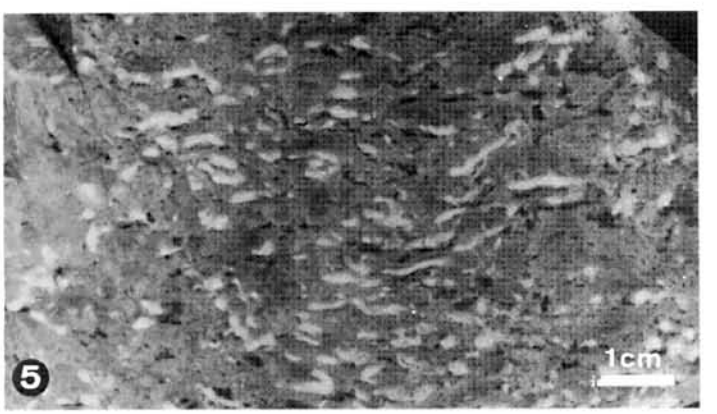
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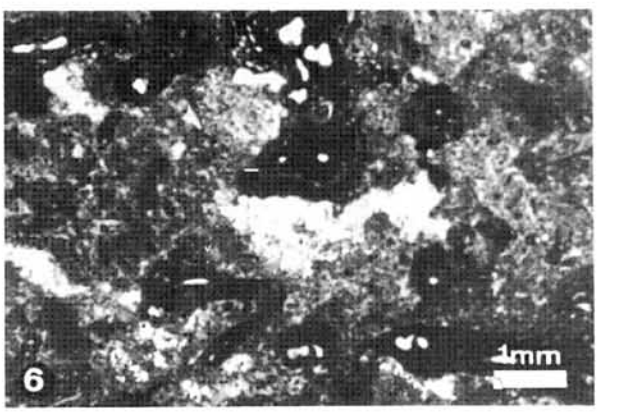
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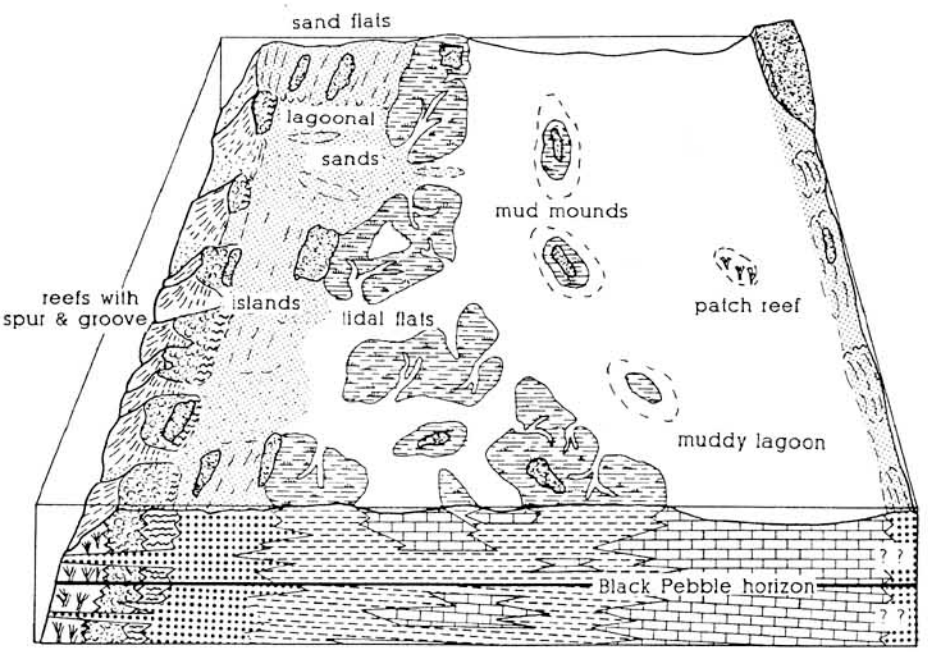


Fig. 9. The depositional model for the exposed part of the Ota Limestone. The aggradational architecture is obvious throughout the platform development and is thought to be caused by the existence of a steep by-pass margin, preventing progradation despite high productivity. The position of the peritidal belt directly behind the reef tract points to high reef productivity. The high-energy reef tract to the west, though apparently crosscut by channels and grooves, gave perfect sheltering to the inner platform areas where low-energy, shallow-water limestones formed autocyclic stacked shallowing-up successions. For more details refer to LEINFELDER (1989, 1991).

obvious. This very shallow setting enabled easy and frequent autocyclic island formation.

4.3 Clues from Inner Platform Characteristics

The overall characteristics of the Ota Reef Complex provide another clue for the shallow character of the reef tract. Effective protection of inner platform areas and, hence a very shallow position of the Ota Reef is indicated by (1) the common micritic intervals within the southern back reef belt, (2) the existence of a tidal belt directly behind the reef tract, and (3) the low-energy character of the, very shallow lagoon (Fig. 9). Occurrence of a tidal belt directly behind the reef tract is known but fairly uncommon in both modern and ancient reefs and can be explained as a result of the high carbonate productivity of the reef. Protection of the tidal zone by the reef belt was more effective in the south than in the north. In the north the peritidal sediments comprise many winnowed, grain-supported sediments which are unusual in the south. Hence towards north, the reef belt might had have larger gaps between reef patches than in the south where apparently a spur-and-groove system prevailed.

4.4 Clues from the Basin Setting

Although it is evident from the above that the Ota Reef grew in very shallow water, hence protecting inner platform areas, one could still argue that this shallow character might not necessarily correspond to high water energy, since the platform could have developed in a protected basin setting

Plate 6 Debris facies and encrusting organisms from the Upper Jurassic Ota Reef of Portugal

Fig. 1. Coral debris/intraclast rudstone, interpreted as storm created 'reef flat rubble', very poorly sorted (reef subfacies 8). Note irregular outline of clasts, indicating imperfect hardening at the time of reworking. Centre: plocoid stylinid coral. Sparitic groundmass exhibits vadose cements (not visible at this scale). Polished slab. x 1.2

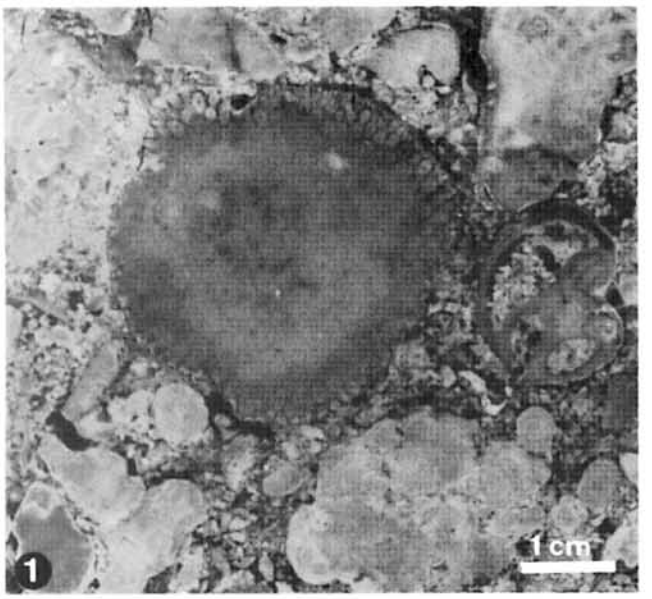
Fig. 2. Partly stabilized micritic reef debris sediment (reef subfacies 5). Although later leaching of aragonite shells occurred (see crystal silt within bivalve mould), the irregular fabric is thought to be due to winnowing of a framework formed by microbial crusts. Packstone patches remained where stabilization was incomplete. Left: calcitic oyster shell of *Lopha*-type. Thin-section. x 3

Fig. 3. Stabilized debris facies with strongly abraded gastropod. Packstone/rudstone fabric (reef subfacies 5). Thin-section. x 5

Fig.4. *Bacinella irregularis* bindstone, rich in fenestrae (reef subfacies 4). This common bindstone type resembles an irregular loferite fabric in the field and is thought to form in reef crest and reef flat settings. Thin-section. x 9

Fig. 5. Bioclastic intraclastic peloidal grainstone (reef subfacies 6) filling a small channel cut into microbial-reef debris bindstone (reef subfacies 3). Thin-section. x 5

Fig. 6. The problematic alga *Thaumatoporella parvovesiculifera*. Detail from a microbial-coral bindstone/bafflestone. Thin-section. x 28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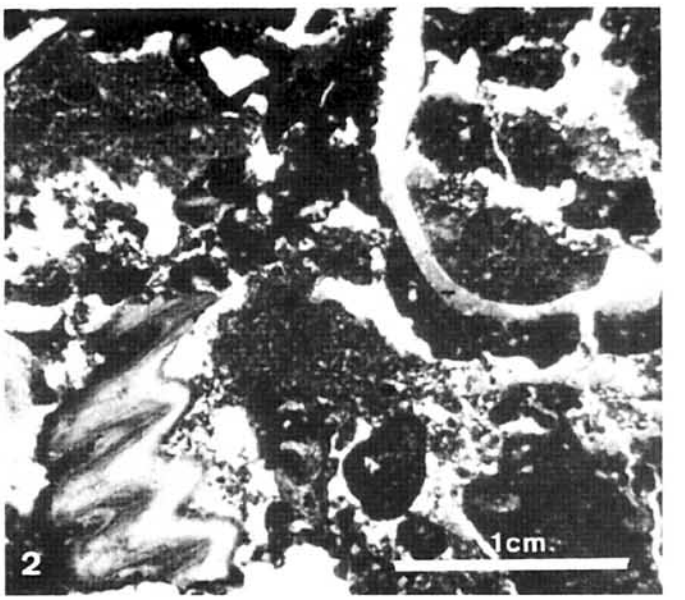
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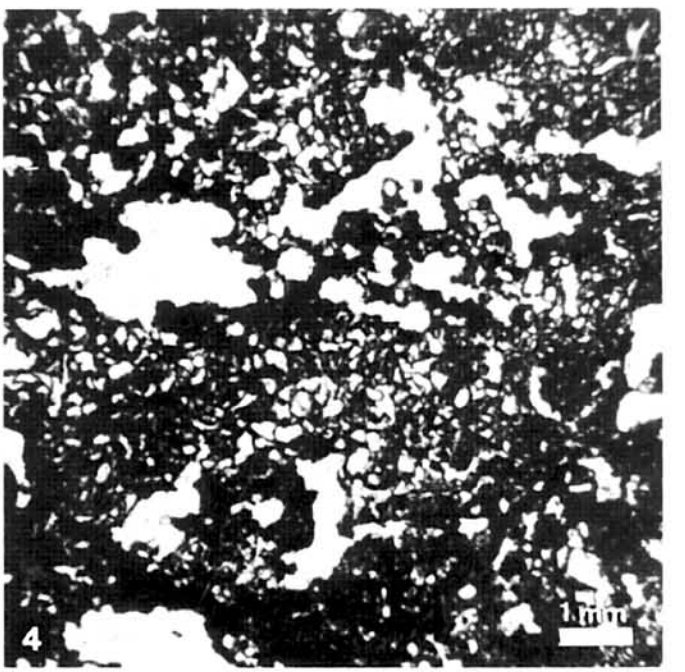
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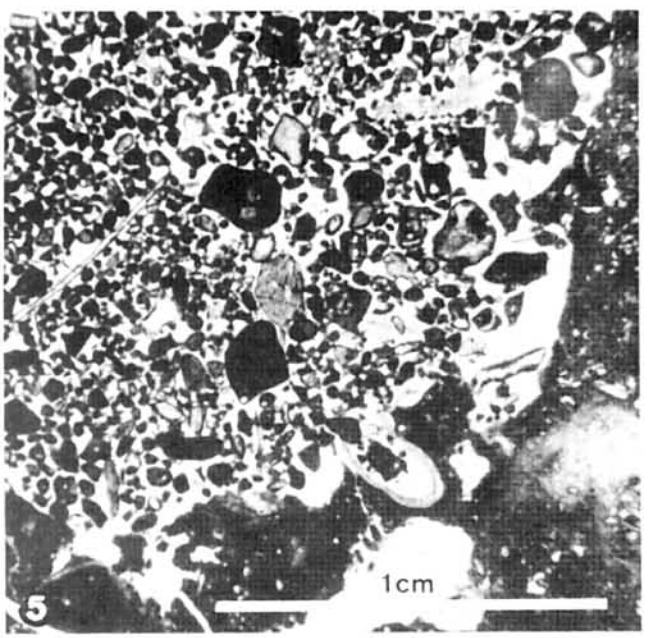
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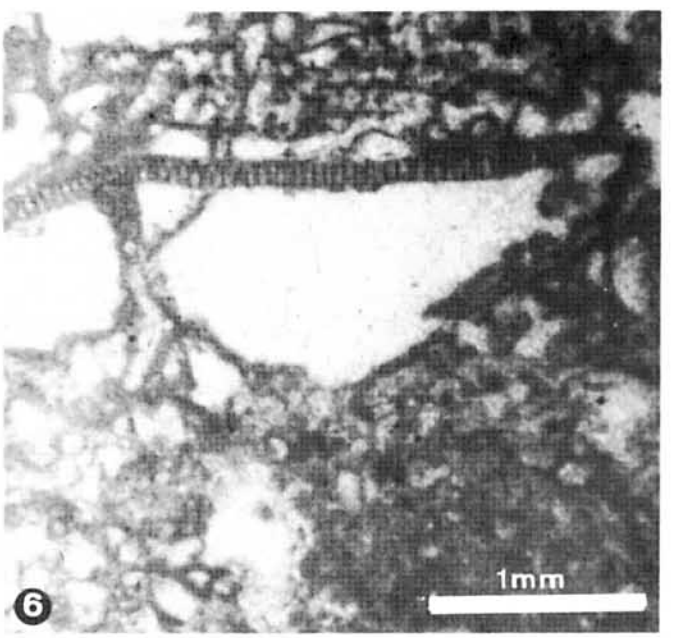
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with low-energy characteristics. Whereas the richness of coarse debris is probably partly derived from bioerosion, the existence of coarse reef flat rubble and groove sediments, as well as the actual setting within the Lusitanian Basin clearly stand against a low-energy interpretation: The Ota Reef Complex formed on an uplifted block close to the eastern margin of a pull-apart subbasin, whose eastern margin also corresponds to the eastern margin of the entire Lusitanian Basin. Crystalline basement was exposed closeby in the hinterland (Fig. 10b), as is apparent from the existence of an east derived conglomeratic submarine fan to fan delta complex of Early to Late(?) Kimmeridgian age, whose apex just lay south to the Ota area (LEINFELDER & WILSON 1989).

There is also direct evidence from the Ota Limestone that siliciclastics actually did outcrop in the vicinity of the Ota Reef Complex. In the eastern part of the lagoonal zone, silt-sized detrital quartz occurs in a few limestone beds. The well sorted, subrounded small quartz grains are floating in the micrites. They are probably airborne, being transported towards the Ota region during storms. Another proof for the existence of a crystalline or siliciclastic hinterland are, up to two centimetre large, detrital, angular quartz pebbles occurring very rarely and completely isolated within the limestones. They are somewhat more frequent in association with local black pebble occurrences related to island formation (cf. LEINFELDER 1987b: Pl. 18/7). This backs an interpretation of transport of these pebbles within the roots of coastal trees which were uprooted during storms and transported towards the sea, where they released their pebbles during floating or, more commonly, after stranding along local islands. The common association of such pebbles with black pebble deposits and the common lack of rounding and etching features excludes an interpretation as stomach stones, e.g. from crocodiles. Consequently, these pebbles might be termed 'driftwood grains' or 'driftwood pebbles'. Transport of mainland-derived volcanic rocks to offshore coral reef islands in the roots of uprooted trees is known from the Carribbean (GEISTER 1975).

Due to the elevated position of the Ota Reef Complex on an uplifted basement block, hinterland-derived coarse to silt-sized siliciclastics, with the exception of the above mentioned cases, settled in the depression landward to the Ota Block or were diverted around the horst towards the basin floor. However, clay-sized terrigeneous siliciclastics would be largely suspended in the upper part of the water column and thus could reach the Ota area. The fact that even the low-energy sediments of the Ota tidal flat and lagoon, except for rare airborne quartz-silt, are completely devoid of terrigeneous contamination may be either explained by a general lack of fine suspended terrigeneous clay fraction or else may indicate the existence of an effective sheltering mechanisms.

The dominance of physical weathering under arid climates often results in a very low amount of clay-sized terrigeneous weathering material available which moreover becomes commonly trapped in coastal sabkhas (e.g. ROBERTS 1987). However, the common occurrence, in the Portuguese Upper Jurassic, of brackish to mesohaline deposits (FÜRSICH & WERNER 1984, 1986) together with the existence of faint annual growth rings in conifer wood and widespread caliche formation (LEINFELDER 1986) indicates a generally subtropical climate with humid and arid seasons. Additionally, the formation of a coeval, large prograding slope system composed largely of northwesterly derived fine siliciclastics (LEINFELDER & WILSON 1989) would also not be possible under arid climate. Consequently, it is obvious that considerable amounts of fine clastics were shed both from the eastern hinterland and from a northwesterly source towards the Ota area. Hence, there must have been an effective sheltering mechanism keeping fine clastics away from the Ota Reef Comlex.

As already outlined, the Ota Limestone is mostly of 'late'

Plate 7 Early diagenesis and intraformational palaeokarst from the Upper Jurassic Ota Reef of Portugal

Fig. 1. Laminated cave fill, caused by differential dissolution of fine aragonitic particles. Larger aragonitic coral clasts and echinoderm fragments (e.g. arrows) still exist but are partly leached. Early intraformational palaekarst pocket from the central reef zone. Polished slab. x 1.2

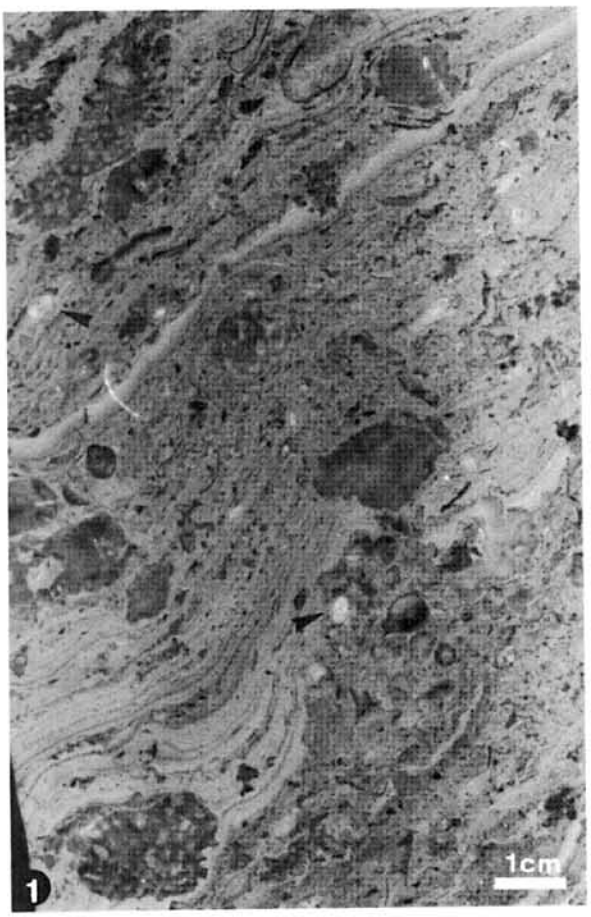
Fig. 2. Early intraformational palaeokarst cave fill. Dissolution processes were longer at work than in the above example, resulting in the almost complete removal of aragonitic particles. Calcitic echinoderm fragments are hence strongly enriched (e.g. arrow: crinoid stalk fragment). The finely laminated top part is the residual end product of this early meteoric leaching, which occurred prior to the transformation of aragonite particles into calcite. Due to the purity of the Ota Limestone, clay content is only slightly increased. Local early palaeokarst formation within the Ota Limestone is thought to be related to autocyclic island formation. Polished slab. x 1.5

Fig. 3. Thin-section photograph of the residual sediment of an intraformational palaeokarst fill. Larger particles exclusively consist of leached echinoderm fragments. x 15

Fig. 4. Ophiuroid fragment (arrow) within residual palaeokarst fill. Thin-section. x 15

Fig. 5. Grainstone from an inter-reef groove, with slightly neomorphic fibrous cement, interpreted as early marine cement. Note that echinoid fragment is not overgrown by syntaxial cement which would be common in meteoric diagenesis. Thin-section. x 20

Fig. 6. Vadose dripstone cements within a peloidal intraclastic grainstone/packstone. Vadose cements within the reef and backreef zone are local features interpreted as autocyclic sand cay and coral cay formation. Thin-section. x 10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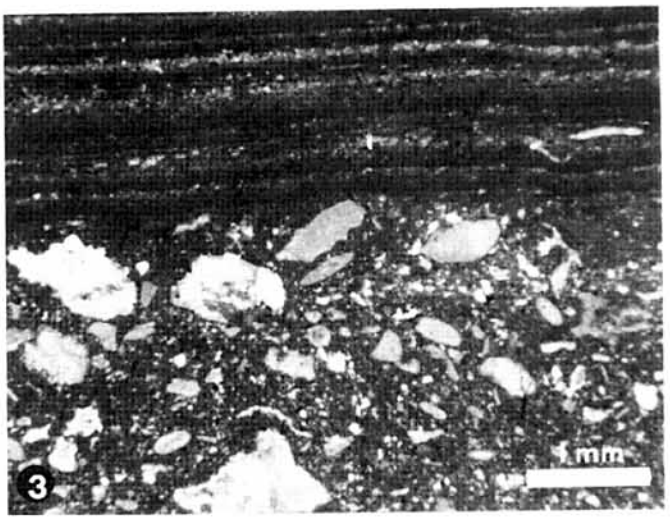
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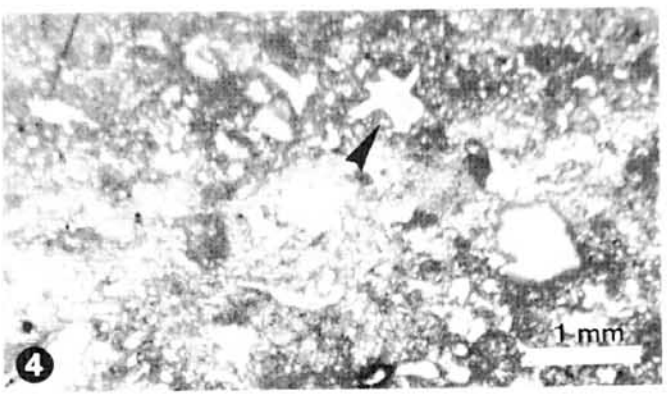
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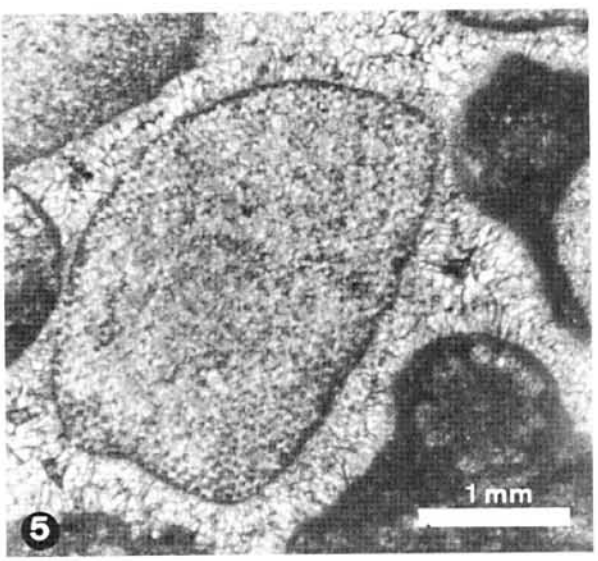
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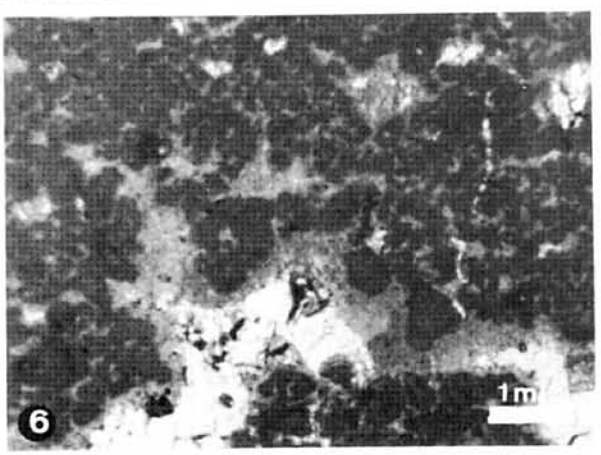
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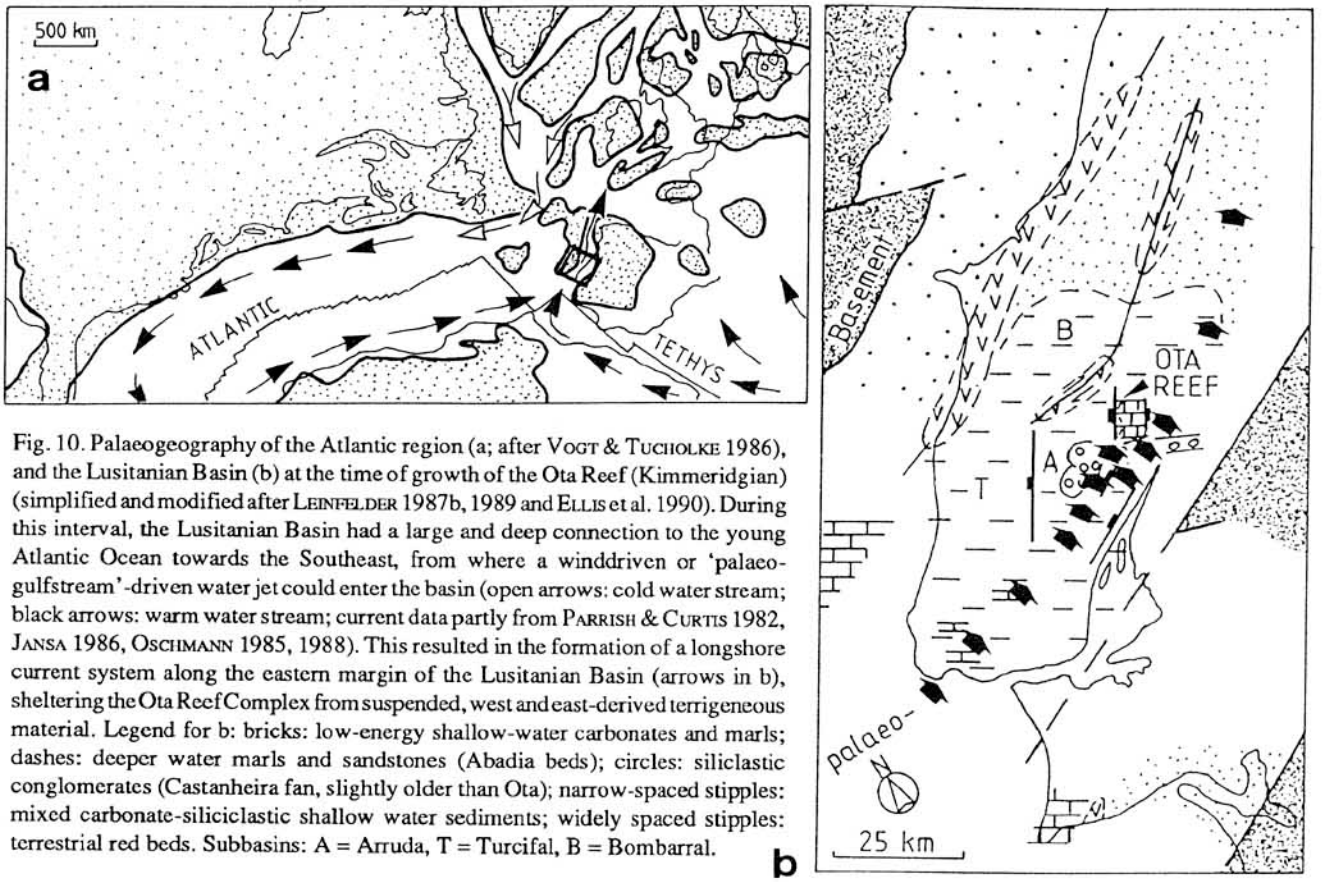

Fig. 10. Palaeogeography of the Atlantic region (a; after VOGT & TUCHOLKE 1986), and the Lusitanian Basin (b) at the time of growth of the Ota Reef (Kimmeridgian) (simplified and modified after LEINFELDER 1987b, 1989 and ELLIS et al. 1990). During this interval, the Lusitanian Basin had a large and deep connection to the young Atlantic Ocean towards the Southeast, from where a winddriven or 'palaeo-gulfstream'-driven water jet could enter the basin (open arrows: cold water stream; black arrows: warm water stream; current data partly from PARRISH & CURTIS 1982, JANSA 1986, OSCHMANN 1985, 1988). This resulted in the formation of a longshore current system along the eastern margin of the Lusitanian Basin (arrows in b), sheltering the Ota Reef Complex from suspended, west and east-derived terrigeneous material. Legend for b: bricks: low-energy shallow-water carbonates and marls; dashes: deeper water marls and sandstones (Abadia beds); circles: siliclastic conglomerates (Castanheira fan, slightly older than Ota); narrow-spaced stipples: mixed carbonate-siliciclastic shallow water sediments; widely spaced stipples: terrestrial red beds. Subbasins: A = Arruda, T = Turcifal, B = Bombarral.

Kimmeridgian age (sensu gallico), though correlation with ammonite biozones is not possible. According to HAQ et al.'s (1987) global sea-level chart, the Late Kimmeridgian was a time of extended, slow sea-level rise of the third order cycle LZA-4.6, although the Ota platform development might have started already earlier. In a tectonically quiet setting such a situation could actually explain a low siliciclastic influence from the hinterland due to trapping of clastics in estuaries and lagoons of a widely flooded shelf (e.g. POSAMENTIER & VAIL 1988). However, there are some hints that the long global LZA 4.6 cycle has to be further subdivided by another, if not two additional sequence boundaries (e.g. COTINI 1989, STROHMENGER et al. 1989, LEINFELDER & BRACHERT 1991, LEINFELDER & WILSON in prep.). Reevaluation of data from the Paris basin yielded similar results (PONSOT & VAIL 1991). Such additional sea level lowstands should account for phases of increased clastic input, nothing of which is noticed in the Ota Limestone.

Still more critical in respect of siliciclastic input is the tectonic activity of the eastern Lusitanian Basin. This activity is apparent by the existence of a submarine conglomerate fan, to the south of the Ota region, throughout almost the entire Kimmeridgian stage, and by the pull-apart character of the Kimmeridgian Arruda Subbasin (Fig. 10), whose eastern margin was characterized by a very narrow shelf and, possibly, by cliff coastlines (LEINFELDER & WILSON 1989, LEINFELDER 1989). In such a tectonic setting, even a rapidly rising global sea level cannot account for a trapping mechanism for siliciclastic sediments.

Despite this tectonic predisposition to strong siliciclastic input almost no terrigeneous material reached the Ota Reef Complex. Could it have been sheltered from terrigeneous input by a chain of islands along its eastern margin? Actually, a small intraformational conglomerate fan, composed of northeast derived limestone clasts, most of which are large black pebbles, points to the existence of an uplifted and subaerially exposed block in the northeastern part of the Ota Reef Complex (Fig. 9; cf. LEINFELDER 1987b). However, such uplifts were clearly local and ephemeral, and cannot account for the complete sheltering of east-derived fine clastics throughout the entire development of the Ota Reef Complex. They also could not explain the sheltering from northwest-derived clastics.

Modern carbonate platforms and reefs are commonly sheltered from terrigeneous input of closeby coastal areas by strong longshore currents. Along the pacific coast of Nicaragua, for instance, enormous quantities of siliciclastics are transported to the shelf, caused by the high tropical precipitation and steep topographic gradients. Due to the strong longshore currents, siliciclastic sediments are, nevertheless, confined to a narrow coastal stripe and reefs and a carbonate platform forms already few kilometres offshore (ROBERTS & MURRAY 1983, MURRAY et al. 1988, ROBERTS 1987, FRIEDMAN 1987). There is strong evidence that a similar control was effective during the growth of the Ota Reef Complex:

Configuration of the Lusitanian Basin during the Kimmeridgian suggests a broad and fairly deep connection of the basin and the young Atlantic towards southwest, in the present position of Lisbon and Sintra, and probably a shallow-

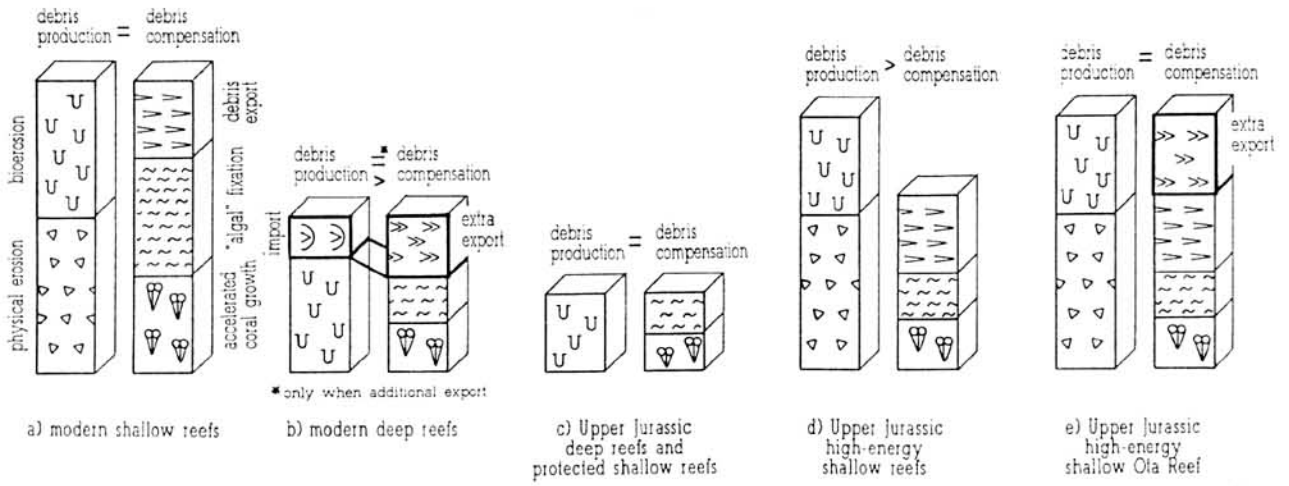

Fig. 11. Sediment balance determining the character of reefs. Modern shallow-water high-energy reefs have an equilibrated sediment balance between debris production and debris compensation. This is particularly due to the existence of encrusting coralline algae which are highly effective sediment binders (a). The lack of these organisms in Upper Jurassic reefs of a comparable setting results in insufficient binding of debris and hence in the drowning of small reef structures within their own debris (d). The less effective Upper Jurassic microbial binders had a chance of sufficiently binding loose debris only in cases where additional gravitational export of debris was possible. This was the case in the Ota Reef (e), which hence exhibits a modern coral-'algal' aspect. For further explanation, see text and Fig. 12.

water connection at the northern end of the basin, in the Porto area (WILSON 1979, LEINFELDER 1987a). For the central Atlantic some authors suggest the existence of a northeastward flowing mass of warm water during the Late Jurassic. Evidence comes from the distribution of carbonates and cold-water microfossils as well as from theoretical, calculated circulation patterns (JANSA 1986, PARRISH & CURTIS 1982, OSCHMANN 1985, 1988). A branch of this 'palaeo-gulfstream' would certainly have entered the Lusitanian Basin and would have caused elevated current speed along its eastward margin (Fig. 10). Alternatively, if the 'gulfstream model' is not valid for the Late Jurassic, westwind fetch from the young central Atlantic into the Lusitanian Basin amounting to about 2000 km, would also explain wind driven high wave energy. Due to a narrow shelf area, loss of current energy by friction would have been minor, except for the northern part of the basin. Isolated preexisting or newly forming narrow buildups such as the Barreiro buildup to the East of Lisbon (ELLIS et al. 1990), or the Ota Reef Complex would have additionally accelerated the speed of the longshore current due to the Bernoulli effect. Actually, the Kimmeridgian Sintra shelf on the southwestern side of the basin exhibits very low-energy characteristics despite its shallow-water character (ELLIS et al. 1990).

Accepting the longshore current theory, this current had three effects on the growth of the Ota Reef Complex:

(1) A coastal boundary current developed which caused complete sheltering of the Ota Reef Complex from east-derived fine siliciclastics.

(2) The entire Ota Reef Complex itself was situated within the longshore current; thus accelerated water flow along the western margin of the Ota prevented contamination from west-derived fine terrigeneous material.

(3) This situation was also responsible for the high-energy character of the Ota Reef. High-energy reef facies ist best developed along the southern and southeastern margin of the Ota Reef Complex, which actually coincides with the highest current speed as expected from the theoretical flow pattern.

5 SEDIMENT BALANCE - THE CAUSE FOR THE MODERN CHARACTER OF THE OTA REEF

Both modern high-energy reefs and the Upper Jurassic Ota reef tract can be characterized as follows:

* A high rate of erosion and debris formation results in only subordinate preservation of in-situ coral framework.
* Stabilization of reef deposits is maintained by sediment binders rapidly encrusting loose debris. In many cases, debris encrustation may be particularly rapid after hurricanes (HAMELIN-VIVIEN & LABOUTE 1986, ZANKL & SCHWABE pers.comm.). Mutual inorganic/organic cementation and destruction results in the creation of rigid reef spurs and larger reef patches (SHINN et al. 1981).
* Larger areas of loose, unstabilized debris within the reef tract are only found in groove systems or in larger gaps between isolated rigid reef patches.

In modern reefs, bioclastic debris is actually produced in excess, both by physical and biological abrasion (STODDART 1969). Yet, reef constructors need stable firm-bottom conditions, so that flourishing of a reef community is dependent on the rapid stabilization of parts of this debris material and export of surplus debris material to forereef and backreef settings. This export is executed by the sweeping action of constant wave breaking and surging, by both wind driven and tidally driven waves, as well as by gravitational basinward transport (FAGERSTROM 1987). Seaward and lagoonward transport is commonly maintained through reef grooves (SHINN et al. 1981, GEISTER 1983).

Hence, a modern high-energy reef reflects a delicately balanced situation between coral growth, fragmentation, stabilization of debris, and export of bioclastic surplus material (Fig. 11a). If surplus debris is not exported or, worse, additional bioclastic debris is even imported into reef areas, reef growth will fade and eventually cease. This happens in some modern deeper water reefs (Fig. 11b). Well studied examples are the reefs along both margins of the the Salt River Submarine Canyon off St. Croix Island, Caribbean:

Reefs on the west side of the canyon flourish, since a steep erosive by-pass margin enables gravitational export of particles. This process is supported by the dominating easterly swell which sweeps sediment away from the reef. However, the reefs along the eastern canyon margin are very impoverished, for shallow water clasts are constantly introduced from the adjacent bank area by the same eastwind driven swell. Only in lower portions of the western canyon margin, where the canyon wall steepens, gravitational export of debris is enhanced and reef growth improves (HUBBARD 1986, HUBBARD et al. 1986).

In a hydrodynamic regime comparable to flourishing modern reefs, bulk production of debris in Late Jurassic times might have been somewhat lower than today, since the biological component of debris formation was not yet as effective as it is nowadays (STENECK 1985). On the other hand, efficiency of stabilizing debris was much less than in modern reefs, where melobesioid coralline algae are very effective in this aspect. Given the same average capacity of export of debris by waves during the Late Jurassic and today in a comparable setting, equilibrium conditions between coral growth, fragmentation and algal stabilization were generally not reached in Upper Jurassic high-energy reefs, since the remaining fraction of the clast material could not be totally fixed by the less effective Upper Jurassic sediment binders, which were largely composed of microbial forms. This resulted in the typical bioclastic piles representing most Upper Jurassic high-energy reefal settings (Figs. 11d, 12a).

During the Late Jurassic, and similarly during older intervals of the Phanerozoic, sediment balance could, however, be achieved by two ways:

(1) *Reduced rate of debris production*: During most of the Mesozoic, deeper or shallow but protected water settings were characterized by reduced rates of debris production (Fig. 11c). In such settings erosion is almost exclusively bound to biological, rather than physical processes. Due to lacking water exchange or, in the case of deeper settings, lowered illumination, such environments mostly exhibited impoverished conditions for hermatypic coral growth, so that resulting reefs commonly were oligospecific coral meadows or microbial-sponge and microbial-coral-sponge reefs.

Though some coralline reef sponges have symbiotic, oligophotic cyanobacteria, most other sponges are completely independent of light (KÜHLMANN 1984). With the exception of coralline sponges, modern siliceous sponges have their maximum distribution in waters deeper than 200 metres (REID 1968). This might be partly due to the fact that they are able to tolerate low oxygen levels (REID 1968) and that they can create their own water exchange system. For instance, one examined specimen of a medium sized sponge pumped 1575 l/day through its tissue (KÜHLMANN 1984).

Hence lowered rates of debris production and a very low sedimentation regime (DROMARD 1989) in a generally tranquil environment seem to be the most important factors favouring accelerated growth of microbial crust/sponge reefs. However, the nature of the associated microbial crusts is as yet unclear. Very low light intensities are sufficient for many crust-forming cyanobacteria; other crust-producing cyanobacteria and bacteria may be completely independent of light and live heterotrophically (e.g. KRUMBEIN 1977, MONTY 1977, LEINFELDER & HARTKOPF-FRÖDER 1990). Modern microbial mats occur in depths down to several kilometres (GRASSLE 1985). According to BRACHERT (1991) many smaller microbial-sponge mounds seem to have grown under lowered and fluctuating oxygen levels, conditions which also indicate deeper settings closely above and sometimes within the upper part of the oxygen minimum zone. In core samples much of the South German Upper Jurassic succession is fairly dark, though finely dispersed pyrite is not always obvious (GWINNER, personal communication), and the crust-sponge facies grades basinwards into bituminous deep-water limestones of the Helvetic zone (Quintner Kalk) (e.g. SELG & WAGENPLAST 1990). On the other hand, microbial crusts from the shallow-water, high-energy Ota Reef share many similarities, such as common peloidal character, dome formation, and accompanying micro-organisms (*Tubiphytes, Bullopora, Placopsilina*, nubeculariids etc.) with such deep water crusts. It seems that a low-oxygen situation is not a necessary factor for crust formation, it simply might be tolerated if occurring, or possibly, even enhance crust formation in deeper settings (cf. GERDES & KRUMBEIN 1987, KEMPE 1990, RIEGE et al. 1991. Occurrence of *Bacinella, Lithocodium* and

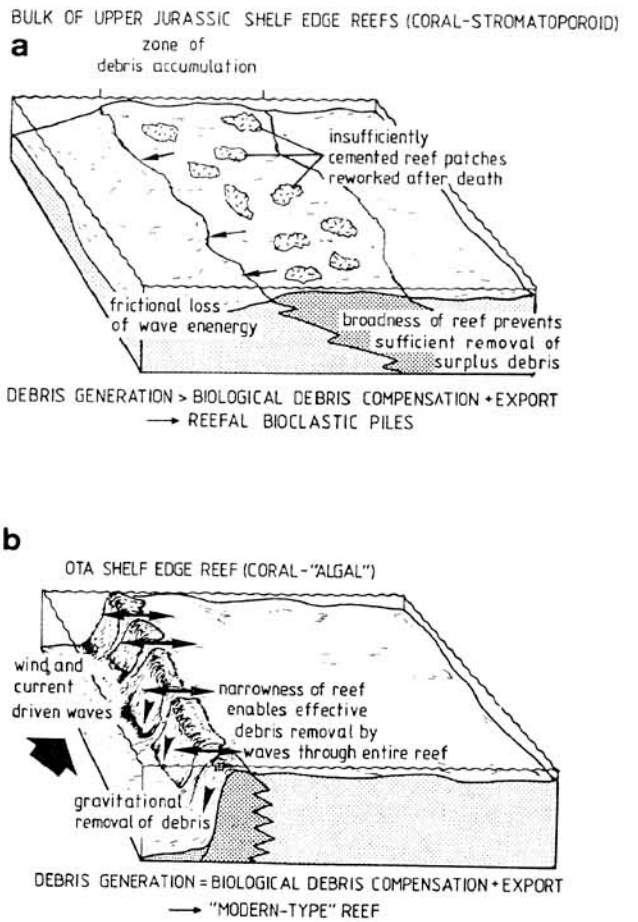

Fig. 12. Generalized reef models to illustrate the importance of debris export in determining the character of Upper Jurassic high-energy reefs. a) A depositional margin does not allow sufficient removal of debris. The remaining debris cannot be stabilized due to the lack of efficient sediment binders in Jurassic times. Consequently, the platform margin is rimmed by a broad zone of unstabilized debris with only subordinate amounts of small cemented reef patches. Such 'bioclastic pile reefs' represent the majority of Upper Jurassic high-energy reefs. b) The existence of a steep by-pass margin allows better winnowing of the reef and an enormous increase of gravitational export of debris. Available sediment binders (microbes) are then able to sufficiently stabilize and cement reef framework and remaining reef debris.

Thaumatoporella-type structures within microbial crusts seem diagnostic for a shallow-water character, whereas clotted peloidal, thrombolitic and stromatolitic types as well as many additional, mostly problematic elements may occur over a very wide bathymetric range. *Tubiphytes*, for instance, seems to appear from very shallow (yet possibly somehow protected) to moderately deep water (e.g. in the Kimmeridgian Treuchtlingen Limestone of Southern Germany, KEUPP et al. 1990). Some authors suggest that Upper Jurassic microbial-sponge reefs may indeed have inhabited fairly shallow water, and were possibly occasionally exposed. Although the given (mostly diagenetic) evidence is as yet far from being conclusive, some microbial-sponge reefs might in part have grown in shallow, yet low-energy settings (discussions in KEUPP et al. 1990 and SELG & WAGENPLAST 1990).

(2) *Elevated export rate of surplus debris*: Modern high-energy reefs exhibit either depositional or steep by-pass fore reef slopes or a mixture of it. Depositional, low-angle slopes cause a certain loss of hydrodynamic energy due to bottom friction. A broad reef tract also results in frictional loss towards the interior of the reef. Nevertheless, the remaining energy is still sufficient to sweep the reef clean from unstabilized debris. In comparable Upper Jurassic high-energy reefal settings, debris stabilization by binders was less effective, leaving larger amounts of loose debris within the reef than in modern reefs. This loose material could not be completely removed from the reef by the same hydrodynamic energy as in modern reefs, what lead to continuous piling-up of debris within the reef and hence to the typical Upper Jurassic high-energy reefal bioclastic piles (Fig. 12a).

Only with additional export sediment balance could be achieved (Fig. 11e). This case can be deduced for the Ota Reef from its richness of microbial crusts. The high-energy Ota Reef was apparently characterized by a steep, most likely vertical by-pass margin: Although an expected base-of-slope debris apron is not exposed, evidence for the structure of the margin comes from the seismic record and from the lack of progradation of the Reef Complex despite high productivity. (LEINFELDER & WILSON 1989, ELLIS et al. 1990). The position of the tidal belt directly behind the reef tract and the shallowness of the lagoon show that reef productivity was indeed considerably high. Taken the high productivity of the Ota Reef into account, the very moderately rising, if not oscillating sea-level of the late Early and Late Kimmeridgian (sensu gallico) (cf. HAQ et al. 1987, PONSOT & VAIL 1991) could not be responsible for the aggradational architecture of the complex, so that a tectonically induced steep by-pass margin is the only possible explanation for the lack of reef progradation. Much of the loose debris material was transported gravitationally towards basinal settings along this by-pass margin. The characteristics of the margin were also responsible for the narrowness of the reef belt, what in turn facilitated sweeping and removal of surplus material by unfrictioned waves reaching the reef belt (Fig. 12b). Hence, both the by-pass margin of the Ota Reef Complex and the position of the reef within a zone of elevated current speed resulted in export rates of debris material from the reef core greater than compared with other Upper Jurassic high-energy reefal settings and thus accounted for the equilibrated sediment balance and the modern character of the Ota Reef.

6 CONCLUSIONS AND EPILOGUE

Reef flourishment is, besides many other ecological factors, also greatly dependent on the achievment of equilibrium conditions between production of debris material and compensation of this material by upward growth of reef constructors, sediment fixation by binders, and export of remaining surplus material from the reef. In low-energy settings, i.e. deeper or protected shallow environments, debris production is mainly due to bioerosion and bioabrasion which could be easily compensated by sediment binders, mostly microbes and algal-like organisms, throughout most of the Phanerozoic aeon. However, the reduced rate of water exchange, and the related loss in oxygen contents in these cases leads to the accelerated growth of such microbial forms adapted to these conditions, and to the impoverishment of other reef biota which in such settings are commonly dominated by siliceous sponges in Upper Jurassic reefs.

In high-energy settings, bioabrasion and bioerosion is accompanied by high rates of physical debris production. Even in modern reefs, highly effective sediment binders - to a large part represented by the meliobesioid coralline algae- often cannot stabilize the entire debris production. Consequently, sediment balance can be only achieved through

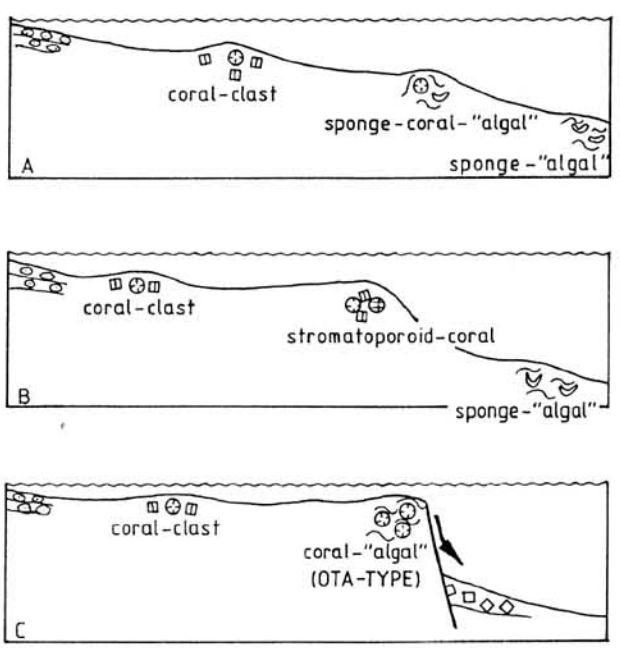

Fig. 13. Inclusion of the Ota example into the CREVELLO & HARRIS (1984) and SCOTT (1988) models for Upper Jurassic reefs (partly simplified). A: reefs in shallow to deeper ramp settings; B: reefs within and on the depositional margin of rimmed shelves. Sponge-'algal' reefs occur in lower slope to basinal setting; C: reefs within and on the by-pass margin of rimmed shelves.Reefs rich in 'algal' (i.e. microbial) crusts may not only occur in deep or very protected shallow settings but also in a high-energy setting, provided export of debris is enhanced by the existence of a steep by-pass margin (arrow). All Upper Jurassic high-energy reefs are very rich in debris; the Ota-type, however, contrast the other high-energy reefs by its high proportion of biogenically stabilized debris, hence giving it a 'modern' aspect.

export of surplus debris material towards seaward and lagoonward areas, mostly along groove systems. Jurassic high-energy reefs had much less effective sediment binders available (cf. FAGERSTROM 1987). Consequently, export rates of surplus material had to be considerably higher than in modern reefs, in order to reach sediment balance. Apparently, such balance was normally not achieved, so that Jurassic high-energy reefal settings are commonly characterized by loose bioclastic piles containing only very subordinate amounts of reef framework. Only in cases where export rates could be increased, there was a chance for reaching sediment balance, which then results in a rather modern sedimentary aspect of such reefs.

The Ota Reef from the Upper Jurassic of Portugal is an example for increased export rates of debris, caused by its position within a coastal boundary current and by the existence of a steep by-pass margin allowing gravitational removal of surplus material. Consequently, the Ota Reef is, like modern high-energy reefs, characterized by small areas of in-situ coral-algal or coral-microbial framework, encased by large algal/microbial-cemented debris areas, both of which build up boundstone pillars interpretable as reef spurs and larger reef patches. These coral-algal/microbial boundstone areas are apparently crosscut by channels and grooves filled with loose debris material which represent the only areas in the reef tract where larger amounts of unstabilized bioclastic debris accumulated.

Somewhat similar to the Ota Reef situation are some Upper Jurassic Plassenkalk reefs from the Austrian Northern Calcareous Alps, which are characterized by small reef patches encased in partly biocemented debris material (STEIGER & WURM 1980). Like the Ota example, these reefs also grew on uplifted blocks bounded by steep margins. The steep margin situation in the Austrian examples is apparent by the occurrence of calcareous turbidites transporting material not only from the reefs but also from eroded underlying older sediments into the Tethyan deep-water basin (Barmstein turbidites, STEIGER 1981).

Palaeozoic tabulate-stromatoporoid reef communities might have had a higher ability of sediment fixation than Jurassic and, possibly Upper Triassic reef communities, since not only algae and microbes but also the stromatoporoids themselves could participate in sediment binding. Possibly, the degree of bioerosion was still very low during the Palaeozoic (cf. FAGERSTROM 1987), so that less bulk debris material was produced. However, growth of modern stromatoporoids is very slow (REITNER, pers.commun.). If Palaeozoic stromatoporoids grew as slow, their sediment binding efficiency was also low and it remains to be proven for many of the Palaeozoic examples, whether these reefs actually grew up to the same high-energy level as did many Cenozoic reefs and the Ota Reef.

Concluding, besides the known main factors determining reef growth, such as climate, salinity, depth, oxygen and nutrient levels and hydrodynamic energy, considerations on the sediment balance should be incorporated into Phanerozoic reef models. For the Upper Jurassic, Fig. 13 gives a version of the CREVELLO & HARRIS model which is modified in this aspect.

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