Cyanophyte Calcification Morphotypes and Depositional Environments
(Alenquer Oncolite, Upper Kimmeridgian?, Portugal)

Kalzifikationsmorphotypen und Ablagerungsmilieu von Cyanophyten
(Alenquer Onkolith, Oberes Kimmeridgium?, Portugal)

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SUMMARY

Terrigenous red siliciclastics of Upper Kimmeridgian(?) to Portlandian age around Alenquer, Portugal, comprise a narrow level of oncoid-bearing limestones. Oncoid cortices are composed of cyanophytes which appear in different calcification morphotypes according to changing physico-chemical parameters. Recent examples reveal that in most cases each calcification morphotype is related to one single species or one defined association. Hence, the characteristic calcification patterns are mostly biologically rather than abiotically controlled. Oncoid shapes, sizes and arrangement, on the other hand, are mainly determined by the hydraulic parameter within the depositional environment.

Accompanying biota as well as sedimentological and diagenetic characteristics suggest a combination of paralic, lacustrine, marsh and fluvial environments with salinities ranging from hypersaline to freshwater conditions. This variety of sub-environments was created by a rapid but short-lived transgression into a graben- or half-graben-like subsiding depression along the active fault system of Vila Franca de Xira.

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1 INTRODUCTION

The Mesozoic Lusitanian Basin of Portugal, a marginal basin of the slowly developing Atlantic, underwent intensive silting-up in the course of the Upper Jurassic in an overall southward direction (e.g., WILSON 1979). During the Upper Kimmeridgian and Portlandian, the coast was shifting around a line north of Lisbon. It extended somewhere from Torres Vedras in the west to Alenquer in the east, with the northern part dominated by the clastic regime and grading southwards into marly and calcareous deposits (LEINFELDER 1985).

The general regression is reflected in a sequence of reefoid and lagoonal limestones, the Corálico and the Ota unit, which is overlain by deltaic silts and sandstones, the Sobral unit, and by red terrestrial sandstones and caliche-bearing silts of the Torres Vedras unit. Superimposed are some oncolitic beds, which we term Alenquer Oncolite because they are distributed around the town of Alenquer in the district of Vila Franca de Xira (Fig. 1). The beds are overlain by coarse red siliciclastics of the Upper Sandstone unit which extends to the Cretaceous. Hence, the oncolite beds represent a calcareous intercalation within a siliciclastic terrestrial sequence. Actually, they correspond to the marly calcareous "Pteroceriano" unit developed further south.

Fig. 1. Locality map. Black arrows, outcrops of the Alenquer Oncolite. Large arrow, location of section shown in Fig. 2.

The purpose of this paper is to discuss this peculiar oncinite under genetic aspects, with special emphasis on establishing and interpreting cyanophyte calcification morphotypes. Furthermore, the development of the oncinites within a continuous terrestrial clastic series reflects an interference in delicate environmental conditions which will be analysed and discussed with regard to their paleogeographic implications.

2 THE HOST ROCK

Brownish gray to predominantly reddish, medium to thick-bedded oncolites form a
Fig. 2. Detail at Quinta de Cabeça, west of Meca (see Fig. 1): The Alenquer Oncolite, represented here by two horizons of variable thicknesses, embedded in marine to brackish marl and micritic limestone. The entire set is intercalated within red terrestrial clastics. For further explanations see text. Determinations of carbonate and siliciclastic content as well as grain size are qualitative/semiquantitative.

- micritic oncocids and algal lumps of the *Rivularia haematitae* Morphotype.
- microsparitic oncocids, mostly of the *Phormidium inornatum* Morphotypes.
- caliche nodules
- birdseyes
- nodular bedding surfaces

**Grain size**
- C = clay, S = silt, FS/MS/C = fine/medium/coarse sand, FS = fine gravel

**Content of siliciclasts**
- q% black: free quartz, cross-hatched: encrusted quartz

**Size parameters**
- $S_q$: sorting of free quartz
- $R_q$: roundness of free quartz
- $S_n$: sorting of oncocids
- $N_o$: nucleus of oncocids, $q$ = quartz, $o$ = organic
- $D_o$: mean diameter of oncocids, largest values in brackets
2-3 meter thick set of two calcareous horizons, which are usually separated by several decimeters of, usually unexposed, silty marl. Occasionally the transition from the clastics to the lower oncoid horizon is represented by one meter of marl with rare thin cerithid gastropods, grading into a several decimeter thick bed of silty microsparitic peloid packstone with scattered intraclasts and ostracods. The oncoid set may be overlain by 150 centimeters of gray, nodular, slightly marly, lime mudstone with rare gastropods, isolated spar-filled fenestrae (birdseyes) and irregular shrinkage cracks (Fig. 2). More commonly, however, only the proper oncules are intercalated into the red clastics or only one oncoid horizon is developed.

Though the oncules most commonly exhibit distinct bedding planes and constant thicknesses, they may also thin out gradually, display downcutting surfaces or change into sandstone beds. Terrigenous detrital quartz, both free and algal-encrusted, occurs throughout the set, varying largely in amount, grain size and sorting (Fig. 2).

3 Oncoids

Oncoids and their clasts may float as individual particles in a sandy, calcareous matrix. More often, however, they form a closed packstone/rudstone fabric. A closed fabric is sometimes restricted to downcuts with fining-up of components in the trough filling, whereas sands lacking oncoids are deposited on the trough shoulders (Fig. 2).

Fractured oncoids and cyanophyte lumps are apparently more common in the lower horizon. In the upper level oncoids may form autochthonous algal pillows characterized by a polygonal component fit.

Oncoid shapes differ widely, yet individual beds are usually dominated by one prevailing shape. Round and ovoid oncoids often form rudstones with a partly sparitic groundmass, whereas flattened irregular oncoids are normally embedded in a silty micritic matrix, often forming a closed fabric. Common as well are subcircular oncoids with bumpy protrusions (botryoidal oncoids).

From all of these types a grain-boundary-fitting polygonal fabric may occasionally develop by polar growth into oncoid interstices (Pl. 30/1). Unidirectional growth also rarely results in the development of large stromatolitic structures up to 15 cm in size (Pl. 29/1).

Oncoid nuclei are commonly made up of detrital quartz grains, caliche clasts, oncoid fragments, fan-shaped algal bundles, or aggregates consisting of a bulbous tissue. The aggregates also form discrete nodules measuring up to 3 cm in diameter. They may be attributed to the alga? Bacinella? sterni RADOIĆIĆ (Pl. 29/3, 4).

Bacinella? sterni has vesicles ranging from 40 to 140 μm in diameter, normally 80 μm, as can be understood from the original figures of RADOIĆIĆ (1972) who attributes the form with great uncertainty to this probably codiacean genus. In the Bacinella? sterni nodules of the Alenguer Oncolite, vesicle sizes range from 45 - 105 μm, most commonly 70-75 μm (Pl. 29/4). ELLIOT (1966) interpreted similar aggregates as an intergrowth of cyanophytes and nubecularian foraminifers.

Different sorts of nuclei are related to different oncoid beds. In some localities, the upper oncoid horizon bears considerable numbers of oncoids with nuclei composed of poorly preserved Chara-stems (Pl. 29/8). Small, thin-shelled, low trochospiral and planispiral gastropods and thin bivalve shells, serving rarely as nuclei, are also restricted to a few sites only.

Oncoid diameters range from 0.4 to 35 mm, normally 5 to 10 mm. Cortices are generally much thinner than oncoid cores. The lower oncoid horizon, however, may start with a bed of very superficially encrusted quartz grains (Pl. 29/9). Oncoidal cortices display a more or less pronounced layered microfabric. Thicknesses of the individual laminae vary from very fine, several μm
thick coats up to 1 cm thick sheets. Laminae may be smooth, crenulate or show botryoidal protrusions on their distal surfaces. Regular concentric oncoids with smooth outer layers may nevertheless exhibit strongly crenulate laminae in their inner parts (Pl. 30/3). Sometimes laminae are missing on one side of the oncoids.

Thus, the oncoid configuration types C (vertically stacked regular concentric layers), R (randomly stacked subconcentric layers with protrusions) and I (inverted stacked layers with discordances) of LOGAN (1964) and RADWANSKI & SZULCZIEWSKI (1966) are developed.

Individual laminae form three main microfabrics, a predominantly micritic, a spongy and a microsparitic/sparitic microfabric.

4 CYANOPHYTE ASSOCIATION

Most of the cortical structures of the oncoids are clearly organogenic, being derived from cyanophyte growth:

Modern calcifying cyanophyte associations have undergone thorough examination during the last decade so that knowledge has increased considerably in this respect. Of special interest are calcifying forms of the Hormogonia algae. They are characterized by organic filaments with simple structures which reproduce by false branching, due to auto-fragmentation of trichomes, into short, mobile pieces (FOTT 1971).

Most currently cited are the genera Schizothrix and Phormidium of the order Oscillatoriales and Saytonema, Calothrix, Diachelonema. Schizothrix and Rivularia of the Order Nostocales (taxonomic classification after GOLUBIĆ 1976):

MONTY (1976) reported cyanophyte structures from the freshwater tidal marshes of Andros Island, Bahamas and Shark Bay, Australia, which he attributed to Saytonema, Schizothrix and Phormidium inoaratum. SCHÄFER & STAFF (1978) investigated freshwater oncolites from Lake Constance, West Germany formed by Phormidium - Calothrix/ Diachelonema, Schizothrix and Rivularia cf. haematites. MONTY & MAS (1981) described oncoids composed of calcified Phormidium foueslanum and P. inoaratum from the Bois d' Hautmont Creek, Belgium. SCHNEIDER et al. (1983) mention crusts of Rivularia and Schizothrix from the Attersee, Austria.

Fossil examples are interpreted in an analogous way: Rivularia haematites is described from brackish water oncoids of the Pleistocene in the eastern Mediterranean (RICHTER & SEDAT 1983). Freshwater oncolites exhibiting Rivularia- and Phormidium-like structures also occur in the Eocene of Spain (ANADON & ZAMARRENO 1981, NICKEL 1983). Oncolites and stromatolites with similar microstructures from the Spanish Wealden (Lower Cretaceous) are also interpreted as freshwater deposits (MONTY & MAS 1981). HUDSON (1970) compared Cayeuxia nodosa from Middle Jurassic limestones of Scotland to Recent Saytonema and also detected Schizothrix-like structures. He suggested a supratidal freshwater marsh environment which occasionally underwent hypersaline conditions.

Since exact taxonomic differentiation of Ancient cyanophyte structures is virtually impossible, particularly in rocks older than the Pleistocene, normally only comparisons with Recent algae are carried out, without attributing the Ancient forms to Recent taxa.

However, when evaluating studies of Recent examples, it becomes evident that certain cyanophytes form certain calcareousmorphotypes which may be recognized in the fossil record. Saytonema, for instance, never seems to be intensively calcified. It apparently acts as a sediment binder rather than a lime "producer" and often forms a micritic fabric with large fenestrae due to organic decay (MONTY 1976). On the other hand, heavily calcified laminae are preferably produced by several species of Phormidium: P. inoaratum becomes prominently calcified only in Spring. This enhanced calcification might be dependent upon a sudden increase in alkalinity, a
Tab. 1. Possible paths leading to different algal calcification morphotypes in relation to changing environmental parameters. Note that only case 1 would be induced solely inorganically and is possibly not realized in nature. See examples in text.

<table>
<thead>
<tr>
<th>Calcification of cyanophytes due to</th>
<th>Environmental change (p/T, chem., hydraul. causing)</th>
<th>Resulting in</th>
<th>Calcification change due to</th>
</tr>
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<tbody>
<tr>
<td>physiological behaviour (CO₂/HCO₃⁻ uptake)</td>
<td>no biotic change</td>
<td>different calcification pattern, same species</td>
<td>abiogenetic factors alone</td>
</tr>
<tr>
<td>physiological behaviour (CO₂/HCO₃⁻ uptake)</td>
<td>establishing of new species</td>
<td>different calcification pattern, different species</td>
<td>new species with differing physiological behaviour (CO₂/HCO₃⁻ uptake)</td>
</tr>
<tr>
<td>non-calified but calcifying associated microbes</td>
<td>change in the microbial association</td>
<td>different calcification pattern, same species</td>
<td>different microbial association triggering different calcification pattern</td>
</tr>
<tr>
<td>species-determined direct calcification</td>
<td>establishing of new species</td>
<td>different calcification pattern, different species</td>
<td>species-determined direct calcification differing from former species</td>
</tr>
</tbody>
</table>

Drop in temperature and a decrease in the magnesium/calcium ratio of interstitial waters, the latter of which is most often due to intermittently agitated bottom waters (CROSS & KLOSTERMAN 1981, see also RIDING 1982). Thus, the species exhibits different calcification patterns related to seasonally differing physico-chemical characteristics.

On the other hand, however, *Phormidium foveolatum* generally occurs only in a coarsely calcified way with crystal orientation determined by the tiny organic filaments (MONTY & MAS 1981). One may theorize that the species is rather micro-environment-selective or that it controls carbonate precipitation directly.

It is widely assumed that calcification of the prokaryote cyanophytes is only a chemical response to organically altered microenvironments, particularly due to CO₂/HCO₃⁻ uptake during photosynthesis (e.g. FLÜGEL 1982:336, SCHNEIDER 1976). KRUMBEIN (1978), however, showed that in Recent subtropical cyanophyte mats calcification is managed by bacteria and is not necessarily related to photosynthesis. Moreover, GOLUBIC & CAMPBELL (1981) could prove that calcification of two Recent marine *Rivularia* species takes place within the extracellular mucilaginous sheath in such a way that species-diagnostic, biologically controlled carbonate aggregates are produced (Tab. 1).

### 4.1 CYANOPHYTE CALCIFICATION MORPHOTYPES

It can be concluded that one or a few calcifying cyanophyte taxa lead to a distinct and characteristic calcification morphotype apparently controlled by growth form, by selective environmental and related physico-chemical preferences, by non-calified microbes, and, at least partially or occasionally, by species-determined direct organic precipitation. Hence, it appears useful to establish distinct calcification morphotypes, most of which are named here after the most typical Recent cyanophyte representative producing a similar fabric: yet we must also bear in mind that other cyanophytes and even chlorophytes may account for the same pattern as well (see, e.g., GOLUBIC & CAMPBELL 1981), particularly in the fossil examples.

Nevertheless, a parataxonomic morphological classification based on Recent taxa is preferred to a paleontological "ortho"-taxonomy, since in the present example not only the morphotypes but also their environmental distribution are apparently
Table 2. The cyanophyte calcification morphotypes of the Alenquer Oncolite.

strongly resembling the Recent counterparts.

The ten morphotypes occurring in the Alenquer Oncolite are listed and characterized in Table 2.

4.1.1 MICRITIC MICROFABRIC

Schizothrix Morphotype

The micritic microfabric is most difficult to interpret. Dense films in Recent freshwater oncoids are most often formed by heavily encrusted blooms of Schizothrix, an endoepithetic taxon which micritizes the substratum by boring and triggers calcification by CO₂/HCO₃⁻ uptake (Schneider et al. 1983). Micritic rims may, however, also represent interruptions in the growth of other cyanophytes e.g. Phormidium incrassatum or be caused by abrasion (Monty & Mas 1981). In the latter case, a regular concentric rim will develop. In any case, these rims, here called Schizothrix Morphotype (cf. Monty 1976, Fig. 21E, 22B; Schäfer & Staff 1978, Fig. 15), mark interruptions of a continuous cyanophyte sheet development due to slightly changing environmental conditions and are most probably related to phases of higher energy.

Rivularia haematites Morphotype

Bushes of radiating spar-filled tubes with diameters of 20–30 µm may form macroscopic pillows composed of densely packed cyanophyte nodules (Pl. 29/2). The documented organism closely resembles Rivularia haematites which now occur in lakes, mainly in the splash zone, and rivers but also tolerated brackish and shallow subtidal marine water (Rivularia haematites-Morphotype, cf. Schäfer & Staff 1978, Fig. 19; Richter & Sedat 1983, Fig. 4).

Schizothrix-Seytonema Morphotype, Seytonema/Calothrix Morphotype A
Micritic laminae composed of erect, often diverging micritic filaments or filament bundles are one of the most predominant laminae types, accounting for the bulk of regular oncoids (Pl. 30/3, 9). They may be compared well compared to Recent micritic cemented Saytonema or Calothrix crusts (Saytonema/Calothrix Morphotype A, cf. MONTY 1976, Fig. 24). Often interpenetrating micritic films form a fine reticulate pattern (Saytonema-Saytonema Morphotype, cf. MONTY & MAS 1981, fig. 12C, 16B).

4.1.2 SPONGY MICROFABRIC

Saytonema Morphotype B
A primary lower calcification led to the spongy microfabric commonly found in large oncoids and smallstromatolites (Saytonema Morphotype B; cf. MONTY 1976, Fig. 19, 25, 34; MONTY & HARDIE 1976, Fig. 11). Elongate tubular microfenestrae (Pl. 29/1) are most probably due to oxidation of filament bundles as is common in Saytonema mats growing in Recent freshwater marshes of the Bahamas. Fenestrae formation is also most probably intensified by internal solution and bioerosion (see MONTY 1976, SCHNEIDER et al. 1983). Further vadose diagentic solution, as evidenced by internal crystal silt in solution vugs, may destroy the original fabric completely.

Primary and early vadose solution features coupled with a high degree of organic decay indicate that this kind of cyanophyte crust underwent periodic subaerial exposure.

Coccolid Algae Morphotype
Coccolid algae or bacteria may be responsible for layers or even whole nodules of thrombolitic fabric which is mainly created in non-freshwater settings (HALLEY 1976, MONTY & MAS 1981) and is assigned here as the Coccolid Algae Morphotype (cf. MONTY 1976, Fig. 26; FOLK & CHAFETZ 1983, Figs. 2-5). Internal solution of micritic microfabric, however, could also lead to similar structures.

Diochothrix Morphotype
The most common spongy microfabric of oncites is represented by arrays of radiating, paintbrush-like micritic tufts which start from a narrow base and extend locally up to 1 cm without interruption (Pl. 30/7). Interstices between the individual tufts are filled with clear spar (Diochothrix Morphotype; cf. SCHRÄFER & STAFF 1978, Fig. 12; GOLUBIC 1976, Fig. 4, p. 138).

Originally, the fabric was rather open with empty, non-calcified spaces between the strongly erect growing filament bundles, resembling the modern freshwater cyanophyte Diochothrix (Pl. 30/6). Often the Diochothrix Morphotype is interbedded between coarse crystalline crusts of the Phormidium inorustatum Morphotypes (Pl. 30/8) (see below). Hence, the Diochothrix-like cyanophyte may represent a fast-growing pioneer form, with growth starting from selected points on a hard surface layer after changed environmental parameters, radiating and branching rapidly to occupy the available space. Changing environments then led to the re-establishment of the Phormidium inorustatum Morphotypes. The fact that oncoid nuclei are often represented by the Diochothrix Morphotype also strengthens the pioneer character of the related cyanophyte taxon.

Small dolomite rhombohedrons which occur at times in these core-zones indicate that complete calcification of the crust was perhaps primarily inhibited by an elevated Mg-content which led to later diagentic dolomite formation (Pl. 30/7). Common is also a collapsed microfabric with algal fragments lying in a sparitic groundmass, often associated with crystal silt. Because of occasionally very straight, often low-angle boundaries of the spar areas, and because structural collapse does not occur in the overlying or underlying laminae, one may assume that gypsum crystals were formed which were subsequently leached (Pl. 30/2).

4.1.3 SPARITIC MICROFABRIC

Phormidium inorustatum Morphotypes A & B
Microsparitic to spartic laminae are of major importance in almost all oncocids. They are dominant in regular concentric oncocids with quartz nuclei. The upper boundary of the individual laminae often shows convex bumpy protrusions (botryoidal), whereas the lower surface is smooth or indistinct (Pl. 30/3). Laminae also frequently wedge out.

The small crystals composing the crust are arranged roughly radially, forming fan arrays which extend in diffuse radial lines under cross-polarized light. Normally these cement-like crusts resemble certain caliche or coniatolite deposits (e.g., JAMES 1972, FRUSER & LOREAU 1973, HARRISON 1977, BRAITHWAITE 1979). Although an occasional vadose diagenetic inorganic accretion during exposure times cannot be excluded completely, CROSS & KLOSTERMAN (1981) impressively demonstrated that radially oriented algal tufts may recrystallize entirely to form neomorphic botryoidal crusts. This explanation is also valid here, since most microsparitic laminae exhibit mimic radiating filament bundles (Pl. 30/8).

A predominantly radial arrangement of microsparitic crystals is also quite visible under the scanning electron microscope (Pl. 30/4). The radiating fabric is crossed by tangential linear voids, representing decayed tangential cyanophyte films. Of special interest are also the frequent rounded voids (Ø 1–5 μm) which in accordance with Recent examples should represent former organic filaments (Pl. 30/6, compare strikingly similar features from freshwater cyanophyte formations in Green Lake, New York, as illustrated by EGGLESTON & DEAN 1976, Figs. 4-6).

The fabric may be best compared with similarly calcified mats of modern Phormidium incrustedum (Phormidium incrustedum Morphotype A: MONTY & MAS 1981, Fig. 18; CROSS & KLOSTERMAN 1981, Fig. 5D).

Note that the taxon determined as Phormidium incrustedum in Figs. 7 and 8 in MONTY (1976) is most probably a Lyngbya martenstiana var. calcarea (MONTY & MAS 1981, p. 111, footnote). This might also be the case for the alga pictured in Fig. 11 in SCHÄFER & STAFF (1978), assigned as a probable Phormidium, since the tube diameters are too large to justify this generic determination (cf. MONTY & MAS 1981).

Strongly neomorphic crusts (Pl. 30/2) may be termed Phormidium incrustedum Morphotype B (cf. CROSS & KLOSTERMAN 1981, Fig. 4b).

Crusts of the Phormidium incrustedum Morphotypes may also exhibit micritic tangential films, attributed to the Schizothrix Morphotype, and horizontally elongated, 1 mm wide, 0.5 mm high, spar-filled convex fenestrae, situated on top of or in the upper part of the crusts (Pl. 29/7). These fenestrae could well be compared with chironomid or similar larvae (ANADON & AMARRENO 1981, pl. 1/2, MONTY 1976, Fig. 7: note that the scale in the photograph is not 200 μm but 6 mm, after MONTY & MAS 1981, p. 111).

As already outlined above, these crusts probably developed during altered chemical and physical environmental conditions, thus promoting the growth or at least the intensive calcification of a Phormidium incrustedum-like form.

Occasional gradual transitions from the Dichothrix Morphotype to a superimposed Phormidium incrustedum Morphotype (Pl. 30/8) could, however, lead to the interpretation that the same cyanophyte was responsible for the formation of both types of crusts, differing only in the degree of calcification due to different ecological conditions.

Such a point of view automatically leads to taxonomic problems. Prokariotic cyanophyte "algae" are grouped together with bacteria into a common phylum, the Schizophyta (e.g., MASSE 1979), which is a largely asexually reproducing group, so that even for modern taxa the application of the species concept is difficult. Often the pragmatic ecological niche concept (one species - one niche) of HUTCHINSON (1968) is applied. If this concept is logically developed, a difference in environmental conditions and thus in habitat would also imply that two different "taxa" were responsible for the formation of the respective crusts.

Habitat, however, may be broadly defined.
The Recent Phormidium hendersoni, for instance, occurs in a variety of coastal environments, yet always produces similar crusts (GOLUBIC & FOCKE 1978).

Nonetheless, a wide range of morphologic variation and transition from one "taxon" to another may also be recognized by the occasional transition from coccolid algal (or cyanobacterial) shrubs to the Dichothrix Morphotype (Pl. 29/6). Actually modern bacteria exist, e.g. Thiocapsa, Thioploca, which appear to be apochlorotic (i.e., unpigmented) forms of cyanophytes, appear in this case Phormidium and Schizothrix (STANIER & vanNIEL 1941; TAPPAN 1980:29).

Sparitic, mainly Isopachous, Radial Fibrous Crusts
These 30-70μm thick, clear crusts composed of radially oriented prismatic crystals occasionally occur on top of crusts of the Phormidium incrustatum Morphotypes and could be explained as early cementation during an interruption in algal growth or sometimes as syntaxial diagenetic overgrowth starting from the sparitic morphotype and growing into the surrounding micritic lamina.

Most commonly these radial-fibrous crusts occur as simple (rarely double or triple) rings around detritic sand-sized quartz grains in sparitic sandstones directly underlying the Alenquer Oncolite (Pl. 29/9). Because of the rather high regularity of the envelopes, the grains have to be identified as ooids with a radial fabric. In cross-bipolarized light, however, one occasionally detects a fan-like, radially diverging arrangement of microcrystals which also transsects the boundary between adjacent rings (Pl. 29/10). Consequently, these radial-fibrous crusts might also represent strongly recrystallized Phormidium incrustatum Morphotypes which obtained their smooth regular surface through abrasion in turbulent water, an interpretation which is also backed up by transitions to Phormidium-type ooids.

Very interesting in this aspect is the modern coastal hypersaline Solar Lake at the Gulf of Elat. Interestingly enough, in the Solar Lake both ooids with fibrous and transparent layers and radial ooids occur together and also exhibit transitions into each other (FRIEDMAN 1978). FRIEDMAN's interpretation is that the radial ooids are also a product of algal precipitation. This also seems valid for the example given here, yet we are aware that this is probably not a general explanation for the apparently multigenetic existence of radial ooids (for survey see RICHTER 1983).

Further development of calcareous organic nodules was then eventually prohibited by the influx of fine-grained clastics.

5 ENVIRONMENTAL INTERPRETATION

All the cyanophyte calcification morphotypes described here with the exception of the coccolid type are based on modern freshwater counterparts and do not occur in modern marine environments (for restrictions, see above). Bearing in mind that filamentous cyanophytes, particularly the "cayeuxians", occur widely in the fossil record, one must be cautious about transferring modern examples to the past.

Actually, comparable freshwater communities had already existed at least from the Middle Jurassic onwards and remained unaffected until the Recent (HUDSON 1970, MONTY & MAS 1981), whereas cyanophytes almost completely disappeared from marine environments in the course of the Cretaceous (BIGNOT 1981, RIDING 1982). Consequently, environmental interpretation of the Alenquer Oncolite cannot be based on the cyanophyte associations alone.

Indications of a predominantly freshwater origin of the oncolites are:
- Recent examples
- Good preservation and calcification of cyanophytes. In saltwater environments calcification normally results only in the formation of thrombolitic aggregates.
- Charophyte stems serving as oncid nuclei, rare gygonites. (Although modern charophytes may rarely grow in brackish and very rarely even in marine settings, CORILLION 1957. Moreover, they may be easily transported over short distances).
- rare thin-shelled, globoid and planispiral gastropods resembling freshwater *Valvata* and *Planorbus* type, serving as oncocid nuclei
- trough fillings and fining-up sequences of oncocids
- common reddish coloration of oncolite beds
- solution features and "vadose" silt
- intercalation of oncocids between clearly terrestrial clastics
- total difference to marine oncocids of the equivalent "Pterocerianos"-unit nearby (LEINFELDER 1985)

Indications of saline influence are:
- oncocid nuclei and whole nodules composed of *Bacinella? sterni*
- thrombolitic oncocid nuclei and nodules
- locally, gray "*Cerithium" marls at the base of oncocites
- dolomite crystals and questionable pseudomorphs after gypsum in the *Diocthophris* Morphotype
- locally, the top of oncocites formed by marine nodular lime mudstone
- possible connection of the Alenquer Oncolite with marine oncocites, in any case with marine sediments further South

Rare ostracod and bivalve shells are no help in the determination of salinity.

Consequently, the section given on Fig. 2 may be interpreted in the following way:

Salinity increased from the basal floodplain deposits to brackish "*Cerithium"-marls to eventually more saline basal peloid packstones. Freshwater input was then increased considerably as is well documented by the high influx of siliciclastics but was intermittent enough to allow incipient oncocid formation in non-clastically influenced periods. The degree of salinity during these periods is unclear but was certainly variable.

The nodules composed of *Bacinella? sterni* as well as thrombolitic nodules occurring then may have grown under rather saline, perhaps even hypersaline conditions. Together with radial ooids, here interpreted as superficial oncocids, they were swept together to form a subsequently spar-cemented, poorly sorted closed fabric with a high fragmentation rate of *Bacinella? sterni* nodules. The superimposed upper oncolite horizon is very complex. Large parts are represented by out thinning cyanophyte pillows composed of closely packed, boundary-fitting nodules of the *Rivularia* haematites Morphotype. These pillows grew under freshwater or brackish conditions (RICHTER & SEDAT 1983) in a shallow, often exposed position (TAPPAN 1980:59).

This algal pillow swamp, which was free of quartz, was cut by fluvial hardwater cutting channels in which a particular cyanophyte association composed of well-rounded oncocids dominated by dense *Schizothrix-Seytonema* and *Seytonema/Diocthophris* Morphotypes grew during interruptions in clastic input and possibly during partial subaerial exposure. When heavily flooded, fragments of the surrounding algal pillows as well as coarse to very coarse quartz sand were admixed and components were deposited to form a fining-up sequence.

Renewed marine conditions are once more evidenced by the overlying, very shallow subtidal, restricted marine nodular lime mudstones, before the fluvial regime took over completely.

Other sites of the Alenquer Oncolite show different characteristics. Usually, there is no framework of marine deposits which may, however, be due to very early reworking of the overlying clastics.

Again channels are developed fairly often. After they were complete filled up, small domal stromatolites composed of the spongy *Seytonema* Morphotype B occurred occasionally and are preserved in-situ.

Beds with large quartz-cored concentric oncocids composed of smooth fine micritic layers represent fillings of larger channels where oncocids grew under more constant conditions of fairly high energy.

In the nearby suburbs of Alenquer, regularly bedded reddish oncolite beds with framboidal oncocids composed predominantly of an interlayering of spongy *Diocthophris* Morphotype and microsparitic *Phormidium*
crustatum Morphotypes are typical. Oncoid nuclei are often missing; sometimes, however, they are composed of charophyte stem fragments. Oncoids are frequently flattened or of the I-type and occasionally form a fitting fabric without distinct outer oncoid boundaries (Pl. 29/6). Tiny stromatolites occur as well.

These deposits clearly represent a supratidal algal marsh environment with seasonally flooded ponds and lakes developing on a former clastic fluvial plain. The Dichothrix Morphotype-crusts with possible pseudomorphs after gypsum and common vadose solution features developed during dry periods, whereas the Phormidium incrastatum-type layers are interpreted as freshwater flooding stages, arising after heavy seasonal rainfalls or fluvial floodings. The oncoids show all the signs of in-situ growth, such as bumpy protrusions, flat shapes, outthinning or lack of laminae on lower sides of oncoids as well as polygonal component fit.

In-situ growth of oncoids is particularly possible on coarse-grained substrata because of their ability to reflect diffuse light (Monty & Mas 1981), though it may also occur on fine-grained sediments, a process which is not fully understood yet (Jones & Wilkinson 1978).

This mixed hypersaline/freshwater algal swamp with many ponds and lakes grades several hundred meters further north into a charophyte freshwater marsh (Vale do Junco, see Fig. 1.).

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Fig. 3. Depositional environments at the time of oncolite formation and distribution of cyanophyte calcareous morphotypes to different environments. coc/Bac: lumps of the Coccoid Algae Morphotype and Bacteriella? steril-nodules; Riv: nodules of the Reticularia haematites Morphotype A; ScyB: oncoids and algal pillows of the Scytonema Morphotype B; Pho: oncoids dominated by the Phormidium incrastatum Morphotypes.
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Fig. 3. Depositional environments at the time of oncolite formation and distribution of cyanophyte calcareous morphotypes to different environments. cocc/Bac: lumps of the Coccoid Algae Morphotype and Batinella? sterni-nodules; Riv: nodules of the Rotalaria haematitidae Morphotype A; ScyB: oncoids and algal pillows of the Scytosoma Morphotype B; Pho: oncoids dominated by the Phormidium incrustatum Morphotypes.
6 Conclusions

1. The development of the unique Alenquer Oncolite is restricted to a belt around the town of Alenquer and along the western margin of the Serra da Ota, thus setting very delicate environmental prerequisites for its formation. This formation is most likely structurally related to a graben- or half graben-like subsidence of the area, allowing the sea to prograde locally in an otherwise generally regressive period.

After the initial deposition of lagoonal to estuarine "Cerithium" marls, the dominant progression of clastic sedimentation led to paralic-lacustrine conditions in the abandoned lagoonal bay. This happened in such a way that more or less sea-connected, relic, ephemeral lakes and ponds with salinity values varying from hypersaline to freshwater conditions developed in a fluvial/marsh environment (Fig. 3).

2. Oncoids grew during times of clastic non-deposition. The apparently purest freshwater conditions are represented by oncolites with charophyte and Valvata/Planorbis-type oncolid nuclei. Partial drying up of some ponds, on the other hand, led to occasional hypersaline conditions as evidenced by dolomite and gypsum? precipitation. Radial ooids, genetically interpreted as superficial oncolids, and Bacinella? eterm nodules are also attributed to these conditions.

3. Oncoid shapes are largely controlled by the hydrodynamic and thus physico-graphic characteristics of the depositional environment. Regular concentric oncolids developed in river channels, whereas framboidal oncolid shapes are related to lower energy shallow lake, pond and flooded swamp environments. Low-energy in-situ growth also resulted in the formation of cyanophyte pillows composed of oncolids and nodules with a component-fitting fabric. These pillows and the rarely occurring stromatolites are attributed predominantly to exposed areas, such as river banks, lake shores, swamps, abandoned channels and ephemeral shallow lakes.

4. The oncoid- and nodule-forming organism can well be compared to modern calcifying cyanophytes, if comparison is restricted to calcification morphotypes alone.

The old concept that cyanophyte calcification is determined merely by abiogenetic factors is becoming more and more undermined with the increase in studies on cyanophyte calcification mechanisms. Hence, a shift to another micro-environment would appear to be accompanied by a shift to another calcification morphotype, reflecting the organic response to the altered conditions.

This response may be due to
- a compositional change in the microbial association
- the establishment of a genetically different cyanophyte taxon with similar organic morphologies (filament diameter, radiation pattern), yet with differing calcification or calcification-triggering characteristics, or
- a very high variability in one genotype, with the ability to reorganize itself into different phenotypes (Tab. 1).

Environmental interpretation based on sedimentological and oncoid shape analysis supports the theory that the environmental demands of the morphotypes discussed here have apparently remained fixed since Upper Jurassic times. Hence, the Solythrix Morphotype represents fairly agitated freshwater conditions, whereas the Baytonema/Calothrix Morphotypes tolerate frequent subaerial exposure. The Phormidium incrustatum Morphotypes represent increased hardwater conditions of moderate to high energy levels and possibly more tolerance of hypersalinity. The Dioiothrix Morphotype is interpreted as a pioneer type, also highly tolerant of occasional drying-up.

The Rivularia haematites Morphotype is commonly found near brackish deposits, suggesting it was predominantly distributed in swamps adjacent to the shoreline.
Finally, the Coccoid Algae Morphotype is most closely related to marine, probably hypersaline environments.

While the use of a morphotype classification based on comparison with Recent taxa is justified for freshwater and coastal environments, the establishment of an analogous morphotype concept for the marine realm is handicapped by the lack of modern counterparts in the same setting. Hence, description of ancient calcareous marine cyanophytes is classically carried out by using "paleontological" taxa, which are, however, also solely determined by the morphological features of their calcareous remains.

For the last years, marine "paleontological" taxa, such as Cgenus, Ortonella, Girovella etc., are also compared with modern freshwater forms (e.g., RIDING 1977a, b, WRAY 1977, SCHÄFER & SENOWBARI-DARYAN 1983), without reasonably giving up the Ancient taxa. SCHÄFER & SENOWBARI-DARYAN (1983), however, also established morphological/ecological form groups ("formgruppen 1-9") for Upper Triassic marine porostromate algae (cyanophytes and some chlorophytes). Astonishingly, different species of one single "paleo"-genus have to be grouped under different form groups, also indicating the artificial character of formal paleontological cyanophyte taxonomy.

Applying SCHÄFER & SENOWBARI-DARYAN's more general form group concept to the here established morphotypes, the Schissothrix Morphotype may be attributed to "Formgruppe 1", the Saytonema/Galothrix Morphotype A to "Formgruppe 2", the Saytonema Morphotype B to "Formgruppe 4", the Dicyothrix Morphotype to "Formgruppe 4" or "5", and the Phormidium inornatum Morphotype A eventually to "Formgruppe 5". Naturally, the ecological interpretation of the form groups differs completely from that of the here established morphotypes (see SCHÄFER & SENOWBARI-DARYAN 1983, fig 8).

5. In rivers in warm climates transport of calcium carbonate is hindered by high water temperatures. Hence, the local exceptional availability in the case of the Alenquer Oncolite was certainly due to a sporadically high input of river water carrying dissolved carbonate from a nearby, subsequently eroded limestone province (Fig. 3), which is represented most likely by the uplifted and heavily paleokarstified Ota Limestone (LEINFELDER & RAMALHO in prep.).

The samples illustrated in this paper are stored in the collections of the Institut für Geowissenschaften, Mainz, under GPIM-XS 1-6, GPIM-XP 1-2, GPIM-XH 1 and GPIM-REM 1.

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REFERENCES


ELLIOIT, G.F. (1966): Algal nodules from the Lias of the Middle East.- Geol. Romana, 5, 291-301, 3 pls., Rome


FOIT, B. (1971): Algenkunde.- 581 p., 904 figs., Stuttgart (Fischer)

FRIEDMAN, G.M. (1978): "Solar Lake": a sea-marginal pond of the Red Sea (Gulf of Agaba or Elat) in which algal mats generate carbonate particles and laminates.- In: W.E. KUMBEIN (ed.): Environmental Biogeochemistry and Geomicrobiology, 1, 227-235, 4 figs., Collingwood (Ann Arbor)


HUDSON, J.D. (1970): Algal limestones with pseudomorphs after gypsum from the Middle Jurassic of Scotland.- Lethaia, 3, 11-40, 11 figs., Oslo


LOGAN, B.W., REZAK, R. & GINSBURG, R.N. (1964): Classification and environmental significance of algal stromatolites.- J. Geol., 72/1, 68-83, 5 figs., Chicago

RIDING, R. (1977a): Calcified Plectonema (blue-green algae), a Recent example of Girvanella from Aldabra Atoll.- Palaeont., 20, 33-46, 5 figs., 1 pl., Oxford
TAPPAN, H. (1980): The paleobiology of plant protists.- 1028 pp., numerous figs and tab., S. Francisco (Freeman)
Plate 29

The Alenquer Oncolite (Portugal): Sediment, Oncoids and Algal Nodules, their Microfabrics and Corresponding Calcification Morphotypes.

Der Alenquer Onkolith (Portugal): Sediment, Onkoide und Algenknollen, deren Mikrostrukturen und entsprechende Kalzifikationsmorphotypen.

Fig. 1. Stromatolitic cyanophyte pillow, x 0.6. Detail, exhibiting the Sytonema Morphotype B. x 2.5. Freshwater swamp, north of Bairro. Polished slab, GPIM-XH 1; acetate peel GPIM-XP 1

Fig. 2. Nodule of the Rivularia haematites Morphotype. Brackish to freshwater bay, lake or river banks, Qta. de Cabeça. Acetate peel, GPIM-XP 2. x 30.

Fig. 3. Large nodules of the questionable codiacean alga Bacillariella sterni floating in a lime-rich sandstone. Hypersaline? bay, Qta. de Cabeça, Thin-section, GPIM-XS 1. x 9.

Fig. 4. Detail of Plate 29/3. x 40.

Fig. 5. Charophyte stems, rare ostracods and planorbid gastropods (arrow) in a siltty, pelmicritic matrix. x 8.5. Detail: Chara-gyrogonite. x 35. Ephemeral freshwater lake/swamp, north of Vale do Junco. Thin-section, GPIM-XS 2

Fig. 6. Slightly flattened, spongy oncoid; note indistinct outer boundary. Morphotype sequence from central region to distal parts: Coccolid Algae Morphotype; microsparitic Phormidium inorustatum? Morphotype B; Coccolid Algae Morphotype, partially grading into Dictichora Morphotype; thick protrusional microsparitic Phormidium inorustatum Morphotype A; Dictichora Morphotype. Seasonally marine influenced hardwater pond, south of Alenquer. Thin-section GPIM-XS 4. x 3.5.

Fig. 7. Detail of another oncoid with same sequence of morphotypes as in Plate 29/6. Note spar-filled half-moon voids within and on top of a Phormidium inorustatum Morphotype A layer, resembling Recent chironomid larvae (white arrow), and microstromatolitic projections (black arrow). Same sample as Plate 29/6. x 5.

Fig. 8. Sandy algal packstone, consisting predominantly of strongly recrystallized charophyte stems partially encrusted by cyanophytes. Ephemeral river, south of Alenquer. Thin-section, GPIM-XS 3. x 8.

Fig. 9. Coated quartz grains, resembling radially structured ooids. c: nodule of the Coccolid Algae Morphotype. Shoreline of hypersaline? bay, Qta. de Cabeça. Thin-section, GPIM-XS 4. x 40.

Fig. 10. Coated quartz grain with radially structured cortex, resembling microsparitic cyanophyte layer. Arrow: crystals arranged in fan array. Same sample as Plate 29/9. x 35.
Plate 30

The Alenguer Oncolite (Portugal): Oncoidal Micro- and Nannofabrics and Corresponding Calcification Morphotypes.

Der Alenguer Onkolith (Portugal): Onkoidische Mikro- und Nannostrukturen und deren entsprechende Kalzifikationsmorphotypen.

Fig. 1. Component fitting fabric of oncoinds due to cortical digitate protrusion (center). Leached spongy fabric on top. x 5. North of Alenguer. Thin-section GPIM-XS 6. x 4.5.

Fig. 2. Collapsed Dixoithrix Morphotype with questionable pseudomorphs after gypsum. Note crystal silt (arrow). Superimposed is a microsparitic/sparitic crust of the Phormidium incrastatum? Morphotype B. Same sample as before. x 25.

Fig. 3. Large regular oncoind. Outer part is mainly composed of the Soytonema/Calo-thrix-Morphotype A (see 9), whereas core area is represented by the Dixoithrix Morphotype (see 7) surrounded by a protrusional layer of the Phormidium incrastatum Morphotype A (arrow). Hypersaline pond (central core), fluvial channel, Qta. de Cabeça. Thin-section, GPIM-XS 5. x 3.

Fig. 4. Nannofabric of microsparitic crust, exhibiting elongate arrangement of crystals. Horizontal voids probably represent Schizothrix-like films (arrow). Qta. de Cabeça. Scanning electron microscope, GPIM-REM 1. x 1650.

Fig. 5. Microvoids in microspar and spar crystals, representing decayed cyanophyte filaments (arrow). Sample as Plate 30/4. x 875.

Fig. 6. Detail of oncoidal cortex sequence, from base to top: Bacinella? sterna interwoven with cyanophytes (a), overlain by Soytonema/Calo-thrix Morphotype A with Schizothrix-like films (b). Superimposed are a thin crust of Phormidium incrastatum Morphotype (c) and bush-like tufts of the Schizothrix Morphotype with growth starting from selected points (d). Top represented by another Phormidium-like crust (e). Note vadose leaching structures on left side. Ephemeral hardwater lake, south of Alenguer. Thin-section, GPIM-XS 6. x 15.

Fig. 7. Tufts of the Dixoithrix Morphotype. Note paintbrush-like growth habit and pronounced upward growth. Arrow: Dolomite crystals. Core of oncoind as shown in Plate 30/3. x 27.

Fig. 8. Dixoithrix Morphotype, slightly collapsed, intercalated between two layers of the Phormidium incrastatum Morphotype A. Note mimic filament bundles (arrow). Hardwater pond, south of Alenguer. Thin-section, GPIM-XS 4. x 20.

Fig. 9. Micritic fabric composed of the Soytonema/Calo-thrix Morphotype A. Note horizontal micritic sheets representing the Schizothrix Morphotype. Cortical region of oncoind as shown in Plate 30/3. x 40.