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Rhodolith formation induced by reef erosion in the Red Sea, Egypt

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Abstract. Along the northwestern margin of Safaga Island (Northern Bay of Safaga, Red Sea, Egypt) a small fringing reef (several hundred meters long, up to 2 m high) and small patch reefs are developed due to the local current regime which is favorable for coral growth. Corals and reef rock are encrusted by coralline algae, predominantly by branched *Lithophyllum kotschyanum.* Owing to destructional processes dominated by sea urchin activities, fragmentation of (1) corals, (2) reef rock, and (3) coralline algae takes place resulting in the formation of almost monospecific, branched *Lithophyllum kotschyanum* rhodoliths. Rhodolith formation takes place in various reef environments: (1) in depressions on the reef flat where ellipsoidal rhodoliths develop, with interlocking and fusing branches leading to a coralline algal framework; (2) in discharge channels where smaller elongated rhodoliths occur; (3) in leeward positions between reef flat and seagrass meadows, where a dense belt of spheroidal to ellipsoidal rhodoliths is formed; scattered rhodoliths occur in adjacent seagrass beds. The formation and preservation of rhodoliths requires a complex interplay of destruction, growth, transportation, movement, and stabilization.

Introduction

Crustose coralline algae are one of the most important frame builders in Cenozoic tropical to subtropical coral reefs (Kauffman and Fagerstrom 1993). Their most important contribution to the reef frame is the encrustation of stony corals and other skeletonized organisms strengthening the frame against mechanical destruction (e.g., by high water energy). Unattached crustose coralline algae, occurring as branched rhodoliths or maërl, are considered to be of minor importance in modern coral reefs or in tropical shallow water carbonates in general (Steneck 1986). Although several reports on modern tropical/subtropical rhodolith occurrences exist (see Bosence 1983b, for review; 1985; Braga and Davies 1993; Piller and Rasser 1993), they remain of subordinate importance compared to temperate (e.g., Bosence 1976, 1980, 1983b) and arctic examples (e.g., Freiwald 1993, 1995, for review; Freiwald and Henrich 1994). Although rhodolith formation has been discussed in detail (e.g., Bosellini and Ginsburg 1971; Bosence 1985), the data base from direct observations remains relatively small (Freiwald 1995).

In the course of a detailed research in the Northern Bay of Safaga (Red Sea, Egypt; Fig. 1) dealing with bottom facies (Piller and Pervesler 1989), sedimentology (Piller and Mansour 1990), and microfacies (Piller 1994), coralline algae were studied in addition to various organism groups with fossilization potential [e.g., foraminifera (Haunold et al. in press), corals and boring bivalves (Kleemann 1992), and echinoids (Nebelsick 1991)]. Their general depth distribution and the occurrence and formation of rhodoliths are of particular interest. Inside the bay several occurrences of rhodoliths have been discovered which are different in growth form and taxonomic composition, as well as in mode of formation and environmental requirements. In this study we discuss one of these rhodolith occurrences and develop a model to relate their formation and morphology in response to specific subenvironments.

Study area and methods

The Northern Bay of Safaga is a topographically highly structured, relatively low energy shallow-water area with a maximum depth of 55 m (Fig. 1). A great variety of facies occurs in a small area. As usual in the northern Red Sea, salinities are high (40–46‰) and water temperature ranges between 21 °C in winter and 29 °C in summer; tidal range is < 1 m (Piller and Pervesler 1989).

The rhodolith occurrence under study is located at the northwesternmost tip of Gazirat Safaga (Safaga Island) (asterisk in Fig. 1). This distal part of the island represents a rocky intertidal flat. Its western and northwestern margin marks the eastern boundary of the "Southwest channel". The latter is the connection between the Northern and Southern Bay of Safaga and unites the relatively weak currents running through the Northern Bay in various branches (Piller and Pervesler 1989, Fig. 5). These currents meet the northwestern tip of Gazirat Safaga and produce favourable living condi-

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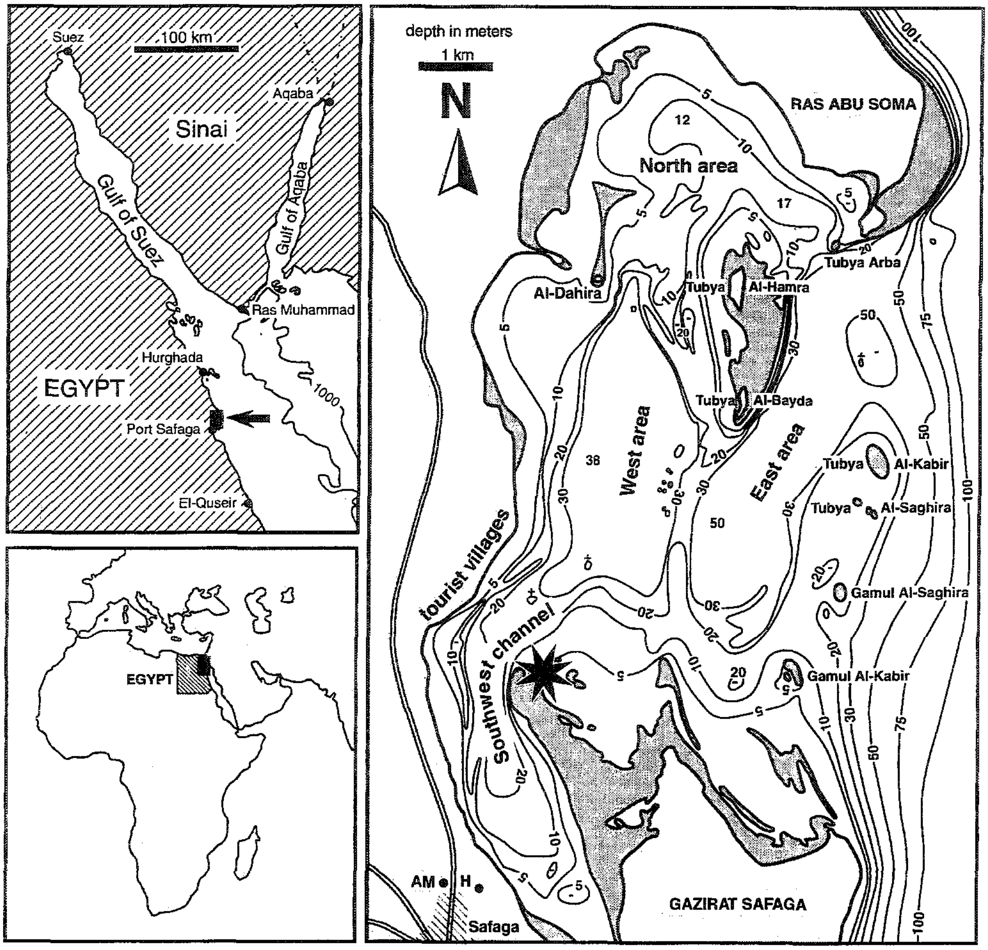

Fig. 1. Location map of the Northern Bay of Safaga (after Piller and Mansour 1990). *Right map* exhibits general topography and location of the described rhodolith area (*asterisk*)

tions for corals. As a result, a small fringing reef has developed between the northwestern tip of the island and its eastern end, as well as small patch reefs. This area (Fig. 1; compare also Enclosure 1, coloured map, in Piller and Pervesler 1989) shows a rugged topography, particularly at its eastern end. The depicted intertidal area and the fringing reef are interrupted by irregular channels and depressions (down to several meters) which isolate small patch reefs. Depth of the reef slope is mostly 1–3 m.

Rhodoliths occur frequently in this area. For a detailed description of the different aspects of occurrence and processes of formation we selected a small patch reef which shows most of the important features. This patch reef called "Reef Shahad", in honour of our boatsman, was mapped using measuring tape and compass, by snorkeling and scuba-diving (Fig. 2). From both the reef flat and the leeward rhodolith belt, a $0.25\,m^2$ area of rhodoliths coverage was removed, resulting in 103 specimens from the reef flat and 63 specimens from the rhodolith belt. For their taxonomic investigation and study of internal structure 30 palaeontologic thin sections were prepared from the rhodoliths.

The outline of the patch reef is triangular (90 × 45 m), with a reef flat occupying the main part and a very narrow reef crest and reef slope. The reef slope is best developed at the eastern tip (Fig. 2, inset 1) and the northern front where it is steep to nearly vertical. The total depth is around 2 m. In the southern and southwestern part the reef flat slopes gently leeward and the reef slope is poorly developed (Fig. 2, insets 2–4).

The reef is surrounded by a flat seabed of gravel and sand (down to 5 m water depth), commonly covered by a dense seagrass meadow (*Cymodocea*). The dominant organisms on the reef slope and crest are scleractinian corals (predominantly *Acropora*, but also *Porites* and brain corals) and *Millepora* (Fig. 3C). The orientation of the latter clearly reflects the prevailing current direction as the fan-like colonies are oriented NW-SE, perpendicular to the current coming from the northeast. Coral coverage is dense at the eastern tip and northern front, poor to nearly absent in the south and southwest (Fig. 2). The reef flat represents mainly reef rock covered by coralline algal crusts, rhodoliths, soft corals, and single colonies of scleractinians or small scleractinian patches. The morphology is highly rugged with depressions reaching 0.5 m into the reef flat (Fig. 3A).

Results

On the reef crest and windward slope, thin coralline algal crusts cover dead parts of stony coral colonies as well as dead coral rock. Protuberances and branches frequently arise from crusts reaching up to several centimetres in height with branch diameters of 2–4 mm. These branched coralline algae are almost exclusively *Lithophyllum kotschyanum* (Unger) Foslie. On the seabed, between coral colonies, fragments of corals are frequently found also encrusted by thin coralline algal crusts and branched *L. kotschyanum*.

The coral rock of the reef flat, partially covered by coralline algal crusts, is heavily affected by sea urchins (*Echinometra mathaei*) producing an interconnected system of cavities and borings which weaken the substrate.

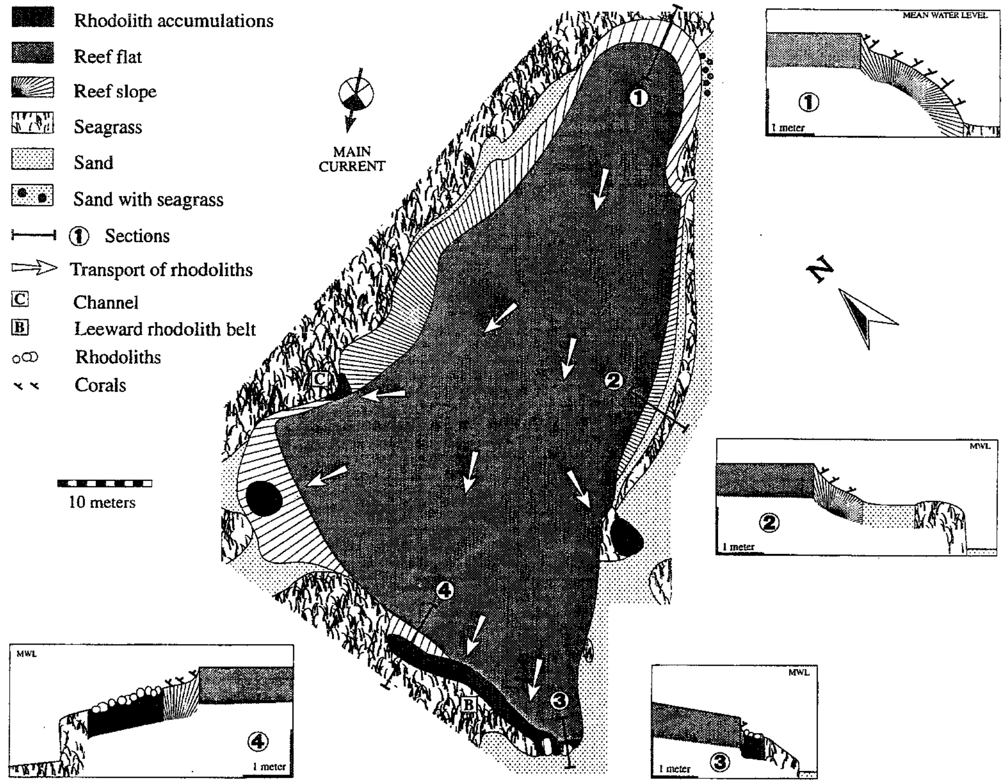

Fig. 2. Facies map of Reef Shahad and four sections (*insets 1–4*) showing lateral variations of the reef edges

Large fragments of corals, coral rock encrusted by branching *L. kotschyanum* and large rhodoliths (up to 15 cm ∅) of *L. kotschyanum* are present in depressions on the reef flat. Rarely, laminar *Neogoniolithon* rhodoliths, with non-protuberant knobby surfaces, also occur. Some of these depressions are totally filled with rhodoliths and/or gravel, some only partially. In the case of partial filling, an asymmetrical wedge-like accumulation of loose material occurs on that side of the depression, which faces the current. In these wedges a transition between gravel and rhodoliths is observable, meaning that the particles range from fragments with only occasional encrustations over thickly encrusted examples, to rhodoliths whose shapes are completely independent from the nucleus. The shape of these rhodoliths is generally flattened ellipsoidal, the branching mode is dichotomous with a branching density ranging between III and IV (according to Bosence 1983a); their long axis diameter ranges between 2.5 and 15 cm. In those depressions which are mainly or totally filled by rhodoliths, these aggregates are stabilized by a filamentous algal mat which forms a dense cover on parts of the reef flat as well as on the rhodoliths (Fig. 4A). The branches of these rhodoliths are often interlocking, sometimes also coalescing to produce a true coralline algal framework. Several superimposed layers of interlocking rhodoliths are present depending on the depth of the reef flat depressions. The rhodoliths are frequently settled by homotrematid foraminifers; bryozoa, serpulids and acervulinid foraminifera also occur.

On the reef slope discharge channels (approx. 1 m wide) interrupt the dense coral settlement. The channel floors are covered by gravel encrusted by crustose and branched coralline algae and by some smaller rhodoliths (Figs. 3C, 4B).

On the leeward slopes, directly adjacent to the reef flat or with a denser coral zone in between, a sand bottom occurs grading laterally into a dense belt of rhodoliths (Fig. 2, Fig. 4C, D). The latter is present only where seagrass meadows occur further leeward. In the case of Reef Shahad this rhodolith belt is laterally restricted (Fig. 2). In the lee of the contiguous reef flat area, adjacent to Reef Shahad, the rhodolith belt, as well as the seagrass area, are laterally persistent over hundreds of metres. In the rhodolith belt, the sandy/gravelly substrate is almost totally covered by rhodoliths (Fig. 4D). The width of the belt remains relatively constant between 1 and 2 m. The sand/gravel bottom is covered by one rhodolith layer only, not producing a framework as on the reef flat. The rhodolith shape is ellipsoidal to spheroidal, branching mode is dichotomous and branching density between III and IV; their diameter along the longer axes ranges between 2 and 18 cm (Fig. 4E). They are constructed almost exclusively by *L. kotschyanum* (Fig. 5A, B) and are only occasionally intergrown with *Lithoporella* crusts. Settlement by homotrematid foraminifers is rare compared to the reef flat rhodoliths. Laminar, smooth to knobby rhodoliths occur occasionally, composed predominantly of *Neogonialithon* which reach only a few centimetres in diameter.

In the *Cymodocea* seagrass meadows adjacent to the rhodolith belt scattered branched rhodoliths occur. Away from the rhodolith belt, rhodoliths are absent from the seagrass. Generally, no rhodoliths have been observed

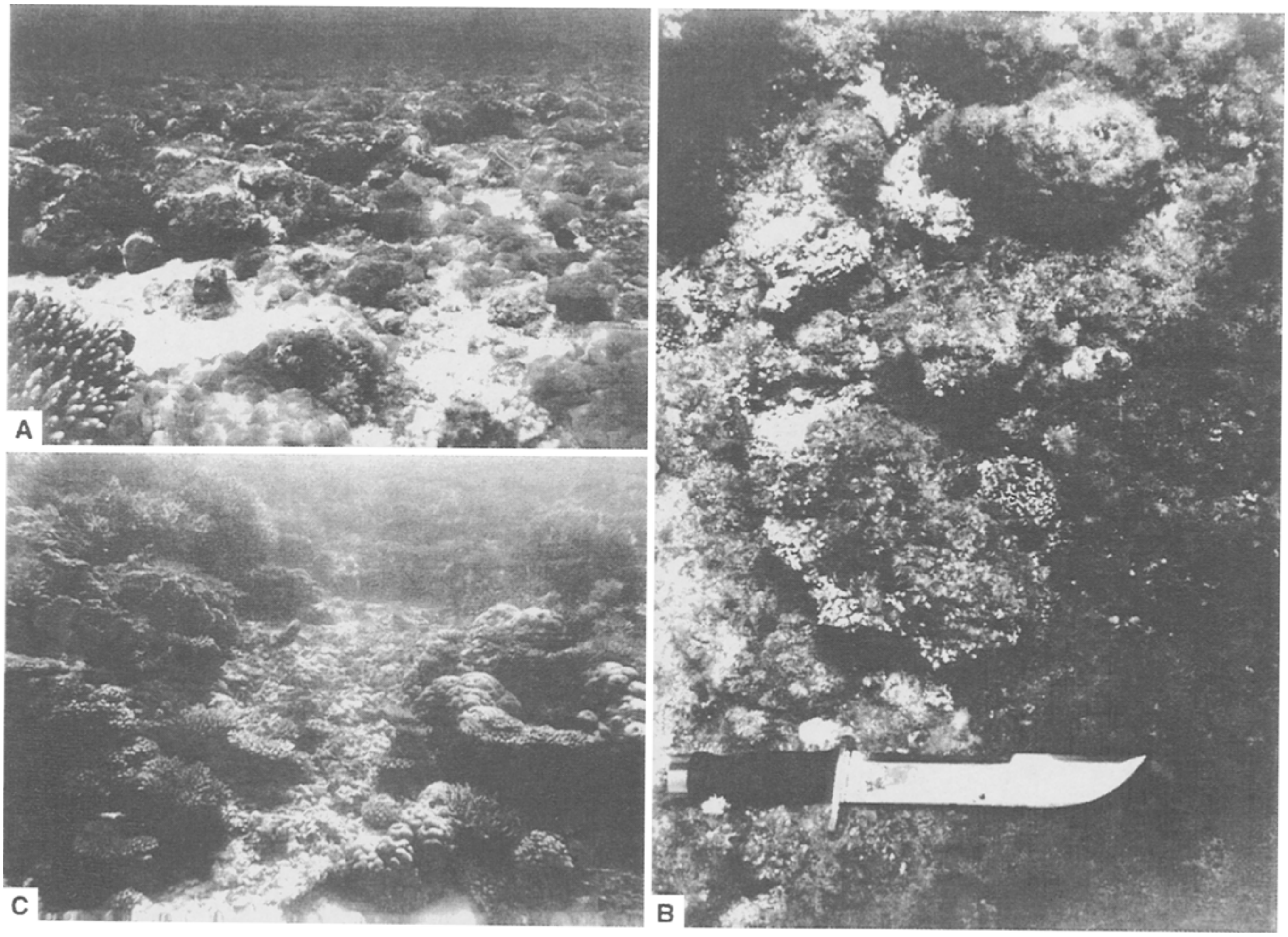

Fig. 3A–C. Reef flat and slope of Reef Shahad (Fig. 2). **A** Reef flat with abundant soft corals, only few scleractinians and highly irregular surface. Depressions are filled either with gravel and sand, or partially with rhodoliths (left foreground). Water depth is approximately 0.5 m. **B** Close-up of the reef flat showing branched coralline algal encrustations (length of knife: 32 cm). **C** Reef slope with typical coral associations (*Acropora, Porites*) and a discharge channel ("C" in Fig. 2) covered by coral gravel encrusted by coralline algae and rhodoliths. Channel width: 0.5–1 m; water depth at reef base is approximately 2 m

below 2–3 m water depth and outside the described accumulations.

Discussion

Attached branching coralline algae (mostly *L. kotschyanum*) occur on dead parts of living scleractinian corals or on reef-rock substrate both on the reef slope/crest and the reef flat. They are more common on rocky substrates than on corals. The encrusted coral fragments as well as the rhodoliths of the reef flat, the slope channels, the rhodolith belt, and the seagrass beds are all represented by *L. kotschyanum*. Within the branched rhodoliths neither a taxonomic-ecologic succession of coralline algal species occurs (due to almost monospecific composition) nor is an ecologic succession of growth forms of *L. kotschyanum* present. Branching coralline algae, as algal heads and as branched rhodoliths, are also reported as dominating organisms at a reef flat south of Jeddah, Saudi Arabia (Montaggioni and Bosence 1992). There, however, the algae are represented mainly by two species: *Hydrolithon reinboldii* and *Lithophyllum kotschyanum*.

Due to this almost monospecific occurrence of *L. kotschyanum*-rhodoliths in the Northern Bay of Safaga we deduce the following model of rhodolith formation (Fig. 6):

The source material for rhodolith nucleation includes: (1) coral fragments with or without pre-existing coralline algal incrustations, or (2) fragments of reef rock, or (3) reworked branch fragments of coralline algae which grow further by redirection. The latter give rise to non-nucleated rhodoliths (Freiwald 1995). All three mechanisms, which represent essentially destructional processes, were observed. Owing to the high abundance and obvious activ-

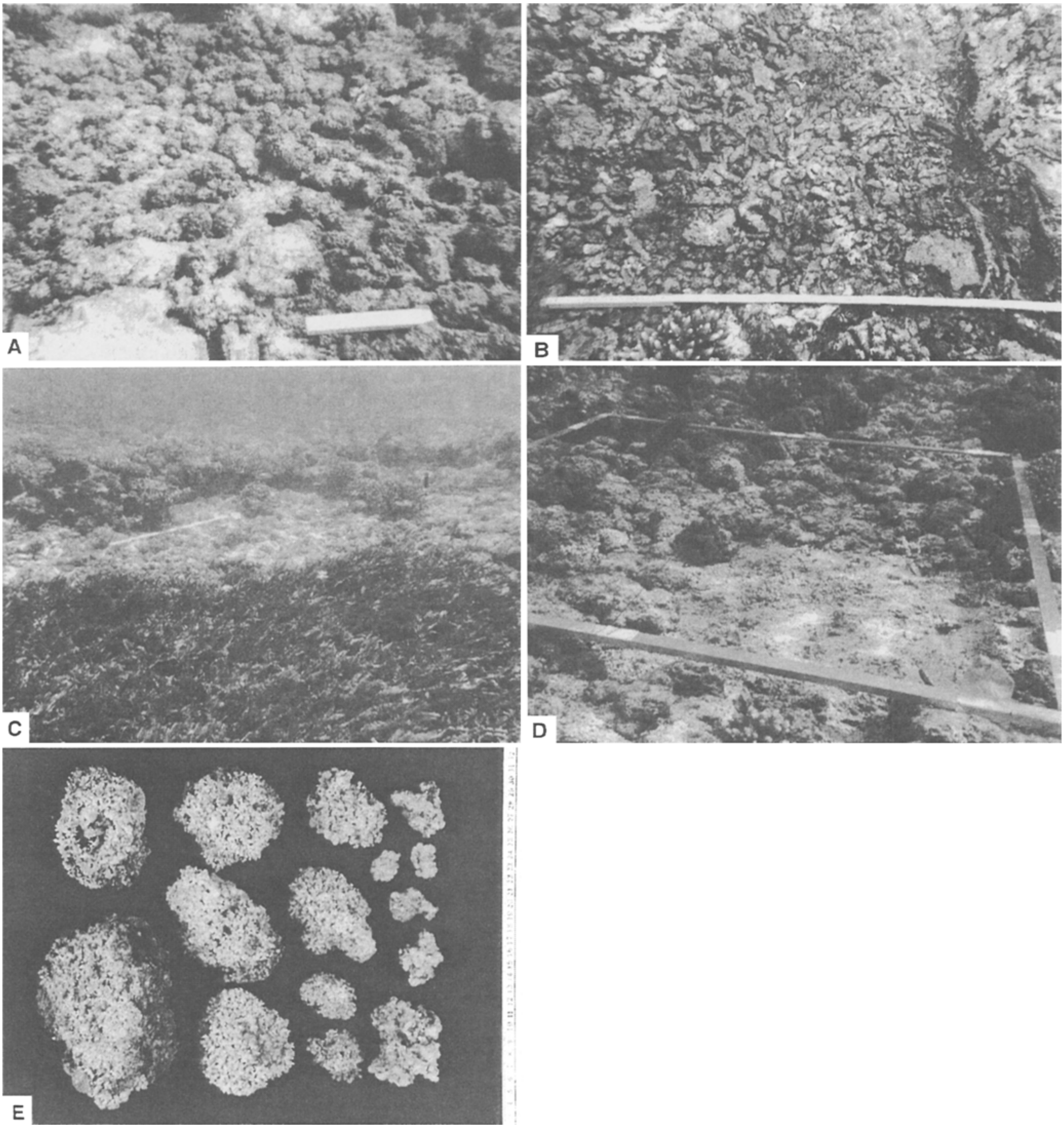

Fig. 4A–E. Rhodolith accumulations. **A** Rhodolith accumulation in a depression on the reef flat. Note the cover of rhodoliths and rock bottom by filamentous algal mats (scale: 23 cm). **B** Slope channel with coral rubble encrusted by branched coralline algae and elongated ellipsoidal rhodoliths (width of photograph approx. 1 m). **C** Leeward rhodolith belt at Reef Shahad ("B" in Fig. 2), between the reef edge, with scattered coral colonies (mainly *Acropora*), and *Cymodocea* meadow in the foreground (scale: 1 m). **D** Close-up of rhodolith belt in **C**. *Rectangle* represents 1 m^2 with 0.25 m^2 of rhodoliths removed. Note total coverage of the bottom by rhodoliths in remaining 0.75 m^2. **E** Selected set of rhodoliths removed from area shown in **C**

ities of regular sea urchins, these organisms are thought to be the most important agents of destruction. They either directly produce reef rock fragments or weaken the substrate which leads to destruction by strong waves during periods of rough weather. The importance of sea urchins in reef destruction is generally well known (Bak 1994) and coincides with our observations.

Most fragments fall on the reef flat and are subsequently washed into one of the following areas: (1) reef flat depressions, (2) slope channels, (3) the leeward slope, and (4)

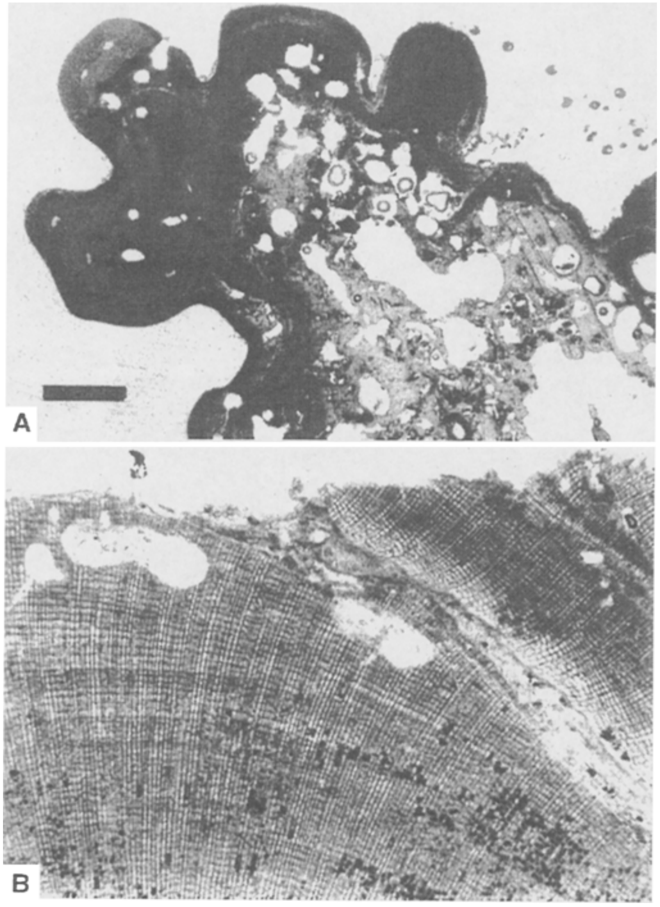

Fig. 5. **A** Internal structure of rhodolith showing coral fragment as nucleus (*lower right*), overgrown monospecifically by *Lithophyllum kotschyanum* affected by borings. Thin section: EC 92-10; scale: 2 mm. **B** Thin section of *L. kotschyanum* with typical regular perithallial cell tissue and tetra/bisporangial conceptacles, as well as basal dimerous organisation with primigenous filament of larger cells and curving postigenous filaments (*upper right corner*). Thin section: EC 92/10-1B; scale: 300 μm

adjacent seagrass beds. During transport over the reef flat some of the fragments grow in all directions forming rhodoliths.

1. Those fragments or newly formed rhodoliths which are washed into reef flat depressions are easily stabilized and are then overgrown by filamentous algae or other non-skeletal organisms. In this way they are protected against mechanical destruction. They grow predominantly in a lateral direction, which leads to a flattened growth form. They interlock with neighboring rhodoliths or even coalesce with them forming a rigid, highly porous coralline algal framework. Stabilization may also result in abundant settlement by homotrematid foraminifers.
2. Those fragments and rhodoliths which are swept into the slope channels, grow slowly, and usually do not reach large sizes with shapes independent from th nucleus shape; also spatial coverage remains relatively low.
3, 4. Fragments and rhodoliths transported onto the leeward slope develop as follows:

(A) Where a seagrass bed is present in the lee of the reef, usually the fragments and rhodoliths are stabilized between the reef and the seagrass bed and are turned only occasionally. This relative stability permits good coralline algal growth, with occasional movement allowing growth in all directions. This leads to a more spherical shape of the rhodoliths than on the reef flat. In this very specific environment, a dense rhodolith belt in the lee of the reefs develops. These rhodoliths are not turned by water energy, even during moderate storms (personal observations). Instead, movement by activities of various benthic organisms, e.g., sea urchins, crabs, or fish, appears more probable. A few of the rhodoliths are also transported into the adjacent seagrass beds; their density, however, remains low.
(B) In areas where no seagrass is present no rhodoliths occur, owing to the absence of the stabilizing effect of seagrass and therefore coralline algal fragments and even

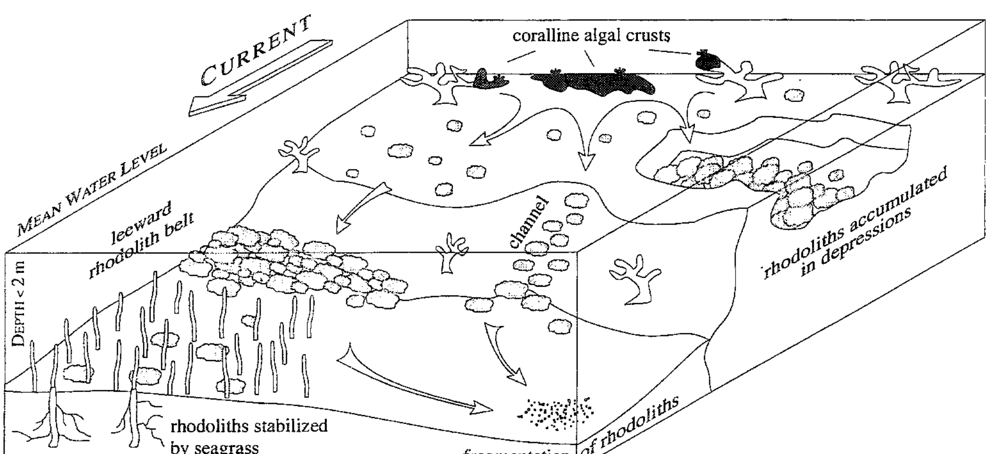

Fig. 6. Model of rhodolith formation

rhodoliths transported into these areas are fragmented and incorporated into the sediment.

Seagrass beds are known as a common production area of shallow water, back reef rhodoliths (e.g., Bosellini and Ginsburg 1971; Montaggioni 1979; Bosence 1983). From these seagrass beds the rhodoliths may be transported outside into adjacent sandy areas (Bosellini and Ginsburg 1971). In our example, where a rhodolith belt is developed in a "backreef-environment", rhodoliths are only formed on sandy/gravelly substrate between the leeward reef slope and seagrass beds, but not inside the seagrass meadow. The scarce rhodoliths present in the seagrass bed are swept in from the reef flat.

Coralline algal diversity is generally high in tropical/subtropical areas such as in the Red Sea. Also in rhodolith composition, different taxa are usually involved (e.g., Scoffin et al. 1985; Braga and Davies 1993) which produce a combined taxonomic-ecologic succession (Bosence 1983b). The branched rhodoliths described here from the Northern Bay of Safaga are, however, almost monospecific. Similarly, in shallow and quiet waters of the Mascarene Islands, W. Indian Ocean, monospecific, branched rhodoliths also occur, formed by *Lithophyllum* (Montaggioni 1979). Also from the Bermudas, Bosellini and Ginsburg (1971, p. 676) reported a monospecific composition of branched rhodoliths constructed by *Lithothamnion occidentale*. Monospecific subtropical coralline algal occurrences have also been reported by Bosence (1985) from the Florida Keys. There, *Neogoniolithon strictum* (Foslie) Setchell and Mason (assigned to *Spongites* by Woelkerling 1988) produces different growth forms: framework, rhodoliths, gravel patches. This framework was interpreted as being formed in situ and produces positive relief. The framework in the Northern Bay of Safaga is produced by rhodoliths growing predominantly in a lateral direction with interlocking and even fusing branches. Rhodolith formation seems to be similar in both areas, with nucleation of coral fragments and other particles or coralline algal branch growth by turning and redirected growth. A consistent growth form succession inside rhodoliths is usually interpreted as being due to changing environmental conditions (Bosence 1983b). Its absence points to environmental stability in this part of Safaga Bay or to fast growth.

Laterally interlocking branches of rhodoliths into a semi-rigid framework were also described by Scoffin et al. (1985) from the Cook Islands as resistant structure against raised water energy.

The monospecific branched rhodolith composition of tropical/subtropical areas, as well as their mode of formation, is very similar to rhodolith occurrences reported from the temperate maërl (Bosence 1976, 1980) and the Arctic (Freiwald 1995, Fig. 4). Differences exist in taxonomic composition (*Lithophyllum kotschyanum* vs *Phymatolithon calcareum* and *Lithothamnion corallioides* from Ireland, and *Lithothamnion* cf. *glaciale* from the Arctic) and in nucleation. In the rhodoliths of Safaga Bay (and also of Florida – Bosence 1985) both rhodoliths with and without nuclei have been observed, whereas in the Norwegian examples only non-nucleated rhodoliths occur. The shallow and quiet water rhodoliths from the Mascarene Islands, however, also display the lack of a distinct nucleus (Montaggioni 1979).

Conclusions and geological implications

1. In tropical/subtropical climates, branched rhodoliths are formed in shallow and quiet waters. In sheltered locations they are spherical, while in areas with higher energy flattened ellipsoidal shapes dominate. The latter are able to interlock laterally to form a coralline algal framework.
2. Rhodoliths with internal consistent growth forms point to stable environmental conditions and/or fast growth.
3. Monospecific branching rhodoliths occur not only in temperate and arctic waters but also in tropical/subtropical climates, though general species diversity is much higher in warmer climates.
4. The same coralline algal species can form rhodoliths on reef flats as well as in the lee of reefs. Growth and preservation in the lee, however, is possible only in areas where rhodoliths are stabilized for longer periods, e.g., in front of seagrass beds.

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