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REPORT

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Coral frameworks revisited–reefs and coral carpets in the northern Red Sea

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Abstract Coral communities were investigated in the northern Red Sea, in the Gulfs of Suez and Aqaba, for their framework building potential. Five types of coral frameworks were differentiated: *Acropora* reef framework, *Porites* reef framework, *Porites* carpet, faviid carpet, and *Stylophora* carpet. Two non-framework community types were found: the *Stylophora*-*Acropora* community, and soft coral communities. Reef frameworks show a clear ecological zonation along depth and hydrodynamic exposure gradients, with clear indicator communities for each zone. By definition, coral carpets build a framework but lack distinct zonation patterns since they grow only in areas without pronounced gradients. In the northern Red Sea they show a gradual change with depth from *Porites* to faviid dominance. A *Stylophora* carpet is restricted to shallow water in the northern Gulf of Suez. Although growth rates of carpets may be somewhat less than those of reefs, the carbonate accumulation is considered to be higher in carpet areas due to their significantly higher areal extension. In addition, reefs and carpets have different sediment retention characteristics – the carpet retains, the reef exports. The in situ fossilization potential of coral carpets is expected to be higher than that of reef frameworks.

Key words Reef framework · Coral carpet
Coral community · Fossilisation potential
Carbonate production · Sedimentation · Red Sea

Introduction

An important portion of carbonate production in tropical/subtropical carbonate systems is thought to occur in coral reefs (Hopley 1982; Tucker and Wright 1990; Rao 1996; Camoin et al. 1997). Modern reef frameworks tend to follow the relief of previous framework building episodes (Hopley 1982; Montaggioni and Faure 1997) or are found on existing topographical highs (Hopley 1982; Multer and Zankl 1988; Cabioch et al. 1995). Numerous studies have shown how fossil structures strongly influence the distribution of Holocene reefs (Shinn et al. 1989; Ginsburg and Shinn 1993; Burke 1993). However, recent information from Australia (Jones 1995) and the Caribbean (Blanchon and Jones 1997) indicates that some reef frameworks may be Holocene buildups which do not follow a paleo-relief in their morphology, but are shaped by a combination of coral growth and environmental constraints (Jones 1995; Blanchon and Jones 1997; Blanchon 1997).

Several framework types have been described (Geister 1981, 1983, 1992; Multer and Zankl 1988; Hopley et al. 1989; van Woesik and Done 1997) and models for their lithological representation in the fossil record have been developed (Geister 1981, 1983; Scoffin 1992). It is also well known that different framework types are made up by different (paleo) communities (Hopley 1989; Cortes et al. 1994; Cabioch et al. 1995; Montaggioni and Faure 1997).

In the northern Red Sea, coral reef development follows mainly tectonically generated topographic highs and the mostly steep continental margin (Strasser et al. 1992; Gvirtzman 1994; Piller and Pervesler 1989). However, in areas with low topographical differentiation, extensive framework building coral communities exist in addition to reefs (Piller and Pervesler 1989; Riegl and Piller 1997). We call these communities coral carpets (sensu Reiss and Hottinger 1985) and believe that they represent good modern examples of biostromes (Kershaw 1994).

In this paper we examine (1) the different coral framework types in the northern Red Sea, (2) the ability of coral carpets to build frameworks, (3) the importance

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of coral carpets for carbonate production, and (4) the fossilization potential and likely facies which will be represented in the fossil record.

Methods

Study area

Coastal and offshore sites were investigated in the Gulfs of Aqaba and Suez and the Egyptian Red Sea (Fig. 1). The quantitative sampling took place mainly in the Straits of Gubal and the Hurghada area. Qualitative observations were made in the Gulf of Aqaba north to Eilat in Israel, to Ain Sukhna in the Gulf of Suez and in the Red Sea down to Ras Banas (Egypt). All existing coral habitats in the Egyptian northern Red Sea were investigated.

Terminology

For the purpose of this study, coral carpets were defined as more or less continuous veneers of coral framework following the existing sea-floor morphology. They are not distinctly three-dimensional and are therefore ecologically relatively uniform. We consider coral carpets to represent biostromes (Cumings 1932), or more precisely autobiostromes (sensu Kershaw 1994). Riegl and Piller (1997) used the term coral carpet in a broader sense for all low-relief coral communities in Safaga Bay, irrespective of framework building potential, and therefore also included soft coral communities. In the present paper we only define communities with framework building potential as carpets, in order to focus on the geological perspective. We defined reefs, on the other hand, as distinctly three-dimensional structures, often growing on and adding to a pre-existing fossil structure. Such structures thus result in a stronger ecological differentiation of animal and plant communities than in the coral carpet. We consider reefs to represent bioherms (Cumings 1932).

The term framework is used according to Fagerstrom (1987, p. 5) as "… the mass of large, colonial or gregarious, intergrown skeletal organisms in general growth position …". The term community is used sensu Kidwell and Bosence (1991, p. 118) "… to denote recurrent groups of living organisms, Recent or ancient". This differs from the term coral community used by Geister (1983, p. 178) as "incoherent growths composed of only a single generation of framebuilders …". It also differs from the terminology used by Riegl and Piller (1997, p. 144) who reserved the term community for quantitative descriptions. Coral growth form terminology follows Wallace (1978), Veron and Wallace (1984), Veron (1986), and Riegl (1995).

Quantitative methods

Line intercept transects of 10 m length were used. The ideal transect length had been established by previous studies in the area (Riegl and Velimirov 1994). Along these transects, the intercepts of all underlying coral species, benthic invertebrates and macro-algae were recorded to the nearest centimeter. The type of substratum, which was classified as either sand, limestone, or rubble, was also recorded. Transects were placed parallel to the depth contour, at 1 m depth increments.

To detect patterns within the data-set, agglomerative hierarchical cluster analyses using the Bray-Curtis similarity measure or Euclidean distance as the distance measure and group average method of grouping were computed (Digby and Kempton 1987; James and McCulloch 1990). Cluster analysis has advantages for delineating groups in a very distinct community setting (Field et al. 1982; Kenkel and Orloci 1986) as could be expected due to previous experience in the area (Riegl and Velimirov 1994; Riegl and Piller 1997). The statistically obtained groupings were compared with the situation in the field, and when found to coincide, were used to describe community patterns. Analyses were performed using PRIMER and SPSS statistical software. After the different communities and framework types were statistically described, we visually examined several other localities and assigned the encountered communities to those quantitatively described. In order to gain information about the spatial distribution of coral carpets, we mapped the distribution of coral associations in northern Safaga Bay. The results are published in Riegl and Piller (1997) and were re-used for this paper.

Determination of framework thickness in reefs and coral carpets was based on visual observations along natural or artificial (dynamite damage) scars since drilling was not permitted by the local authorities. Therefore reliability of framework thickness estimation remains problematic. Thicknesses given in this paper represent minimum estimates. We are therefore only able to speculate on coral and framework growth rates or carbonate accumulation rates.

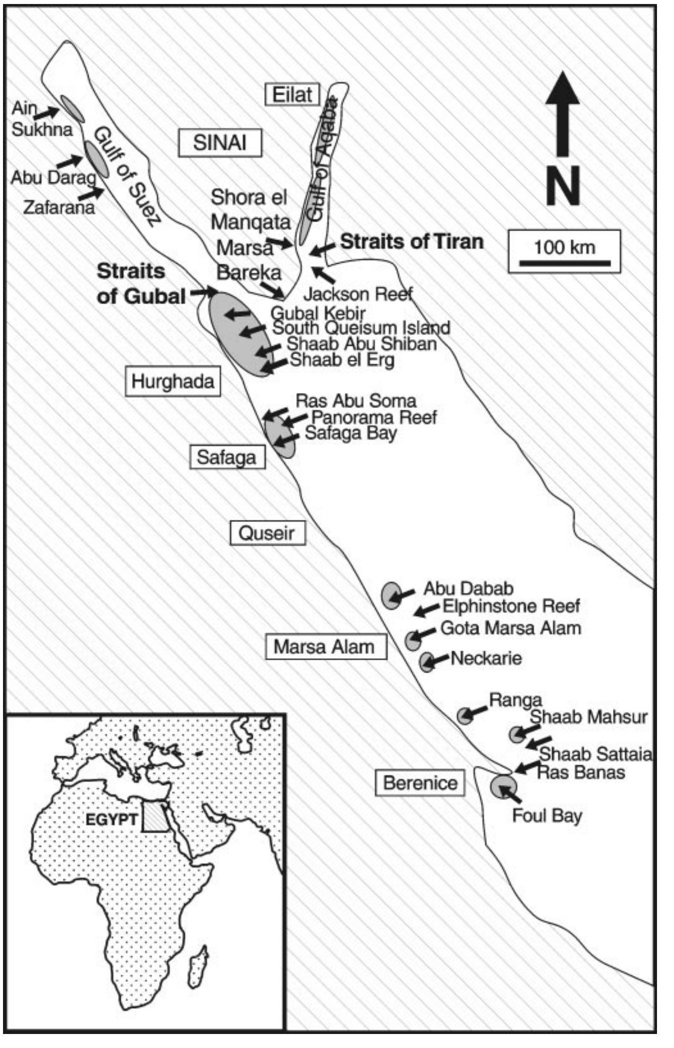


Fig. 1 Location map indicating the study area (Egyptian Red Sea) and names mentioned in the text. The approximate areas of important coral carpet development are *shaded*. Coral carpets are tied to shallow shelf areas. In the Gulf of Suez they replace fringing reefs north of Zafarana. In the Gulf of Aqaba they occupy the sloping sea-floor in the fore-reef areas

Results

Based on a cluster analysis of 150 line transects, several coral communities could be differentiated. They can be interpreted as reef communities, coral carpets, and non-framework coral communities (Fig. 2).

Reef communities

Reef communities received detailed quantitative treatment in Riegl and Velimirov (1994) and were reviewed in Riegl and Piller (1997). These studies showed a clear ecological subdivision of the coral communities on reefs along a depth and hydrodynamic gradient. The extended study area presented in this paper adds new data, which are summarized in Table 1. The table gives an overview of the biological characteristics of scleractinian reef communities that can be allocated to framework types illustrated in Fig. 3A–F. This characterization is not valid for reefs with vertical reef slopes exposed to strong currents (for example Jackson reef, Panorama reef, Elphinstone reef, parts of Shaab Sattaia), whose coral community is dominated by soft corals (usually *Dendronephthya* spp.) and where

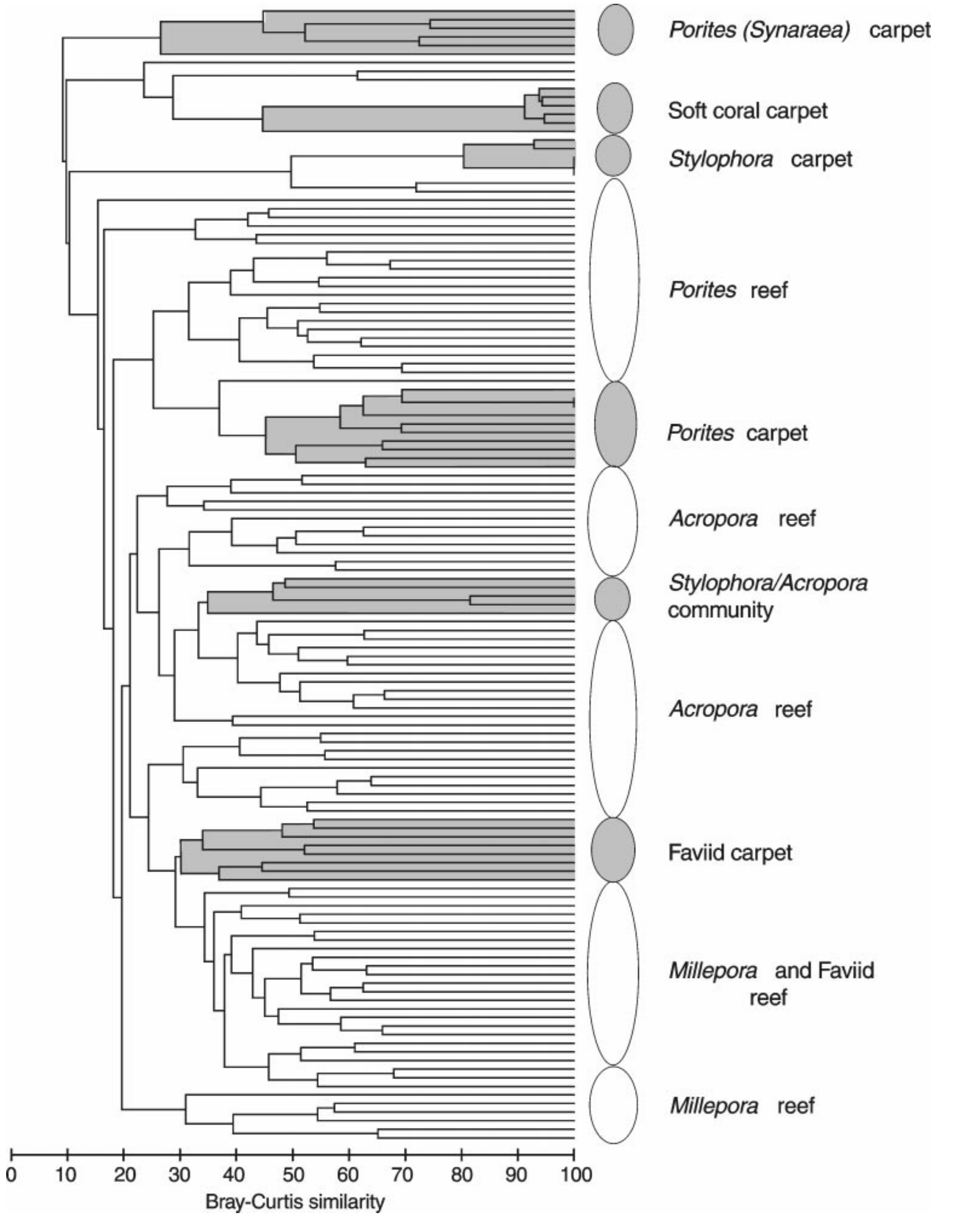


Fig. 2 Dendrogram of line transects representing reef and carpet frameworks. Reefs are further characterized in Table 1

Table 1 Ecological zonation and average living coral cover values on northern Red Sea reefs. Data modified from Riegl and Velimirov (1994), Riegl and Piller (1997)

	Exposed	Semi-exposed	Sheltered
Reef crest	*Pocillopora verrucosa*, *Acropora gemmifera*, *Stylophora mordax* Average cover: 43 ± 18%	*Stylophora pistillata* *Acropora secale* Average cover: 48 ± 10%	*Stylophora pistillata*, Faviidae Average cover: 24 ± 17%
Reef edge	*Acropora hyacinthus* group Average cover: 54 ± 11%	*Millepora dichotoma* Average cover: 58 ± 16%	*Porites lutea* Average cover: 68 ± 30%
Reef slope	Various *Acropora*, diverse without clear dominance Average cover: 59 ± 18%	*Millepora dichotoma* and various massive species Average cover: 56 ± 14%	*Porites lutea* and various massive species Average cover: 85 ± 29%
Slope base	Tabular *Acropora* (*A. clathrata*, *A. divaricata*) Average cover: 58 ± 25%	*Acropora hemprichi* Average cover: 29 ± 6%	Tabular *Acropora* (*A. clathrata*, *A. divaricata*) Average cover: 26 ± 11%

no major framework building on the reef slope is observed.

The coral patches sensu Piller and Pervesler (1989) area special reef type, which are also described by Riegl and Piller (1997). They are only a few meters in diameter and do not show clear ecological zonation. They grow in a hydrodynamically exposed position in less than 20 m depth and are dominated by *Acropora* and a diverse assemblage of faviids. The dominant species are tabular and open arborescent (Fig. 3G, H). They are not included in Table 1.

Coral carpets

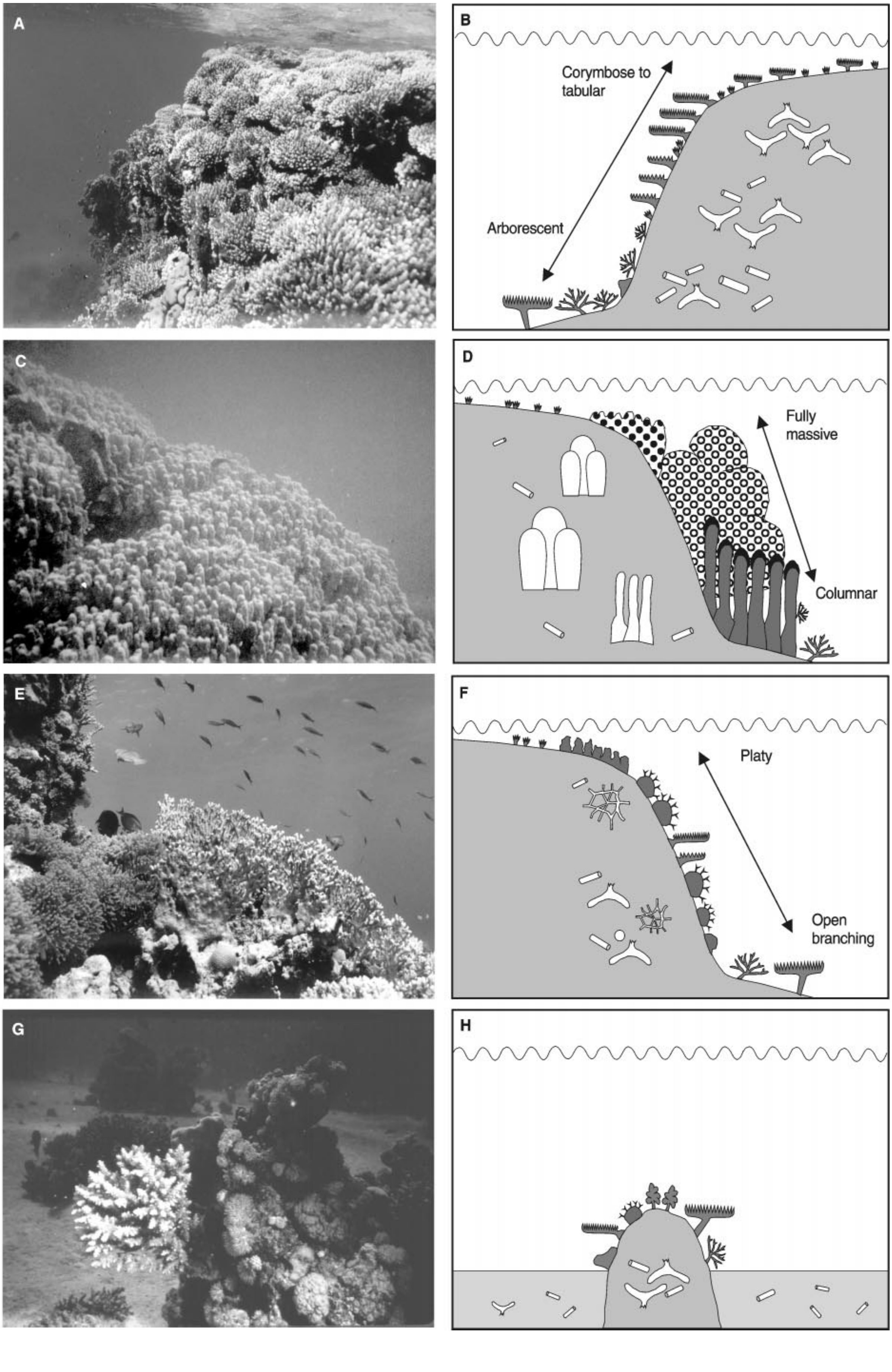
Coral carpets do not produce an accentuated three-dimensional relief, but roughly follow the underlying morphology. The apparent framework thickness above the surrounding seabed can reach a maximum of 8 m. The density of the framework is laterally variable depending on community type. Against their periphery, carpets tend to thin out and/or disintegrate into isolated patches. Coral carpets were represented by three types in the Red Sea proper (*Porites* carpet, *Porites* (*Synaraea*) carpet, faviid carpet), two types in the Gulf of Suez (*Stylophora* carpet in the north, faviid carpet in the south) and one type in the Gulf of Aqaba (faviid carpet).

The *Porites* carpet

This carpet type typically occurs between 5 and 15 m depth in areas of low topographical relief. It is not found in most of the Gulfs of Aqaba or Suez and increases in the Red Sea in areal extent and framework-thickness towards the south. As the name implies, the *Porites* carpet is defined by *P. columnaris*, *P. lutea*, and *P.* (*Synaraea*) *rus*. These species typically have columnar growth forms (on reef slopes *P. lutea* is often massive). The *Porites* carpet is an area of vigorous framework building. The thickest *Porites*-built framework in the Hurghada/Safaga area was 2–3 m (sampled at Shaab Abu Shiban, Shaab el Erg, Ras Abu Soma, Tubya al-Hamra, northwest of Gazirat Safaga) which increased in the Abu Dabab Group to > 8 m (Fig. 1). The framework is characterized by numerous caverns between the stick-like *Porites* columns, with live tissue and coral growth being restricted to the tips (Fig. 4A, B). Dead parts of the *Porites* columns are settled by other corals, particularly encrusting and platy species (*Montipora* spp., *Echinophyllia aspera*, *Mycedium elephantotus*, *Echinopora lamellina*, *Turbinaria mesenterina*) and small, corymbose *Acropora* (*A. valida*, *A. granulosa*, *A. humilis*). Faviids and alcyoniids are rare. Xeniids are common, although not as much as in other associations, like the faviid carpet (see below).

The *Porites* carpet only occurs to a depth of 15 m near the mainland coast, or to about 20 m on offshore

Fig. 3 Rigid reef frameworks: **A** *Acropora* reef framework at Erg Wadi Gimal. Species are *A. gemmifera* and *A. digitifera* on the shallowest parts, and mainly *A. polystoma* on the slope. Individual *Favia stelligera* and *Millepora dichotoma* are also seen. **B** Schematic representation of framework. The recent coral communities are sketched as is the probable fossil expression (signature in hatched areas). **C** *Porites* reef framework at Ras Banas, dominated by *P. lutea*. **D** Schematic representation. **E** *Millepora* reef framework at Tubya al-Hamra (Safaga Bay, 3m depth), consisting mostly of *M. dichotoma* and a small *Goniastrea retiformis* in the foreground. **F** Schematic representation. **G** *Acropora* dominated patch at Tubya al-Bayda (Safaga Bay, 15 m depth). The small reef frameworks (knolls) are seen in the background. **H** Schematic representation.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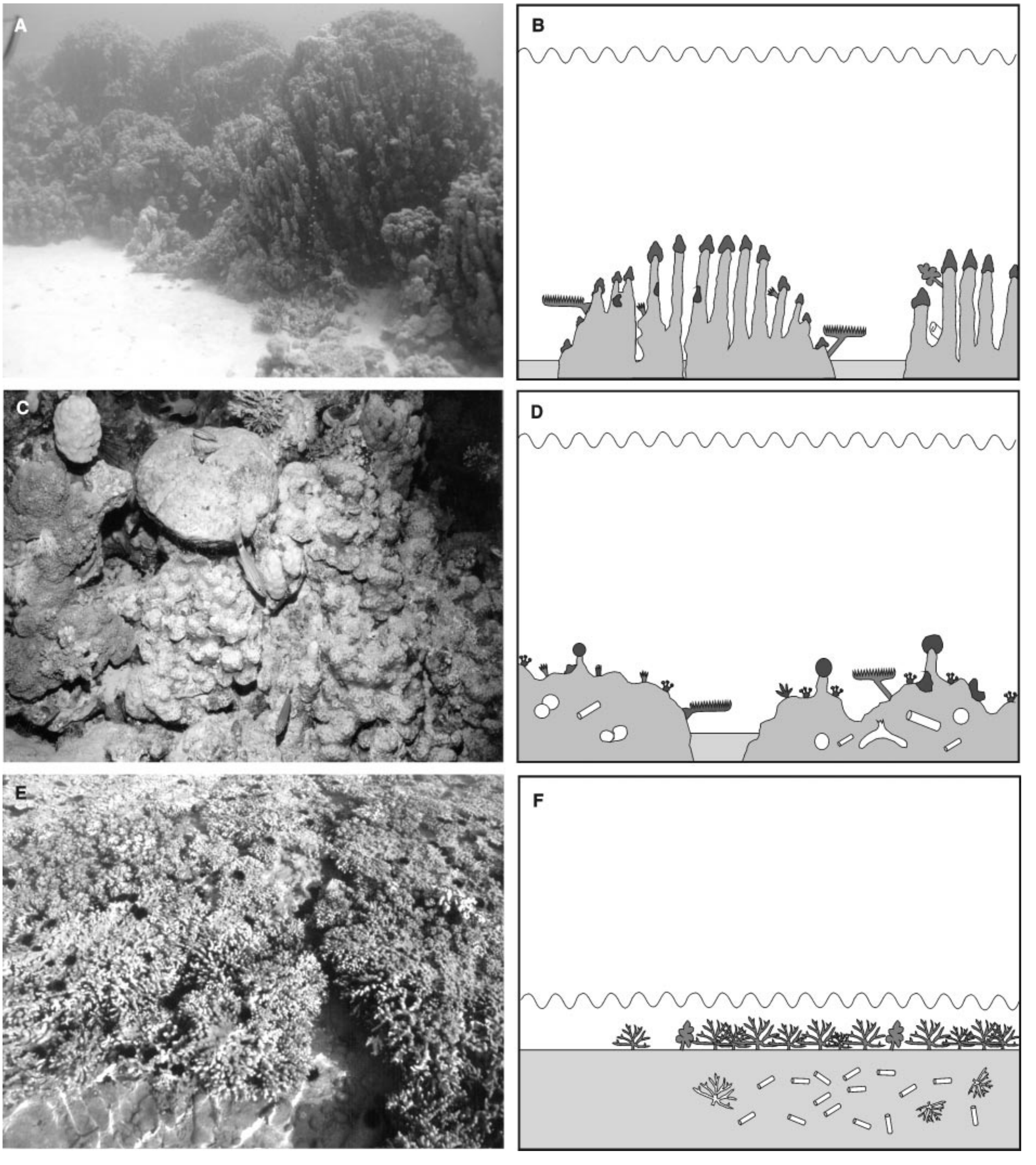

reefs. *Porites lutea* and *P. columnaris* are replaced by *P.* (*Synaraea*) *rus* at 20–25 m depth. This situation is frequently encountered on reefs in southern Egypt (Shaab Mahsur, Gota Marsa Alam). At greater depth the *Porites* carpet is replaced by a faviid carpet. If light availability is lower, the *P.* (*S.*) *rus* carpet is not developed and the faviid carpet is directly adjacent to a *P. lutea* or *P. columnaris* carpet (Shaab Abu Shiban, Shaab el Erg, Ranga, Neckarie). Typical live coral cover is between 60 and 90%.

Fig. 4 Rigid coral carpet frameworks **A** *Porites* carpet at Gota Marsa Alam (15 m depth), consisting of *P. lutea* and *P. columnaris*. The scale stick is 2 m long. **B** Schematic representation. **C** Faviid carpet at Marsa Bareka (20 m depth), mainly made up by *Goniastrea pectinata* (*center*), *Montipora danae* (*right*), and *Porites solida* (*top left* and *center*). **D** Schematic representation. **E** *Stylophora* carpet at Abu Darag (Gulf of Suez), water depth 0.5 m. **F** Schematic representation.

The *Faviid* carpet

This is the most widely distributed coral community at depths of 10 m or more (lower limit approximately 30–45 m) throughout the Gulf of Aqaba and the Red Sea. It is highly diverse. The coral built framework is on average 50–100 cm thick and has a rugged surface topography, with individual coral colonies forming columnar protrusions which extend above the rest of the carpet by several tens of centimeters (Fig. 4C, D).

The carpet is dissected by fissures, caves and gullies which are the habitat for a rich semi-cryptic to cryptic community. Typical corals in this association are *Goniastrea* (Fig. 3 C) , mostly *G. pectinata*, *G. retiformis*, and *Platygyra lamellina*, as well as various *Favia*, *Favites*, *Leptastrea*, *Cyphastrea*, *Pavona*, *Echinopora*, *A. granulosa* and the rare *A. squarrosa*. The most frequent tabular species is *A. pharaonis*, although large tabular colonies are missing. Fungiids are common. Platy corals (*Turbinaria mesenterina*, *Echinophyllia aspera*, *Mycedium elephantotus*) increase towards the lower depth limit, where they can form a specific community—the platy scleractinian assemblage of Riegl and Piller (1997). Soft corals, *Sarcophyton* and xeniids, can make up an important percentage (up to 50%) of all colonies. Total live coral cover of all substrata including sand is typically between 20 and 30%. This does not conflict with the higher values (60–90%) in Riegl and Piller (1997), which relates only to coverage of available hard substratum.

The *Stylophora* carpet

North of Ras Zafarana, in the Gulf of Suez, unique coral carpets exist in the near-shore area. They are largely monospecific thickets (Fig. 4E, F), composed almost entirely of *Stylophora* cf. *pistillata* (or a so far undescribed *Stylophora*) with few massive corals (*Platygyra*, *Favia*, *Porites*) interspersed. The soft coral *Litophyton* sp. is common on the edge of the framework and in breaks. The skeletons of adjacent *Stylophora* colonies fuse, and the entire carpet thus forms a very open, but continuous framework. Framework thickness can reach approximately 1 m and carpets grow to the low-water mark, becoming exposed to air at spring low tide. Space coverage by coral skeletons is 100% within the framework; frequently, however, only the colonies on the landward and seaward sides are alive, while the central framework is almost exclusively made up of dead corals.

Non-framework communities

Two communities were found which have less than 30% total coral cover and did not build a framework. They are described here because they may have the potential to act as incipient carpets.

The *Stylophora*-*Acropora* community

This community occurs in shallow (< 5 m) sandy areas, where a substantial amount of rocky substratum is available. Individual coral heads or small coral patches settle there (Fig. 5A, B). The characteristic coral is *Stylophora pistillata*, which forms dense bushy colonies of up to 30 cm (Fig. 5A). *Acropora robusta*, *A. tenuis*, *A. pharaonis*, *A. anthocercis* form large corymbose or tabular colonies. The bases of these colonies are usually densely packed with xeniids. Characteristic massive corals are *Platygyra lamellina*, *Porites lutea* and *P. solida*, which can form big microatolls of up to several meters. Besides xeniids, the alcyoniids *Litophyton arboreum*, *Sarcophyton* spp. and *Lobophytum* cf. *venustum* are common. This community does not form a framework but consists only of widely spaced colonies. Live coral cover varies between 5 and 20%.

Soft coral communities

A *Sarcophyton* dominated community (Fig. 5C, D) is widely distributed off Hurghada and in Safaga Bay at between 10 and 30 m depth (Fig. 1). A *Lobophytum* dominated carpet was observed at South Queisum island in the Straits of Gubal in the same depth range. The most typical scleractinia are *Siderastrea savignyana*, *Astraeopora myriophthalma* and fungiids. *Porites* and *Acropora* are rare. A mixed *Lobophytum*/*Sarcophyton* community occurs in Foul Bay (Fig. 5C) between 1 and 10 m depth. As described above, xeniids are widespread and can dominate, particularly in water depths greater than 20 m. Since such communities have virtually no fossilization potential, these areas were assigned to rock bottom in Safaga Bay by Piller and Pervesler (1989). Although numerous scleractinia occur, they are usually small and no framework building takes place in either community. Live (mainly soft) coral cover is between 10 and 20% for the *Sarcophyton* and *Lobophytum* community and up to 60% for the xeniid community.

Spatial distribution of coral frameworks

The study area included several shelf areas (offshore Hurghada) and shallow bays (Safaga Bay, northern Foul Bay) where extensive coral carpets occurred (Fig. 1). Since northern Safaga Bay is mapped in great detail, we used it as an example to demonstrate the spatial extension of coral frameworks (Fig. 6). From the map, we roughly calculated that reef frameworks occupy approximately 1.5 km^2 within northern Safaga Bay, while coral carpets occupied about 16.6 km^2 and scleractinian non-frameworks occupied 20.3 km^2. The *Acropora*-dominated patches were included in this calculation with the non-frameworks, as they do not form

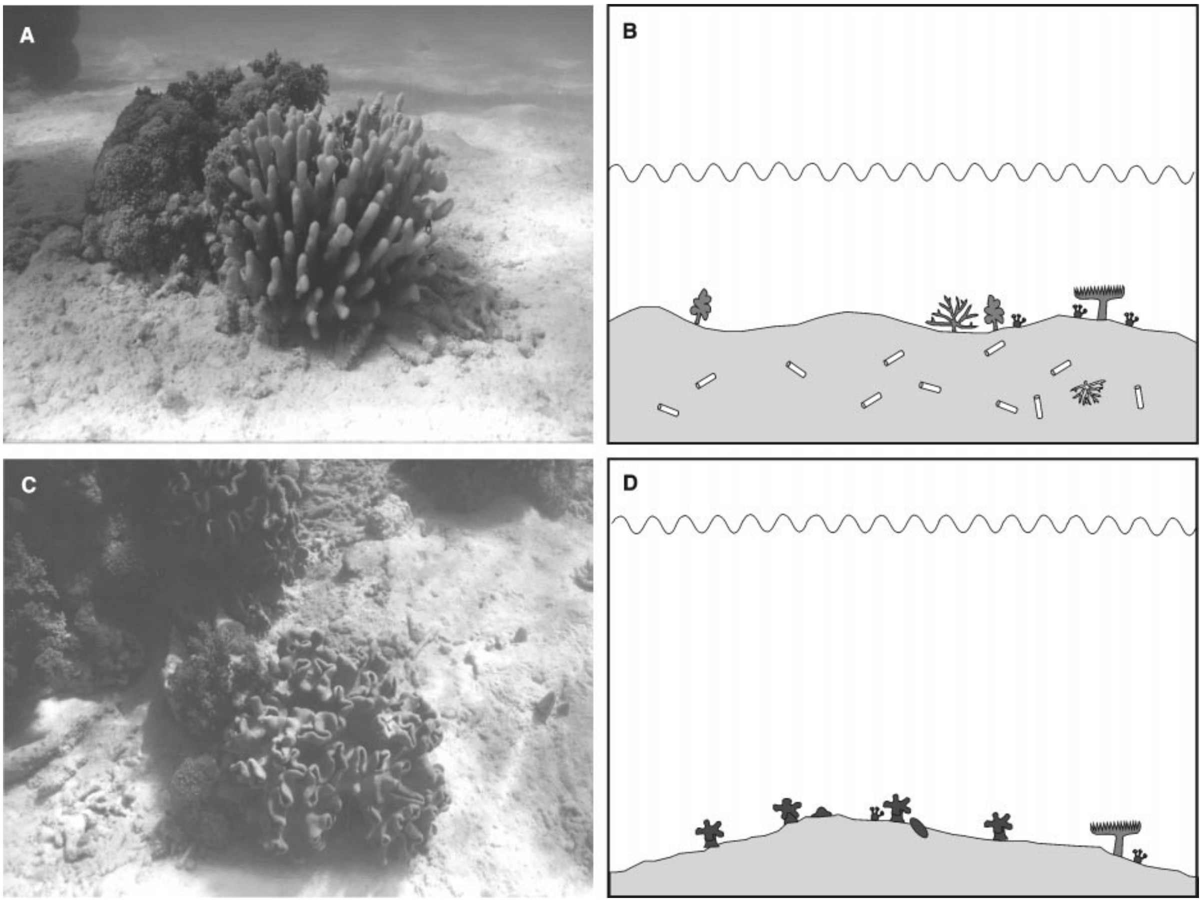

Fig. 5 Non-frameworks: **A** *Stylophora*/*Acropora* non-framework community consists of isolated colonies like this *S. pistillata*. Northern Safaga Bay, 2 m depth. **B** Schematic representation. **C** The soft coral communities are characterized by a high living cover of soft corals (*Sarcophyton* sp.) with few intermixed scleractinia, Foul Bay, 4 m depth. **D** Schematic representation

a continuous framework. In terms of total surface area, carpet frameworks are approximately ten times more expansive than reef frameworks in northern Safaga Bay.

Discussion

Mechanisms of framework-building by corals were discussed among others by Geister (1983, 1992) and Multer and Zankl (1988). A generalized scheme for framework-types in the Caribbean was presented in Geister (1983), who differentiated between a rigid framework, formed by settlers of a hard substratum, and a non-rigid framework, formed by settlers of an unstable substratum. A similar system was proposed by Multer and Zankl (1988), who differentiated into a rigid (type 1), non-rigid (type 2) and a combination of both (type 3) framework. These models were developed for the Caribbean, a system with a limited number of coral species available for framework building.

For the Indo-Pacific, Hopley et al. (1989), Kleypas (1996), and van Woesik and Done (1997) differentiated between reefs, "incipient reefs" and "coral communities without framework". Our approach in differentiating between reefs, coral carpets and non-framework communities is similar. We prefer the term coral carpet to the term incipient reef to clearly denote that reefs and coral carpets are two different systems. The term coral carpet was coined by Reiss and Hottinger (1984) from the Gulf of Aqaba and was extensively used by Piller and Pervesler (1989) in their description of bottom facies from Safaga Bay. Braithwaite (1982) used the term "coral rock frame" for comparable structures in the Sudanese Red Sea. Riegl and Piller (1997) added an ecological definition to the term coral carpet. The coral carpet was shown to possess unique coral communities, which were defined as low gradient/low relief communities in opposition to the high gradient/high relief communities on the reef (Riegl and Piller 1997). The high framework-building potential and resultant geological importance was clearly mentioned as a specific property of the faviid and *Porites* carpets.

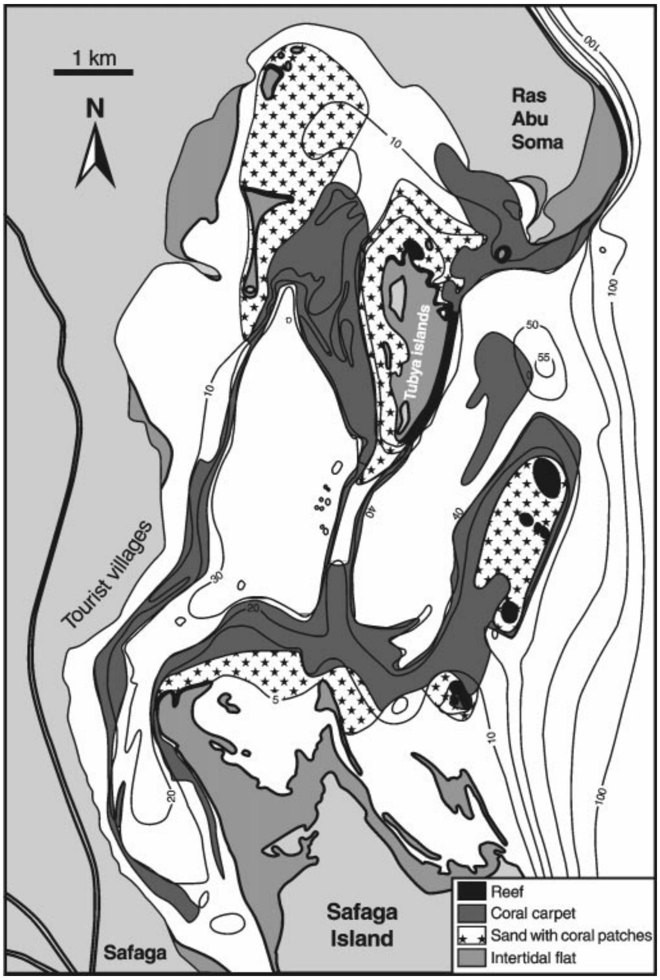

Fig. 6 Map of Safaga Bay indicating the coverage by coral carpet frameworks and reef frameworks

Reef frameworks

Four types of rigid framework are formed on Red Sea reefs: the windward *Acropora* reef framework (Fig. 3A, B), the semi-exposed *Millepora* framework (Fig. 3E, F), the leeward *Porites* reef framework (Fig. 3C, D), and, in some localities a coralline algal framework on the reef crest (Montaggioni and Bosence 1992, Piller and Rasser 1996). The few coralline algal systems observed in northern Red Sea reefs were not equivalent to the algal ridges of the Caribbean and Indo-Pacific (Rosen 1975; Adey and Burke 1976; Adey 1978; Geister 1983; Bosence 1984; Perrin et al. 1995), as they formed either a thin veneer of crusts (Rasser and Piller 1997) or a framework of laterally fused rhodolith layers in depressions on the reef flat (Piller and Rasser 1996). Rigid framework type F (= Melobesieae framework) sensu Geister (1983) is not represented in the northern Red Sea. Furthermore, the general importance of coralline algae as framework builders is a matter of debate (Macintyre 1997).

The *Acropora* reef framework is best developed in water less than 20 m deep. It consists of several species which dominate in different depth zones (Table 1; Riegl and Velimirov 1994; Riegl and Piller 1997). Wave resistance is high since the bases of the colonies are well calcified and cemented to the reef. Apical parts and branches are frequently broken and exported. In the shallowest parts, the typical coral growth form is corymbose or tabular, which is a modification of the basic corymbose branching pattern (Wallace 1978; Veron and Wallace 1984). At reef edges, coral morphology reflects the hydrodynamic conditions. In highest exposure conditions, reef edges are dominated by digitate or low corymbose species (*Pocillopora* spp., *Acropora gemmifera*, *A. digitifera*, *Stylophora mordax*; Fig. 3A). Under moderate exposure, modified corymbose or tabular species dominate (*Acropora hyacinthus* group sensu Veron and Wallace 1984, and in more sheltered areas *A. anthocercis*). On the upper reef slope, a zone of small corymbose species, such as *A. polystoma* is developed. On the upper to lower reef slope a transition of corymbose to arborescent growth form occurs. On the lower reef slope open arborescent species (*A. hemprichi*) are characteristic. This transition in growth form characteristics within the framework is roughly comparable to that observed in the Caribbean from the *Acropora palmata* (modified corymbose, platelike = special form of tabular) framework at the highest exposure (type B sensu Geister 1983) to the *A. cervicornis* framework (open arborescent) at lower exposures (type A sensu Geister 1983). Riegl and Piller (1997, Fig. 3) did not observe the *Pocillopora* community in Safaga Bay, however, this community is present in exposed southern Egyptian reefs (see Table 1).

Due to the frequent exposure to high hydrodynamic forces, in situ fossilization of *Acropora* frameworks will depend strongly on baffling and binding of fragments by other organisms in order to avoid export (Hopley 1982) and it is likely that this community will produce a coral rudstone (Fig. 3B; Wilson 1975; Flügel 1982) as described from other Indo-Pacific localities, for example by Montaggioni et al. (1997, Mauritius) and Kan et al. (1995, Ryukyus). The in situ preservation potential of unfragmented *Acropora* frameworks is also considered to be low in the Caribbean (Hubbard 1985; Hubbard et al. 1997; Hubbard et al. 1998; Jordan-Dahlgren 1997). However, Davies and Hopley (1983) obtained entire cores with near 90% recovery occupied by *Pocillopora* and *Acropora* on windward reef margins in the Great Barrier Reef (Hubbard et al. 1998).

The *Millepora* reef framework is made up by *M. platyphylla* in shallow water and *M. dichotoma* in deeper, or more sheltered locations (Fig. 3E). Additionally, *M. exaesa* acts as an efficient binder and encruster. *M. platyphylla* is highly wave resistant and is also frequently found on *Acropora* frameworks. The *Millepora* reef framework is built primarily by the well calcified basal plates of the colonies, which are strengthened by multiple fusions. Spaces between the plates are filled by rubble and sediment (Fig. 3F). This is equivalent to the frame type C of Geister (1983). The fossilization potential is unclear, however, as *Millepora* is rare even in Pleistocene deposits.

The *Porites* reef framework consists of skeletons of various poritids, mainly *Porites lutea* (Fig. 3C). Also, in this framework type a differentiation of growth form with depth is observable (Fig. 3D). In shallow areas, most colonies are massive, while columnar forms become more common with depth. Corals grow on the dead in situ skeletons of previous generations which leads to a rigid framework. Due to its massive construction it is mechanically more stable than the *Acropora* framework. The *Porites* framework type is roughly comparable to type D (*Montastrea annularis*, *M. cavernosa*, *Diploria strigosa*, etc.) of Geister (1983), except that it is built by *Porites* and not by faviids. In fossil reefs this reef framework would appear as a densely packed coral framestone of massive and columnar coral skeletons with little space between colonies (Fig. 3D). The fossilization potential is high. True *Porites* framework is only found in the Red Sea proper; they were not observed in the Gulf of Suez and only few examples in the Gulf of Aqaba were encountered at Nabq, near Shora el Manqata, close to the Straits of Tiran. The Sinai coastline is considered to be too hydrodynamically exposed and, at least in its southern part, too steep for *Porites* frameworks.

Coral carpets

Coral carpets create a rigid framework. If the terminology of Geister (1983) was used, it could be called a rigid reef framework (Geister 1983, p. 200). According to Hopley et al. (1989) and van Woesik and Done (1997) we would have to call them incipient reefs. While it is true that in some cases (*Porites* carpet) carpets may grade into reefs, and thus really represent incipient reefs, many carpets do not. Furthermore, it is well-known from the fossil record that the majority of biostromes never develop into reefs (bioherms). Therefore, we consider it necessary to separate carpet and reef as two different and independent rigid framework building systems. However, a transition from biostromes into bioherms is possible, and vice versa. Both cases are documented by examples during the earth's history (Kershaw 1994).

The *Porites* carpet is a rigid framework formed by numerous adjacent columns of the constituent species growing directly on each other, which leads to an uninterrupted, upward oriented framework (Fig. 4A, B). The framework is strengthened further by encrusting, branching and massive corals growing inbetween the *Porites* columns. This framework type is not yet reported from any other area. The maximum observed thickness above a sandy substratum was 8 m. This is possibly an underestimation of the true framework thickness, since much could be covered by sand. Heiss (1994) and Schuhmacher et al. (1995) showed that growth rates of *Porites* in the Red Sea (South Egypt) did not change significantly within the first 20 m depth. Therefore, the carbonate accumulation potential in carpets is expected to be higher than in reefs, because they have the same growth rate but have a larger total areal coverage. Furthermore, the slightly deeper and more sheltered situation makes the environment more stable and continuous and the produced carbonate remains in place and is not exported. After fossilization, this association would form a coral framestone with in situ *Porites* sticks (Fig. 4B).

The faviid carpet is the most widespread carpet type in the northern Red Sea and Gulf of Aqaba. In Safaga Bay it covers 55% of the total carpet-covered area (Fig. 6; 5% by *Porites* carpet, 40% by *Acropora* patches). It is made up of a diverse array of small massive species (Fig. 4C, D), leading to a compact framework. The visually observable thickness above the sand is usually less than 1 m and it has a high packing density of its components. When fossilized, it would be recognizable as a coral framestone (Fig. 4D). The average size of coral components is much smaller than in the *Porites* carpet. This framework is equivalent to the type D rigid framework of Geister (1983), however, it is not a reef framework but a carpet framework (biostromal, Kershaw 1994).

Both the *Porites* and the faviid carpets produce framestones with numerous cavities that will be infilled by sediment (Fig. 4B, D). Depending on the size of the cavities, either rudstones, composed predominantly of coral rubble or floatstones, packstones or wackestones will result. The high fraction of fine grains in the infilling sediments was described by Piller and Mansour (1990) and Piller (1994). This corresponds well with the situation in fossil autobiostromes (Kershaw 1994).

The replacement of the *Porites* carpet by the faviid carpet is tied to light availability (Riegl and Piller 1997) which was also deduced from data on growth rates in different depths by Heiss (1994) and Schuhmacher et al. (1995) from the northern and central Red Sea. Therefore, the *Porites*-faviid transition is deeper in clearer offshore waters than on more turbid nearshore reefs. The varying thickness of the *Porites* and faviid carpets is most likely due to differences in light availability, and thus growth rates. The thinner frameworks are probably a result of smaller average coral size, which would be caused by the lower irradiance on the deeper faviid carpets. With a further decrease in irradiance, the faviid community changes to a predominantly platy growth form. Due to the reduction in coral cover, the carpet grades into a non-framework community.

The *Stylophora* frameworks of the northern Gulf of Suez form dense thickets with fused branches (Fig. 4E, F). The open space between the branches will be infilled by sediment. These are rigid (type 1) frameworks according to Multer and Zankl (1988). If infilled by sediment and cemented early enough, a framestone could be formed. It is just as likely, however, that the framework is broken up and a rud- or floatstone is formed (Fig. 4F). With respect to Geister's (1983) typology, they are most similar to the type A rigid framework (*Porites porites* var. *furcata*). However, in this framework type branches do not fuse.

The *Acropora*-dominated coral patches represent an intermediate position between reef and coral carpet. The individual patches are constructed by a real framework. Due to their small size (only a few meters in height and diameter) they do not have a pronounced ecological zonation. According to Piller and Pervesler (1989) they have the potential to form either coral carpets by lateral growth, or patch reefs by vertical growth.

Non-framework communities

The *Stylophora*-*Acropora* community is a non-framework community (Fig. 5A, B). In the current state of development, branching colonies settle the area sparsely (Fig. 5A). They frequently topple over or become partially buried in sediment. Parts regenerate and continue growth. Often dead and partly buried colonies serve as the substratum for new coral settlement. This community bears some resemblance to the "coral community" and the loose framework type A (*Porites porites* var. *furcata*) of Geister (1983) and the "coral community" and the "incipient reef" of Hopley et al. (1989), Kleypas and Hopley (1992), Kleypas (1996), and van Woesik and Done (1997). It would be recognizable after fossilization as a coral floatstone or, if winnowed, a rudstone made up of branching coral fragments (Fig. 5B) and could form a para- or allobiostrome sensu Kershaw (1994).

The soft coral community forms no framework at all and therefore also has a low fossilization potential. It could only be reconstructed as a shelly hardground or a bafflestone with sparse and rare scleractinia and a diverse mollusk association (Zuschin and Piller 1997). Although some soft corals, e.g. *Sinularia*, are able to produce significant spiculite deposits (Reinicke and Schuhmacher 1996; Schuhmacher 1997), such forms are not frequent enough to substantially enhance carbonate production.

A further difference between reefs and coral carpets is the amount and fate of the produced sediment. Due to the carpet's sheltered position, sediment production by physical breakdown is much less than in reefs. Furthermore, the produced sediment (e.g. by biological breakdown) remains within the carpet, filling the open spaces. In reefs, stronger physical forces produce more sediment, which is either transported in a leeward direction over the reef flat or exported down the slope (Dullo et al. 1996; Hughes 1999). Hubbard (1985) also differentiated between the two modes of sediment transport in reefs (leeward versus down-slope); in both cases the sediment is transported away from the framework. Therefore, carbonate net accumulation is considered to be potentially higher in coral carpets than in reefs, since no substantial export occurs in the former.

Concerning the absolute thickness of the carpet frameworks, we can presently only provide hypotheses. We were able to measure a maximum thickness of 8 m above the sand in a *Porites* carpet at Abu Dabab and could infer a maximum thickness of 11 m nearby, although a continuous outcrop was not available. This thickness compares well with the 10–14 m vertical Holocene reef accretion in Florida (Shinn et al. 1989) but is less than in Mauritius reefs (Montaggioni and Faure 1997). Coral carpet vertical accretion in the southern Egyptian Red Sea (Abu Dabab) could be in the range of 1–2 m per 1000 years, which is at best equal to reef accretion in Hawaii (2 m per 1000 years, Grigg 1998) but only about half of the reef accretion rates calculated for many other areas of the southern Red Sea and Indo Pacific (Hopley 1982; Cabioch 1995; Dullo et al. 1996; Webster et al. 1998). If carpets really accrete more slowly than reefs, this may be primarily due to the relative rarity of fast-growing branching species and the dominance by slower-growing massive species, the growth rates of which are also frequently affected by depth (Hudson and Robbin 1980; Huston 1985; Heiss 1994; Schuhmacher et al. 1995). Additionally, having started in deeper water and not on a preexisting high, it may simply take the carpets longer to catch up to the surface than it takes the reefs. Another reason for some coral carpet frameworks (in particular the faviid carpet) to be potentially thinner than reef frameworks, may be delayed initiation caused by the less suitable substratum which has more sand. It may take carpets longer to get established initially (Kleypas 1996; van Woesik and Done 1997), thereby leading to variable framework thicknesses between older and younger carpets, or overall reduced framework thickness compared with reefs. However, even if coral carpets have thinner frameworks than reefs, they cover a much greater area (ten times more in the study area) and therefore accumulate significant amounts of carbonate.

Coral carpets have so far not received exhaustive attention and their geological importance has been underestimated. At our current state of knowledge we suggest that coral carpets form predominantly in areas with low topographical relief. This absence of relief does not allow a distinct ecological differentiation along a hydrodynamic gradient in shallow water or along a light gradient in deep water. In contrast, coral reefs form primarily in areas with high topographic relief, resulting in distinct ecological zonations over short distances. We believe that coral carpets have a high carbonate production and accumulation potential and that some coral carpets may accumulate even more carbonate than steep reef communities. This is primarily due to the greater area covered by coral carpets and sediment retention within the carpet system. The importance of coral carpets, however, is tied to sea-floor topography. In the northwestern Red Sea such systems are relatively small. However, in typical shelf seas (e.g. Southeast Asia: McManus 1997) they appear to cover vast areas. Their global importance still needs to be properly evaluated.

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