Reefs and coral carpets in the northern Red Sea as models for organism–environment feedback in coral communities and its reflection in growth fabrics

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Abstract: Coral framework construction and resultant growth fabrics in response to environmental factors were studied in the northern Red Sea, and the Gulfs of Suez and Aqaba. The dependence of growth fabric types on sea-floor topography, oceanography and the ecology of constituent coral species was investigated. Five types of coral frameworks and their growth fabrics were differentiated: *Acropora* reef framework (platestone to mixstone facies); *Porites* reef framework (domestone facies); *Porites* carpet (columnar pillarstone facies); faviid carpet (mixstone facies); *Stylophora* carpet (thin pillarstone facies). Two non-framework community types were found: *Stylophora–Acropora* community and soft coral communities. Reef frameworks and resultant growth fabrics show a clear ecological zonation along depth and hydrodynamic exposure gradients. Coral carpets build a framework lacking a distinct internal zonation since they only grow in areas without pronounced gradients. In the northern Red Sea they show a gradual change with depth from *Porites* (pillarstone) to faviid (mixstone) dominance.

The initiation of frameworks was governed by bottom topography (reefs on steep slopes and highs, coral carpets in flat areas). According to environmental conditions, different coral communities produce different framework and growth fabric types. In step with framework growth the environment is modified. The modified environment in turn modifies the coral communities. Thus an environment–organism–environment feedback loop exists.

Coral reefs, both fossil and modern, have long been recognized as systems of intricate environment–organism interaction (Rosen 1975; Longman 1981; Frost 1981; Hopley 1982; Done 1982, 1983; Perrin *et al.* 1995; Riegl & Piller 1997; Wood 1999) that are largely brought about by the corals' ability to build a solid reef structure (Insalaco 1998). The ecological structure of the reef and its imprint in the geological record is strongly dependent on a combination of environment, species availability and ecology, both for initiation and as shaping factors during its growth (Longman 1981; Leinfelder 1997; Guozhong 1998). Once a solid reef structure is established, this in turn modifies the environment. As the reef structure grows and modifies its own environment, constituent coral communities and accretion rates change (Montaggioni & Faure 1997; Smith *et al.* 1998) creating an organism–environment feedback.

The composition of coral communities, which in the fossil record is recorded by its growth fabric (Insalaco 1998), is influenced not only by physico-chemical factors in the water column, but also by basin geometry and bottom topography which govern the availability of space for the development of reefs or non-reef building communities (Hopley 1982; Done 1982; Kleypas 1996; van Woesik & Done 1997; Insalaco 1998).

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 & Pervesler 1989). However, in shallow shelf areas, extensive framework-building coral communities exist in addition to reefs (Piller & Pervesler 1989; Riegl & Piller 1997, 1999). We call these communities 'coral carpets' in accordance with Reiss & Hottinger (1984). The systems 'reef' and 'coral carpet' differ both in their ecological and frame-building response to environmental factors, as well as in their influence on the environment and their representation in the geological record (Riegl & Piller 1999). However, they should not be seen as mutually exclusive systems but rather as different stages into which frame-building coral communities can develop according to environmental constraints.

In this paper we provide a model for how organismic response to the physical environment translates into different types of reef and non-reef frameworks which in turn change their

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environments. We examine: (1) the different coral framework types in the northern Red Sea; (2) the ability of coral carpets to build frameworks (3) the expected lithological representation in the fossil record; (4) the interaction of the environment with the frame-building coral communities; (5) the feedback of the organisms to the environment via different frame-building capacity.

Material and methods

Study area

Coastal and offshore sites, representing most coral habitats available in the northern Red Sea, were investigated in the Gulfs of Aqaba and Suez as well as the Egyptian Red Sea (Fig. 1). The quantitative sampling sites were located in the Straits of Gubal and the Hurghada area. Additionally, 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 main Red Sea basin south to Ras Banas (Egypt).

Geomorphological features in the northern Red Sea region are mainly controlled by tectonism and salt diapirism (Dullo & Montaggioni 1998). Since the Oligocene, the sedimentary evolution of the Red Sea basin has been tectonically controlled, as evidenced by the orientation of major fault structures and the orientation and shape of the reefs which frequently follow and are determined by such structures. Salt diapirism, which again frequently follows the major tectonic lineaments, is another factor creating highs suitable for extensive coral settlement (Orszag-Sperber *et al.* 1998). Purser *et al.* (1998) showed how the tilting of fault blocks influenced carbonate and siliciclastic sedimentation, where fault-line depressions funnel siliciclastics while carbonates develop on top of, or on the seaward sides of, structural highs (mostly tilt blocks or diapiric structures). These processes also provide the structural diversification into highs with reefs and moderately deep (<50 m) shelves settled by coral carpets as discussed in this paper.

Meteorologically, the region enjoys stable conditions which result in stable oceanographic conditions over most of the year. Dominant wind and swell direction for about 80% of the year is from the northwest with an average speed of 10 knots (Roberts 1985). In winter, eastward-travelling depressions can cause changes in wind direction to SE or E (Edwards 1987). It is therefore possible to talk about mostly exposed (windward, N-facing) and mostly sheltered (leeward, S-facing) reef sides (see windrose on Fig. 1).

Terminology

For the purpose of this study, coral carpets were defined as laterally more or less continuous veneers of coral framework following the existing sea-floor morphology. They do not create a distinct three-dimensionality and are therefore ecologically relatively uniform (Fig. 2). Riegl & 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. Riegl & Piller (1999) defined only communities with framework-building potential as carpets. From a geological perspective, coral carpets form biostromes (Cumings 1932; Kershaw 1994).

Reefs were defined as distinctly three-dimensional structures producing a stronger ecological differentiation of animal and plant communities than coral carpets. Our definitions are compatible with and expand that of Wainwright (1965) quoted in Stoddart (1969), namely that in '. . .structural coral reefs, corals are actively contributing by skeletal accumulation to the topographic development of the reef. . .'. The definitions of Rosen (1990), which is a condensation from several other definitions – '. . . organic framework, raised relief, wave resistance, photic zone restriction and tropical (or warm water) distribution. . .' – and Longman (1981, p. 10) – '. . .biologically influenced buildup of carbonate sediment which affected deposition in adjacent areas . . . and stood topographically higher than surrounding sediments during deposition. . .' also support our claim that carpets are indeed different from reefs, mainly because of the absence of clear relief since they may frequently be at almost the same level of the surrounding sediment (see also Wood (1999): '. . .a discrete carbonate structure . . . that develops topographical relief upon the sea floor. . .').

Fagerstrom (1987, p. 13) remarks that '. . .among Holocene photic and aphotic zone reefs there is an unbroken size gradation from isolated solitary corals, to weakly colonial, to strongly colonial of various sizes, to clusters of large, massive coralla, to coral knolls, knoll reefs, and patch reefs with entire reef systems' where 'reefs rarely occur in isolation . . . they occur in variously spaced clusters; each cluster is commonly called a "reef system" or if the cluster is enormous . . . it may be called a "reef province". Reefs plus reef systems (provinces) and the adjacent (external) sediments constitute a "reef complex". . .' (Fagerstrom 1987, p. 7). It

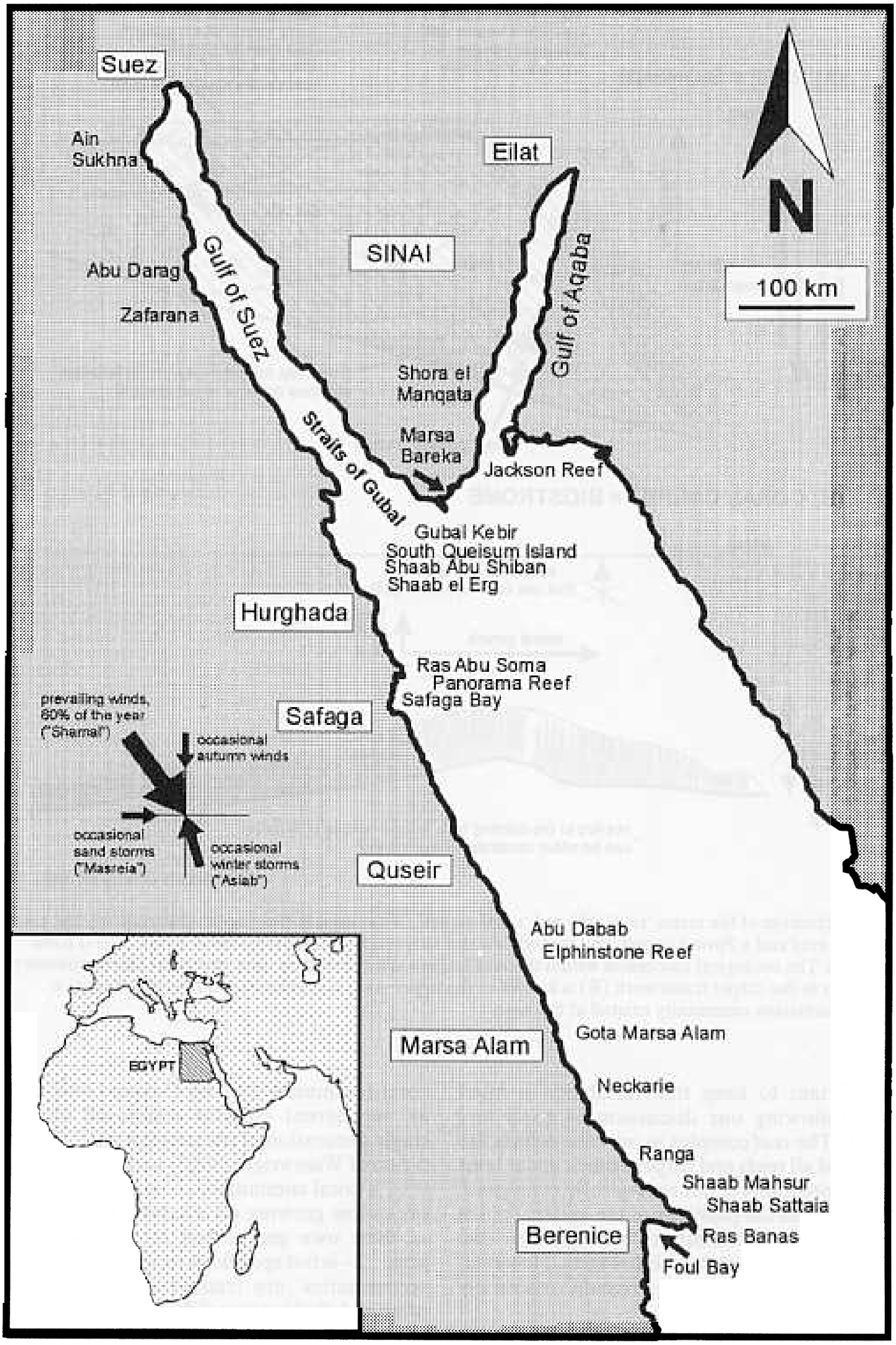

Fig. 1. Location map indicating the study area (Egyptian Red Sea) and names mentioned in the text. Coral carpets are tied to shallow shelf areas. In the Gulf of Suez they replace fringing reefs north of Zafarana. In the Gulf of Aqaba they occupy the sloping seafloor in the fore reef areas.

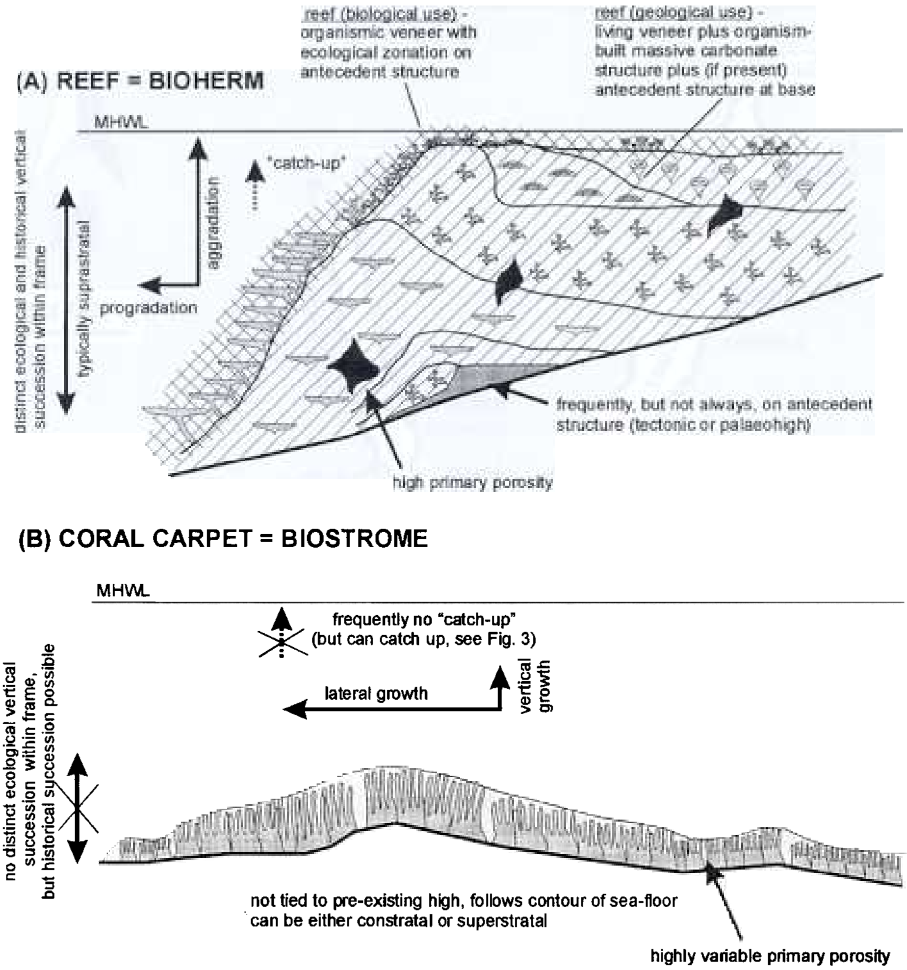

Fig. 2. Definition of the terms 'reef' (**A**) and 'coral carpet' (**B**) as used in this paper, illustrated by the cases of a fringing reef and a *Porites* carpet. (A) is modified and adapted from Montaggioni & Faure (1997) from Mauritius. The ecological succession within the reef framework is based on their research. The community succession in the carpet framework (B) is known in the upper part; it is unknown, however, whether a different initiation community existed at the base.

is important to keep this variability in mind when following our discussion of reefs and carpets. The reef complex in our case defines the totality of all reefs and carpets which are at least in close proximity if not ecologically connected. This indicates the plasticity of the system, which may allow any transition between the two systems and the resultant lithologies. However, in most observed cases they remain structurally distinct.

The term 'community' is used in this paper *sensu* Kidwell & 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. . .'. The definition of Wainwright (1965) and Stoddart (1969) – '. . .a coral community . . . is an assemblage of organisms growing on a substratum other than of their own production in shallow, tropical seas. . .' – is not specific as to whether their 'coral communities' are frame-building at all. Our present definition also differs from the terminology used by Riegl & Piller (1997, p. 144) who reserved the term 'community' for quantitative descriptions of entities of ecologically well defined and distinct groups of organisms. In their study of Pleistocene coral communities on Grand Cayman, Hunter & Jones (1996) follow Whittaker (1975) and Kauffmann & Scott (1976) in defining communities as '. . .species that lived together and interacted with each other and their environment. . .'. This is also comparable to the definition of communities given by Fagerstrom (1987, p. 154) as '. . .consisting of numerous interacting species, having a broadly predictable composition, and occupying a broadly predictable habitat. . .'. It is unfortunate that the term 'community' is introduced into the ecological as well as the geological literature. In order to avoid confusion, the term 'coral community' *sensu* Wainwright (1965) and Geister (1983) should best be referred to as 'non-framework coral community'.

Drawing attention to further uses of the term 'reef', it is also necessary to differentiate between the use of the term as acceptable to ecologists studying the distribution of biota along gradients and to geologists looking for actual carbonate buildup. In an ecological sense, even a thin veneer of corals covering a fossil reef will exhibit differentiation into different communities along gradients (usually most notably depth and hydrodynamic exposure), and look like a real reef in a geological sense, as defined above (see also Fig. 3). Therefore any structure covered by coral communities exhibiting such an ecological differentiation tends to be called 'reef' in the biological literature, regardless of whether it would be called a reef by geologists. This has, however, nothing to do with the differentiation made by Dunham (1970) and James (1983) into stratigraphic reef (several superimposed bioherms) and the ecologic reef ('. . .rigid, wave-resistant structure generally formed during one specific period of time'), yet another conflicting use of the term.

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. . .', which corresponds well with that of Rosen (1990). Framework lithologies were defined according to Insalaco (1998). Although Insalaco (1998) advocates the use of the term 'growth fabric' rather than framework, we still use it extensively in this paper because working on Recent structures, we have the luxury of being able to watch living frameworks as they form and can recognize all the critical components. In order to give our findings palaeontological relevance, we also discuss which growth fabrics (*sensu* Insalaco 1998) could be formed. This interpretation is based on a quantitative evaluation of the Recent coral communities and experience with the local Pleistocene and Miocene. Primary porosity was evaluated visually: large pores or cavern systems are easily visible in Recent frameworks.

Quantitative methods

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

The dataset was explored by means of agglomerative hierarchical cluster analyses using the Bray-Curtis similarity measure or Euclidean distance as distance measure and group average method of grouping (Digby & Kempton 1987; James & McCulloch 1990). Cluster analysis was used because it has advantages for delineating groups in a very distinct community setting (Field *et al.* 1982; Kenkel & Orloci 1986) as established from previous experience in the area (Riegl & Velimirov 1994; Riegl & Piller 1997) and with similar datasets. When the statistically obtained groupings were compared to the situation in the field and found to coincide they were used to describe community patterns. Analyses were performed using the PRIMER and SPSS statistical software.

In order to gain information about the spatial distribution of coral carpets, it was necessary to map the distribution of coral associations in a sample area, in our case northern Safaga Bay. After the different communities and framework types were obtained by statistical analysis, we visually examined other localities throughout the study area and assigned the encountered communities to those quantitatively described. The results are published in Riegl & Piller (1997) and were reused for this paper.

Since we were unable to obtain permission for either drilling or seismic surveys, we had to limit our evaluation of framework thickness in reefs and coral carpets to visual observations along natural or artificial (resulting from dynamite damage) scars and cracks. Therefore reliability of framework thickness estimation is problematic. Thicknesses given in this paper represent minimum estimates and we are presently unable to provide serious data either on framework growth rates or carbonate accumulation rates.

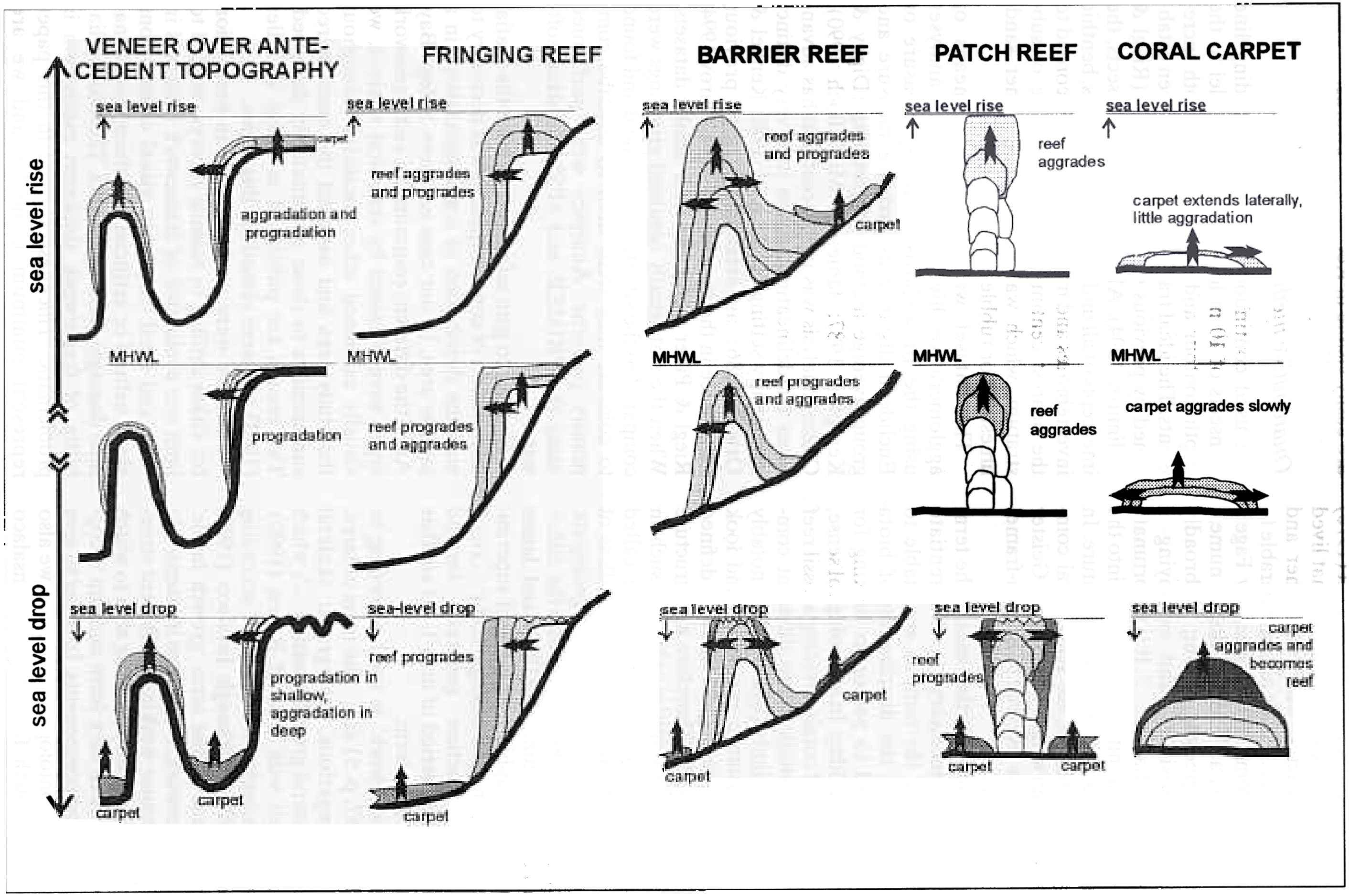

Fig. 3. Conceptual models illustrating several possibilities of coral reef and carpet growth, with spatial relationships and inferred differences in growth patterns. The growth geometries and sequences were inspired by the literature (Longman 1981; James & Macintyre 1985; Liu *et al.* 1998; Camoin *et al.* 1998; Schlager 1992, 1998) and are not based on actual data obtained during this study. Only some mechanisms of reef or carpet growth (simple aggradation and progradation) are illustrated while others, like backstepping or downstepping, were ignored because the added complexity would have done little to clarify the point.

Results

Spatial distribution of coral frameworks

The study area included several shelf areas (e.g. offshore Hurghada and Gulf of Suez) and shallow bays (Safaga Bay, northern Foul Bay) where extensive coral carpets occurred (Fig. 1). Safaga Bay was used as our central model for distribution of framework types in relation to bottom topography. Figure 4 shows how coral carpets occupy mainly the areas of flat, medium deep sea floor (5–30 m) while reefs are primarily tied to topographical highs, such as the steep mainland coastline at Ras Abu Soma and the Tubya islands. Patch reefs are found on the Tubya-Gamul ridge. From the map (Fig. 4) we 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 (patches and non-framework coral communities) occupied 20.3

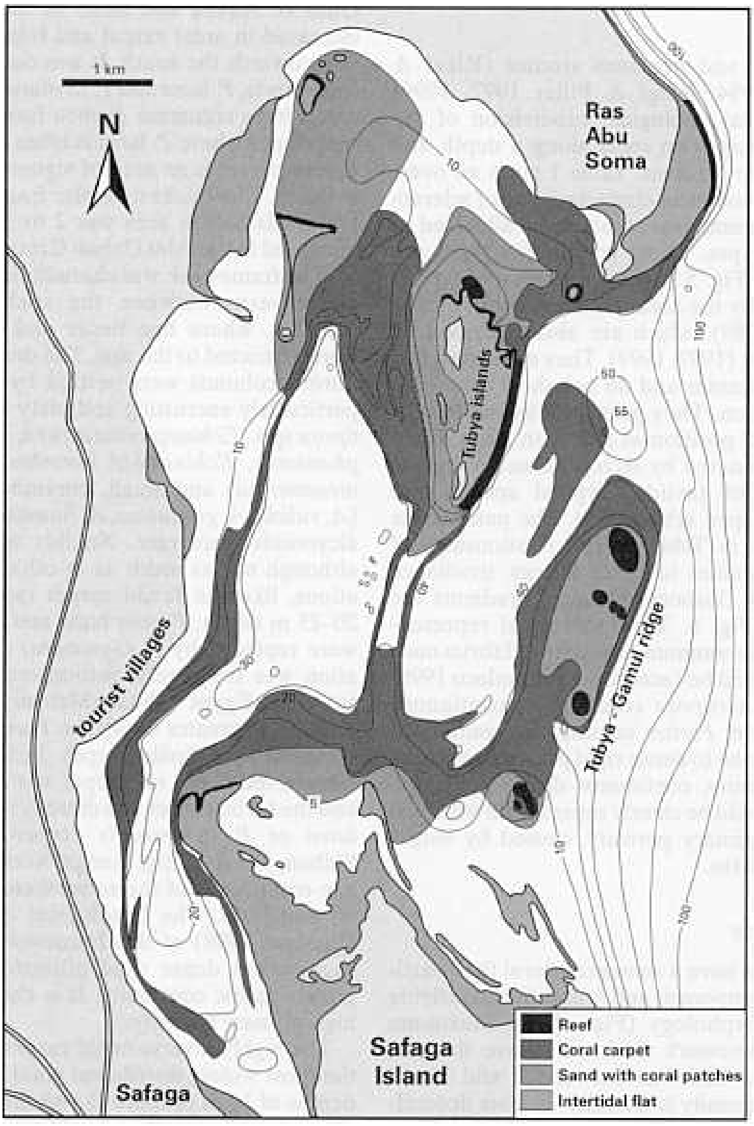

Fig. 4. Distribution of coral framework types in northern Safaga Bay, Red Sea, Egypt (modified after Riegl & Piller 1999).

km². The *Acropora*-dominated patches were included in this calculation with the non-frameworks, since they do not form a continuous framework. In terms of total surface area, carpet frameworks cover approximately ten times more space than reef frameworks in northern Safaga Bay.

The cluster analysis of 150 line transects allowed the differentiation of several coral communities that could be interpreted as reef communities, coral carpets and non-framework coral communities.

Reefs

The present and previous studies (Riegl & Velimirov 1994; Riegl & Piller 1997, 1999) showed a clear ecological subdivision of the coral assemblages on reefs along a depth and hydrodynamic gradient. Table 1 gives an overview of the biological characteristics of scleractinian reef communities that can be allocated to framework types. These community types are illustrated in Fig. 5 A–C. A special reef type is represented by the coral patches *sensu* Piller & Pervesler (1989), which are also described by Riegl & Piller (1997, 1999). They are only a few metres in diameter and do not show clear ecological zonation. They grow in a hydrodynamically exposed position at less than 20 m depth and are dominated by *Acropora* and a diverse assemblage of faviids. Typical species are tabular and open arborescent. The patches are not included in Table 1. The relationships of these communities to water energy, irradiance and turbidity (inshore–offshore) gradients are outlined in Fig. 6. The lithological representation of these communities' growth fabrics once fossilized would be (according to Insalaco 1998) as follows: *Acropora* community, continuous rigid mixstone; *Porites* community, continuous rigid domestone to dense rigid pillarstone; *Millepora* community, continuous dense rigid mixstone. All would be clearly superstratal with well developed primary porosity, caused by ledges and overgrowths.

Coral carpets

Coral carpets have a stronger lateral than vertical growth component and follow the underlying sea-floor morphology (Figs. 2, 3). Maximum apparent framework thickness above the surrounding sea bed was between 8 and 11 m. Framework density 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 four types in the Red Sea proper (*Porites* carpet, *Porites (Synaraea)* carpet, faviid carpet, platy scleractinian carpet); (Fig. 6), 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 growth fabric of these frameworks is more variable than in reefal frameworks but always remains superstratal. However, the primary porosity is more variable than in the reefal growth fabrics: low in the platy growth fabric type, high in the columnar (pillarstone) type.

The *Porites* carpet (Fig. 5D) was typically found between 5 and 15 m depth except in the Gulfs of Aqaba and Suez. In the Red Sea, it increased in areal extent and framework thickness towards the south. It was dominated by *P. columnaris*, *P. lutea* and *P. (Synaraea) rus*. These corals have columnar growth forms (except on reef slopes where *P. lutea* is often massive). The *Porites* carpet is an area of vigorous framework building. The thickest *Porites* framework in the Hurghada/Safaga area was 2 to 3 m thick and increased in the Abu Dabab Group to >8 m (Fig. 1). The framework was characterized by numerous caverns between the stick-like *Porites* columns, where live tissue and coral growth were restricted to the tips. The dead parts of the *Porites* columns were settled by other corals, particularly encrusting and platy species (*Montipora* spp., *Echinophyllia aspera*, *Mycedium elephantotus*, *Echinopora lamellosa*, *Turbinaria mesenterina*) and small, corymbose *Acropora* (*A. valida*, *A. granulosa*, *A. humilis*). Faviids and alcyoniids were rare. Xeniids were common, although not as much as in other deep associations, like the faviid carpet (see below). At 20–25 m depth, *Porites lutea* and *P. columnaris* were replaced by *P. (Synaraea) rus.* This situation was frequently encountered on reefs in southern Egypt (Shaab Mahsur, Gota Marsa Alam). At greater depth the *Porites* carpet was replaced by a faviid carpet. In low light conditions, the *P. (S.) rus* carpet was not developed and the faviid carpet was directly adjacent to a *P. lutea* or *P. columnaris* carpet (Shaab Abu Shiban, Shaab el Erg, Ranga, Neckarie). Typical live coral cover of the substratum was between 60 and 90%. The lithological representation (Insalaco 1998) of this framework would be a superstratal dense rigid pillarstone with high growth fabric continuity. It is characterized by high primary porosity.

The highly diverse faviid carpet (Fig. 5E) was the most widely distributed coral assemblage at depths of 10 m or more (lower limit *c.* 30–45 m) throughout the Gulf of Aqaba and the Red Sea. The coral-built framework was on average 50–100 cm thick and had an irregular surface topography. The carpet was dissected by fissures,

Table 1. *Ecological zonation (indicator species), average living coral cover values and growth fabric type on northern Red Sea reefs*

		Exposed			Semi-exposed			Sheltered		
Position	Depth (m)	Indicator species	Average cover (%)	Growth fabric type	Indicator species	Average cover (%)	Growth fabric type	Indicator species	Average cover (%)	Growth fabric type
Reef crest	0–1	*Pocillopora verrucosa*, *Acropora gemmifera*, *Stylophora mordax*	43±18		*Stylophora pistillata*, *Acropora secale*, Faviidae	48±10			24±17	
Reef edge	-3	*Acropora hyacinthus* group	54±11	Platestone	*Millepora dichotoma*	58±16	Mixstone		68±30	Domestone
Reef slope	3–15	Various *Acropora*, diverse without clear dominance	59±18	Mixstone or platestone	*Millepora dichotoma* and various massives	56±14	Mixstone	*Porites lutea* and various massive species	85±29	Domestone
Slope base	15–25	Tabular *Acropora* (*A. clathrata*, *A. divaricata*)	58±25	Pillarstone	*Acropora hemprichi*	29±6	Pillarstone	Tabular *Acropora* (*A. clathrata*, *A. divaricata*)	26±11	Pillarstone
Carpet	5–35	Diverse carpet (faviid carpet with *Acropora*)	28±3	Mixstone	Diverse carpet (usually faviid carpet)	28±3	Mixstone	*Porites* carpet and/or faviid carpet	85±15	Pillarstone, Mixstone
Deep areas	35–50	Platy scleractinia (*Turbinaria mesenterina*, *Echinophyllia aspera*, *Leptoseris papyracea*)		Sheetstone	Platy scleractinia *Turbinaria mesenterina*, *Echinophyllia aspera*, *Leptoseris papyracea*		Sheetstone	Platy scleractinia *Turbinaria mesenterina*, *Echinophyllia aspera*, *Leptoseris papyracea*		Sheetstone

Species named are the visually dominant species within the reef zone. Modified from Riegl & Velimirov (1994), Riegl & Piller (1997, 1999). Depths are approximate and can vary according to exposure and reef morphology. Depths indicated for coral carpets overlap with those for reefs since they can occur in different, independent, settings

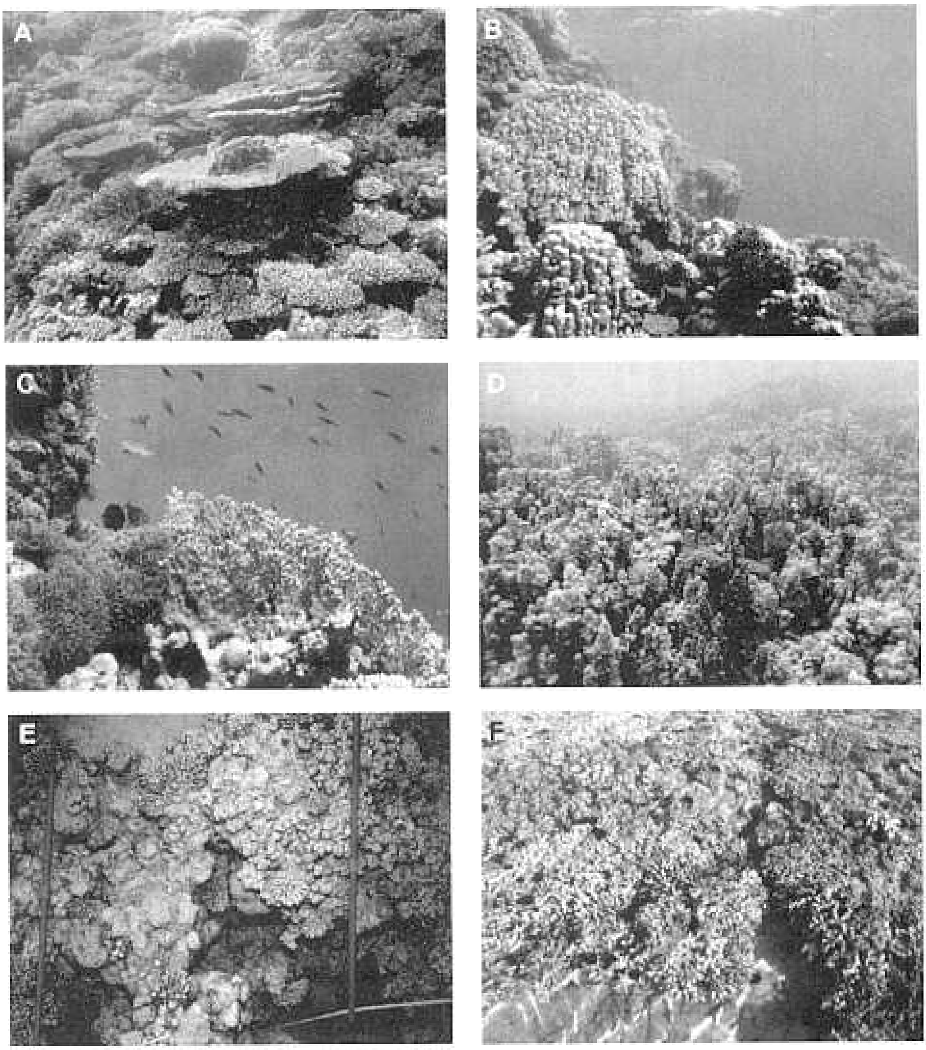

Fig. 5. Illustration of framework types in the northern Red Sea. (**A**) Windward *Acropora* reef at Tubya kebir, Safaga Bay. Species are *A. gemmifera* and *A. digitifera* on the shallowest parts, and mainly *A. polystoma* on the slope with prominent *A. hyacinthus* tables. The framework produced in areas of pure *Acropora* dominance would be a continuous superstratal rigid platestone. (**B**) Leeward *Porites* reef framework at Abu Dabab, southern Egypt. The dominant corals are *Porites lutea*. The framework produced would be a continuous superstratal rigid domestone to dense rigid pillarstone. (**C**) Semi-exposed *Millepora* reef framework at Tubya al-Hamra (Safaga Bay), 4 m depth, showing *M. dichotoma* dominance and a small *Goniastrea retiformis* in the foreground. The framework produced would be a continuous dense rigid mixstone. (**D**) *Porites* carpet framework at Gota Marsa Alam, southern Egypt, 10 m depth. Dominant corals are *P. lutea* and *P. columnaris.* The framework produced is a superstratal dense rigid pillarstone. (**E**) Faviid carpet framework at Marsa Muqebla, 15 m, Gulf of Aqaba. The dominant framebuilders are faviids (mainly *Goniastrea* spp.) with interspersed *Acropora* and *Stylophora.* The framework produced would be a superstratal rigid non-uniform mixstone. (**F**) *Stylophora* carpet framework, Abu Darag, Gulf of Suez. The framework produced would be a superstratal sparse pillarstone.

caves and gullies which were the habitat for a rich semi-cryptic to cryptic community. Visually dominant corals were *Goniastrea*, mostly *G. pectinata, G. retiformis* and *Platygyra lamellina,* as well as various *Favia, Favites, Leptastrea, Cyphastrea, Pavona, Echinopora, Acropora granulosa* and the rare *A. squarrosa.* The most frequent tabular species was *A. pharaonis* but

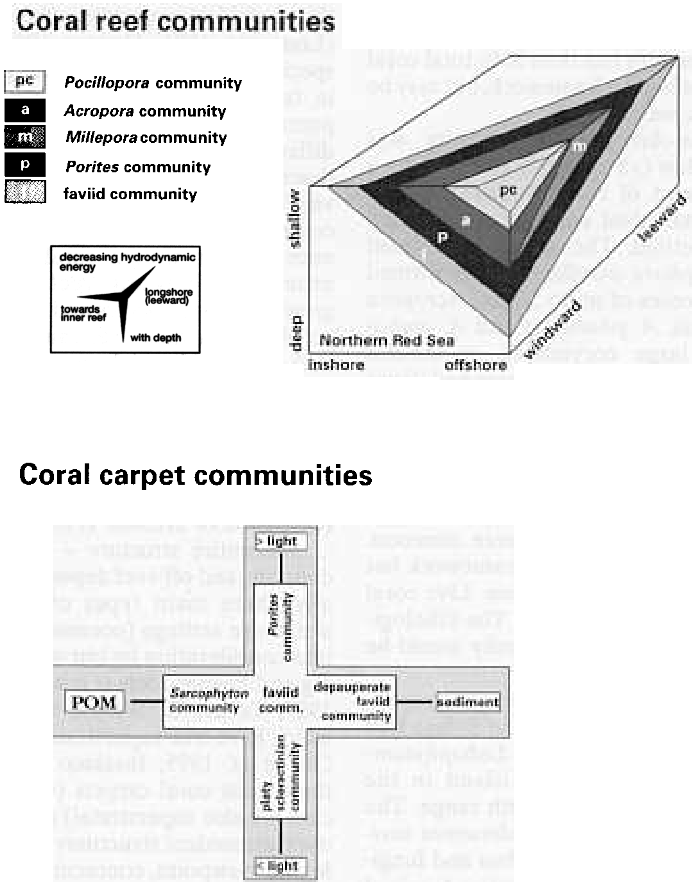

Fig. 6. Schematic representation of the distribution of northern Red Sea coral assemblages on coral reefs and carpet frameworks. Adapted from Riegl & Piller (1997).

large tabular colonies were missing. Fungiids were common. Platy corals (*Turbinaria mesenterina*, *Echinophyllia aspera*, *Mycedium elephantotus*) increased towards the lower depth limit, where they formed a specific community: the platy scleractinian assemblage of Riegl & Piller (1997, 1999). Soft corals (*Sarcophyton* and xeniids) made up an important percentage (up to 50%) of all colonies. Total live coral cover of all substrata including sand was typically between 20 and 30%. The lithological representation of the regular faviid carpet framework according to Insalaco (1998) would be a superstratal rigid non-uniform mixstone. The platy scleractinian assemblage would be a continuous to discontinuous rigid to loose (if growing on reef-base unconsolidated sediment) sheetstone. Both growth fabrics have low primary porosity.

The *Stylophora* carpet (Fig. 5F) was only found north of Ras Zafarana, in the Gulf of Suez in the nearshore area. Largely monospecific thickets consisted almost entirely of *Stylophora* cf. *pistillata* (or another yet undescribed *Stylophora*) with some individual massive corals (*Platygyra, Favia, Porites*). The alcyonacean soft coral *Litophyton* sp. was also common. The skeletons of adjacent *Stylophora* colonies fused, and the entire carpet thus formed an open, continuous framework. Framework thickness reached approximately 1 m and carpets grew to the low-water mark, becoming exposed to air at spring low tide. Coral skeletons made up the entire framework, which was very porous; frequently, however, only the colonies on the landward and seaward side were alive, while the central framework was made up almost exclusively of dead corals. The expected lithology according to Insalaco (1998) would be a sparse to dense superstratal pillarstone, which could be either loose or rigid.

Non-frameworks

Two communities with less than 30% total coral cover that did not build a framework, but may be incipient carpets, were found.

A *Stylophora–Acropora* community was observed in shallow (>5 m) sandy areas, where a substantial amount of rocky substratum was available and individual coral heads or small coral patches settled. The visually dominant coral was *Stylophora pistillata*, which formed dense bushy colonies of up to 30 cm. *Acropora robusta*, *A. tenuis*, *A. pharaonis* and *A. anthocercis* formed large corymbose or tabular colonies. The bases of these colonies had dense xeniid growth. Characteristic massive corals were *Platygyra lamellina* and *Porites lutea* and *P. solida*, which formed big microatolls of up to several metres across. Besides xeniids, the alcyoniids *Litophyton arboreum*, *Sarcophyton* spp. and *Lobophytum* cf. *venustum* were common. This community did not form a framework but consisted of widely spaced colonies. Live coral cover varied between 5 and 20%. The lithological representation of this community would be rudstone or floatstone.

The soft coral communities were *Sarcophyton*-dominated off Hurghada and in Safaga Bay between 10 and 30 m depth, and *Lobophytum*-dominated at South Queisum island in the Straits of Gubal in the same depth range. The most typical Scleractinia were *Siderastrea savignyana*, *Astraeopora myriophthalma* and fungiids. *Porites* and *Acropora* were rare. A mixed *Lobophytum/Sarcophyton* community occurred in Foul Bay between 1 and 10 m depth. Xeniids were widespread and dominated in water depths greater than 20 m. Although numerous Scleractinia occurred, they were usually small and no framework building took place in either community. Live coral cover was between 10 and 20% in the *Sarcophyton* and *Lobophytum* community and up to 60% in the xeniid community. It would be difficult to recognize this community in the fossil record since the visually dominant species in the Recent do not fossilize well. It would be recognizable at best as a shelly hardground.

Discussion

Our study shows that several types of framework and non-framework coral communities exist in the northern Red Sea in response to bottom topography and oceanographic factors (Figs. 5, 6). Several levels of feedback between environment and organisms can be inferred. Oceanographic and topographic factors shape the ecological properties of coral communities (Longman 1981; Dupraz 1999), for example species composition and successional stage. This in turn defines and controls frame-building potential since different coral communities build different frames (Figs. 4, 8), a situation also described from other reef areas (Kleypas 1996; van Woesik & Done 1997). The frameworks can create environmental conditions that can influence the constituent coral communities. For example, windward reef communities, by growing into the waves and thus creating a sheltered side in their lee, cause a differentiation into windward and leeward reef communities with concomitant differences in accretion speed (Figs. 5, 6; Smith *et al.* 1998).

Laterally, reef and coral carpet frameworks as well as non-framework communities can grade into each other within the same reef complex (definition of Henson (1950) and Ladd (1977): '. . .the entire structure – surface reef, lagoon deposits, and off-reef deposits. . .'). Conventionally, three main types of reef are found in nearshore settings (oceanic reefs are not taken into consideration by our model) – patch, fringing and barrier reefs (Geister 1983; Fagerstrom 1987; Tucker & Wright 1990; Wood 1999) – which have true superstratal frameworks (*sensu* Gili *et al.* 1995; Insalaco 1998). Additionally there exist coral carpets (which in the studied case are also superstratal) and veneers of corals over antecedent structures (Fig. 3). From a biological viewpoint, concerning the functioning of their benthos, the latter are very similar to reefs (and are frequently treated as such, especially in the biological literature). From a geological viewpoint they differ from a 'true' reef since they only cover an already existing structure without adding substantially to it.

Reef frameworks frequently, but not exclusively, develop in areas of pre-existing topographic highs, where it is easier for the reef to initiate, 'catch up' and 'keep up' (*sensu* Neumann & Macintyre 1985). This leads to the deposition of the biohermal, ecologically structured, massive, often lenticular bodies. By the process of catching up and growing to the surface, the environmental setting, most notably the light availability and hydrodynamic regime, is changed by the reef structure itself (Smith *et al.* 1998). This leads to the observed differentiation of facies (Montaggioni & Faure 1997; Webster *et al.* 1998) (Fig. 2). Once these systems are initiated, their further development is strongly dependent, among other factors, on sea-level behaviour (Hopley 1982; Tucker & Wright 1990; Schlager 1992, 1998; Pomar *et al.* 1996; Pomar & Ward 1999). When sea-level remains relatively stable, all systems will aggrade to fill accommodation space and then prograde (Schlager 1992; Pomar 1991).

Carpet frameworks operate in a more indeterminate setting: many grow too deep to reach sea level; however, some may be able to catch up in the future and some initiate in very shallow water (e.g. *Stylophora* carpet). Therefore coral carpets should not be seen *a priori* as 'give-up reefs' nor as 'incipient reefs' (van Woesik & Done 1997; Kleypas 1996), since many may not develop into reefs at all. If they grow deep, their position may be caused by delayed initiation or indeed by slower vertical accretion than reefs (due to lower light levels in deep water; Fig. 3, middle row). If sea level rises, all systems will have to aggrade in order to keep up. Once that is achieved, progradation will continue. Rising sea levels will disadvantage the coral carpets in deeper areas, since the additional water column will decrease available light and slow growth rates further. We can assume decreased vertical accretion rates, but probably maintained lateral expansion. Some coral carpets could initiate in areas that had previously been too shallow or too harsh an environment (in our model, for example, lagoonal areas between the barrier reef and the shoreline; Fig. 3, lower row). The coral veneer covering the top of an antecedent structure could also take the appearance of a coral carpet, if no or little ecological differentiation is visible laterally and vertically throughout its frame (Fig. 3). Falling sea level will cause subaerial exposure and erosion of the shallow reef areas and progradation of the reef and veneer. The coral carpets, now in shallower water, will receive more light and will therefore aggrade more quickly. Some carpets may develop into reefs if they catch up to the surface. The process of catching up and the resultant differences in environment along the structure will lead to ecological differentiation of the constituent communities resulting internally in different, ecologically distinct facies. According to our definition, the carpet will have changed into a reef (see definitions in Fig. 2). Several new carpets may be initiated in areas which were previously too deep for corals, but are now within their tolerance limits (Fig. 3, lower row).

Changing water depth does not simply cause accelerated or reduced carpet growth, but also has the potential to change the composition of the constituent coral community (Fig. 6). Carpets can develop an internal sequence of communities by two processes. Firstly, repeated changes in environment, for example by sea-level fluctuations, could lead to layers of facies dominated by different species. However, these would typically be closely related facies. In deep carpets these would be different deeper-water facies, in shallow carpets different shallow-water facies. These zonations are not ecological, resulting from environmental gradients within a continuous community, but a historical succession ('discontinuous communities') reflecting different environments. Secondly, and in clear contrast to the first possibility, by catching up to the surface a continuous ecological gradient of facies (deep to shallow) will be developed.

The carpets described here have some affinity with the incipient reefs and non-frame-building coral communities described from the southern Great Barrier Reef by van Woesik & Done (1997) and Kleypas (1996). The setting is similar but in Australia these systems were switched off (*sensu* Buddemeier & Hopley 1988) by turbidity and tidal range. The Red Sea carpets described possibly represent a similar system in a more benign environmental setting where the carpets are switched on and framework production was able to proceed. Even though frame-building activity in carpet areas may be delayed, they are areas of important carbonate production and accretion, additional to reefs. In the study area, carpet frameworks cover more space than reef frameworks and we believe that they are as important as the latter in the carbonate budget (see Fig. 4 for spatial distribution). Davies & Peerdeman (1998) describe similar systems of laterally extensive areas of coral and algal dominance forming a coral–algal rubble bank, and suggest that these form the subreef facies of the Great Barrier Reef. This facies could be interpreted as a thin coral carpet without strong framebuilding (Davies & Peerdeman 1998, figure 11) and could further demonstrate the importance of carpets in early stages of reef building. However, there is not necessarily a gradation from one system into the other, as shown by the numerous fossil biostromes that never developed into reefs; (Piller 1981; Kuss 1983; Piller *et al.* 1996; Kershaw 1994; Nose 1995; Insalaco 1996).

Coral carpets have a stronger lateral than vertical component. This gives rise to the biostromal nature and explains the absence of strong internal ecological gradients. Gradients in coral assemblages within carpet frameworks are weak and driven primarily by irradiance and sedimentation/turbidity (Fig. 6). We believe that ecological dynamics provide a stable coral community state in deeper coral carpets (*Porites* and faviid carpet) that is not conducive to rapid 'catch up'. In the study area, deep coral carpets grow in areas virtually free of disturbances (i.e. below storm wave base, no terrigenous influx,

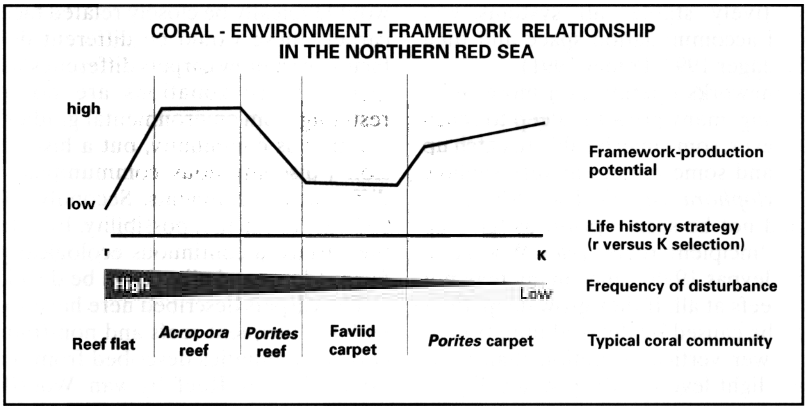

Fig. 7. Schematic relationship between biological characteristics of coral communities and coral frameworks in the northern Red Sea.

minimum sedimentation stress). Since these disturbances are major factors influencing successional stages of coral communities, their absence favours K-selected, near-climax communites (Pianka 1970; Potts *et al.* 1985; Done & Potts 1992). For example, in *Porites* carpets the dominant corals (*Porites lutea*) have a growth rate of 6.17 mm a^{-1} (Gulf of Aqaba) to 6.42 mm a^{-1} (southern Egypt; Heiss 1994, p. 79) which is about a factor of ten slower than in *Acropora* (100–200 mm a^{-1}, Heiss 1994, p. 109). However, owing to the reef's closer proximity to the surface it is subject to more frequent disturbances (e.g. hydrodynamic, temperature anomalies, UV irradiation; Done & Potts 1992; Riegl & Velimirov 1994; Riegl & Piller 1997). The assemblages of the *Acropora* reef framework are more r-selected with a higher turnover rate but also a high frame-building potential due to fast growth rates (Fig. 7). The disturbances, however, have the potential to reduce the actual frame accumulation by breakage and downslope export of skeletons subsequent to coral death (Hughes 1999; Riegl & Piller 1999). This is not the case in the generally deeper and more protected carpets, where due to the flat morphology and the high primary porosity (especially in *Porites* carpets) most produced sediment and fragments are more likely to be retained.

Table 1 and Fig. 5 show that the frameworks described here made up by specific, environmentally controlled coral communities can be described in terms of the descriptive nomenclature and classification of growth fabrics by Insalaco (1998). It should be possible to use the environmental model presented here for the development of specific growth fabrics and apply it to younger Neogene deposits for palaeoecological analyses (Perrin *et al.* 1995). Some lack of clarity remains concerning the term 'platestone' and whether the windward *Acropora* communities develop into platestones or mixstones. Kan *et al.* (1995) and Webster *et al.* (1998) illustrate cases where tabular *Acropora* communities apparently form platestones. We believe that parts of Red Sea *Acropora* reef slopes (especially the reef edges and upper reef slopes in certain wave exposure) can form platestones *sensu* Insalaco (1998). In the reefs investigated for this study, however, we are hesitant to call the entire reef slope a platestone facies.

A similar downslope sequence of domestone to pillarstone to platestone facies as observed in sheltered Recent Red Sea reefs could be interpreted based on the descriptions from the Upper Miocene reefs of Mallorca (Perrin *et al.* 1995; Pomar *et al.* 1996) where the palaeoslope is still preserved, and the Alicante-Elche basin (Calvet *et al.* 1996). Alternations of *Porites* pillarstone and faviid domestone facies are also found in Tortonian and Messinian patch reefs in southern Spain (Martin *et al.* 1989; Braga *et al.* 1990; Esteban *et al.* 1996), which, however, grew in a different environment.

The coral reef/carpet system – and the resulting growth fabrics – provide us with evidence for environment–organism–environment feedback on several hierarchical levels (Fig. 8). The central unit for our model is the coral community since it builds the carbonate framework that alters its own environment. The largest-scale factors are geological processes triggering oceanographic change (Longman 1981; James & Macintyre 1995; Insalaco 1998; Wood 1999). Plate movements, sea-level changes and changes in current patterns or sea temperature cause

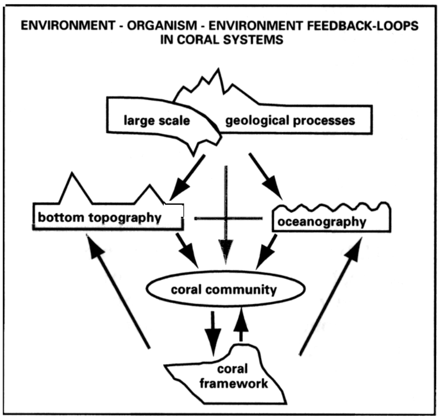

Fig. 8. Suggested interactions between geological and biological processes in coral framework production (inspired by Longman 1981).

restriction or expansion in the biota available for framework construction (Edinger & Risk 1994; Kershaw 1998) as seen in the differences between local faunas in the tropical Atlantic and Indo-Pacific (Veron 1995). Furthermore, geological processes influence bottom topography which in turn influences coral frameworks (Longman 1981; Leinfelder 1994, 1997). Our study area shows how different modes of faulting led to environments favouring different framework types. Block faulting (Roberts 1985; Purser & Bosence 1998) has led to wide shelf areas with coral carpet frameworks in the Gulf of Suez and the adjacent northern Red Sea area. Strike/slip faulting has led to steeper basin margins which favour reef growth rather than coral carpets, e.g. in the Gulf of Aqaba.

On both small and large scales, bottom topography and basin geometry influence oceanography by influencing currents and waves. Physical and chemical factors coupled with climatic influences shape coral communities (Rosen 1975; Glynn 1993; Leinfelder 1994; Perrin *et al.* 1995; Riegl & Piller 1997). The structure of the coral community is critical for the type of framework produced (van Woesik & Done 1997). Many studies show that in the Indo-Pacific, most vigorous coral growth and reef accretion are concentrated in shallow areas, particularly in *Acropora* communities (Braithwaite 1982; Montaggioni & Faure 1997; Kan *et al.* 1995; Webster *et al.* 1998). These are the typical reef framework 'catch-up' and 'keep-up' settings where accretion is limited by accommodation space. In addition to this, our study shows that significant framework accretion potential also exists in shallow shelf areas (10–40 m depth in the study area). There, coral carpet frameworks are produced which in most areas do not catch up, or have not yet caught up, to sea level.

Conclusion

- Coral framework initiation and growth is governed by oceanography and bottom topography.
- Two different coral framework types exist in the study area – coral reefs and coral carpets – which are built by different coral communities.
- Coral reefs and all coral carpets described here (faviid carpet and *Porites* carpet) are superstratal.
- Growth fabrics are: platestone to mixstone facies (windward *Acropora* community); mixstone facies (semi-exposed *Millepora* facies and faviid carpet); domestone facies (leeward *Porites* community); pillarstone facies (*Porits* carpet, *Stylophora* carpet).
- In the northern Red Sea, reefs grow on steep slopes and highs, coral carpets in areas with little topographic differentiation.
- Coral community successional stage and life history attributes differ between reefs and carpet. The highest growth potential is on shallow reefs where coral communities are fast growing, r-selected and have a high turnover. Coral carpets are slow-growing, K-selected systems.
- Reefs grow towards the surface and thus modify their own environment (light availability, hydrodynamic exposure) which feeds back into their coral communities (windward–leeward, reef edge–reef slope). Coral carpets grow mainly laterally in deeper water and interfere much less with their environment. They build a highly structured hard substratum that increases settlement space and has a high sediment retention potential.

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