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Holocene Reef Growth and Recent Carbonate Production in the Red Sea

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Area of Study: Northern Red Sea
Environment: Shallow-water coral reefs
Stratigraphy: Holocene
Organisms: Scleractinians
Depositional Setting: Reef crest, forereef
Constructive Processes: Coralgal framework
Destructive Processes: Macro-bioerosion
Preservation: superb
Research Topic: Reef growth, carbonate production, bioerosion

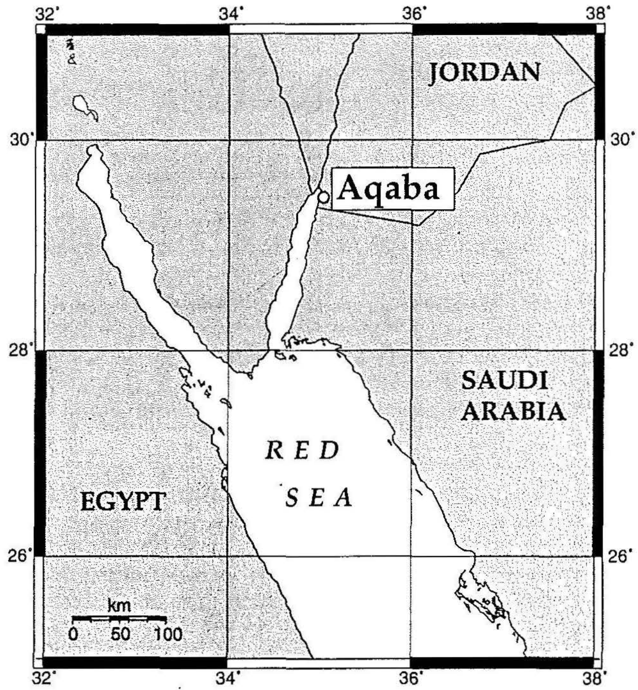

Fig. 1: Map of the northern Red Sea.

Abstract

Holocene reef growth, present date bioerosion and recorded carbonate production were studied in the fringing reef at Aqaba, Red Sea. Water depth, wave impact as well as nutrient availability were considered.

The carbonate production was measured for several coral samples. Samples of *Porites*-colonies were collected from several depths and sites near the Marine Science Station at Aqaba. Growth rate depends on water depth, size and age of colonies. Within the coral optimum of water depth growth rates vary between 5 and 16 mm/yr. Coral carbonate production was calculated on the base of annual growth increments and skeletal density using transects from shallow subtidal down to 40 m water depth. High resolution stable isotope data were measured to prove the origin of growth increments. Long-term trends of sea surface temperature and carbon isotope shift (1800-today) fit to the known global deviations.

Bioerosion rates were determined using standard dead coral substrates exposed in different water depths and environmental settings. Rates vary between 0.6 and 1.4 kg/m^{2}yr. Sediment export evaluated by means of simple sediment traps ranges between 0.3 and 0.7 kg/m^{2}yr.

Gross carbonate production, mainly built up by scleractinian corals, amounts to ca. 1.57 kg/m^{2}yr. Bioerosion alters approx. 1.3 kg/m^{2}yr of hard substrates into sediment. Sediment export is estimated to be ca. 0.4-0.6 kg/m^{2}yr. Thus a net production of ca. 0.7 to 0.9 kg/m^{2}yr should remain in the present reef, which is proved by the recorded carbonate production (reef drillings). Net production preserved in the reef can be given with ca. 800 kg/m^{2}kyr (=0.8 kg/m^{2}yr).

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1 Introduction

The main objective of the present study was the qualitative and quantitative evaluation of present day processes governing recent carbonate production of a fringing reef and to compare these results with Holocene reef accretion.

The recent fringing reef off the Marine Science Station (MSS) at Aqaba, Jordan (29°27' N) was chosen as it has been topic of several investigations (SCHUHMACHER et al. 1995 cum lit).

Stony corals are the main producers of carbonate in these reefs. Growth rates, density and calcification rates of *Porites* were investigated in order to establish calculations of gross carbonate production for the reefs in this area (HEISS 1995). The loss of biogenically produced carbonate from the reef system was estimated by quantification of bioerosion of carbonate substrate and investigations on sediment export out of the reef. These three main aspects: Production, destruction and export of biogenic carbonate in the recent fringing reef of Aqaba were the basis of our carbonate budget for this region.

The carbonate production of the recent reef was then compared to the vertical Holocene reef accretion. This comparison of recent processes and carbonate budget of a recent reef with the Holocene reef are unique to this area and present insight into the fossilization potential of reef carbonate.

A further objective of the present study was to compare bioerosion and bioaccretion of the fringing reefs of Aqaba with two sites off Zabargad Island, Central Red Sea (23°36' N, 36°12' E).

2 Materials and Methods

2.1 Recent Carbonate Production

The carbonate production of the fringing reef at Aqaba was measured for several coral samples. Samples of *Porites*-colonies were collected from several depths and sites near the Marine Science Station at Aqaba.

The annual growth rates of these colonies as well as of cores of larger colonies were measured from X-radiographs which were taken of 3-5 mm slices (Fig. 2). Gross production by scleractinian corals is calculated from potential productivity and coral coverage.

Long term trends in growth rates as well as growth patterns were measured in cores from large *Porites*-colonies. We recovered a vertical and a horizontal core (cores 18 and 19) of 320 cm length of a colony (colony A) in the fore-reef of Aqaba (HEISS et al. 1993). These two cores met each other at the base of the colony, close to the area where the colony started to grow ca. 210 years ago. Another core was drilled from a colony in the vicinity of colony A, which reached the base of the coral at an age of ca. 150 years.

Subannual stable isotope samples of these long cores were drilled using a computer-controlled drilling device in a distance of 1 mm using a 0.5 mm dental drill along the maximum growth axis (Fig. 2).

2.2 Recent Bioerosion

The bioerosion of dead coral substrates due to grazing and boring and the bioaccretion on the same substrates was determined by experimental studies. Three sites were compared: Aqaba and two sites off Zabargad Island, Central Red Sea, a sheltered site to the SE of the island and an exposed site to the north.

Uniform blocks of freshly sampled and cleaned coral substrates (*Porites*) were mounted on plastic tubes (Fig. 3) (KIENE 1988). These tubes were installed at 5 m, 15 m, 25 m and 40 m at all sites. Samples were collected after one year and two years of exposure. Accreting organisms were described, counted and measured after the first year of exposure. Subsequently the samples were cleared of organic matter, dried and weighed. The rate of bioerosion was calculated as the weight difference of the substrates between submersion and recovery projected to 1 m^2 of dead surface.

2.3 Recent Sediment Export

Sediment export was investigated at 4 sites. The locations at the Marine Science Station (MSS) and Osama's Reef (OR) both represent Wadi-influenced reef-systems, while the Touristic Camp sites (TC- North and South) can be seen as a carbonate system with only restricted, wind-driven terrigenous input. The sediment export from the reef to the basin occurs mainly through channels. Several simple sediment traps were installed in these channels at different depths (7.5 to 39 m). The sediment collected by the traps was retrieved after several time intervals to estimate the rate of carbonate export.

2.4 Recent Carbonate Budget

The carbonate budget of the recent reef at Aqaba was calculated using the gross production rates of scleractinian coral, the rates of bioerosion and the estimated rates of sediment export.

Using the results obtained from vertical and horizontal reef transects at various depths the carbonate production was calculated to 1 m^2 of reef.

2.5 Holocene Reef Growth

In order to determine the vertical accretion rate of the Aqaba fringing reef in the Holocene we drilled several cores along a transect into the reef body. The outermost core was drilled into the 'outer pillar' (MERGNER & SCHUHMACHER 1974) and reached the sediment underneath this reef pillar in a depth of 5 m.

The material consists of parts of massive (*Porites*, *Montipora*) and branching (*Acropora*) corals, coral rubble encrusted by calcareous algae, and coarse carbonate sediment. Several samples of massive corals were dated using U/Th-TIMS method.

3 Results

3.1 Recent Carbonate Production

Carbonate production of small *Porites*-colonies decreases linearly with depth as a function of decreasing growth rates and increasing skeletal density. Calcification rate of *Porites* is highest in shallow water (0-5 m depth) with 0.94 g/cm^2yr and decreases to 0.49 g/cm^2yr below 30 m. Maximum coral gross production at Aqaba occurs at the reef crest (0.29 g/cm^2yr) and in the middle fore reef from 10 to 15 m water depth (0.21 to 0.27 g/cm^2yr). Production is low in sandy reef parts. Below 30 m depth values are still at 0.14 g/cm^2yr.

Growth Rates

Individual growth rates of the genus *Porites* show high variations even in colonies growing close to each other. Core samples of *Porites* in the northern Gulf of Aqaba furthermore revealed large variations in the growth rate of this genus over the last 20 years (HEISS in press). A general increase in linear extension rate was observed for several cores from a relatively healthy reef area at a depth range from 1 m to 15 m. In contrast a *Porites*-core taken from a colony growing in the vicinity of the phosphate loading berth at Aqaba demonstrated a drastic decrease in growth rate over the same time range.

Growth rates of a large *Porites* -colony (colony A) vary between 8.60 and 12.52 mm/yr. The average linear extension rates show strong oscillations and a general increase since 1880 could be observed. The comparison between a horizontal and a vertical core of this colony reveals strong similarity of extension rates during some periods (1810-1840, 1880-today), while in other periods (e.g. 1840-1880) the extension rates differ significantly. The comparison of the vertical cores of colony A with another colony situated 200 m farther south shows stronger similarities in growth rates than does the comparison of the horizontal and vertical core of colony A. Changes in extension rates of the two colonies occur simultaneously and are of the same range.

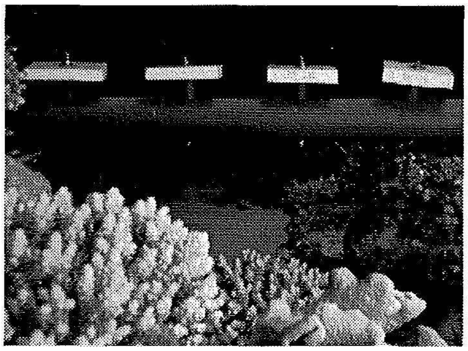

Fig. 3: Experimental setup of dead coral substrates on plastic tube at 5 m water depth.

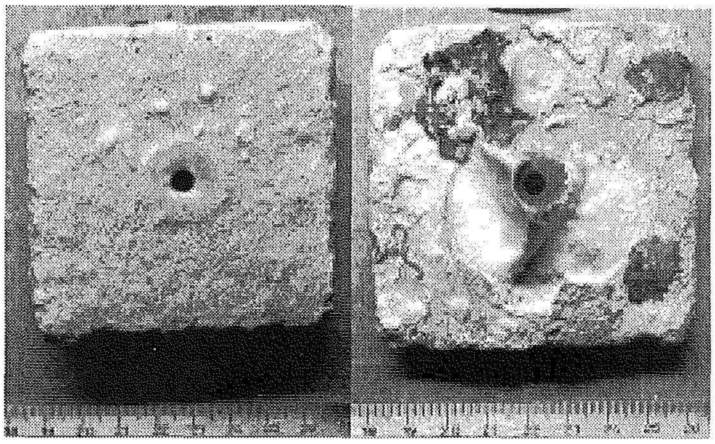

Fig. 4: Photograph of a sample from Aqaba 40 m depth (tube 16, no. 5) after 2 yrs of submersion. Note the traces of grazing on the edges of the top side (left) and the encrusting serpulids and bivalves on the bottom side (right) of the sample.

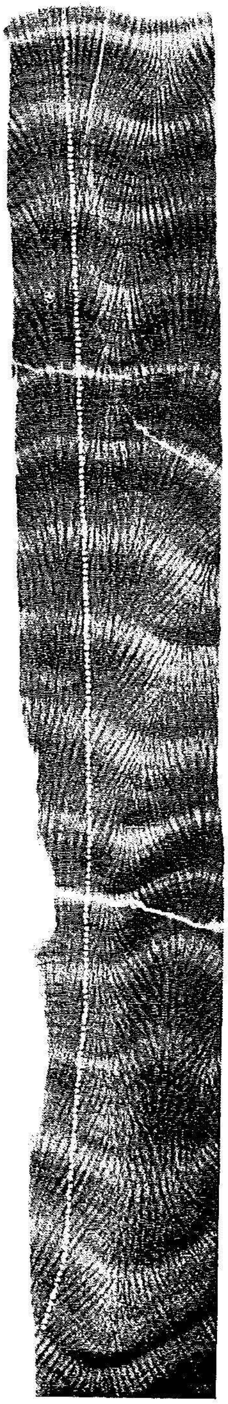

Fig. 2: X-Radiography of the upper part of horizontal core 19 (colony A) with drill holes for high resolution sampling. Annual density banding is clearly developed.

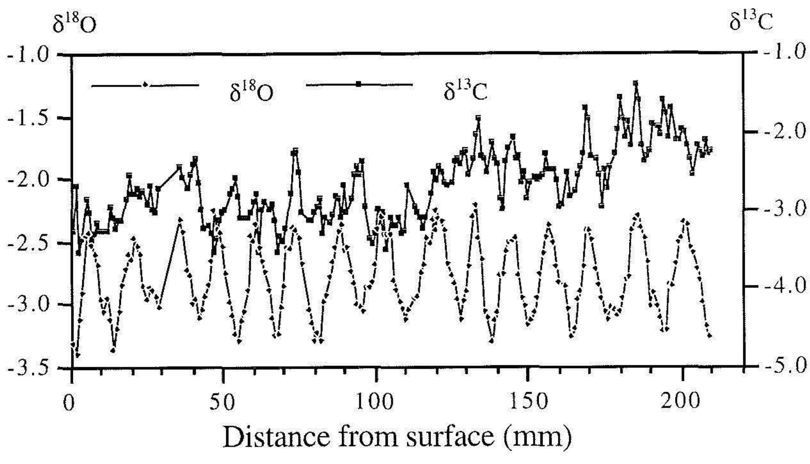

Fig. 5: Stable oxygen and carbon isotope values for core 19. Seasonal variation of $\delta^{18}O$ reflects temperature changes. $\delta^{13}C$ decreases to lighter values and seasonality is less clear.

Carbon and Oxygen Isotopes

The analysis of carbon and oxygen isotope samples taken from the vertical and the horizontal core of colony A reveals different patterns over time (HEISS 1994, HEISS et al. subm.).

The annual isotope values of $\delta^{18}O$ decrease in both cores at a more or less constant rate from the end of the 17^{th} century until today. There is no significant difference between the record of the horizontal and the vertical core. The observed decrease in $\delta^{18}O$ of about 0.4‰ indicates a warming of sea water temperature by ca. 2°C, if this shift is related to be the main mechanism for oxygen fractionation.

The carbon isotope composition records a strong excursion to negative values from 1960.

Site	Marine Science Station (MSS)	Osama's Reef (OR)	Touristic Camp-N (TC-N)	Touristic Camp-S (TC-S)
kg/m^{2}yr	0.3 – 0.5	0.4 – 0.6	0.4 – 0.6	0.4 – 0.7

Tab. 1: Annual carbonate sediment export for different sites at the Jordanian Red Sea coast.

High Resolution Isotope Analysis

Using high resolution isotope analysis the seasonal variability of the signals of stable carbon and oxygen isotopes was studied in selected parts of cores 18 and 19 from colony A (Fig. 5).

The high sampling resolution of ca. 10-12 samples per year allowed the determination of the monthly variation of $\delta^{18}O$ (temperature indicator). The $\delta^{18}O$ variation clearly reflects the seasonal variation of sea surface temperatures (SST). Density of the skeleton is highest shortly after time of the lowest SST (usually in September). The annual nature of the density banding as well as a strong coupling of skeletal density to seasonal environmental variations could be confirmed from the isotope profiles.

3.2 Recent Bioerosion

The first striking feature was the significant difference between the top and the bottom sides of the substrates (Fig. 4) where the top sides showed signs of bioerosion due to grazing and boring whereas the bottom sides were colonized by carbonate producing as well as non-carbonate producing organisms. This difference was particularly pronounced in Aqaba where high accretion rates of carbonate building organisms (serpulids, bryozoans, bivalves and others) were found on the bottom sides of the samples. The amount of accretion by these suspension feeders increased significantly with depth. At 40 m water depth accretion by carbonate producers in fact outweighed the effects of bioerosion. These suspension feeders were rare or missing in the Zabargad samples.

The quantitative results found at Aqaba were similar to those found at Zabargad SE, with maximum bioerosion rates at 15 m and 25 m (-0.6 kg/m^{2}yr) after one year of submersion. The highest bioerosion rates of all sites were found at Zabargad N at 5 m water depth (-1.4 kg/m^{2}yr), decreasing rapidly with depth. At 40 m water depth bioerosion was negligible at both Zabargad sites, while at Aqaba the substrates showed a slight weight increase.

In order to estimate the bioerosion rate of the coral reef at Aqaba these rates were corrected for surface roughness and percent of dead surface area in the reef using line (LOYA 1972) and chain transects (HUBBARD et al. 1981). After the first year of exposure the maximum bioerosion rate at Aqaba amounted to -1.4 kg/m^{2}yr for the reef at 25 m.

After the second year of submersion the above mentioned relationships between sites and water depth with regard to bioerosion and bioaccretion were more pronounced. The bioerosion rates increased at all sites. The bioerosion was between 2 and 3 times as high as for the first year of exposure.

3.3 Recent Sediment Export

The slope of the sediment surface close to the traps is between 8° and 36°. Mud-supported as well as grain-supported sediments are deposited, with 36° the critical value for slope stability is already passed (KENTER 1990). The amount of sediment transport differs between the 4 sites. MSS and OR are influenced by strong terrigenous input, TC-N is intermediate and TC-S a carbonate system. From the first sampling the carbonate sediment export (corrected for the siliciclastic input) for the sites is given in Tab. 1.

3.4 Recent Carbonate Budget

From the data gathered in this project a first carbonate budget can be established for the fringing reef at Aqaba. Gross carbonate production, mainly built up by scleractinian corals, amounts to ca. 1.57 kg/m^{2}yr (HEISS 1994). Bioerosion alters approx. 1.3 kg/m^{2}yr of hard substrates into sediment. Sediment export is estimated to be ca. 0.4-0.6 kg/m^{2}yr. Thus a net production of ca. 0.7 to 0.9 kg/m^{2}yr should remain in the present reef.

3.5 Holocene Reef Growth and Recorded Carbonate Production

The maximum age measured at a core depth of 3.5 m was 5,000 (±600) years. Calculating from this age the vertical accretion rate is 0.67 m/kyr for the last 5 kyr. The period from 5 kyr to 3 kyr BP had a slower accretion rate, and is 4.45 m/kyr in the youngest part.

A first estimate for the net production preserved in the reef can be given with ca. 800 kg/m^{2}kyr (average density for the carbonate: 2 g/cm^3; recovery 60 %, vertical accretion 0.67 m/kyr).

4 Discussion and Conclusion

4.1 Recent Carbonate Production

Mean potential carbonate production of colonies and gross carbonate production of the whole coral community at Aqaba was lower than in tropical reefs (HEISS 1995). However, carbonate production is higher than in reef areas at the same latitude in the Pacific, thus indicating a northward shift of reef productivity in the Red Sea.

Coral growth rates of the genus *Porites* in the northern Gulf of Aqaba are unexpectedly high for reefs at this latitude and seem to be enhanced by increase of water temperatures. For the last two centuries the major changes in growth rates in colony A are generally parallel in the horizontal and the vertical core, especially severe events are documented in the growth rates of both cores. A good example is the dramatic decrease of growth in the 1960s and the following acceleration to maximum values. A reduction in terrestrial sediment influx is the most likely reason for an accelerated growth (HEISS et al. 1993).

From these results we can conclude that cores from single colonies reflect regional variations in growth rates of scleractinian corals. Long-term trends of environmental influences result in similar changes of extension rates in different colonies. However, local or short-termed influences are not necessarily recorded in all corals of a specific area.

4.2 Recent Bioerosion

The comparison between top and bottom sides of the recovered substrates clearly demonstrates that bioaccretion as well as bioerosion strongly depend on habitat. Generally traces of grazing were prominent on the top sides. The settlement of organisms on exposed substrates is believed to be governed by grazing (SCHUHMACHER 1988). Accretion was only high on the bottom sides of the substrates which were protected against continuous abrading by scarids and echinoderms.

The increase in bioerosion rate after the first year of exposure is most probably due to the adaptation of the substrates as „microhabitats" to the environment. Right after submersion the microenvironment on the samples was extremely artificial, as carbonate surfaces clear of any living organisms do not occur in that form in nature. During the first months, as the substrates were colonized by a succession of microscopic and macroscopic organisms (SCHUHMACHER 1977), the situation became more and more 'natural'. So that we can assume that the higher rates after the second year represent the natural situation more closely than the results obtained after the first year of exposure.

In contrast to the rates at Zabargad N, the similar rates of bioerosion found at Aqaba and Zabargad SE might be due to the impact of wave energy (RIEDL 1964). The latter sites both represent sheltered reefs, whereas the former is exposed to the impact of the predominantly northerly winds and waves.

High accretion rates of suspension feeding animals at Aqaba indicate higher nutrient concentrations at Aqaba than at Zabargad (HALLOCK 1988).

The results of both years confirm our original interpretations. The differences between the sites can not be attributed to latitude, but are overprinted by factors such as were due to local environmental factors (HASSAN & DULLO 1995) such as nutrient availability and energy regime. The interaction between such factors determines both bioerosion and bioaccretion and does not only influence the carbonate budget quantitatively but govern the modification of the substrate as well.

4.3 Recent Carbonate Budget and Holocene Reef Accretion

The net production of ca. 0.7 to 0.9 kg/m^2yr measured for the present reef is in good agreement with the Holocene net production which has been determined from the core data to be ca. 800 kg/m^2ky. The reef at St. Croix in the Caribbean, That was studied using similar methods (HUBBARD et al. 1986, 1990), showed accretion rates of 900 kg/m^2yr. Considering that Aqaba lies 12° farther to the north values of net production are remarkably high. These results confirm the finding that the reefs at Aqaba do not mark the northernmost ecophysiological outpost of the Indian Ocean. Reefs would occur at even higher latitudes, if the Gulf extended farther north (SCHUHMACHER & MERGNER 1985).

The results of investigations conducted on recent reefs using various methods can in fact be compared to the geological past and provide insight into the controlling factors and mechanisms of reef accretion.

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