Coral Reefs (1986) 5:127–150

Coral Reefs

© Springer-Verlag 1986

The modern reef complex, Jeddah area, Red Sea: a facies model for carbonate sedimentation on embryonic passive margins

L. F. Montaggioni[1], A. K. A. Behairy[2], M. K. El-Sayed[2] and N. Yusuf[2]

[1] Laboratoire de Géologie, Université Française de l'Océan Indien, BP 5, F-97490 Sainte-Clotilde, France D.O.M., and Mission Océanographique Française au Moyen Orient, Université de Nice, Parc Valrose, F-06034 Nice Cedex, France
[2] Faculty of Marine Sciences, King Abdulaziz University, P.O. Box 1540, Jeddah, Saudi Arabia

Accepted 19 August 1986

Abstract. The modern reef complex north of Jeddah comprises an offshore knoll platform and a fringing reef, subdivised into several depositional zones: tops and upper flanks of offshore reefs; lower flanks of offshore reefs and nearby inter-reef areas; fringing forereef, reef flat and backreef zones, and beach. Sixty-seven sediment samples were collected from the different zones and have been analysed in order to define relationships between the distribution of sedimentary facies and the depositional environments, and to furnish a reliable facies model by using multivariate analysis. Six types and subtypes have been objectively differentiated on the basis of total biogenic component and foraminiferal associations. Grain size data allowed us to discriminate three textural types, whereas five chemotypes have been recognized according to trace element concentration. Regarding the offshore reef platform, poorly sorted, medium sands of molluscan-coralline algal-*Amphistegina* and Cd types are restricted to the lower flanks of buildups and to the adjacent inter-reef deposits, whereas the tops and upper flanks of theses buildups are characterized by moderately sorted, coarse sands of coralline algal-*Tubipora*-*Amphistegina*-encrusting foraminiferal-bryozoan types, with a Mn chemotype. Concerning the fringing reef system, backreef areas exhibit poorly sorted, fine sands of molluscan-*Ammonia*-*Peneroplis* and Fe–Cu types. Moderately sorted, coarse sands of coralgal-*Calcarina*-*Spiroloculina* and Fe–Zn types are found on the reef flat. The forereef zone is characterized by poorly sorted, fine sand of *Triloculina*-encrusting foraminiferal-bryozoan and Zn–Mn types. The lateral limits of the various biotypes roughly coincide with the distribution of the relevant living organic communities. Trace elements appear to be either bound to the reef-associated silicate fractions or incorporated into the carbonate skeletons. On the basis of prevailing water conditions, physiography, biological and sedimentological attributes, the fringing reef can be regarded as an asymmetrical structure, with bidimensional (lateral and vertical) facies zonation; in contrast, the offshore platform is a symmetrical structure, with one dimensional (depth-dependent) facies zonation. This system is believed to represent a modern example of a laterally undifferentiated, offshore reef tract in a relatively enclosed basin, at an embryonic passive continental margin.

Introduction

A great deal of attention has been devoted for years to interpret the facies and environmental reconstructions of reef complexes in both the modern and fossil record (see Laporte 1974; Toomey 1981; James 1983). However, as emphasized by Longman (1981), the general tendency to regard all reefs as having similar shapes and facies distribution has caused confusion in interpreting paleoenvironments in ancient reefs. Adequate comparison of reef facies requires a better knowledge of morphological reef types. Most modern reefs are wave-related structures, best developed on the windward sides of shelves and associated with significant lateral water energy gradients. They belong to widely open water, asymmetrically reef-rimmed platforms (in the sense of Ginsburg and James 1974), i.e. forming continuous or semi-continuous reef rims around or along outer shelf margins. In contrast, relatively symmetrical structures (such as banks, knoll and patch reef platforms) which grow in relatively enclosed, laterally undifferentiated energy areas, are rare in the modern ocean (e.g. Arabian Gulf) and, therefore, are poorly documented, while analogues seem to have been common in geological times (Wilson 1975; Toomey 1981). The latter are recorded from ancient epicontinental, shallow marine provinces, some of them considered to be oceans in the making.

Recent investigations carried out on the reef complex of Jeddah area (Red Sea) furnished an opportunity to illustrate the relationships between physiological and depositional environments and sedimentary facies distributions which exist in a modern, relatively sheltered, offshore knoll reef system. The data so obtained were compared with those from an adjacent fringing reef system. The present paper describes the various sedimentary types which were discriminated on the basis of several independent parameters (i.e. skeletal components, foraminiferal types and assemblages, trace element concentrations, grain size distributions). Such a description provides a basis for the definition of a facies model and its interpretation with respect to benthic community distribution, trace element source and energy conditions. Multivariate analysis was used to assess the degree to which the sedimentary parameters taken into account reflect the relevant depositional environments.

Environmental setting

Regional geology

The Red Sea, which is regarded as an embryonic ocean, forms an elongated rift stretching for over 1,800 km. It took on its present-day configuration as a result of Late Tertiary and Holocene tectonic activity (El Sharzy 1983).

The study area is located at lat. 21°35′–22°00′ N and long. 38°50′–39°10′ E, and is 30 to 60 km North of Jeddah (Fig. 1). As a part of the eastern Red Sea shelf region, this area consists lithologically of a Precambrian plutonic and metamorphic basement. The metavolcanic rocks outcrop only sporadically in the northern part of the area under study. Vast zones in the North and North-East have been

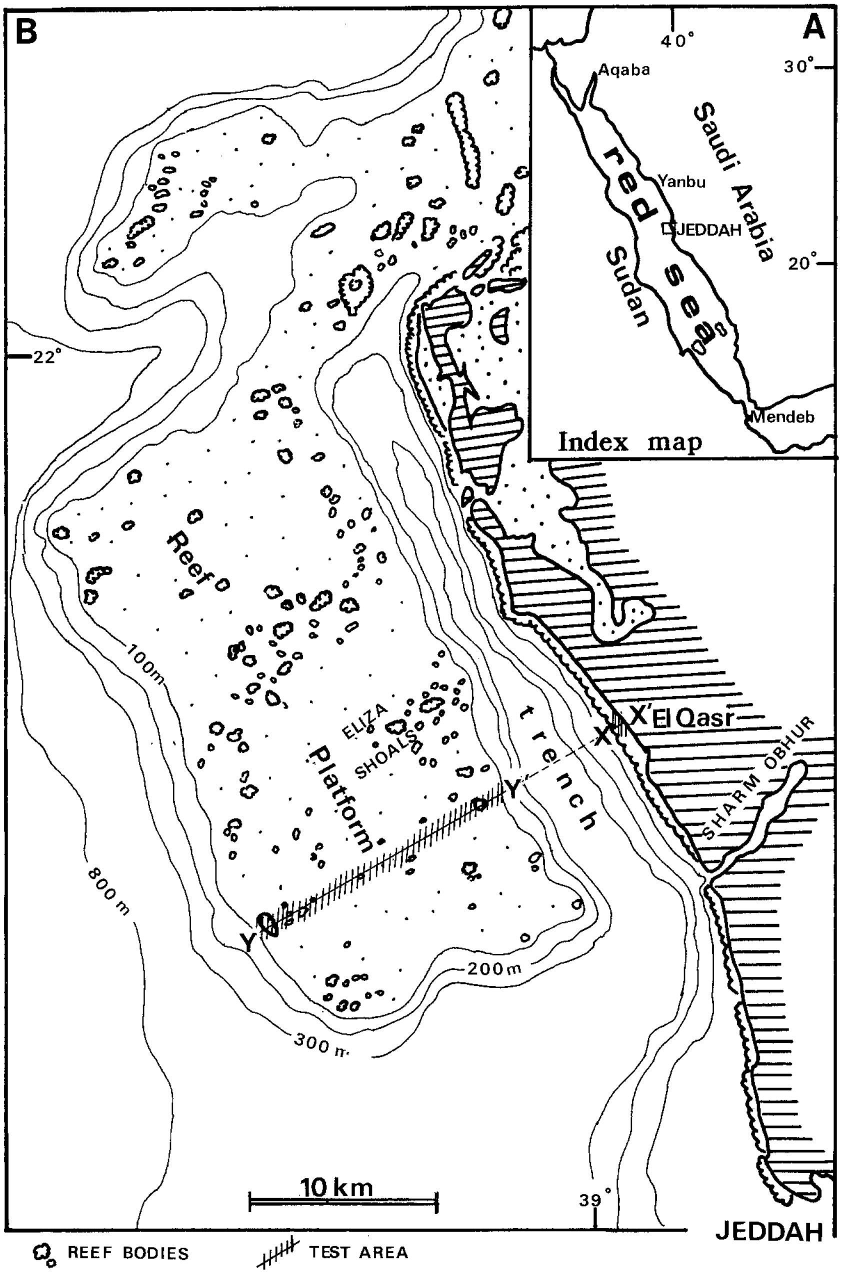


Fig. 1. **A** Map of the Red Sea showing the location of the Jeddah reef area;
B General physiography of the reef complex North of Jeddah and location of the test area. Lines of cross-section X–X′ and Y–Y′ are shown in Fig. 2

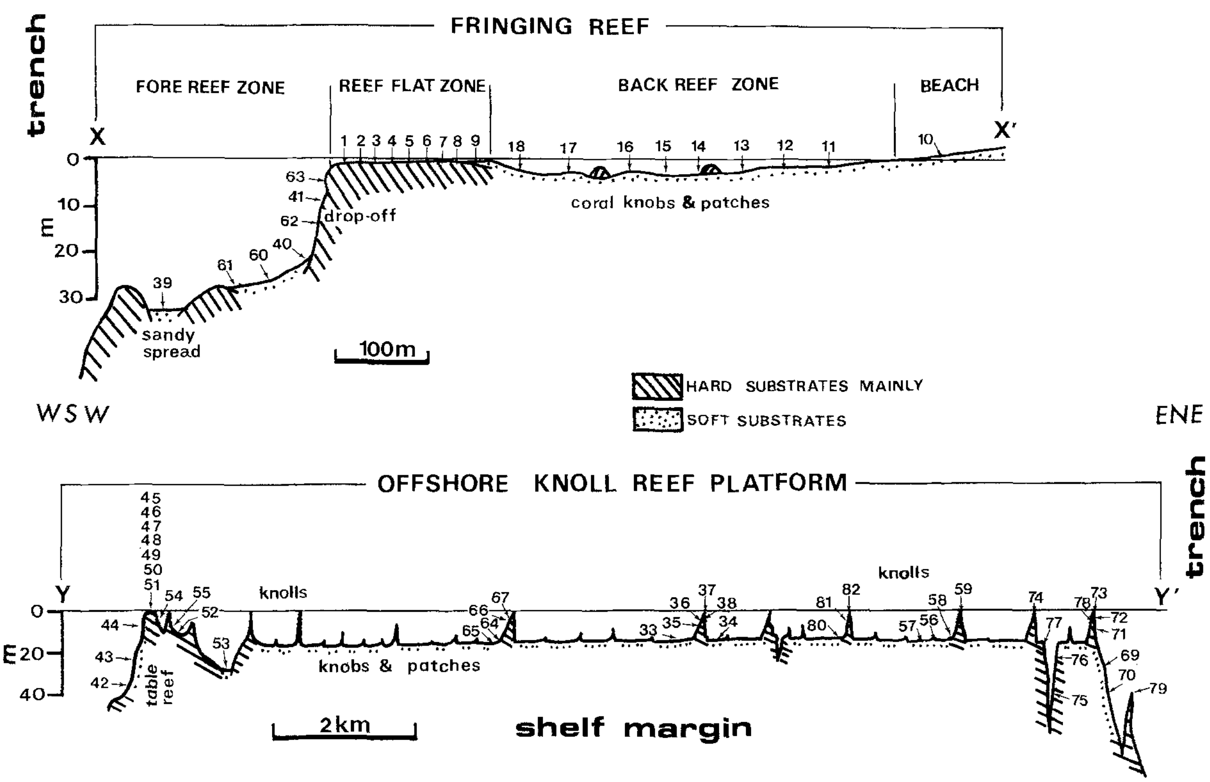


Fig. 2. Schematic profiles of the test area and sample locations. The sea bed profiles (X–X′ and Y–Y′ of Fig. 1) are based partly on echosounding recordings, SCUBA diving observation and chart data. Numbered arrows indicate identification number and location of the sediment samples collected in the test area

overflowed by basaltic lavas which lie discordantly on the Precambrian strata and Cenozoic deposits. The latter, ranging in age from Maestrichtian to Lower Miocene, form a thin strip of both marine and non-marine sequences along the coastal plain. Quaternary strata are found in the form of bedded series which from the base upward include the following: red or green siltstones and gypsiferous formations, reefal limestones, clay-rich conglomerates and basalts (Skipwith 1973; Behairy 1980; Jado and Zötl 1984).

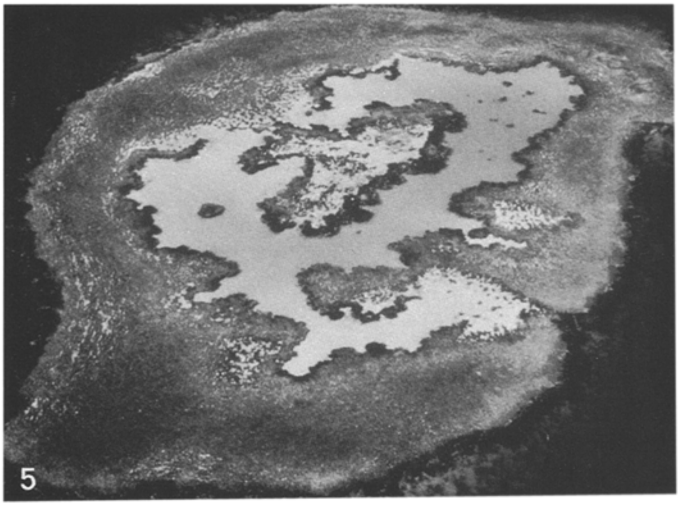
In the vicinity of Jeddah and along the major part of the Saudi Arabian western coasts, coral reefs occur as two morphologically distinct systems: the fringing reef and the offshore reef platform (Fig. 2). The former constitutes an almost continuous belt along the shore and possesses wide backreef zones from place to place. About 3 km offshore, the marginal shelf area under study consists of a shallow (average depth: 20 metres) and regular platform, covering a surface area of 800 square km, bound seaward as well as shoreward by near-vertical escarpments marking the edge of the Red Sea trough; attention has been drawn to the steep, ocean-facing topography with rapid drops to depths of 400–800 m (Behairy and El-Sayed 1983). These lines of evidence suggest that the offshore platform, along with the main coastal alignments and the coast-paralleling trench deeper than 350 m, have been defined by large-scale faults (Guilcher 1955, 1982; Coleman 1977). The platform is occupied by a system of scattered coral-built bodies (Figs. 3–5), rising from inter-reefal sandy bottoms. Four reef body types as different stages of an evolutionary morphogenetic model can be identified: inframetre-sized, anastomosed coral knobs; isolated, submerged, metric to decametric coral patches; isolated decametric to pluridecametric knolls; crescentic to elongate, hectometric to plurihectometric table reefs (Montaggioni and Bouchon 1984). A clear lateral physiographical zonation is lacking: the various reef body types are similarly developed along both the seaward and landward portions of the platform. Seismic and drilling data reported by Berry et al. (1966) from the nearby Sudanese reef platforms indicate that the modern Central Red Sea reefs are plastered onto the surfaces of Pleistocene reef limestones that are about 200 m thick which, in turn, lie on the eroded surface of a Tertiary marine series. The total thickness of Holocene reef growth is uncertain (Braithwaite 1982).

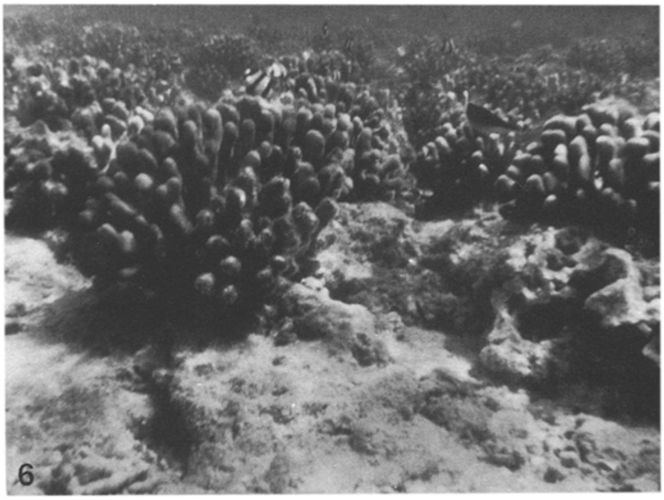
Prevailing physical conditions

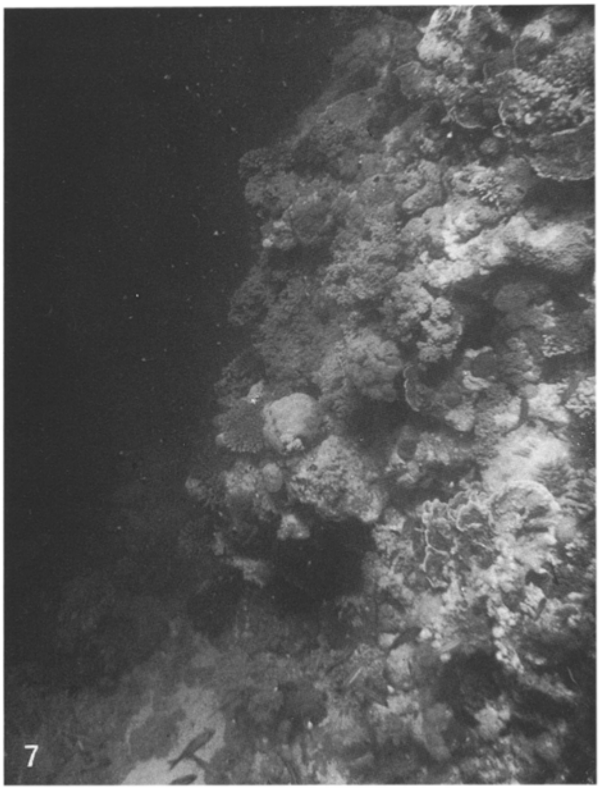
The climate around Jeddah is arid and hot. The annual rainfall amounts to some 50 mm on average. Hot storm winds blow from South and East may be followed by thunderstorms with local flooding (Jado and Zötl 1984). The prevailing winds are frequently North-Northwest, but this direction is reversed towards the NNE in winter. Moreover, Behairy et al. (1981) estimated evaporation from the open sea at Jeddah coast is between 1,450 and 2,200 mm per year. Lack of rainfall, very limited fresh


3

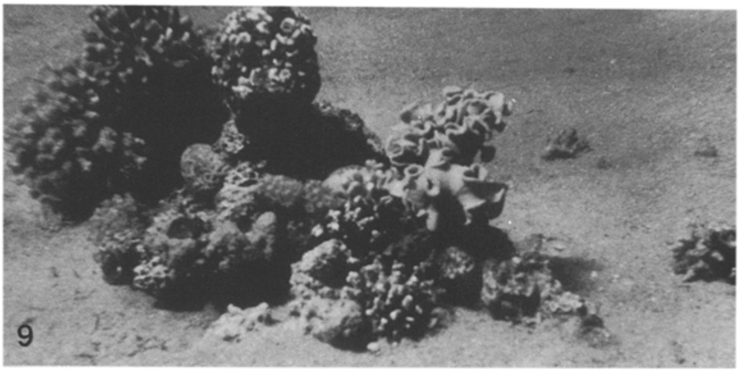

4


5


6


7


8


9

water in-flux due to the absence of rivers and excess in evaporation result in high salinity of the waters with very little seasonal variations. The surface salinities vary from 39‰ to more than 40‰ (Behairy and Jaubert 1983). The sea surface temperature in June averages 31.5 °C and falls to 26.5 °C in January. The tidal range is normally around 0.30 m. Moreover, seiches of meteorological origin may frequently lower the water level and thus restrain coral growth (Guilcher 1982). The water column from the offshore reef platform is well oxygenated; according to Behairy and Jaubert (1983), dissolved oxygen concentration here reaches 4.6 to 5.6 mg per litre during March-April, while the values measured in the fringing back reef zone are lower (4.3–4.7 mg/l). In fact, there is no long-term stagnation in the innermost parts of the fringing reef, where there is an irregular inflow of oxygenated water. High turbidity in the fringing reef area is indicated by Secchi disc readings ranging from 1.7 to 2.3 m deep. In contrast, the open sea water has a relatively high transparency (Secchi disc values: 14 to 25 m deep).

The main surface water currents are to the North West from the Indian Ocean through the straits of Mandeb. The circulation pattern is completed by the more saline subsurface waters which flow back from the North at a depth of 150–200 m and out over the sill at Mandeb.

Zonation of depositional environments

Based on physiographical and biological criteria, the reef complex under survey can be divided into the following zones (biological data from Colantoni and Taviani 1982; Behairy and Jaubert 1983).

(1) The offshore reef bodies. The tops of the still-stand reef bodies consist of poorly zoned reef flats (Figs. 4 and 5), mainly occurring as a dead organic pavement with scattered coral colonies. The coral community of the innermost part is dominated by *Stylophora pistillata* (Fig. 6). Seawards, the assemblages become gradually more diversified with the occurrence of *Pocillopora*, *Porites*, *Cyphastrea*, *Goniastrea*, *Platygyra*, *Acropora*, *Millepora* and the octocorallian *Tubipora musica*. Coralline algae are represented by masive branching and crustose forms *(Lithothamnium, Porolithon)*. The soft sediments deposited on top of reef frameworks form either scattered and ephemeral sandy pockets, 2–10 cm thick or largely developed bodies, up to 1 m thick, likely to be retained permanently within wide ponds (Fig. 5). The latter house molluscan assemblages including gastropods *(Cerithium, Polinices, Conus)* and bivalves *(Tellina)*, and foraminiferal populations dominated by amphisteginids.

The upper parts of the steeply sloping reef flanks are typically settled by the hydrocoral *Millepora*. Some scleractinians are also characteristic of this zone *(Pavona, Goniastrea, Leptoria, Hydnophora, Oulophyllia, Symphyllia)*. Skeletal material occurs as sediment pockets infilling cavities in the coral-built framework (Fig. 7).

The base of the reef flanks consists of a gentle sloping sandy talus with scattered framework outcrops of up to 1 m relief (Fig. 8). Reaching in depth 15 to 38 m, this zone is biologically characterized by a high species diversity. Rocky outcrops have a patchy cover of coral species belonging to the genera *Stylocoeniella*, *Acropora*, *Astreopora*, *Alveopora*, *Pachyseris*, *Podabacia*, associated with alcyonarians. Molluscs exploit various ecological niches all along the reef walls. Vermetids, *Lopha*, *Spondylus*, *Tridacna* live fixed to hard substrates while soft sediments shelter chiefly burrowing bivalves (lucinids, venerids, tellinids, *Lyochoncha*) and gastropods *(Rhinoclavis)*. Other components of the community are sponges and foraminifers.

(2) The offshore inter-reef areas. They form sandy bottoms, occupied by scattered to densely packed coral knobs and patches (Fig. 9). Some coral forms are linked particularly to this kind of sandy biota *(Psammocora, Acropora scandens, Cycloseris, Fungia, Siderastrea)*. The algae include *Halimeda*, *Udotea* and *Caulerpa* and serve as substrate for a variety of foraminifers (amphisteginids, alveolinids, nummulitids, soritids). The molluscan community is dominated by the gastropods *Cerithium*, *Polinices* and *Conus* and the bivalve *Tellina*.

(3) The fringing forereef zone. It consists of a vertical, 20–25 m high drop-off, changing seawards into a gentle sandy slope (Fig. 10) then a sandy spread (Fig. 11). The top of the forereef exhibits biological communities which are quite similar to those mentioned from the offshore upper reef flanks. The coral forms which dominate this zone are *Millepora*, *Pavona*, *Goniastrea*, *Leptoria*, *Acropora* which colonize the margins of grooves (Fig. 12). The sea urchin *Heterocentrotus mammillatus* is common here. In deeper waters, large heads of *Porites*, associated with *Montipora*, *Favia*, *Favites*, *Platygyra* and alcyonarians are encountered. At the foot of the walls, under overhangs, dominating corals are *Acropora*, *Astreopora*, *Alveopora*,

◄

Fig. 3. Aerial side view of the offshore reef platform (North of Jeddah) showing several knoll reefs. Approximate diameter of the foreground knoll: 50 m

Fig. 4. Aerial side view of a table reef typified by a poorly zoned reef flat. Outer offshore reef platform area. Maximum width of reef: 200 m

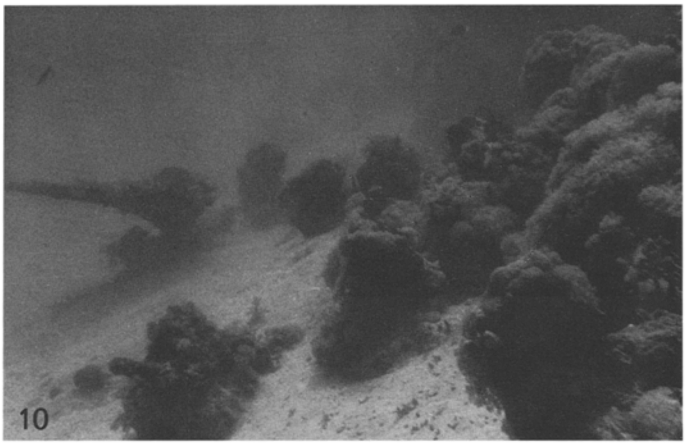
Fig. 5. Aerial side view of a table reef showing a poorly zoned reef flat and inner sediment deposits. Central offshore reef platform area. Maximum width of reef: about 200 m

Fig. 6. *Stylophora*-dominated reef flat, top of a knoll reef. Width of foreground: 0.50 m

Fig. 7. Upper steeply sloping flank of a knoll reef. Height of view: 5 m

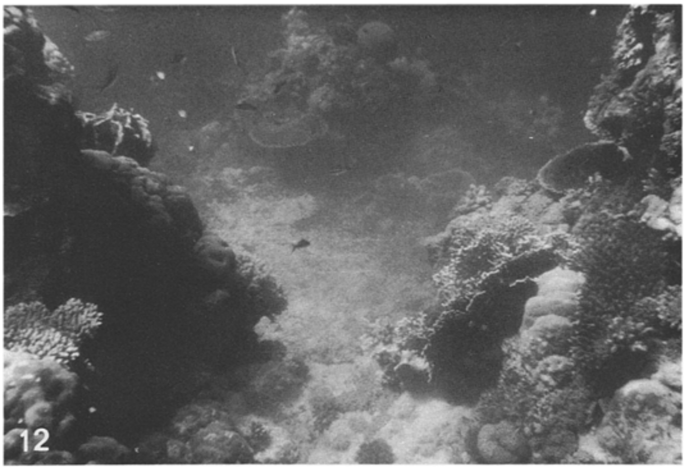
Fig. 8. Lower, gentle sloping flank of a knoll reef. Width of foreground: 1 m

Fig. 9. Inter-reefal area with sandy bottoms and scattered coral knobs. Height of knob: 0.50 m

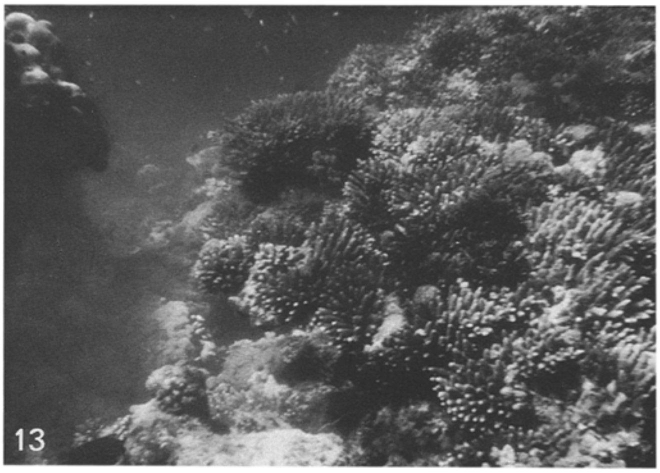


10

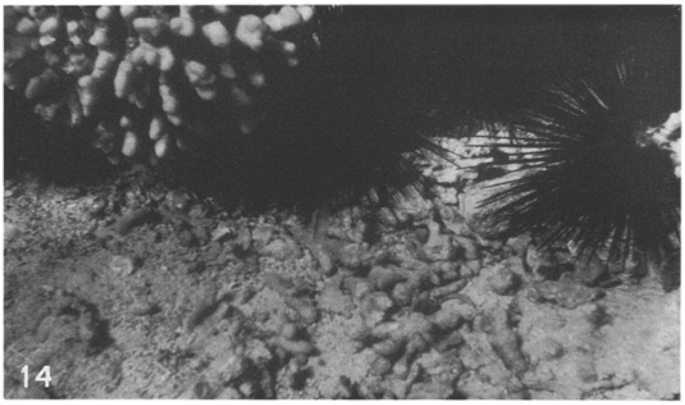
11



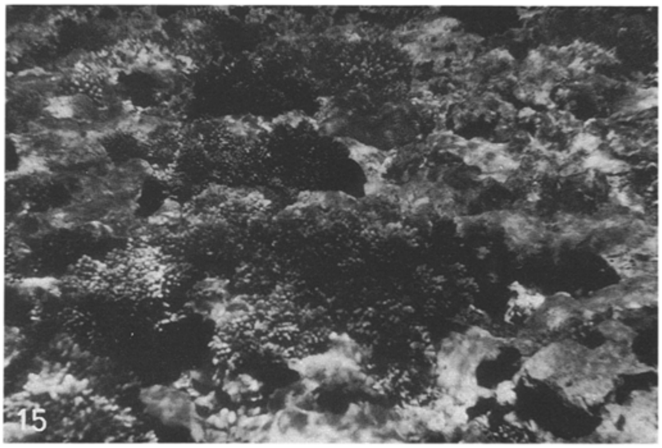
12



13



14



15

16

17

Echinophyllia and *Pachyseris*. Sediment infillings of cavities within the framework are inhabited by numerous bivalves (lucinids, venerids, tellinids) and gastropods. The same forms are found in the outer sandy spread the sediment of which is strongly bioturbated by the crustacean *Callianassa*. The great homogeneity in the community composition and distribution of both the fringing reef and the offshore reef platform reflects the lack of lateral changes in ecological conditions between the two systems. Only the foraminiferal assemblages dominated by miliolids and peneroplids appear to be markedly different in composition.

(4) The fringing reef flat zone. This area, about 0.30 m deep with respect to mean sea level and 200 m wide, is an erosional platform, displaying five basic units from the outer limit shorewards: gently sloping outer platform cut by grooves (Fig. 13), microatoll flat, flat with scattered coral colonies (Fig. 15), dead coral pavement, sea grass flat. In its outermost part, this zone is rich in corals; this community is comparable to those from the offshore reef tops. Dominant forms are *Stylophora*, *Porites*, *Acropora*, *Platygyra*, *Pocillopora*, *Millepora*. Among red algae, the coralline *Lithothamnium* and *Porolithon* are the commonest. Other sessile organisms include foraminifers (homotrematids, acervulinids) and molluscs *(Chama*, *Tridacna*, *Vermetus)*. In the middle part of the reef flat, massive forms of *Porites*, *Cyphastrea*, *Psammocora* are also found, in competition with the octocorallian *Xenia*. Sea grasses *(Thalassia*, *Halodule)* and brown algae *(Cystoseira*, *Turbinaria)* develop in the inner reef flat as dense patches which shelter foraminifers (miliolids, calcarinids), gastropods *(Cerithium*, *Polinices*, *Conus)* and bivalves (tellinids). Coral communities here are composed of scarce and small colonies (stylophorids). The sediment deposits are of two types, similar to those described from the offshore reef flats: in the outer parts of the area, thin and ephemeral gravel and sand pockets (Fig. 14); in the inner parts, relatively thick, sandy beds trapped into ponds (Fig. 16).

(5) The fringing backreef zone. About 400 m wide and 4 m deep, this zone is occupied by muddy sands with fields of mounds and funnels resulting from the burrowing activity of *Callianassa* (Fig. 17). Vegetation is locally found as scattered and irregular beds (*Thalassia* and *Halodule* sea grasses). Algae are mainly chlorophytes *(Halimeda*, *Caulerpa*, *Avrainvillea*, *Dictyosphaeria)*, associated with rhodophytes *(Laurencia)* and phaeophytes *(Padina*, *Lobophora*, *Cystoseira)*. A prolific population of foraminifers (miliolids and peneroplids) inhabits the plants as well as the sediment. Likewise, gastropods (strombids, conids, nassariids, cerithids) and pelecypods (tellinids, lusinids and venerids) occupy the vegetated sands. The mobile fauna includes echinoderms *(Fibularia*, *Holothuria*, *Synaptula*, *Tripneustes*, *Diadema)*. Isolated, metre to plurimetre sized coral knobs and patches are made up mainly of three largely dominating species *(Stylophora pistillata*, *Porites lutea*, *Echinopora fruticolosa)*; subordinate forms are represented by *Acropora pharaonis*, *Coscinarea* and *Goniopora*.

(6) The beach zone. Overlapping coastal, raised reef units of Late Pleistocene age, beach sands consist primarily of skeletal carbonate grains and minor amounts of silicate particles. Macro-benthos is practically lacking in the sediment, while the rocky outcrops are populated by the typical *Nerita-Nodilittorina* assemblage.

In brief, the distributional pattern of the fauna and flora appears to be laterally very homogeneous across the offshore reef system. The lateral biological zonation is, to a great extent, independent of water energy. In contrast, decrease of water energy with depth is probably one of the major ecological factor, together with decrease of light and substrate effect, controlling the vertical distribution of sediment-producing organisms.

Material and methods

The test area corresponds to a transect strip, 25 km long, situated in front of the El Qasr site, about 30 km north of Jeddah (Fig. 18). Complementary surveys were conducted on reefs up to 20 km north of the transect, in order to obtain more information on physigraphy and biology. Sixty-seven surface sediment samples were collected using SCUBA diving from the various depositional settings previously described, up to 38 m deep.

The sediment samples were treated with hydrogen peroxide to remove organics, washed in fresh water, dried and split into two fractions. One fraction served for analysis of component composition, foraminiferal association and grain size distribution. A second fraction served for chemical analysis. For the quantitative modal composition analysis, each sample was sieved into >2.5 mm, 2.5 to 1 mm, 1 to 0.50 mm, 0.50 to 0.25 mm, 0.25 to 0.05 mm, and <0.05 mm size fractions and weighed; 500 to 1,000 grains within the subfractions coarser than 0.25 mm were point counted under a stereo-microscope. The grains were catalogued in 13 component types, i.e. corals, coralline algae, molluscs, free benthic foraminifers, encrusting foraminifers, *Tubipora, Halimeda,* echinoderms, alcyonarian spicules, bryozoans, crustaceans, serpulids and "others" (which included sponge spicules, unidentified carbonate

Fig. 10. Base of the fringing forereef zone (depth: 24 m), dominated by dense alcyonarian colonies

Fig. 11. Outer sandy spread, fringing reef area. *Callianassa* mounds from fine-grained sands. Depth: 26 m

Fig. 12. Upper part of the fringing forereef zone (depth: 3 m). Spur-and-groove system cutting through the top of a drop-off. Width of foreground: 2 m

Fig. 13. *Acropora*-rich, outer fringing reef flat (depth: 1 m), with an incipient groove (left). Width of foreground: 1.50 m

Fig. 14. Pocket of sand and gravel produced by stylophorid corals and echinids *(Diadema)*, outer fringing reef flat. Width of foreground: 0.30 m

Fig. 15. Outer fringing reef flat with scattered *Acropora* colonies (depth: 1 m). Width of foreground: 1.50 m

Fig. 16. Pond from the inner fringing reef flat, infilled with stable, gravel sand beds (depth: 0.50 m). Width of foreground: 1.50 m

Fig. 17. *Callianassa* mounds on the fringing backreef floor sediment, colonized by dense *Thalassia* patches (depth: 1.50 m). Width of foreground: 0.80 m

grains and terrigenous grains). In addition, the free-living foraminiferal species were identified from 33 representative samples of the various environmetal zones. The percent abundance of each species was determined by counting the relevant number of individuals in a total of 500 grains. Grains size analyses were made using the French AFNOR standard sieves. The results were expressed as weight percentage in each of the 25 size classes of the $\sqrt[10]{10}$ millimetric scale used (from 10 to 0.040 mm). The pipette method was used for analysing the grain size distributions of fractions finer than 0.04 mm. Then the values of mean size, sorting and skewness were computed by means of the statistical moment method (Davis and Erlich 1970; Isphording 1972).

The second sample fraction was finely ground in an electric agate mortar to pass a 100 μm mesh sieve. The rapid atomic absorption method of Robinson (1980) was applied in order to indentify the following trace elements: Fe, Mn, Cu, Zn and Cd. Acid treatment indicated that insoluble residues never exceeded 2% of the bulk samples.

Finally the raw sedimentological data were classified objectively using factor analyses. Since the grains catalogued as "others" are not quantitatively significant, they were left out from the statistical treatment in order to obtain the differentiation of the data into meaningful groupings. Two methods were used alternatively to extract maximum information between and within sediment types: (I) principal components analysis; (II) correspondence factor analysis which is Benzécri's (1973) generalization of factor analysis. The basic principles of these two procedures can be schematically explained as follows (see Davis 1973, Joreskög et al. 1976, for more detailed explanations). One considers a table (data matrix) describing an assemblage N of X observations (sediment samples) by an assemblage P of Y variables (amounts of each component type, size class and trace element). If one assigns a vector to each measurement made on each sample, at the end of the analysis, the assemblage N is represented by X vectors in a space of Y dimensions, and the assemblages P is represented by Y vectors in a space of X dimensions. The termini of the vectors can be represented by points, each point corresponding to one observation or one variable. The difficulty in understanding the geometrical relationship existing between variable points and observation points in multi-dimensional spaces is remedied by projecting these points on new restricted spaces. Thus factor analysis permits the projection of a large set of points into a very reduced space. This space is defined by a number of *factor axes* (or *factors*). All the axes so defined pass through the gravity centre of the set. The first axis is that corresponding to the largest values of variance of the similarity matrix. The second factor axis is related to the second largest values of variance, and so on. In most cases, the extraction of the first three factors is sufficient to meaningfully describe the variation of the sets of observation points or variable points.

The factor spaces (i.e. planes) proper to variable points and observation points are superimposed in order to appreciate relationships between observations, between variables, and simultaneously between observations, variables and axes, graphically as well as mathematically. Indeed, each point takes a part in defining axes (this property is termed *absolute contribution* of point to axis); reciprocally each factor axis contributes to define the position of a given point with respect to the centre of gravity of the cloud of all the projected points (*relative contribution* of axis to point). The values of these contributions vary within the range 0 to 1. Distinct groupings of points used in the present study for the definition of sediment types have been differentiated on the basis of values of *relative contributions*. The boundaries of any given grouping embody both the sample and variable points which are spatially defined by a relative contribution higher than 0.10. So the precise location of each group is statistically significant with respect to factor axes.

Results

Sediment texture and composition

Some general trends in the distribution of textures, individual components and trace elements within the sediments can be deduced from the raw quantitative data (Tables 1–3).

Grain size displays a physiography-dependent distribution. On fringing reef flats, offshore reef tops and upper flanks, sediments are predominantly coarse sands (1–0.5 mm) and granules (>2.5 mm). Fringing backreef and forereef zones have the highest mean values for fine and very fine sands (0.25–0.05 mm), whereas medium sands (0.5–0.25 mm) are the most prominent in sediment bodies from lower reef flanks and interreef bottoms of the offshore areas.

Coral detritus is ubiquitous, but it occurs in higher abundance along flanks of the offshore reefs and nearby interreef areas, and on the fringing reef flat zone (mean values: 37.6–47.0%). Coralline red algae are the most abundant source of carbonate at the tops and upper flanks of the offshore reefs (43.5%). Molluscan fragments are common throughout the study area, occurring as a major sediment contributor in the fringing backreef zone (35.0%). Free benthic foraminifers are fairly common throughout (1.3–9.6%). Their distribution roughly follows a depth zonation; the greatest frequencies are in the offshore interreef areas (5.9%) and in the fringing forereef and backreef zones (6.9–9.6%). The abundance of crustose foraminifers appear to correlate with proximity of hard substrates; they locally make up a significant fraction of deposits from the offshore reefs and the fringing forereef zone (1.8–4.1%). Fragments produced by the octocoral *Tubipora* have a small contribution to the carbonate budget along the study area. But they are particularly conspicious in coarse sediments near upper flanks of the offshore reefs (5.1%). The green algae *Halimeda* make up a small part of the sediments, reaching maximum amounts of 2.5% in the fringing backreef zone. Evidence of alcyonarian spicules is usually present in the material studied, but their abundance is normally less than 1%. The distribution of bryozoan grains closely follows that of encrusting foraminifers; bryozoans make up between 1.6 and 3.9% of total sediment in the offshore reefs and the fringing forereef zone. Except for the fringing backreef zone, crustacean detritus is fairly common throughout; its contribution varies between 0.7 and 4.7%. Serpulid remains constitute a very small fraction of the sediments, rarely exceeding 2%.

Insoluble residues show variations in mean concentrations, related to distance from nearshore areas. Likewise, among the trace elements analysed, three display a laterally changing abundance; iron and zinc appear to decrease in abundance with increasing distance from the shore (320 to 73 p.p.m., 14 to 8 p.p.m., respectively) while manganese increases in abundance seawards (13 to 30 p.p.m.). Copper is commonly low in amount; its distribution along the transect is fairly regular and reaches values lower than 6 p.p.m. Cadmium concentrations also are very low (about 1.5 p.p.m.) and regularly distributed.

Concerning benthic foraminiferal associations, fifty species belonging to three suborders (Textulariina, Miliolina and Rotaliina) were identified in the El Qasr reef sediments (Tables 2, 3). Miliolina and Rotaliina usually

Table 1. Summary of quantitative sedimentological data from each depositional environment. Mean values and standard deviations (numbers in parentheses) are given. Identification number of samples collected from each depositional environments. Offshore reef platform–reef tops: no. 37, 45, 46, 47, 59, 73, 74, 82; upper reef flanks: no. 35, 36, 38, 43, 44, 48, 49, 50, 51, 54, 55, 66, 67, 71, 72, 78, 81; lower reef flanks: no. 42, 52, 53, 58, 64, 69, 70, 75, 76; interreef areas: no. 33, 34, 56, 57, 65, 77, 79, 80. Fringing reef–forereef zone: no. 39, 40, 41, 60, 61, 62, 63; reef flat zone: no. 1, 2, 3, 4, 5, 6, 7, 8, 9; backreef zone and beach: no. 10, 11, 12, 13, 14, 15, 16, 17, 18. See Fig. 2 for location of the samples in the study area

	Depositional environments							
	Offshore reef platform				Fringing reef			
	Reef tops	Upper reef flanks	Lower reef flanks	Interreef areas	Forereef zone	Reef flat zone	Backreef zone	Beach
Number of samples analysed	8	17	9	8	7	9	8	1
Depth range in m	0–1	1–15	15–38	13–35	10–30	0–1	2–5	–
Grain size								
>2.5 mm	14.2 (15.7)	10.5 (13.9)	4.4 (2.9)	7.0 (5.0)	4.2 (5.7)	15.4 (23.6)	2.6 (3.7)	9.6
2.5–1 mm	20.9 (10.5)	16.4 (11.1)	14.5 (6.9)	16.1 (4.7)	6.7 (5.5)	21.6 (9.7)	9.8 (9.3)	22
1 mm–0.5 mm	32.3 (15.6)	25.4 (11.1)	29.1 (7.6)	26.9 (4.6)	15.2 (5.4)	30.5 (13.2)	18.2 (12.4)	22.7
0.5–0.25 mm	17.4 (10.5)	22.6 (11.7)	31.2 (7.7)	27.6 (5.4)	33.0 (15.2)	23.8 (14.1)	20.2 (9.9)	20.9
0.25–0.05 mm	11.9 (14.7)	21.4 (24.9)	19.8 (13.5)	21.2 (9.7)	39.9 (20.8)	8.6 (8.6)	31.6 (8.6)	24.7
<0.05 mm	3.2 (8.4)	2.6 (4.1)	1.0 (1.5)	1.2 (1.5)	1.0 (0.7)	0.1 (0.2)	0.1 (0.2)	0.1
Sediment components								
Corals %	27.1 (14.5)	37.6 (11.5)	44.0 (6.1)	41.0 (10.4)	31.1 (10.6)	47.0 (16.0)	32.2 (15.0)	31.4
Coralline algae %	43.5 (17.0)	26.1 (10.9)	20.8 (5.7)	19.9 (7.9)	23.0 (7.4)	23.8 (17.5)	8.0 (4.2)	3.9
Molluscs %	16.1 (6.0)	16.2 (4.1)	19.0 (3.5)	18.2 (3.6)	19.8 (3.4)	20.1 (5.9)	35.0 (5.1)	38.1
Free benthic foraminifers %	3.1 (4.4)	2.3 (2.0)	4.0 (1.4)	5.9 (3.5)	6.9 (6.6)	1.3 (1.0)	9.6 (6.8)	15.6
Encrusting foraminifers %	1.8 (1.0)	2.0 (1.4)	1.6 (1.1)	2.9 (3.2)	4.1 (2.0)	1.5 (1.4)	0.1 (0.3)	–
Tubipora %	2.1 (4.9)	5.1 (7.9)	2.3 (2.6)	1.1 (0.8)	0.5 (0.4)	0.4 (0.5)	0.0	–
Halimeda %	0.9 (1.2)	0.6 (0.8)	0.7 (0.9)	1.4 (1.4)	0.9 (0.8)	1.6 (1.0)	2.5 (2.1)	4.7
Echinoderms %	0.4 (0.5)	0.9 (0.6)	1.5 (0.8)	1.6 (0.7)	1.5 (1.1)	0.4 (0.4)	0.1 (0.2)	–
Alcyonarians %	0.03 (0.06)	0.5 (0.4)	0.5 (0.4)	1.1 (0.7)	0.6 (0.4)	0.1 (0.1)	0.0	–
Bryozoans %	0.9 (1.1)	2.0 (1.8)	1.6 (0.8)	1.6 (1.9)	3.9 (2.5)	0.2 (0.5)	0.0	–
Crustaceans %	1.8 (1.1)	3.6 (1.9)	1.5 (1.1)	1.6 (2.1)	4.7 (1.6)	1.8 (1.2)	0.7 (0.5)	1.0
Serpulids %	0.3 (0.4)	0.5 (0.4)	0.2 (0.1)	0.8 (0.6)	0.8 (0.9)	0.2 (0.3)	2.5 (1.7)	0.9
Others %	1.9 (2.4)	3.1 (2.0)	2.5 (2.1)	2.9 (1.8)	3.0 (2.6)	2.1 (3.0)	8.2 (5.1)	4.4
Insoluble residues %	tr	tr	0.2	0.4	1.2	1.0	2.0	1
Trace elements (in p.p.m.)								
Number of samples analysed	6	14	7	5	3	9	8	1
Iron	73.6 (21.2)	92.8 (31.8)	85.5 (13.1)	85.5 (23.9)	178.8 (21.3)	177.2 (29.3)	320.3 (92.3)	348
Manganese	23.1 (10.2)	30.1 (17.6)	18.9 (6.9)	18.8 (12.2)	31.5 (15.0)	19.7 (7.0)	13.8 (2.5)	19.3
Zinc	8.5 (1.6)	8.0 (3.0)	8.4 (0.8)	12.4 (10.7)	14.5 (7.3)	11.6 (8.5)	10.4 (3.2)	31.1
Copper	4.4 (0.9)	4.8 (0.8)	4.5 (0.7)	4.5 (1.7)	5.2 (1.2)	4.5 (1.7)	5.7 (0.8)	6.4
Cadmium	1.5 (0.2)	1.5 (0.2)	1.6 (0.1)	1.5 (0.1)	1.5 (0.2)	1.6 (0.2)	1.5 (0.1)	1.4

constitue more than 90% of the total population. Rotaliina can locally exhibit very high contents (up to 90%), due to dense *postmortem* accumulations of *Amphistegina* spp., *Ammonia beccarii* or *Calcarina calcar* and *Elphidium* spp. *Textulariina* reach less than 10% of the total assemblages or are lacking. Moreover, the abundance of foraminiferal species increases seawards. There is an inverse relationship between the frequency distributions of Miliolina and Rotaliina. In the fringing reef, the foraminiferal assemblages are dominated by Miliolina and/or Rotaliina, while, across the offshore platform, the prominent feature is the dominance of Rotaliina (Fig. 18). The whole test area can be divided into three distinct units on the basis of distribution of microfaunal assemblages. In the fringing backreef zone, *Ammonia* occurs as an ubiquitous form, associated with *Peneroplis*, *Spiroloculina*, *Quinqueloculina* and *Elphidium*. *Calcarina* typifies the fringing reef flat area; additional common forms are *Elphidium* and *Quinqueloculina*. The forereef sediments contain Miliolidae – rich associations. The offshore reef system is characterized by the dominance of *Amphistegina lessonii*; subordinate foraminifers are *Borelis*, *Heterostegina*, *Operculina* and *Eponides*.

Beyond these tenuous generalizations, no systematic pattern is apparent in the raw data. On the whole, as indicated by standard deviation values, each depositional setting has a high degree of heterogeneity; in particular grain size and skeletal component distribution vary largely within a given sedimentary environment. This suggests that sediment types floor the sea bed in the form of relatively scattered mosaics.

Statistical definition of sediment types

Skeletal component types

In an attempt to obtain a more accurate differentiation of the initial raw data into meaningful groups, statistical

Table 2. Checklist of the free-living benthic foraminifers in the Jeddah Reef test area

I. Suborder Textulariina Delage and Herouard
Textularia cushmani Said
T. kerimbaensis Said
Clavulina angularis d'Orbigny
C. tricarinata d'Orbigny

II. Suborder Miliolina Delage and Herouard
Spirolina arietina (Batsch)
Spiroloculina acescata Cushman
S. angulata Cushman
S. clara Cushman
S. hadai Thalmann
S. indica (Cushman and Todd)
Quinqueloculina costata d'Orbigny
Q. crassa (d'Orbigny)
Q. lamarckiana d'Orbigny
Q. limbata d'Orbigny
Q. neostriatula Thalmann
Q. oblonga (Montagu)
Q. pseudoreticulata Parr
Q. quinquecarinata Collins
Q. subpolygona Parr
Massilina granulocostata (Germeraad)
M. secans (D'Orbigny)
M. spinata Cushman and Ponton
Triloculina affinis D'Orbigny
T. bermudzi Acosta
T. irregularis (D'Orbigny)
T. fichteliana (D'Orbigny)
Pyrgo denticulata (Brady)
P. millettii (Cushman)
Articulina sagra d'Orbigny
Sorites marginalis (Lamarck)
Discorbis pellucidus Said
Peneroplis planatus (Fichtel and Moll)
Borelis schlumbergerii (Reichel)

III. Suborder Rotaliina Delage and Herouard
Ammonia beccarii (Linné)
Calcarina calcar d'Orbigny
Elphidium advenum (Cushman)
E. crispum (Linné)
E. striato-punctatus (Fichtel and Moll)
Cellantus craticulatus (Fichtel and Moll)
Operculinella cumingii (Carpenter)
Operculina ammandus (Carpenter)
Eponides repandus (Fichtel and Moll)
Amphistegina bicirculata Larsen
A. lessonii d'Orbigny
A. lobifera Larsen
Cibicides subhaidingerii Parr
Cymbaloporella tabellaeformis (Brady)
Cymbaloporetta bradyii (Cushman)
Heterostegina depressa d'Orbigny
Fursenkoina acerosa (Cushman)

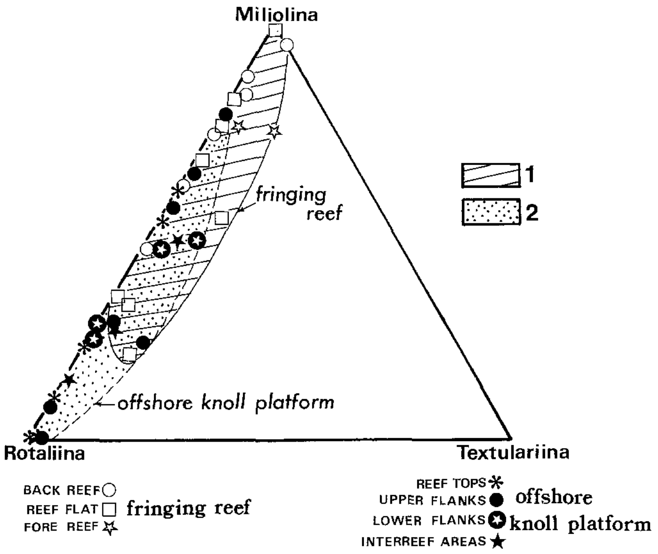


Fig. 18. Triangular diagram illustrating the composition of foraminiferal assemblages in sediments from the Jeddah reef complex. 1 = assemblages from the fringing reef system; 2 = assemblages from the offshore reef platform

treatment was applied to the samples from the offshore reef platform and to those of the fringing reef system separately.

A first principal components analysis was performed from a data matrix comprising 42 observations (samples from the offshore platform) and 12 variables (component categories). The first three factors explain 52.6% of the total variance (Figs. 19 and 20).

Factor 1, extracting 21.7% of the variance, depends upon the variable "coralline algae" (*absolute contribution* AC = 0.17) which is opposed to free foraminifers (AC = 0.14), molluscs (AC = 0.12) and corals (AC = 0.10). Factor 2, extracting 19.7% of the variance, is defined by the variables "bryozoans" (AC = 0.23) and "encrusting foraminifers" (AC = 0.21). Factors 3, extracting 11.2% of the variance, is largely controlled by the opposition between coralline algae (AC = 0.21) and corals (AC = 0.18). Other variables (*Tubipora*, alcyonarians, *Halimeda*, crustaceans) contribute moderately to defining the three axes (AC varying between 0.03 and 0.08).

First, the arrangement of the sample points within the three dimensional space draws up six distinct groups. Groups 1, 2, 4 and 5 mainly retain samples from the reef tops and upper flanks, whereas groups 3 and 6 mainly include samples from the lower reef flanks and the interreef areas. Axis 1 has a relatively heavy influence as far as the spatial distribution of the samples involved in groups 1, 3, 4 and 6 is concerned. For group 1, the *relative contribution* RC ranges from 0.12 to 0.53; for group 3, RC is 0.13–0.56; for group 4, RC is 0.12–0.37; for group 6, RC is 0.18–0.41. Likewise, the samples from group 2 are heavily influenced by Axis 2 (RC = 0.28–0.62), whereas the samples from group 5 are defined with respect to Axis 3 (RC = 0.20–0.49). The location of a number of sample points near the gravity centre of one of the bidimensional spaces (1, 2) or (1, 3) indicates that the influence of the relevant two axes on these samples is very weak within the considered bidimensional space (RC less than 0.10, varying between 0.03 and 0.09). However, the spatial arrangement of such points is well defined in relation to the other bidimensional space.

Secondly, examination of proximities between the variables and the observations provides a faithful picture of the relationships between skeletal components and depositional zones (Figs. 19 and 20). As shown from

Table 3. Frequency distribution of the main free benthic foraminifers in each depositional environment. Mean values and standard deviations (numbers in parentheses) are given. Identification number of samples collected from each depositional environment. Offshore reef platform–tops and upper reef flanks: no. 35, 37, 38, 46, 47, 48, 49, 50, 51, 59, 82; lower reef flanks and interreef areas: no. 33, 34, 53, 55, 58, 70, 71, 72, 75, 79, 80. Fringing reef–forereef zone: no. 61, 62; reef flat zone: no: 1, 2, 3, 4, 5, 6, 7, 8, 9; back reef zone and beach: no. 10, 13, 14, 15, 17, 18. See Fig. 2 for location of the samples in the study area. (See Table 2 for the list of foraminiferal forms catalogued as "others"

	Depositional environments					
	Offshore reef platform		Fringing reef			
	Tops and upper reef flanks	Lower reef flanks and intereef areas	Forereef zone	Reef flat zone	Backreef zone	Beach
Number of samples analysed	11	6	2	8	5	1
Suborder Textulariina						
Textularia spp.	1.3 (3.8)	4.3 (3.9)	8.4 (9.0)	3.6 (5.7)	1.3 (2.4)	6.0
Suborder Miliolina						
Spiroloculina spp.	6.3 (6.4)	1.5 (3.7)	7.2 (0.0)	15.3 (22.2)	13.1 (8.3)	6.0
Quinqueloculina spp.	15.4 (15.6)	17.1 (11.1)	14.6 (10.4)	23.2 (21.4)	18.0 (10.2)	21.2
Triloculina spp.	5.6 (15.1)	6.7 (8.1)	28.2 (8.9)	4.0 (9.8)	12.6 (8.4)	7.6
Sorites marginalis	16.1 (20.8)	9.7 (16.9)	9.6 (1.3)	8.1 (10.9)	8.2 (17.6)	43.8
Peneroplis planatus	2.2 (4.4)	0.7 (1.6)	11.5 (6.4)	7.4 (7.6)	19.4 (9.6)	15.1
Borelis schlumbergerii	1.2 (4.0)	9.4 (12.4)	0.0	0.0	0.0	0.0
Suborder Rotaliina						
Ammonia beccarii	9.8 (20.0)	2.2 (3.7)	2.6 (3.7)	7.1 (14.3)	12.5 (9.3)	0.0
Calcarina calcar	0.0	0.0	7.9 (11.3)	15.8 (22.3)	6.3 (14.5)	0.0
Elphidium spp.	0.0	1.5 (3.7)	3.7 (5.2)	15.6 (11.4)	12.5 (11.8)	0.0
Operculina ammandus	0.5 (1.8)	1.2 (3.0)	1.1 (1.5)	0.0	0.0	0.0
Eponides repandus	1.3 (4.3)	4.6 (7.2)	0.0	0.0	0.0	0.0
Amphistegina spp.	37.2 (25.1)	41.2 (21.0)	4.2 (6.0)	0.0	0.0	0.0
Cymbaloporella tabellaeformis	1.5 (3.0)	0.3 (0.8)	0.0	0.0	0.0	0.0
Heterostegina depressa	1.7 (4.0)	4.9 (6.4)	0.0	0.0	0.0	0.0
Others	1.0 (3.4)	0.8 (1.3)	1.1 (2.9)	0.9 (1.7)	1.2 (2.8)	0.3

groups 1 and 5, coralline algae allow a valid discrimination for the reef tops and the upper reef flanks. In addition, as indicated by groups 2 and 4, bryozoans, encrusting foraminifers and *Tubipora* contribute to the differentiation of sediment types in the uppermost parts of the offshore buildups. From groups 3 and 6, it appears clearly that molluscs and free benthic foraminifers permit the lower reef flanks and the interreef areas to be differentiated.

A second principal components analysis was applied to the samples from the fringing reef system. The data matrix comprised 25 observations and 12 variables. Within the factor spaces (1, 2) and (1, 3), six groupings of samples and variables are clearly distinguished (Figs. 21 and 22). Groups A, B and D include most of samples from the reef flat zone; the associations of observations and variables indicate that coralline algae (AC to Axis 1 $=0.67$) and corals (AC to Axis $2=0.39$) mainly control sediment production on the fringing reef flat. Groups C and E comprise most of samples from the fringing backreef zone and a few samples from the adjacent reef flat; molluscs (AC to Axis $1=0.10$) and free foraminifers (AC to Axis $2=0.37$) respectively allow a meaningful discrimination of these two groups. Group F is concerned with all the samples from the forereef zone; it is clearly differentiated on the basis of bryozoan (AC to Axis 3 $=0.16$) and encrusting foraminifers (AC to Axis $3=0.15$).

Interpretation of the two factor analyses performed from quantitative modal-composition percentage data emphasizes the fact that component assemblages (which represent *sediment types*) are consistently related to environmental zones. Sediments trapped at the upper parts of the offshore buildups are generally of coralline algal type, which can be divided into two subtypes: (I) a *Tubipora* subtype occurring principally at the tops of buildups; and, (II) an encrusting foraminiferal-bryozoan subtype found mainly along the upper reef flanks. Both the lower flanks or reef bodies and the adjacent interreef areas have sediments mainly belonging to the molluscan-free foraminiferal type. Concerning the fringing reef system, the backreef deposits are mainly of molluscan type. As a whole, the reef flat is typified by a coral-coralline algal type (termed "coralgal"), whereas the nearby forereef areas belong to an encrusting foraminiferal-bryozoan type (Table 4).

Free benthic foraminiferal types

A correspondence factor analysis was performed from an initial matrix including 15 variables (numerical percentages of major sediment-contributing foraminiferal forms, listed in Table 5) and 33 representative samples. It clearly indicated that the heavy contribution of 3 samples which contained 50–100% of *Amphistegina* or *Calcarina* caused

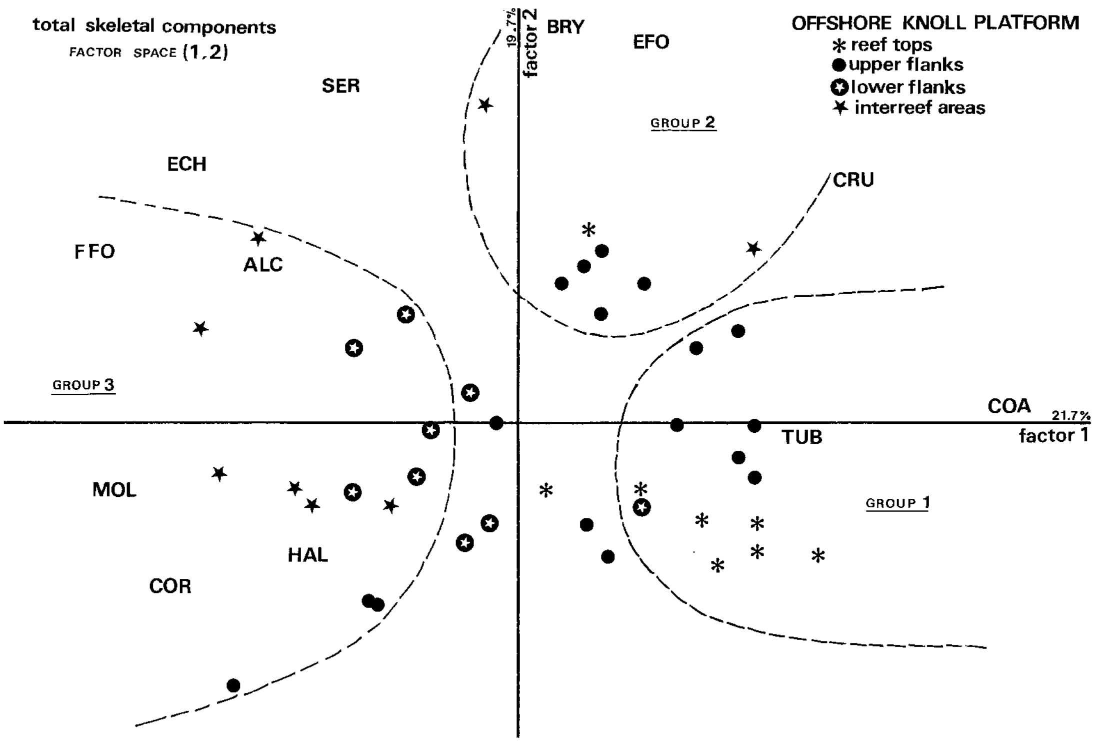


Fig. 19. Offshore reef platform – principal components analysis. Plot of the first two factors axes. Both variables (12 component types) and observations (42 sediment samples) are plotted simultaneously. COR = corals; COA = coralline algae; MOL = molluscs; FFO = free benthic foraminifers; EFO = encrusting foraminifers; ALC = alcyonarians; BRY = bryozoans; ECH = echinoderms; SER = serpulids; CRU = crustaceans; HAL = *Halimeda*; TUB = *Tubipora*

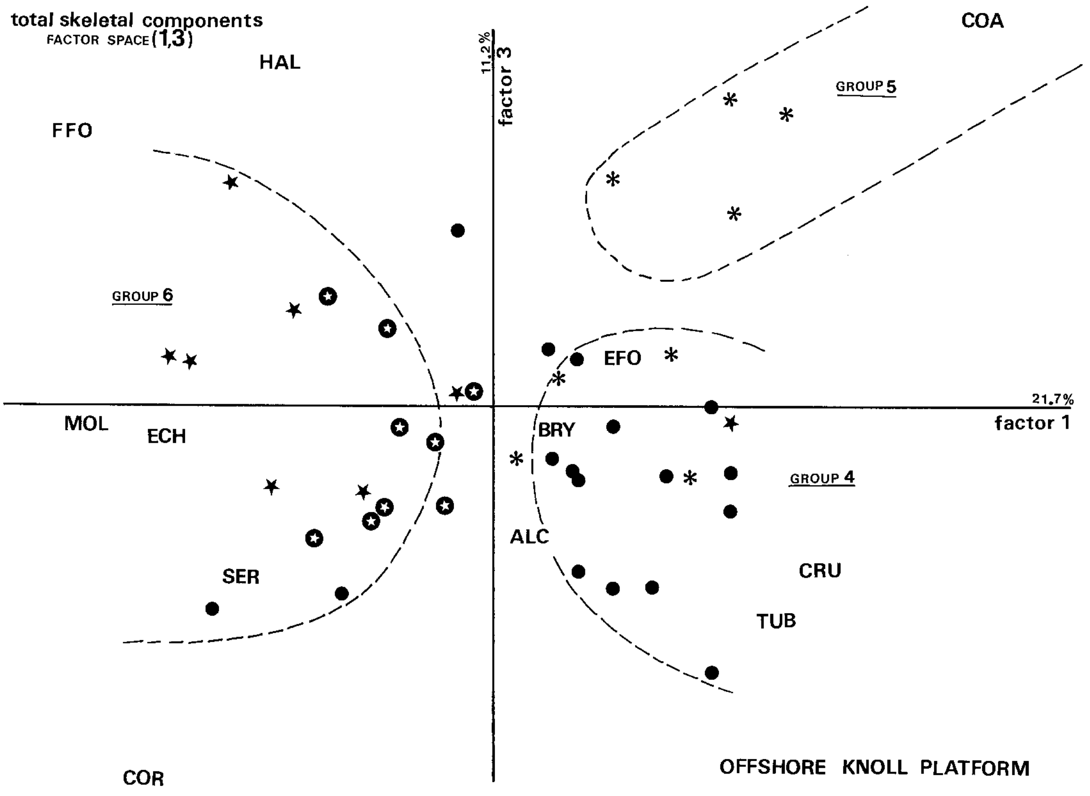


Fig. 20. Offshore reef platform – principal components analysis. Plot of the axes 1 and 3 with simultaneous projection of 12 variables (component types) and 42 observations (sediment samples). See Fig. 19 for the significance of the symbols used

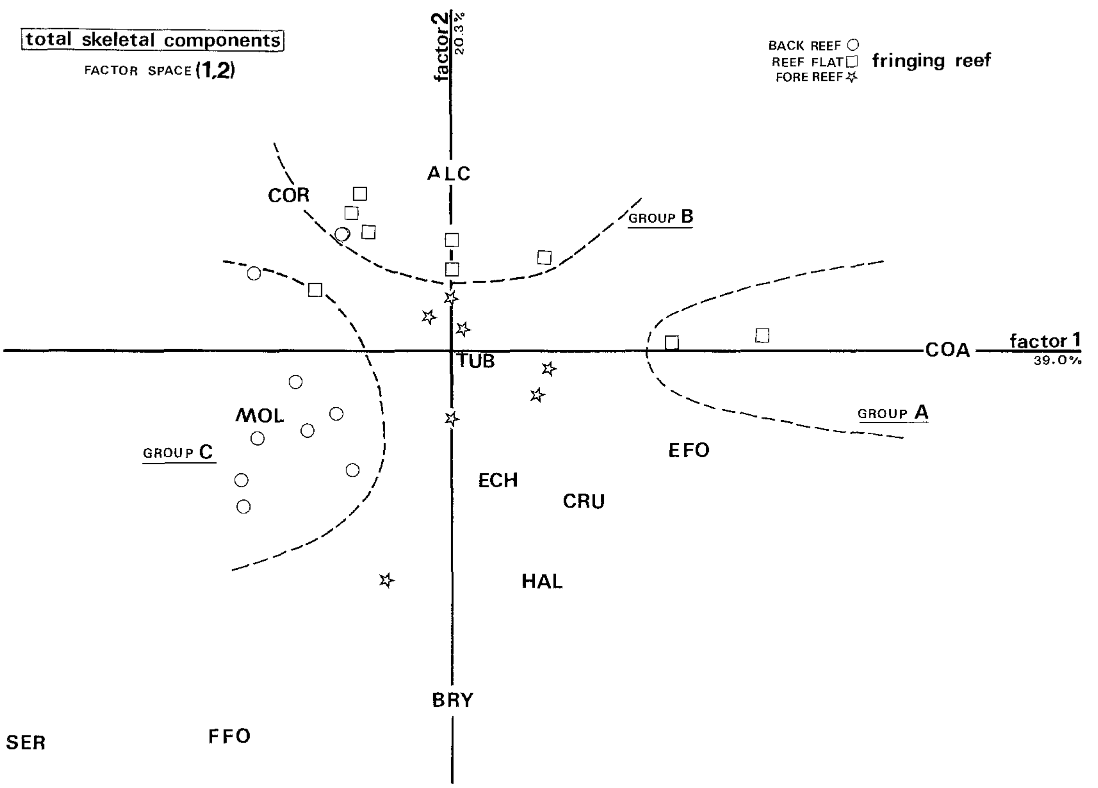


Fig. 21. Fringing reef area – principal components analysis. Plot of the first two factor axes. Both variables (12 component types) and observations (25 sediment samples) are plotted simultaneously. See Fig. 19 for the significance of the symbols used

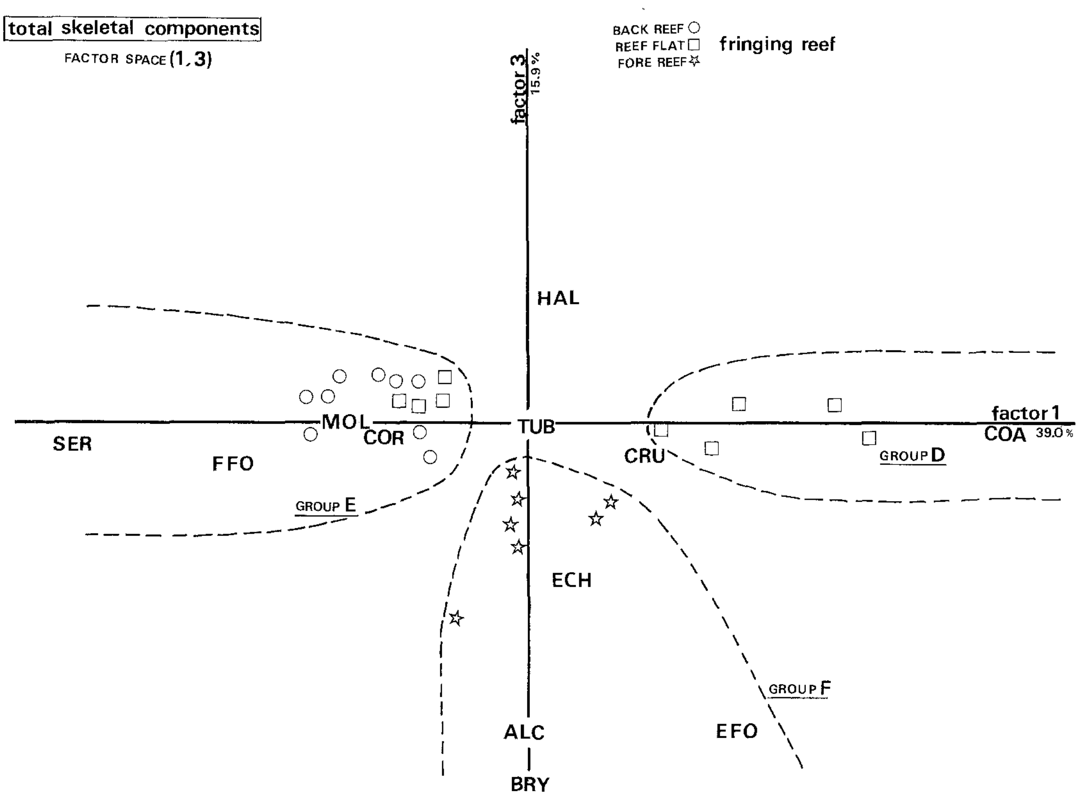


Fig. 22. Fringing reef area – principal components analysis. Plot of the axes 1 and 3 with simultaneous projection of 12 variables (component types) and 25 observations (sediment samples). See Fig. 19 for the significance of the symbols used

Table 4. Statistic of the component types ($\bar{x}$ = mean values; SD = standard deviation; r = range; number in parantheses = number of samples regrouped; values underlined = representative component categories). Identification number of samples falling into each groups of component types (see Fig. 2 for location of sediment samples in each depositional setting). Coralgal type: no. 1, 2, 3, 4, 5, 6, 7, 8, 18, 42, 54, 70; molluscan type: no. 9, 10, 11, 12, 13, 14, 15, 16, 17; molluscan-free foraminiferal type: no. 33, 34, 39, 40, 41, 49, 50, 51, 52, 53, 56, 58, 60, 61, 62, 63, 64, 65, 75, 76, 77, 80; coralline algal type–encrusting foraminiferal–bryozoan subtype: no. 36, 37, 48, 55, 57, 66, 74, 78, 79, 81; coralline algal type–*Tubipora* subtype: no. 35, 38, 43, 44, 45, 46, 47, 59, 67, 69, 71, 72, 73, 82

		Corals	Coralline algae	Molluscs	Free foraminifers	Encrusting foraminifers	*Tubipora*	*Halimeda*	Echinoderms	Alcyonarians	Bryozoans	Crustaceans	Serpulids
Coralline algal type													
Coralgal type (12)	$\bar{x}$	54.2	15.7	20.9	1.9	1.1	0.2	1.4	0.5	0.2	0.4	1.4	0.4
	r	38.1–64.7	6.9–26.0	15.2–31.0	0.2– 5.1	0 –2.7	0 – 0.8	0.1–2.9	0 –1.3	0–1.0	0 –2.1	0.4–3.5	0 –0.8
	SD	8.5	7.7	4.5	1.3	0.9	0.2	1.0	0.4	0.3	0.7	1.1	0.3
Molluscan type (9)	$\bar{x}$	33.1	6.8	34.9	6.3	0.2	0.03	2.8	0.2	–	–	0.9	2.1
	r	18.1–56.3	2.4–10.9	25.9–32.4	2.9–13.8	0 –0.8	0 – 0.4	0 –5.2	0 –0.4	–	–	0.1–1.8	1.1–5.2
	SD	14.5	3.9	5.1	3.6	0.3	0.1	1.7	0.2	–	–	0.5	1.6
Molluscan-free foraminiferal type (22)	$\bar{x}$	39.5	18.5	23.6	10.4	1.6	1.2	1.3	1.7	0.9	1.6	1.3	0.6
	r	16.4–55.6	11.3–27.8	13.8–29.5	1.5–21.6	0.1–4.3	0 – 3.6	0 –3.6	0.6–2.9	0–1.9	0 –3.6	0.7–3.6	0.3–1.7
	SD	12.6	5.0	3.5	6.9	1.6	1.0	1.3	0.7	0.7	1.1	1.0	0.4
Encrusting foraminiferal-bryozoan subtype (10)	$\bar{x}$	34.2	25.8	16.0	4.6	4.5	0.8	0.3	1.5	0.7	4.6	4.1	0.9
	r	14.3–55.3	11.2–36.1	10.3–25.7	1.0–19.7	1.3– 6.3	0.2–1.6	0 –0.6	0.3–2.8	0–1.3	2.0–9.3	1.2–6.4	0.2–2.4
	SD	9.6	7.9	4.5	5.6	2.3	0.6	0.3	0.6	0.4	2.3	1.8	0.7
Tubipora subtype (14)	$\bar{x}$	28.2	39.1	16.1	1.6	2.0	7.2	0.7	0.5	0.3	1.2	2.9	0.2
	r	12.6–42.7	28.1–63.8	9.2–28.3	0.1– 3.3	0.3–4.0	3.8–25.5	0 –2.7	0 –1.4	0–1.3	0 –7.0	0.7–5.7	0 –0.8
	SD	9.6	14.5	5.4	1.0	1.0	7.4	0.9	0.4	0.4	1.8	1.3	0.3

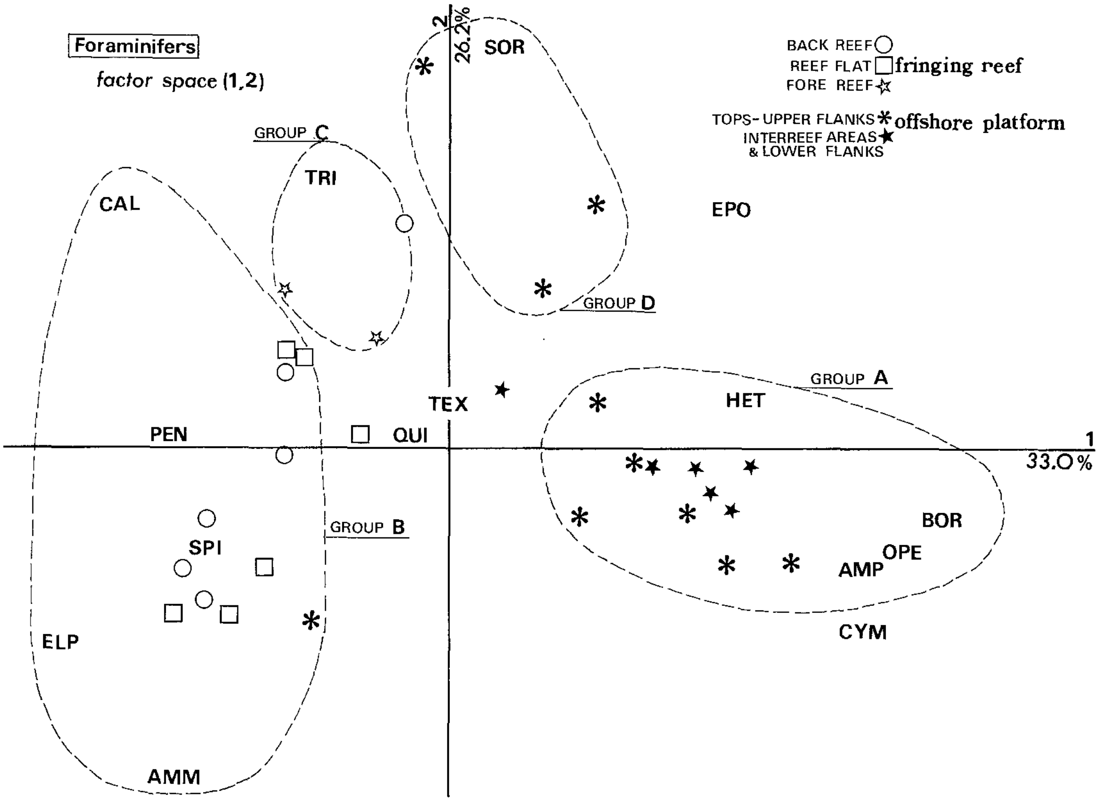


Fig. 23. Correspondence factor analysis. Plot of the first two factor axes. Both variables (15 foraminiferal types) and observations (30 sediment samples) are plotted simultaneously. SPI = *Spiroloculina*; QUI = *Quinqueloculina*; TRI = *Triloculina*; SOR = *Sorites*; ELP = *Elphidium*; AMP = *Amphistegina*; HET = *Heterostegina*; PEN = *Peneroplis*; TEX = *Textularia*; AMM = *Ammonia*; CAL = *Calcarina*; OPE = *Operculina*; BOR = *Borelis*; EPO = *Eponides*; CYM = *Cymbaloporella*

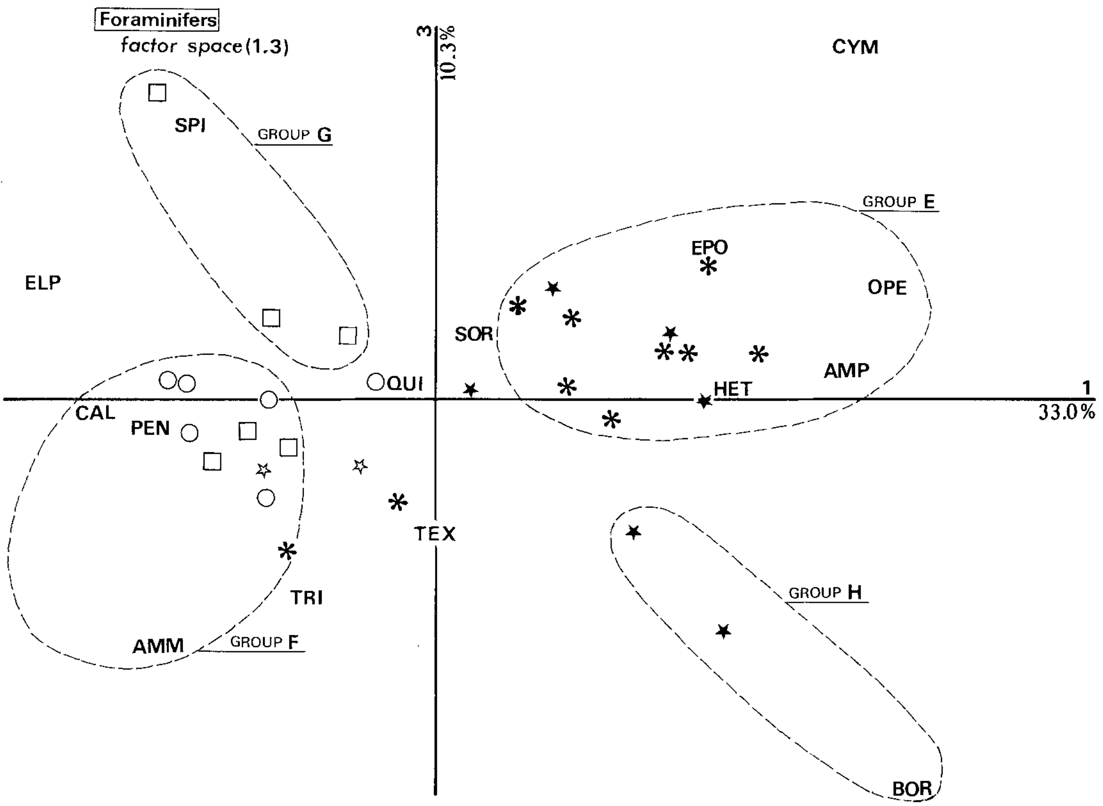


Fig. 24. Correspondence factor analysis. Plot of the factor axes 1 and 3, with both variables (15 foraminiferal types) and observations (30 sediment samples) projected simultaneously. See Fig. 23 for the significance of the symbols used

grouping of a lot of remaining sample points closely to the barycentre. Therefore a second analysis was applied to 30 samples only. In this analysis, total variance extracted by the first three factors is 69.5% (Figs. 23 and 24). Factor axis 1 weighs *Amphistegina* (AC = 0.57) associated with *Borelis* (AC = 0.16) and *Heterostegina* (AC = 0.11) against *Elphidium* (AC = 0.22) associated with *Peneroplis* (AC = 0.18) and *Spiroloculina* (AC = 0.17). Factor 2 is based on the opposition between *Sorites* (AC = 0.50) and *Ammonia* (AC = 0.31). Factor 3 indicates a consistent opposition between *Spiroloculina* (AC = 0.32) and *Ammonia* (AC = 0.23) associated with *Triloculina* (AC = 0.14) and *Borelis* (AC = 0.17). The *Quinqueloculina* points are systematically located near the barycentre which means that it practically takes no part in defining the three axes. This is due to the fact that *Quinqueloculina* contents are appreciably equal in most samples. This foraminiferal form, therefore, cannot provide a meaningful discrimination for sample grouping.

From the spatial ordination of the variable and observation points within the two bidimensional spaces, eight groups can be distinguished (Figs. 23 and 24). Examination of groups A, D, E and H clearly shows that *Amphistegina*, *Borelis*, *Heterostegina* and *Sorites* allow a valid discrimination for the offshore platform areas. In contrast, *Ammonia*, *Elphidium*, *Calcarina*, *Spiroloculina*, *Peneroplis* and *Triloculina* control the sample groupings B, C, F and G mainly corresponding to the fringing reef system. Thus the following foraminiferal types have been identified (Table 5). An *Ammonia-Elphidium* type characterises the whole fringing reef area. However, deposits occurring in the backreef zone tend to be of *Peneroplis* subtype, whereas the sediments trapped on the reef flat rather exhibit a *Calcarina-Spiroloculina* subtype. *Triloculina* type is essentially restricted to the fringing forereef zone. Foraminifers as environmental discriminators are less efficient for the offshore knoll platform. The dominant type is that of *Amphistegina*. The latter, however, may be subdivided into two additional subtypes which permit to roughly differentiate the upper parts of reef bodies from the neighbouring deeper areas: these are *Sorites* and *Borelis-Heterostegina* subtypes respectively.

Geochemical types

Several meaningful groupings have been obtained by applying principal components analysis to the geochemical raw data. Figures 25 and 26 show plots of three factor axes with both variables (concentration of each trace element) and 53 observations (representative samples) projected simultaneously. These three factors account for 76.8% of the total variance. Factor 1 is discriminated by the Fe–Cu association (AC = 0.33–0.30) which is opposed to the variable Mn (AC = 0.21). Factor 2 is largely concerned by an opposition between Cd (AC = 0.40) and Zn (AC = 0.25) associated with Mn (AC = 0.22). Factor 3 expresses the opposition between Zn (AC = 0.33) and Cu (AC = 0.49).

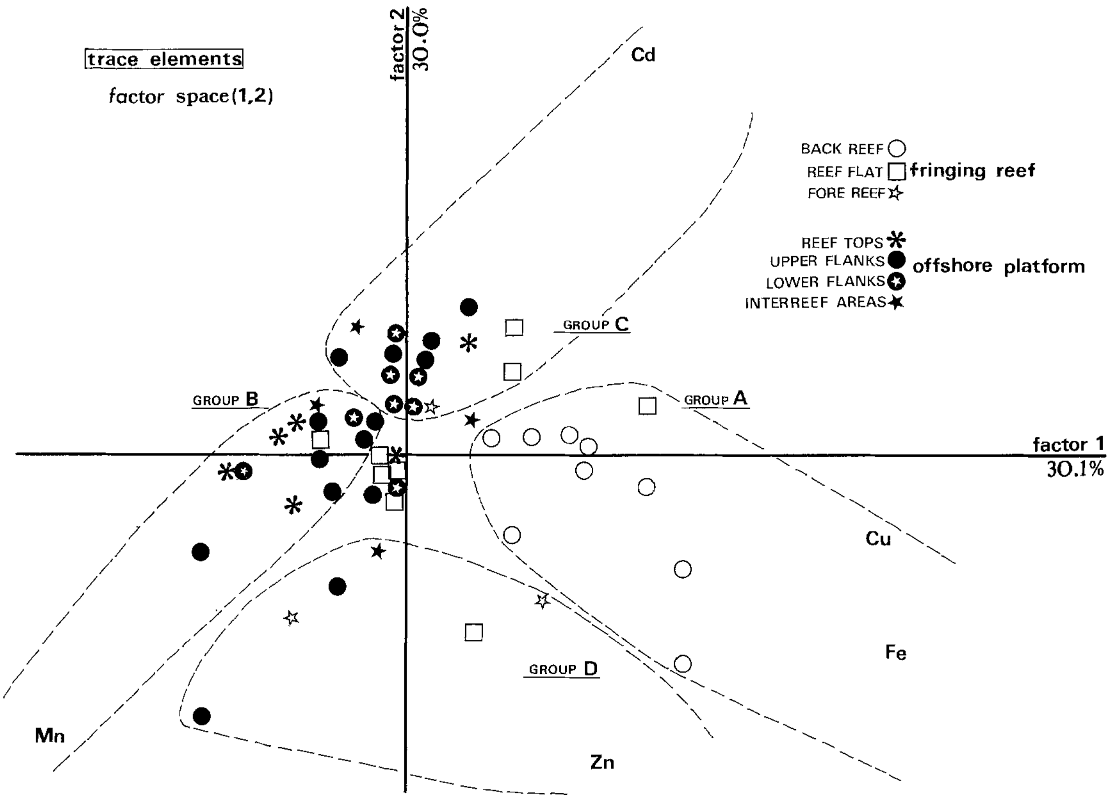


Fig. 25. Principal components analysis. Plot of the first two factors axes. Both 5 variables (trace elements) and 53 observations (samples) are plotted simultaneously. The symbols used (Fe, Mn, Cu, Zn, Cd) are those of the related chemical elements

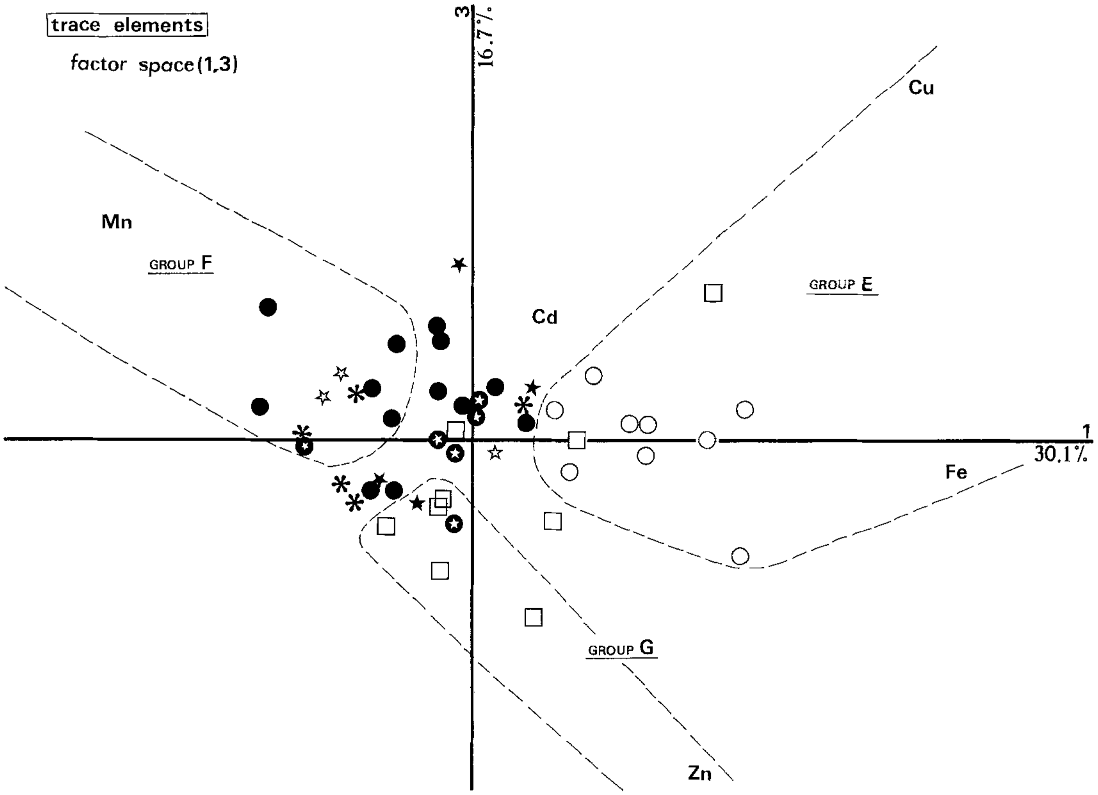


Fig. 26. Principal components analysis. Plot of the factor axes 1 and 3 with 5 variables (trace elements) and 53 observations (samples). See Fig. 25 for the significance of the symbols used

Table 5. Statistics of the foraminiferal types ($\bar{x}$ = mean values; SD = standard deviation; r = range; number in parentheses = number of samples regrouped; values underlined = representative component categories). Identification number of samples falling into each group of foraminiferal types (see Fig. 2 for location of the samples in the study area). *Ammonia-Elphidium* type–*Calcarina-Spiroloculina* subtype: no. 4, 7, 8; *Ammonia-Elphidium* type–*Peneroplis* subtype: no. 5, 6, 9, 13, 14, 15, 17, 18, 51; *Triloculina* type: no. 10, 61, 62; *Amphistegina* type–*Sorites* subtype: no. 46, 47, 48, 71, 72, 75, 82; *Amphistegina* type–*Borelis-Heterostegina* subtype: no. 33, 35, 53, 55, 58, 59, 70, 79

		Spiroloculina	*Quinqueloculina*	*Triloculina*	*Sorites*	*Elphidium*	*Amphistegina*	*Heterostegina*	*Peneroplis*	*Textularia*	*Calcarina*	*Operculina*	*Borelis*	*Eponides*	*Cymbaloporella*	*Ammonia*
Ammonia-Elphidium type																
Calcarina-Spiroloculina subtype (3)	$\bar{x}$	33.9	30.9	–	5.9	11.9	–	–	11.7	–	6.5	–	–	–	–	6.1
	r	15.5–66.7	0 –63.4	–	0 –11.9	0 –33.3	–	–	0 –19.6	–	0–19.6	–	–	–	–	0–18.3
	SD	28.5	31.7	–	6.0	19.2	–	–	10.3	–	11.3	–	–	–	–	10.6
Peneroplis subtype (9)	$\bar{x}$	10.8	21.6	10.8	2.2	14.8	0.8	–	15.3	2.3	1.4	–	–	–	–	20.0
	r	0 –24.0	5.0–36.0	0 –28.9	0 – 6.8	0 –31.8	0 – 7.0	–	3.3–30.7	0 –14.6	0– 6.0	–	–	–	–	0–46.4
	SD	8.7	12.1	11.2	2.7	10.2	2.4	–	9.6	4.8	2.3	–	–	–	–	15.0
Triloculins type (3)	$\bar{x}$	6.9	16.9	21.5	21.0	2.5	2.8	–	12.9	7.7	5.3	0.7	–	–	–	1.8
	r	6.0– 7.4	7.4–22.2	7.5–34.7	8.6–43.9	0 – 7.3	0 – 8.4	–	0 –23.4	2.1–14.8	0–16.0	0–2.1	–	–	–	0– 5.2
	SD	0.8	8.2	13.6	19.9	4.3	4.9	–	11.9	6.5	9.2	1.2	–	–	–	3.0
Amphistegina type																
Sorites subtype (7)	$\bar{x}$	5.8	15.6	7.1	28.8	–	48.2	–	1.7	–	–	0.8	–	2.0	2.1	–
	r	0 –17.7	0 –43.9	0 –50.0	2.2–50.2	–	21.2–82.3	–	0 –11.7	–	–	0–5.8	–	0–14.1	0–8.3	–
	SD	7.6	17.1	18.9	23.1	–	24.0	–	4.4	–	–	2.2	–	5.3	3.7	–
Borelis-Heterostegina subtype (8)	$\bar{x}$	4.4	15.7	6.6	5.1	–	44.5	5.3	0.3	5.0	–	0.9	8.9	1.6	0.3	1.6
	r	0 –12.5	0 –32.9	0 –18.9	0 –12.5	–	32.0–63.6	0–16.1	0 – 2.0	0 –14.8	–	0–7.2	0–31.5	0–12.5	0–2.0	0– 9.0
	SD	5.1	12.1	7.6	4.7	–	12.9	6.2	0.7	4.5	–	2.6	11.4	4.4	0.7	3.3

Five chemotypes can be inferred from the examination of the seven associations of variables and samples defined within the factor spaces (1, 2) and (1, 3). From Groups A and E, the iron-copper type permits the fringing backreef zone mainly to be discriminated, while the reef flat area is concerned by the iron-zinc association (Groups E, G). Sediments from the fringing forereef zone have to be considered transitional, as they belong to a zinc-manganese type (Groups D, F). Indeed, the offshore reef platform is examplified clearly by manganese, associated with cadmium (Groups B, C, F). A manganese type appears to roughly differentiate the upper parts of offshore reef (Groups B, F), whereas the cadmium type concerns the deeper areas of the offshore reef system more specifically (Group C). Table 6 gives statistical values for each geochemical type.

Textural types

With a view to obtain a valuable graphic identification of textural types, correspondence factor analysis was applied to the matrix of grain size data which included 30 variables (weight percentage of sediment within each of the 30 size ranges used) and 67 observations (sediment samples). The resulting first three factors explain 73.8% of the total variance (Figs. 27 and 28). Factor 1 is based on the opposition between the very fine sand classes (0.12 to 0.03 mm) and the gravel-very coarse sand classes (8 to 1 mm). Factor 2 is defined by the medium-fine sand classes (0.5 to 0.16 mm). Factor 3 expresses variations in the range of coarse sands (1.25 to 0.5 mm).

From the five groupings of samples and objects defined in the factor spaces (1, 2) and (1, 3), three textural types can be identified (Table 7); they are roughly related to the main depositional settings. From Groups A and D emerges type 1; this refers to gravels, granules, very coarse and coarse sands, moderately sorted, symmetrically to positively skewed. It principally occurs at the upper parts of offshore reefs and on the fringing reef flat. Related to Group B, type 2 exemplifies medium-fine sands, moderately sorted, and positively skewed. Though they are not preferentially restricted to a given reef area, these sediments are more common at the lower parts of offshore reefal bodies and in the adjacent interreef bottoms. Groups C and E validate type 3 which refers to very fine sands and silts, displaying a generally poor sorting and slightly negative skewness. It is common in the fringing backreef zone and at the foot of the forereef as well as in some upper parts of offshore reefs.

Discussion

Significance of the distribution of the sediment types

The sediment types defined are not found exclusively in any given environment (Tables 4–7). With a view to assess the degree of heterogenity to be expected within each of

Table 6. Statistics of five geochemical types (values are given in p.p.m.; $\bar{x}$ = mean values; SD = standard deviation; r = range; numbers in parentheses = number of samples regrouped). Identification number of samples falling into each geochemical types (see Fig. 2 for location of the samples in the study area). Fe–Cu type: no. 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18; Fe–Zn type: no. 1, 2, 3, 4, 5, 6, 7, 33, 70; Zn–Mn type: no. 43, 56, 60, 61, 62, 67; Mn type: no. 34, 35, 37, 38, 42, 44, 46, 49, 55, 73, 75, 78, 82; Cd type: no. 36, 47, 48, 50, 51, 53, 57, 58, 59, 69, 71, 72, 76, 80

		Fe	Mn	Zn	Cu	Cd
Fe–Cu type (11)	$\bar{x}$	294.5	13.9	12.2	5.9	1.5
	r	147.6–451.2	10.6–19.3	8.1–31.1	4.5–8.2	1.3–1.7
	SD	101.1	2.9	6.8	1.0	0.1
Fe–Zn type (9)	$\bar{x}$	141.1	24.3	9.8	4.8	1.5
	r	57.3–241.5	14.0–44.0	8.8–12.0	2.7–6.4	1.6–1.3
	SD	56.2	11.8	1.7	1.3	0.1
Zn–Mn type (6)	$\bar{x}$	146.5	38.5	20.3	4.8	1.3
	r	53.6–202.4	12.0–68.0	9.8–32.3	2.7–6.4	1.1–1.5
	SD	57.7	19.6	10.1	1.2	0.1
Mn type (13)	$\bar{x}$	86.0	28.3	7.9	4.1	1.5
	r	51.2–119.5	12.6–39.3	6.9– 9.8	3.6–5.4	1.3–1.7
	SD	21.5	11.7	1.0	0.7	0.1
Cd type (14)	$\bar{x}$	89.9	15.0	8.3	4.7	1.7
	r	64.6–169.5	12.0–20.7	6.6–12.2	3.6–5.4	1.6–2.0
	SD	33.9	3.4	1.6	0.7	0.1

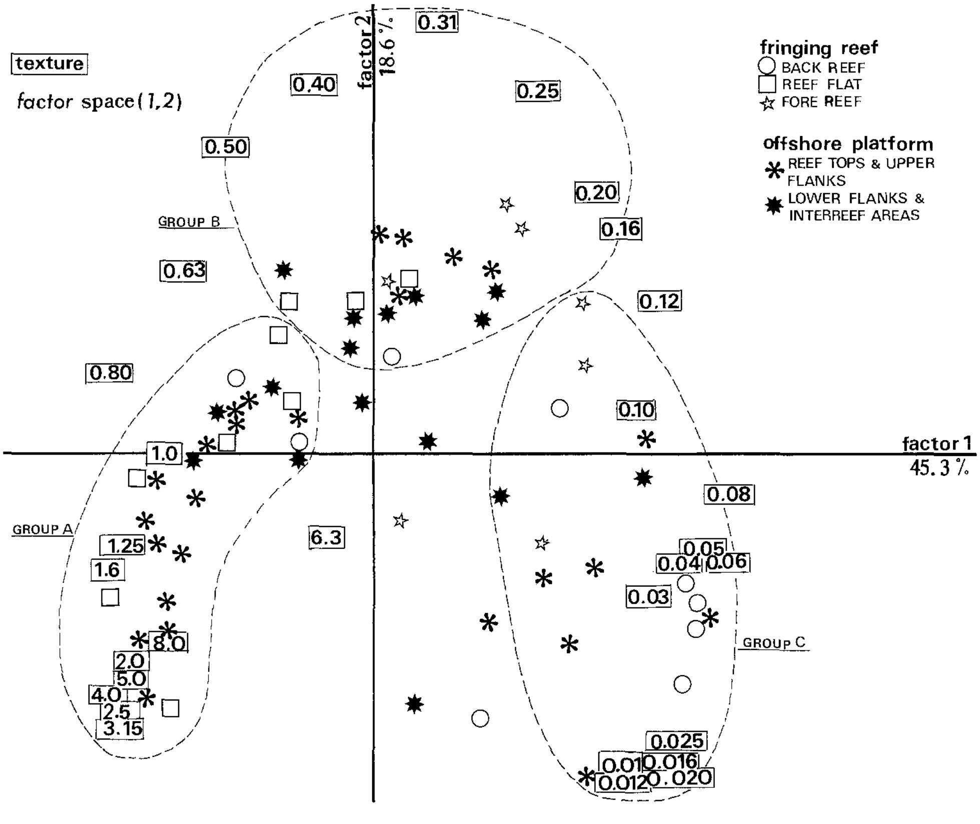


Fig. 27. Correspondence factor analysis. Plot of the first two factor axes. Both variables (30 size classes) and observations (67 samples) are projected simultaneously. Symbols used: the numbers (8.0, 6.3, 5.0 ... 0.012, 0.010) correspond to the 30 size classes of the millimetric scale used

the depositional settings, an attempt is made in the following to integrate in situ observations, experimental evidence and assumptions for each informal sediment types.

(1) Biotypes. The occurrence and distribution of the sedimentary biotypes need to be explained in close relationship with the distributional scheme of the corresponding living benthic communities (basic data from Colontoni and Taviani 1982; Behairy and Jaubert 1983; Montaggioni, personal observation).

The *coral type*, which is restricted to the fringing reef flat, is an over-estimated reflection of the coverage rate of scleractinians and hydrocorals (10–20% of the total

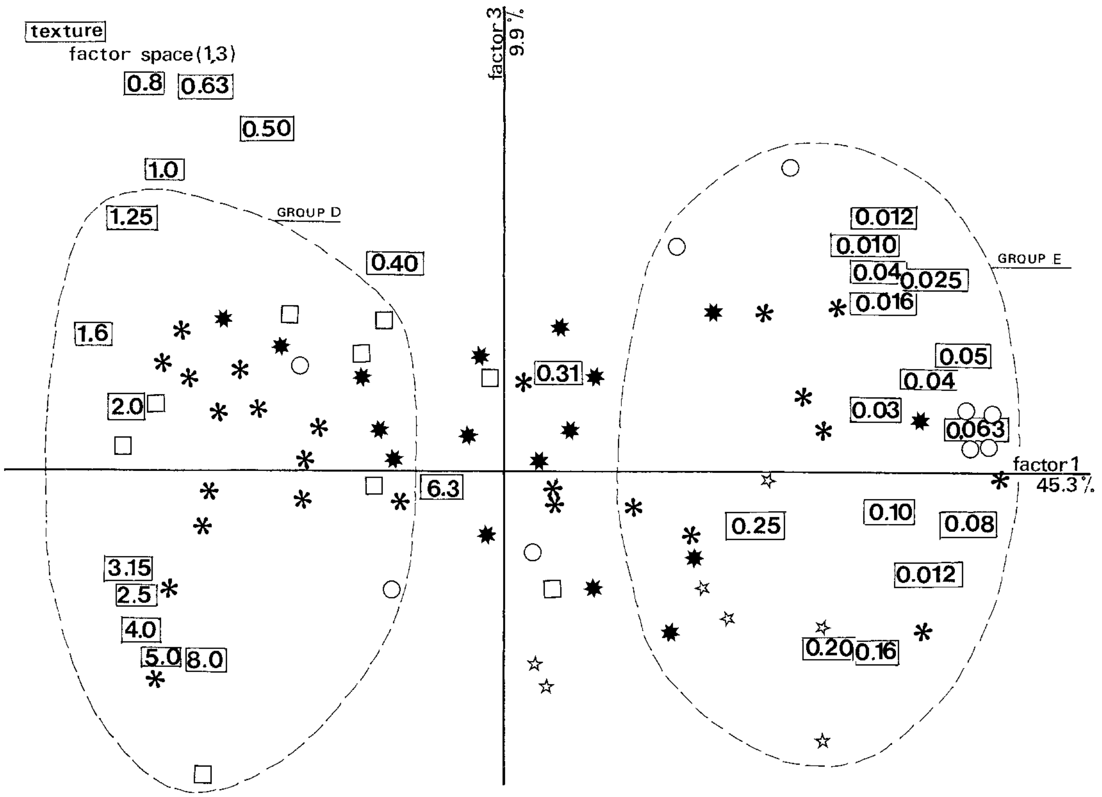


Fig. 28. Correspondence factor analysis. Plot of the factors axes 1 and 3 with 30 variables (30 size classes) and observations (67 samples) are projected simultaneously. See Fig. 27 for the significance of the symbols used

surface available). This is due to the fact that corals are the only substantial sediment contributors in this relatively exposed ecozone, since they compete with smooth algae for substrate. Similarly, the *octocoral (Tubipora)* subtype unfaithfully reflects their role as frame-builders. Although *Tubipora* is found in low abundance (1–2% of the total surface) in shallower sites, it is a profilic producer of skeletal calcium. This is a good example of sedimentogenetic response to physical stress, which emphasizes the complex relation between the degree of resistance of specific tests to disintegration and the clastic productivity of the related organisms.

In the area under study, the distribution of the *coralline algal type* is controlled rather by substrate than by water turbulence. Restricted to the cores of offshore reefs and fringing reefs, it proceeds directly from communities which compete strongly with corals for space. The abundance of coralline particles in reef-core-trapped sediments is a fair reflection of the percent cover of the relevant populations (10–60% of the total surface). This is in accordance with the fact that crustose red algae classically known to be one of the main sediment contributors in modern reef flats and closely adjacent areas (Maxwell 1968; Stoddart 1969).

The differentiation of the *encrusting foraminiferal-bryozoan subtype* is answerable to a similar process. Indeed, although living bryozoans are relegated as minor framework binders in shaded reef sites (Cuffey 1973; Vasseur 1977; Choi and Ginsburg 1983) and, in the present study area, represent less than 1% of the total rock volume, these coelobites release substantial quantities of detritus, particularly on open-water reef fronts, i.e. zones of steeply sloping substrate. Their frequency in sediments, therefore, is a very convenient indicator for proximity of hard surfaces. According to Braithwaite (1982), the central Red Sea region seems to be exemplified by this feature, while reefal sediments from the northern Gulf of Aqaba contain very little bryozoan debris (Erez and Gill 1977; Gabrié and Montaggioni 1982a). Living encrusting foraminifers roughly occupy the same ecological habit as that of bryozoans. The commonest forms in the test area are *Acervulina*, *Miniacina* and *Homotrema*. These act as major framework cementers in or on hard substrates from the Red Sea (Reiss and Hottinger 1984), and mainly contribute to skeletal material in the highest turbulence zones. Related facies systematically typify forereef and adjacent reef flat areas in modern reef systems (Mackenzie et al. 1965; Wallace and Schaferman 1977; Flood et al. 1978; James and Ginsburg 1979; Montaggioni and Mahé 1980; Gabrié and Montaggioni 1982a, b) as well as in ancient counterparts (Buchbinder and Gill 1976; Montaggioni 1982, 1985).

The *molluscan type* is typical of the reef-associated soft bottoms. It is directly superimposed to local mud and sand-inhabiting molluscan assemblages. Despite their relatively low biomass (tissues) values (1.1 to 5.4 dry weight g per m^2), molluscs produce high amounts of carbonate material in the site considered, particularly at

Table 7. Grain size statistics: values of textural parameters in the textural types and mean percentage by mass retained into each class used – numbers in parenthese refer to the number of samples regrouped; values underlined refer to dominant fractions; $\bar{x}$ = mean; r = range; SD = standard deviation. Identification number of samples falling into each textural type (see Fig. 2 for location of the samples in the study area). Type 1 (coarser-sized sediments): no. 1, 3, 4, 5, 6, 7, 10, 18, 35, 37, 38, 43, 44, 45, 46, 47, 57, 59, 64, 65, 66, 67, 69, 73, 76, 78, 82. Type 2 (medium-sized sediments): no. 2, 8, 9, 11, 33, 41, 42, 48, 50, 52, 56, 58, 60, 62, 63, 70, 71, 72, 75, 77, 80, 81; Type 3 (finer-sized sediments): no. 12, 13, 14, 15, 16, 17, 34, 36, 39, 40, 49, 51, 53, 54, 55, 61, 74, 79

		Type 1 (27)	Type 2 (22)	Type 3 (18)
Mean size (mm)	$\bar{x}$	1.20	0.43	0.23
	r	0.58– 3.6	0.31– 0.53	0.04– 0.49
	SD	0.79	0.07	0.12
Sorting	$\bar{x}$	0.38	0.36	0.48
	r	0.23– 0.47	0.27– 0.44	0.23– 0.69
	SD	0.07	0.05	0.12
Skewness	$\bar{x}$	+ 0.032	+ 0.038	−0.022
	r	– 0.04/+0.13	– 0.01/+0.18	– 0.16/+0.10
	SD	0.08	0.09	0.14
Size classes used (in mm)				
Gravels-granules (>2.5)	$\bar{x}$	16.6	4.9	2.1
	r	3.3 –51.8	0.2 –15.9	0.0 – 6.12
	SD	14.4	4.7	2.5
Very coarse sands (2.5–1)	$\bar{x}$	23.2	11.3	8.2
	r	9.6 –29.6	2.9 –22.7	0.5 –26.6
	SD	7.8	5.4	7.0
Coarse sands (1–0.5)	$\bar{x}$	33.1	27.4	15.8
	r	19.4 –62.4	16.1 –36.2	3.61–32.2
	SD	14.8	6.9	9.2
Medium sands (0.5–0.25)	$\bar{x}$	19.1	35.4	19.8
	r	4.4 –29.5	19.5 –51.8	5.4 –34.6
	SD	8.8	9.2	8.2
Fine-very fine sands (0.25–0.05)	$\bar{x}$	7.7	18.4	42.0
	r	0.5 –37.4	0.1 –34.4	14.9 –81.0
	SD	15.1	10.4	19.6
Silts (<0.05)	$\bar{x}$	0.6	0.5	12.0
	r	0 – 4.7	0.0 – 1.7	0.9 –57.3
	SD	1.9	0.5	14.4

the periphery of reef-core environments. This is a normal feature in reefs (Stoddart 1969).

Locally associated with the molluscan type, the *free-foraminiferal type* is restricted to *Amphistegina*-rich, offshore environments. More informative is the distributional pattern of the foraminiferal type defined at a generic level. First, it must be emphasized that the dead assemblages satisfactorily reflect living populations, in spite of sediment mixing by burrowing and sediment influx. As demonstrated by Kitazato (1981), miliolines such as *Spiroloculina* and *Triloculina* live as shallow water epiphytes, while *Ammonia* and *Peneroplis* species frequently dominate shallower, lagoonal assemblages, as mud and hypersalinity-adapted dwellers. In contrast, *Calcarina* lives in relatively higher energy environments. Such a behaviour explains the distribution of foraminifers across the fringing reef system: the microfaunal composition expresses adaptation to both substrate and water turbulence. By comparison, the zonation of foraminiferal types on the offshore platform appears to be dependent mainly on energy. This agrees with Reiss and Hottinger's (1984) observations. These authors reported that, in the Red Sea, the shallow-water *Amphistegina lobifera* develops in zones of higher turbulence, e.g. at the tops of buildups or along their current-swept flanks. *Amphistegina lessonii* dominate the fauna of quieter inter-reef deposits and thus share the habitat of *Heterostegina depressa*. As for *Borelis* and *Sorites*, they live as free or temporarily attached, irrespective of hard or soft surface. Furthermore, it is worthy of note that there is a small-scale geographic isolation between the assemblages in question. Since migration from a substrate type to a remote analogue (for example, from fringing to offshore hard substrates) involves a trip through water masses or travelling down to the sediment, a consistent dissimilarity develops between geographically separated populations; the deep trench which locally parallels the fringing reef line, may act as a barrier. The microfaunal association inhabiting the offshore platform exemplifies open water, well oxygenated environments. It resembles those of largely open reef areas in the Indo-Pacific province: *Amphistegina*, *Heterostegina* and *Sorites* are the dominant forms

(Collins 1958; Todd 1961; Murray 1973; Montaggioni 1981). In contrast, the fringing reef assemblages show a reasonable degree of similarity in the genera types and diversity with those from the Trucial coast of the Persian Gulf (Evans et al. 1973) and from the reef zones of the Gulf of Aqaba (Reiss and Hottinger 1984). All these are *Miliolina*-rich and suggest confined, relatively hypersaline environments.

In conclusion, it can be stated that (1) foraminiferal types replace each other, from the fringing reef to the offshore platform; (2) foraminifers depend on substrate alone or on substrate and water energy simultaneously; (3) foraminifers are relatively independent of depth; (4) the limits of distribution of types coincide locally with limits between vegetated and unvegetated surfaces.

(2) Chemotypes. Considerations of trace element behaviour during deposition indicate that, broadly speaking, the iron-copper-zinc trinomial and the manganese-cadmium binomial form two main anthipathetic groups of parameters, identifying the fringing reef system and the offshore platform system respectively.

Since trace elements are either incorporated into the carbonate or the non-carbonate phases, elemental composition of skeletal sediments infers the original biogenic composition of the material or the accumulation of elements through inorganic flux. Studies carried out in modern carbonate environments (Billings and Ragland 1968; Friedman 1969) showed that the distribution frequency of rare elements result from the different distributions of calcite and aragonite bioclasts respectively, while Wedepohl (1970) and Till (1971) concluded, by way of contrast, that most heavy metals present in carbonates are bound to the terrigenous silicate sedimentary fractions.

In the test area, iron content is correlated with distance from the shore, i.e. concentration increases shoreward. This probably indicates a detrital origin; iron may reach the backreef bottoms in solution or as constituent of clay minerals, generated from the low grade metamorphic rocks and basalts of the Jeddah group (Behairy 1980). Similarly, zinc frequency displays the highest level within the fringing backreef zone. It equals that from the neighbouring shelf sediments which are admixed with metal-rich wadi material (Behairy et al. 1983). Copper concentrations are comparable to values reported from the Aqaba reef sediments (Friedman 1968). These two metals derive presumably from an external source, i.e. Cu–Zn mineralizations which occur onshore in the Tertiary rocks of the coastal plain North of Jeddah, between Yanbu and Aqaba (Skipwith 1973). By comparison with iron, manganese is reversely correlated with distance from the shore, i.e. concentration increases seaward. This strongly supports the fact that this element does not result from a direct deposition of clastic siliceous particles; Mn is probably incorporated into carbonate sites. Cadmium amount in the El Qasr deposits is higher than that found in the marginal shelf silicate-rich sediments around Jeddah (Behairy et al. 1983) and also higher than the background level present in continent-derived material (Turekian and Wedepohl 1961). All these are convincing arguments for the skeletal origin of cadmium in the test area. However, comparison of mean concentration of trace elements between the present study sediments and the major carbonate-secreting reef organisms (see Milliman 1974 for mean abundance data) shows that the distribution frequency of the elements analyzed is strikingly characterized by low levels and broad dispersions. As a consequence, it would be illusive to relate the content of a given element to the taxonomical classification of reef-associated organisms.

Trace element distribution has been used as diagnostic information source for the genetic interpretation of carbonate deposits (see comprehensive discussion in Flügel 1982). Determination of minor element concentration can provide a check on energy index for environments. In the test area, Fe, Cu and Zn, which are more abundant in the coastal silicate-rich sediments, are indicative of lower energy environments, while Mn, which reaches the highest concentrations in open-water reef areas, can be regarded as characteristic of higher-energy zones. Such considerations are quite consistent with data reported from modern carbonate environments (Billings and Ragland 1968; Friedman 1968; Flood et al. 1978) as well as from ancient counterparts; for instance, in Mesozoic rocks from Europe, Bencini and Turi (1974), Coulon (1979) and Pascal (1979) demonstrated that high Mn values generally reflect well oxygenated, high-oxidizing turbulent environments. Besides, Mn content has been useful for differentiating shallow-water and deep water limestones in the fossil record; lower Mn concentration appears to exemplify shallow marine areas (Veizer 1967; Bonnefous and Kubler 1968). Similar conclusions can be drawn from our test area; the overall average concentration of Mn (20 p.p.m.) in the reef complex is significantly lower than that measured by Behairy et al. (1983) in the nearby shelf margin (51 p.p.m.). In contrast, little is known concerning the significance of Cd distribution. St John (1974) stressed that, in the Australian Great Barrier Reef, the typically massive coral forms (poritids, faviids) concentrate more Cd than the typically branching forms (acroporids, pocilloporids). In the site under study, the distributional pattern of corals may explain the coincidence of a Cd facies with the inter-reef areas. Indeed, ramose stylophorids and pocilloporids dominate on the tops of reef bodies, while domal and encrusting forms (faviids and poritids) typify the inter-reef communities.

(3) Textural types. On a reef complex, the pattern of grain size distribution is well known to be dependent on rates of in situ skeletal production, water energy (Stoddart 1969), architecture and hydraulic properties of grains (Maiklem 1968) as well as on the effects of bioturbation (Suchanek 1983; Tudhope and Scoffin 1984; de Vaugelas 1985). In the study area, on reef tops and reef flats where

sediments mainly form superficial and ephemeral pockets of well to moderately sorted, symmetrically to positively skewed, coarse sands, grain size is more strongly governed by physical rather than biological processes. However, the sediments which are trapped into cavities (and which may therefore be preserved in the geological record) are poorly sorted, symmetrically to negatively skewed, medium to fine sands, due to the baffling effect of framework. Similar sediment types occur in reef areas where control of deposition by biological phenomena (burrowing by crustaceans) preferentially operates, e.g. at the surface of thick and perennial sediment bodies from offshore interreef areas, outer sandy spreads and fringing backreef zones.

Three textural types have been identified throughout the test area. This is fairly in accordance with a number of studies on sediments of various present-day reef tracts (Folk and Robles 1964; Stoddart 1969; Flood and Orme 1977; Flood and Scoffin 1978; Flood et al. 1978; Gabrié and Montaggioni 1982a, b). However, contrary to the results obtained from detrital material (Klovan 1966; Chambers and Upchurch 1979), the factor analysis approach of grain size distribution from reefal material cannot be used for adequately separating the major environmental systems of a reef complex. Textural types cannot be regarded as accurate environmental discriminators in reef investigations, since similar textural attributes may be produced in bodies within physiographically different environments.

Defining the facies model

A general facies model can be proposed using as descriptors the major representative sedimentary types (Table 8). The facies defined fit consistently in with the main ecozones and depositional environments. The fringing reef system exhibits a clearly differentiated facies zonation; three successive zonal facies have been recognized: backreef, reef flat and forereef facies. By way of contrast, the offshore knoll platform system has no significant lateral zonation of facies. This is consistent, to a great extent, with the physiographical and ecological attributes of the offshore platform. Knolls and table reefs with poorly zoned surfaces are symmetrically distributed and occur along the sea-facing edge as well as the land-facing edge of the platform. The absence of lateral zonation may be ascribed both to the relatively low diversity of the reef-associated biota which lack the required ecological spectrum (Bouchon, personal communication) and to the apparently homogeneous water energy conditions which prevail across the platform in question. However, just as the offshore buildups are ecologically zoned with respect to depth, distinct sedimentary facies are vertically discernable. These comprise a combined reef-top and upper reef-flank facies and a combined lower reef-flank and inter-reef facies, respectively.

Fossil occurrences of such laterally undifferentiated reef tracts have been reported, for instance, from Mesozoic carbonate sequences (Geister 1984).

Conclusions

1. Facies discrimination emerges from two independent lines of evidence, i.e. skeletal composition and geochemistry of trace elements. The sediment types defined typify five physiographically distinct zones across the Jeddah reef complex: offshore reef-top zone; offshore reef-flank and inter-reef zone; fringing reef flat zone; fringing backreef zone. Biogenic grain types contribute to the identification of these natural zones at different taxonomical levels. Foraminiferal types and assemblages appear to be the best environmental discriminators, since they are significant in terms of both mode of life (free-living forms and encrusters) and taxonomy (generic level). Similarly, the response of trace element distribution to environmental conditions controls the development of two main facies groups (Mn–Cd and Fe–Cu–Zn ones) closely

Table 8. Model illustrating relationships between sediment types, facies and depositional environments

Environments	Offshore reef platform		Fringing reef		
Facies	Reef top and upper reef flank facies	Lower reef flank and interreef facies	Forereff facies	Reef flat facies	Backreef facies
	Coralline algal				
Skeletal component types	*Tubipora*–encrusting foraminiferal-bryozoan	Molluscan–free foraminiferal	Enrcrusting foraminiferal-bryozoan	Coralgal	Molluscan
	Amphistegina			*Ammonia-Elphidium*	
Foraminiferal types	*Sorites*	*Borelis-Heterostegina*	*Triloculina*	*Calcarina-Spiroloculina*	*Peneroplis*
Geochemical types	Mn	Cd	Zn–Mn	Fe–Zn	Fe–Cu
Textural types	Relatively well sorted, coarse sands	Poorly sorted, medium sands	Poorly sorted, fine sands	Relatively well sorted, coarse sands	Poorly sorted, fine sands

related to the different physiographic zones. In contrast, these latter cannot be adequately separated on the basis of textural data.

2. As the Jeddah reef area is controlled by a practically insignificant water energy gradient, lateral facies zonation is weakly differentiated, for biota as well as for sediments. The offshore platform system exhibits one-dimensional facies zonation, i.e. depth-dependent zonation, while the fringing reef system has a bi-dimensional zonation, i.e. vertical and horizontal ones. No large-scale transport of sediments seems to operate across the area considered. This probably explains why the lateral boundaries of the biofacies coincide with those of the relevant organic communities.

3. The facies model so defined may be used as a modern counterpart for symmetrical reef platforms in ancient embryonic shelf margin settings.

Acknowledgements. The present paper is a contribution to the French-Saudi joint research program of cooperation undertaken by the Faculty of Marine Sciences, King Abdulaziz University, Jeddah, and the University of Nice. We gratefully acknowledge financial support by the King Abdulaziz University and the French Foreign Office. Thanks are expressed to the staff of the Faculty of Marine Sciences for their logistic and technical assistance on the project and to Dr. J. Jaubert, co-leader of the program for financial facilities and help in many ways. Dr. C. Gabrié is appreciatively cited for her reliable assistance with sediment component counting and computational treatment of the data. We also thank the two anonymous reviewers whose constructive comments significantly improve this paper.

References

Behairy AKA (1980) Clay and carbonate mineralogy of the reef sediments north of Jeddah, West coast of Saudi Arabia. Bull Fac Sci KAU Jeddah 4:265–270

Behairy AKA, El-Sayed MKh (1983) Bathymetry and bottom relief beyond the reef complex off Jeddah, Red Sea. J Fac Mar Sci Jeddah 3 (1404H):73–80

Behairy AKA, Jaubert J (1983) Ecology of a coral reef complex and a lagoon near Sharm Obhur, Red Sea (Jeddah-Saudi Arabia). Final Rep Joint Res Program KAU-Nice Univ

Behairy AKA, Osman MM, Mesmal AH (1981) Evaporation from the coastal water in front of Jeddah. Jeddah J Mar Res 1:35–45

Behairy AKA, Al-Kholy A, Hashem T, El-Sayed MKh (1983) Preliminary study on the geology and fisheries of the coastal area between Jeddah and Yanbu. J Fac Mar Sci Jeddah 2:1–47 (in Arabic)

Bencini A, Turi A (1974) Mn distribution in the Mesozoic carbonate rocks from Lima Valley, northern Apennies. J Sediment Petrol 14:774–782

Benzécri JP (1973) L'analyse des données. II. L'analyse des correspondances. Dunod, Paris

Berry L, Whiteman AJ, Bell SV (1966) Some radiocarbon dates and their geomorphological significance, emerged reef complex of the Sudan. Z Geomorphol 10:119–143

Billings GK, Ragland PC (1968) Geochemistry and mineralogy of the recent reef and lagoonal sediments south of Belize (British Honduras). Chem Geol 3:135–153

Bonnefous J, Kubler B (1968) Etudes stratigraphiques et géochimiques d'échantillons de terrains jurassiques de Tunisie (région nord-est). Bull Centre Rech Pau SNPA 2:283–319

Braithwaite CJR (1982) Patterns of accretion of reef in the Sudanese Red Sea. Mar Geol 46:297–325

Buchbinder B, Gill D (1976) Numerical classification of multivariate petrographic presence-absence data by association analysis in the study of the Miocene Ziqlag reef complex of Israel. In: Merriam DF (ed) Numerical techniques for analysis of sediments. An international Symposium. Pergamon, Oxford New York Toronto, pp 23–31

Chambers RL, Upchurch SB (1979) Multivariate analysis of sedimentary environments using grain-size frequency distributions. Math Geol 2:27–43

Choi DR, Ginsburg RN (1983) Distribution of coelobites (cavity-dwellers) in coral rubble across the Florida reef tract. Coral Reefs 2:172–173

Coleman RG (1977) Geologic background of the Red Sea. Red Sea Research 1970–1975. Min Resources Bull Jeddah 22C:C1–C9

Collins AC (1958) Foraminifera. Great Barrier Reef Exp 1928–1929. Sci Rep 6:335–437

Colontani P, Taviani M (1982) Morphological and ecological observations in the Sharn Obhor area and nearby coral reefs (Saudi Arabia, Red Sea). 6th Int Sci Symp World Underwat Fed Proc Heriot-Watt 1982:183–192

Coulon M (1979) Milieux de sédimentation, strontium et manganèse dans les calcaires à entroques de Bourgogne (Jurassique Moyen). Bull Soc Géol Fr 7:681–686

Cuffey RJ (1973) Bryozoan distribution in the modern reefs of Eniwetok atoll and the Bermuda platform. Pac Geol 6:25–50

Davis JC (1973) Statistics and data analysis in geology. Wiley, New York London

Davis MV, Erlich R (1970) Relationship between measures of sediment size frequency distribution and the nature of sediments. Geol Soc Am Bull 81:3537–3548

El Sharzy EM (1983) The Red Sea region. In: Nairn AEM, Stehli FG (eds) The ocean basins and margins, vol 6, The Indian Ocean. Plenum, New York London, pp 205–252

Erez J, Gill D (1977) Multivariate analysis of biogenic constituents in recent sediments off Ras Burka, Gulf of Eilat, Red Sea. Math Geol 9:77–98

Evans G, Murray JW, Biggs HEJ, Bate R, Bush PR (1973) The oceanography, ecology, sedimentology and geomorphology of parts of the Trucial coast barrier island complex, Persian Gulf. In: Purser BH (ed) The Persian Gulf. Springer, Berlin Heidelberg New York, pp 233–278

Flood PG, Orme GR (1977) A sedimentation model for platform reefs of the Great Barrier Reef, Australia. Proc 3rd Int Coral Reef Symp 2:111–118

Flood PG, Scoffin TP (1978) Reefal sediments of the Northern Great Barrier Reef. In: Stoddart DR, Yonge CM (eds) The Northern Great Barrier Reef. R Soc London Part A:55–72

Flood PG, Allen J, Orme GR (1978) Multivariate analysis of compositional data of bioclastic carbonate sediments from Lady Musgrave Reef, Great Barrier Reef, Australia. Proc 25th Int Geol Congr. Pergamon, London, pp 1–19

Folk RL, Robles R (1964) Carbonate sands of Isla Perez, Alacran Reef complex, Yucatan. J Geol 72:225–292

Flügel E (1982) Microfacies analysis of limestones. Springer, Berlin Heidelberg New York

Friedman GM (1968) Geology and geochemistry of reefs, carbonate sediments and waters, Gulf of Aqaba, Red Sea. J Sediment Petrol 38:895–919

Friedman GM (1969) Trace elements as possible environmental indicators in carbonate sediments. Soc Econ Paleontol Mineral Spec Publ 14:193–198

Gabrié C, Montaggioni LM (1982a) Sedimentary facies from the modern coral reefs, Jordan Gulf of Aqaba, Red Sea. Coral Reefs 1:115–124

Gabrié C, Montaggioni LM (1982b) Sediments from fringing reefs of Reunion island, Indian Ocean. Sediment Geol 31:281–301

Geister J (1984) Bajocian coral reefs of the Northeastern Paris Basin: paleoecological aspects. Int Soc Reef Stud, Joint Meet Miami 1984:36–37 (abstr)

Ginsburg RN, James NP (1974) Holocene carbonate sediments of continental shelves. In: Burk CA, Drake CL (eds) The geology of continental margins. Springer, Berlin Heidelberg New York, pp 137–157

Guilcher A (1955) Géomorphologie de l'extrémité septentrionale du banc corallien Farsan (Mer Rouge). Ann Inst Oceanogr Paris 30:55–100

Guilcher A (1982) Physiography of the Red Sea coast and coastal waters: a summary of the present state of knowledge, with suggestions for further research. J Fac Mar Sci Jeddah 2 (1402H):27–36

Isphording WC (1972) Analysis of variance applied to measures of central tendency and dispersion in sediments. J Sediment Petrol 42:107–221

Jado AR, Zötl JG (1984) Quaternary period in Saudi Arabia, vol 2. Springer, Wien New York

James NP (1983) Reef environment. In: Scholle PA, Bebout DG, Moore CH (eds) Carbonate depositional environments. Am Assoc Petrol Geol Mem 33:345–440

James NP, Ginsburg RN (1979) The seaward margin of Belize barrier and atoll reefs. Int Assoc Sedimentol Spec Publ 3:1–196

Jöreskog KG, Klovan JE, Reyment RA (1976) Geological factor analysis. Methods in geomathematics, vol 1. Elsevier, Amsterdam

Klovan JE (1966) The use of factor analysis in determining depositional environments from grain size distributions. J Sediment Petrol 36:115–125

Kitazato H (1981) Observation of behavior and mode of life of benthic foraminifers in the laboratory. Geosci Rep Shizuoka Univ 6:61–71

Laporte LF (1974) Reefs in time and space. Soc Econ Paleontoe Min Spec Publ 18:1–256

Longman MW (1981) A process approach to recognizing facies of reef complexes. In: Toomey DF (ed) European fossil reef models. Soc Econ Paleontoe Min Spec Publ 30:9–40

Mackenzie FT, Kulm LD, Cooley RL, Barhart JT (1965) *Homotrema rubrum* (Lamark), a sediment transport indicator. J Sediment Petrol 35:265–272

Maiklem WR (1968) Some hydraulic properties of bioclastic carbonate grains. Sedimentology 10:101–109

Maxwell WGJ (1968) Atlas of the Great Barrier Reef. Elsevier, Amsterdam

Milliman JD (1974) Marine carbonates. Springer, Berlin Heidelberg New York

Montaggioni LM (1981) Les associations de foraminifères dans les sédiments récifaux de l'archipel des Mascareignes (Océan Indien). Ann Inst Océanogr Paris 57:41–62

Montaggioni LM (1982) Pleistocene marine depositional environments from Mauritius island, Indian Ocean. Geobios 15:161–179

Montaggioni LF (1985) Makatea island, Tuamotu archipelago. Proc 5th Int Coral Reef Symp 1:103–158

Montaggioni LM, Bouchon C (1984) Morphogenesis of a modern knoll reef platform, Saudi Arabian shelf margin, Jiddah area, Red Sea. 5th Eur Reg Meet Sediment Marseille 292 (abstr)

Montaggioni LM, Mahé J (1980) Caractérisation faciologique des sédiments récifaux de l'île Maurice par l'analyse factorielle des correspondances. Oceanol Acta 3:409–420

Murray JW (1973) Distribution and ecology of living benthic foraminiferids. Heinemann, London

Pascal A (1979) Utilisation des éléments trace dans la caractérisation des paléomilieux sédimentaires urgoniens basco-cantabriques. Geobis Mem Spec 3:331–345

Reiss Z, Hottinger L (1984) The Gulf of Aqaba: ecological micropaleontology. Springer, Berlin Heidelberg New York Tokyo

Robinson P (1980) Determination of calcium, magnesium, manganese, strontium, sodium and iron in the carbonate fraction of limestones and dolomites. Chem Geol 28:135–146

Skipwith P (1973) The Red Sea and coastal plain of the kingdom of Saudi Arabia: a review. Minist Petrol Min Resources Techn Rec TR-1973 1:149

St John BE (1974) Heavy metals in the skeletal carbonate of scleractinian corals. Proc 2nd Int Coral Reef Symp 2:461–469

Stoddart DR (1969) Ecology and morphology of recent coral reefs. Biol Rev 44:433–498

Suchanek TH (1983) Control of seagrass communities and sediment distribution by *Callianassa* (Crustacea, Thalassinidea) bioturbation. J Mar Res 41:281–298

Till R (1971) Are there geochemical criteria for differentiating reef and non reef carbonates? Am Assoc Petrol Geol Bull 55:523–528

Todd R (1961) Foraminifera from Onotoa atoll, Gilbert islands. US Geol Surv Prof Pap 354-H:171–191

Toomey DF (1981) European fossil reef models. Soc Econ Paleontoe Min Spec Publ 30:546

Tudhope AW, Scoffin TP (1984) The role of *Callianassa* bioturbation in the preservation of lagoon sediments, Davies Reef, Great Barrier Reef, Australia. J Sediment Petrol 54:1091–1096

Turekian K, Wedepohl KH (1961) Distribution of the elements in the major units of the earth's crust. Am Geol Soc Bull 72:175–192

Vasseur P (1977) Cryptic sessile communities in various coral formations on reef flats in the vicinity of Tuléar (Madagascar). Proc 3rd Int Coral Reef Symp 1:95–100

Vaugelas J de (1985) Sediment reworking by Callianassid mud-shrimp in tropical lagoons: a review with perspectives. In: Gabrié C, Harmelin-Vivien M, Salvat B (eds) Proc 5th Int Coral Reef Symp 6:617–622

Veizer (1967) Employing of semi quantitative spectral analysis for stratigraphic and lithofacial investigation in limestones from the Mantle series of the High Tatra Mounts. Geol Sbornik 18:79–85

Wallace RJ, Schafersman SD (1977) Patch reef ecology and sedimentology of Glovers reef atoll, Belize. In: Frost SH, Weiss MP, Saunders JB (eds) Reefs and related carbonates ecology and sedimentology. Am Assoc Petrol Geol Stud Geol 4:37–52

Wedepohl KH (1970) Geochemische Daten von sedimentären Karbonaten und Karbonatgesteinen in ihrem faziellen und petrogenetischen Aussagewert. Verh Geol Bundesamt 4:692–705

Wilson JL (1975) Carbonate facies in geologic history. Springer, Berlin Heidelberg New York