Journal of Coastal Research	18	2	316–328	West Palm Beach, Florida	Spring 2002

Microfacies of Spaanse Water Bay, Curaçao (Netherlands Antilles), with Special Reference to Benthic Foraminifera

Bogumila B. Klosowska, Jan E. van Hinte, Simon R. Troelstra†, and Cees Laban‡

†Faculty of Earth Sciences
Vrije Universiteit
De Boelelaan 1085
1081 HV Amsterdam
The Netherlands

‡NITG-TNO
P.O.Box 80015
3505 TA Utrecht
The Netherlands

ABSTRACT

KLOSOWSKA, B.B.; VAN HINTE, J.E.; TROELSTRA, S.R., and LABAN, C., 2002. Microfacies of Spaanse Water Bay, Curaçao (Netherlands Antilles), with special reference to benthic foraminifera. *Journal of Coastal Research*, 18(2), 316–328. West Palm Beach (Florida), ISSN 0749-0208.

Fifty-one sediment samples from a shallow (<15 m) bay of Curaçao, Spaanse Water, were clustered based on their components and grain size. Three main biofacies, in geographically distinct areas of the bay, are recognized. One, the *Halimeda* Facies, dominated by the remains of the calcareous alga *Halimeda* (70%), is related to coarse sediments (coarse and fine sand) and frames the coastal, shallow areas of the bay. Another, the Ostracod Facies, shows a high ostracod (46%), echinoid spine (11%) and foraminifer (17%) content, and is related to fine sediments, which cover the central basin, the eastern part and the channel of the bay. The third, Gastropod-*Halimeda* Facies, is restricted to the western part of the bay and characterized by a poor microfauna and a relatively high percentage of gastropods (20%). It comprises coarse sediments with a relative scarcity of the finest material and with common dark, coated grains. The Gastropod-*Halimeda* Facies is shown to be a "relict" of the rich *Halimeda* Facies. Its distribution coincides with an area of intense boating activity.

Benthic foraminifera are widely distributed and make up 4–30% of the skeletal components. The assemblages are often related to the recognized facies. Increased abundances of the large, algal symbiont-bearing species as well as *Elphidium poeyanum* and *E.discoidale* are associated with the *Halimeda* Facies, while *Ammonia tepida, Nonion grateloupii, Reussella simplex* and small, thin-shelled miliolids dominate the foraminiferal assemblage of the Ostracod Facies. The distribution pattern of foraminiferal assemblages appears to be related primarily to the nature of substrate (grain size) and light penetration (depth). The highest abundance (50%) of *Ammonia tepida* is found in mangrove areas, where samples contain vegetable matter.

ADDITIONAL INDEX WORDS: *Microfauna, sediments grain-size, cluster analysis.*

INTRODUCTION

Investigations of recent shallow-water carbonate sediments mostly concentrate on large oceanic platforms and reef complexes or focus on specific biological or sedimentological problems. There is relatively little quantitative information on small-scale (hundreds of meters to a few kilometres) carbonate environments. The study of the Spaanse Water bay (Curaçao) illustrates the relationship between depositional environment and sedimentary facies distribution, which exists in a modern embayment, immediately adjancent to the coral reef. The modern coastal environment is the result of interaction of physical and biological processes including the results of human activities. The first objective of our study is to provide the baseline data to interpret the fossil record, i.e. to reconstruct the Holocene development of Curaçao's bays. Also, with the still increasing pressure for further urbanization and development of the bay's coastline, the data can serve as a reference to evaluate the effects of future man-induced disturbance.

A number of earlier studies provide information on the flora (VAN DEN HOEK *et al.*, 1972; KUENEN and DEBROT, 1995; DEBROT *et al.*, 1998) and fauna (VAN DER HORST, 1927; ROSS, 1964, 1971; BAK, 1975; FRANSEN, 1986) of the bay. HOFKER (1964, 1971, 1976) described the foraminiferal fauna from three bays of Curaçao: the Piscaderabaai, Spaanse Water and Fuikbaai. However, a quantitative and ecological study of the benthic foraminifera of the area has never been made.

The present study describes the sedimentary facies and investigates possible correlations between sedimentary components, particle size and depositional environments. The sedimentary facies were discriminated on the basis of grain size, skeletal components, and foraminiferal taxa and assemblage distributions. Cluster analysis was applied to the component and grain-size data to examine possible correlations and define statistically recognizable sediment types.

00167 received 24 November 2000; accepted in revision 3 January 2002.

STUDY AREA

Curaçao is a 444 km^2 large oceanic island, situated about 70 km off the coast of Venezuela, in the southern Caribbean Sea (Figure 1). Its highest point Christoffelberg (375 m) lies in the western part of the island. Around Curaçao the 200-m isobath lies about 1 km off the coast (Figure 1B). The island is directly exposed to the easterly trade winds, which are nearly constant in strength and direction during the whole year. The longitudinal axis of the island runs roughly from southeast to northwest. This causes large differences between the exposed northeast coast and the sheltered southwest coast. There is usually a northwest current along the southwest coast of Curaçao with a velocity rarely exceeding 1 knot. However, the same current on the northeast coast, as well as the currents around the tips of the island, can be much stronger. The island is just south of the most southerly hurricane-tracks, but occasionally some cyclones exert their influence and cause heavy damage in the shallow coastal areas. The mean annual temperature is about 27°C, the difference between highest and lowest monthly means rarely exceeds 4°C. The island falls within the area of low rainfall; mean annual rainfall is less than 700 mm.

The shoreline of the island is interrupted by several characteristic, hand-shaped inland bays. The origin of these bays is related to Holocene sea-level rise. They are considered to be drowned Pleistocene erosional valley-systems, which developed when the sea level was at least 20 m below present level. During the postglacial sea-level rise these valley-systems drowned and large inland bays developed, connected with the open sea through narrow passages (De Buisonjé, 1974). Differential erosion of the rocks during a time of lower sea level caused the characteristic shape of the valleys and consequently the bays.

One of these bays is the Spaanse Water, a shallow (<15 m deep) inshore bay on the southeastern coast of the island (Figure 1C). The bay has a narrow (approximately 100 m wide), relatively deep (max 19 m) channel connection to the open sea and southeastern fringing reefs of the island. Its total surface area is approximately 3.19 km^2. A significant proportion of the bay's coastline (about one fourth) is urban, and the bay is used extensively by numerous yachts as an anchorage. Most of the surrounding area of the bay consists lithologically of Early Cretaceous volcanic rocks namely basalts and diabaze. The islands of the bay, southern coasts and the surroundings of the channel, with hills up to 80m high, consist of coral limestones of Neogene and Quarternary in age. Annual ranges in physical parameters in the bay are as follows: surface water temperature varies between 26°C to 29°C; salinity from 34–39‰ and the pH level is constant at 8.1. The transparency is relatively low, secchi-disc values: 2.1–2.8 m in the central area of the bay (De Kock and De Wilde, 1964; Djohani and Klok, 1988). The restricted range of salinities signifies the oceanic nature of the bay. The diurnal tidal range is little more than 30 cm throughout the year (De Haan and Zaneveld, 1959).

The bay lies within the Curaçao Underwater Park and contains its largest mangrove areas and seagrass and algal meadows, mostly *Thalassia* and *Halimeda* (Kuenen and Debrot, 1995). Such areas are widely recognized as key components of the nearshore marine ecosystems, serving as a nursery and feeding areas for fish fauna and other (juvenile) organisms.

MATERIAL AND METHODS

Thirty-nine sediment surface samples were collected in June 1996 during geological investigations carried out by the Geological Survey of the Netherlands (TNO) around Curaçao (Figure 1C). In June 1999, twelve complementary samples (sw1-sw12) were taken and salinity, temperature and pH were measured.

For grain size analysis, subsamples of approximately 0.5–5 g were selected from 36 sediment samples. A FRITSCH "Laser Particle Sizer" A22[2] was used for analysis. The measured size range is: 0.15–2000 μm. Organic carbon was removed prior to the grain-size analysis by treatment with 30% H_2O_2. Details on the particle sizer used are given in Konert and Vandenberghe (1997).

For the component analysis, equal amounts (25 ml) of all 51 sediment samples were gently washed on a 63 μm-mesh sieve to remove the clay, and were subsequently oven dried. The dry material was then sieved over mesh sizes: 125 μm, 500 μm and 2000 μm and split with a microsplitter to reduce the amount of sediment for analysis. Approximately 300 randomly spread grains from each of two fractions (125–500 μm and 500–2000 μm) were examined under a stereomicroscope, giving a quantitative record of the various biota in the residue. The grains were catalogued in 15 component types, *i.e.,* lithic grains, *Halimeda* and other green algae, coralline algae, bivalves, gastropods, worm tubes, echinoid spines, foraminifers, ostracods, coral fragments, gorgonians, bryozoans, sponge spicules, pteropods, fecal pellets. In addition, from the fractions >125 μm, approximately 200 specimens of foraminifera (live and dead undifferentiated for this study) were picked and identified at generic or species level. The various taxa are expressed as percentage values of the total foraminiferal population of the station.

All cluster analyses in this study were computed with the statistical analysis software package NCSS 6.0.1.

RESULTS

Sediment Texture and Composition

Sorting of the sediments, expressed by the mean square deviation is generally between very poor and poor (1.5–3.37 phi) (Folk and Ward, 1957). The coarsest sediments (<1, 1–2 phi) are found in northern, coastal areas and a larger area in the western part of the bay. Finer sediments dominate in the channel, central basin and eastern part of the bay. Whereas most of these samples have values between 3 and 6 phi, in the central basin and in the inner channel the mean values are >6 phi, representing by far the finest sediments of the bay.

To obtain a more quantitative graphic identification of textural types a hierarchical cluster analysis was carried out using all grain size data (Figure 2). Seven clusters were distinguished. In Figure 2B, clusters 1 and 2 are pooled because

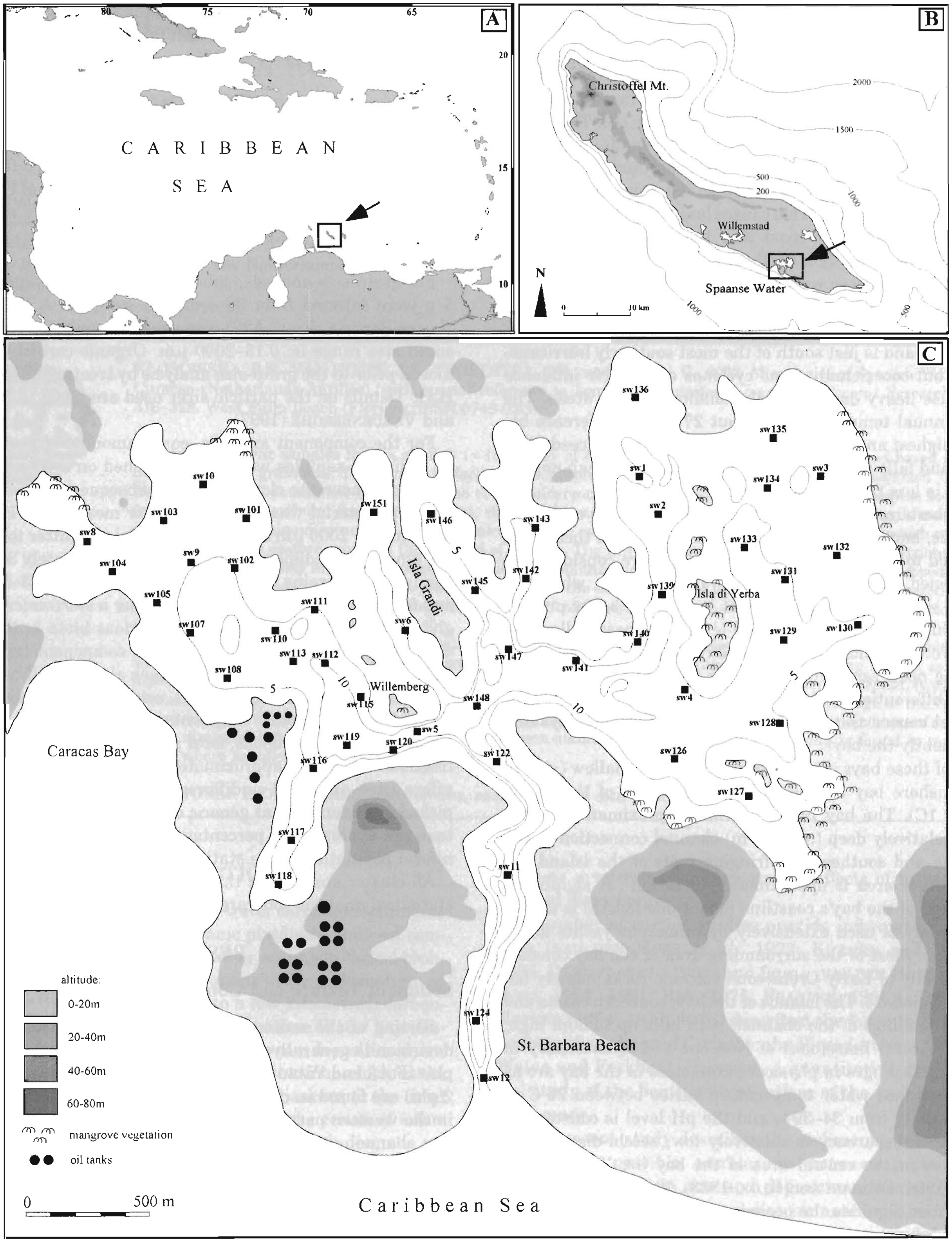

Figure 1. Maps of the Caribbean region (A), Curaçao island (B) and the Spaanse Warer bay (C), the latter showing bathymetry at 5 m intervals and sample locations.

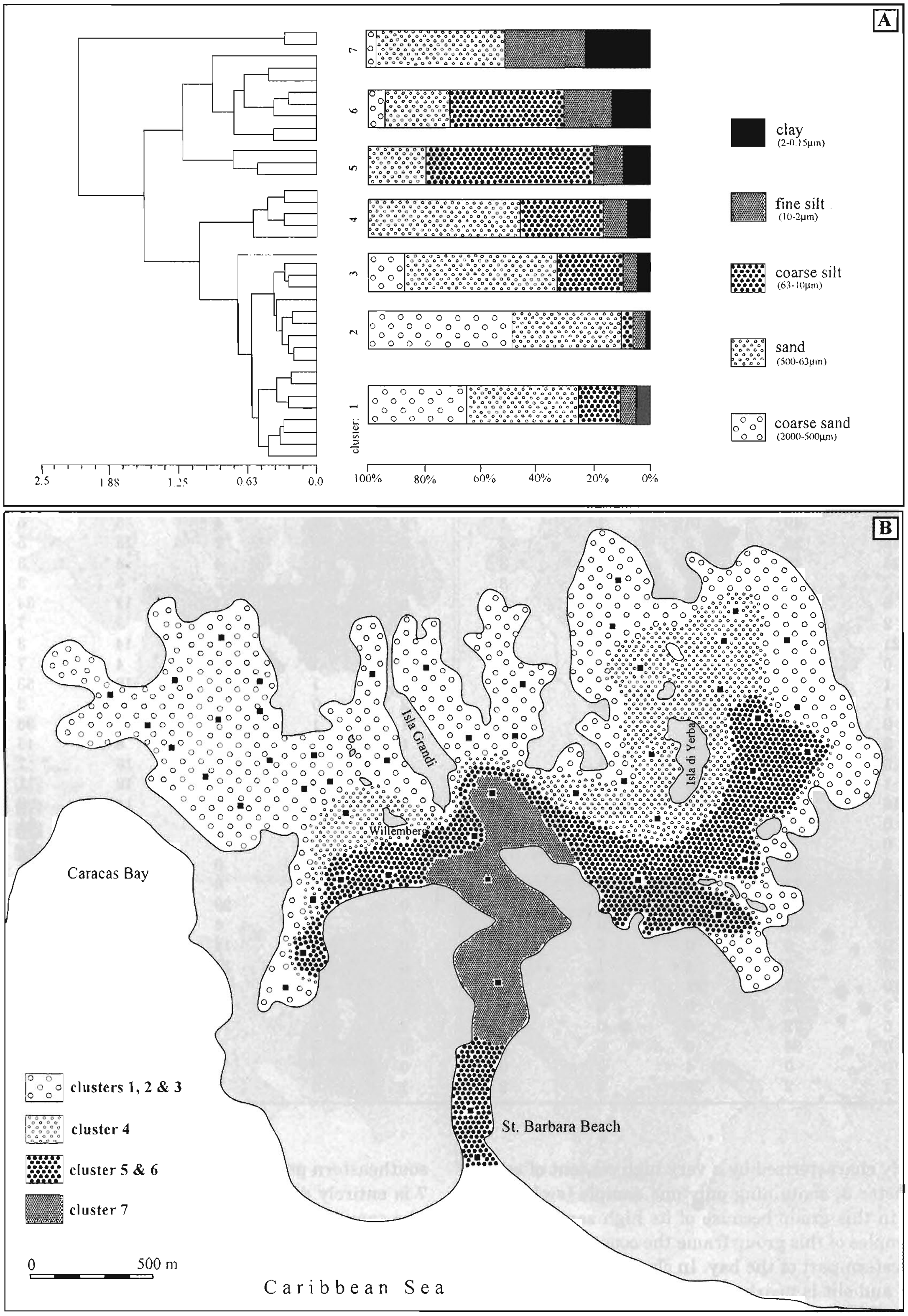

Figure 2. A. Dendrogram of a hierarchical cluster analysis of grain size data combined with the frequency distribution of coarser sand, sand, coarser silt, finer silt and clay. B. Distribution of the clusters of the cluster analysis of grain size data.

Table 1. *Relative abundance (%) of the main components of the Spaanse Water bay samples.*

Samples	Lithic Grains	Halimeda	Coralline Algae	Bivalves	Gastropods	Worm Tubes	Sponges	Echinoid Spines	Forams	Ostracods	Fecal Pellets
sw101	8	72	7	0	1	1	0	0	7	4	0
sw102	16	53	8	1	1	3	1	1	9	4	0
sw103	6	64	3	1	1	3	0	1	16	4	0
sw104	4	75	3	0	1	2	0	0	10	4	0
sw105	9	74	3	1	2	3	0	0	4	4	0
sw107	6	44	7	2	2	3	0	1	30	4	0
sw108	8	43	8	2	5	8	0	1	19	4	0
sw110	6	49	19	2	5	5	0	1	10	1	0
sw111	8	27	17	3	14	7	1	2	17	2	0
sw112	20	28	2	4	13	10	0	3	12	6	0
sw113	1	60	6	5	2	2	1	3	12	6	0
sw115	15	31	4	3	14	3	0	4	15	10	0
sw117	12	36	11	1	9	3	0	2	15	10	0
sw116	5	47	7	1	6	6	0	2	19	2	0
sw118	10	44	8	1	9	8	0	1	15	2	0
sw119	2	39	8	5	7	1	1	7	11	15	0
sw120	8	8	1	2	11	0	3	9	21	31	2
sw122	1	20	14	5	3	1	2	3	13	34	0
sw124	15	10	34	0	0	1	2	1	13	15	0
sw126	0	1	1	2	4	0	0	6	14	72	0
sw127	9	38	8	0	3	3	0	6	14	9	7
sw128	1	6	2	3	4	0	0	13	18	52	1
sw129	15	49	18	1	1	2	0	4	5	5	0
sw130	45	28	2	0	2	2	0	2	13	5	0
sw131	26	46	3	2	3	4	0	4	8	3	0
sw132	7	69	2	2	3	1	0	5	8	3	0
sw133	6	24	2	3	1	0	0	17	12	34	0
sw134	2	54	16	1	2	1	0	7	9	7	0
sw135	21	46	7	0	2	3	0	4	14	3	0
sw136	0	84	2	0	0	0	1	2	4	7	0
sw139	1	8	1	1	1	0	1	14	18	53	3
sw140	1	69	10	3	2	2	0	4	6	2	0
sw141	0	22	21	2	4	1	1	1	12	36	0
sw142	2	52	9	2	5	1	0	5	8	15	0
sw143	3	50	4	1	12	6	0	1	16	7	0
sw145	1	30	15	1	13	5	0	3	19	11	0
sw146	16	56	3	1	3	4	0	2	11	3	0
sw147	0	12	19	4	3	1	1	3	14	34	8
sw148	0	0	1	0	3	0	0	2	21	67	4
sw151	3	83	0	0	2	1	0	0	3	8	0
sw1	1	73	6	0	0	1	0	0	8	10	0
sw2	1	3	1	0	1	0	0	29	22	44	0
sw3	6	68	6	0	0	1	0	4	10	5	0
sw4	0	0	0	3	1	0	0	14	16	65	2
sw5	3	7	4	1	9	0	0	11	18	39	4
sw6	0	27	12	2	14	12	0	0	28	5	0
sw8	3	77	0	0	0	1	0	0	17	1	0
sw9	5	72	5	0	3	4	1	1	6	3	0
sw10	0	84	0	0	0	0	0	0	4	10	0
sw11	0	0	4	0	0	0	5	0	14	75	0
sw12	1	2	25	1	2	1	0	1	6	14	0

they are clearly characterized by a very high content of sand (70–90%). Cluster 3, containing only one sample (sw143) is also included in this group because of its high sand content (67%). The samples of this group frame the coastal areas, and most of the western part of the bay. In cluster 4, the relation between sand and silt is nearly equal (52% vs. 48%). Coarse sands (fractions: >500 μm) do not occur in this cluster. The distribution of samples of this cluster is related to inner parts of the bay. In Figure 2B, clusters 5 and 6 are also combined; they are clearly characterized by a high silt content (70–80%). The samples of these clusters are from southern, especially southeastern parts of the bay, and the outer channel. Cluster 7 is entirely dominated by the silt and clay fractions (95%). The samples of this cluster cover the middle part of the central basin and the inner channel.

Concerning the component analysis, nearly all of the 15 distinguished grain categories represent skeletal particles, composing more than 95% of the sediments of the bay (Table 1). Fragments of green calcareous algae, represented exclusively by the genus *Halimeda,* are the most dominant particles in the bay (Figure 3A). They occur in most samples, but vary considerably in abundance. Areas with about 70% and

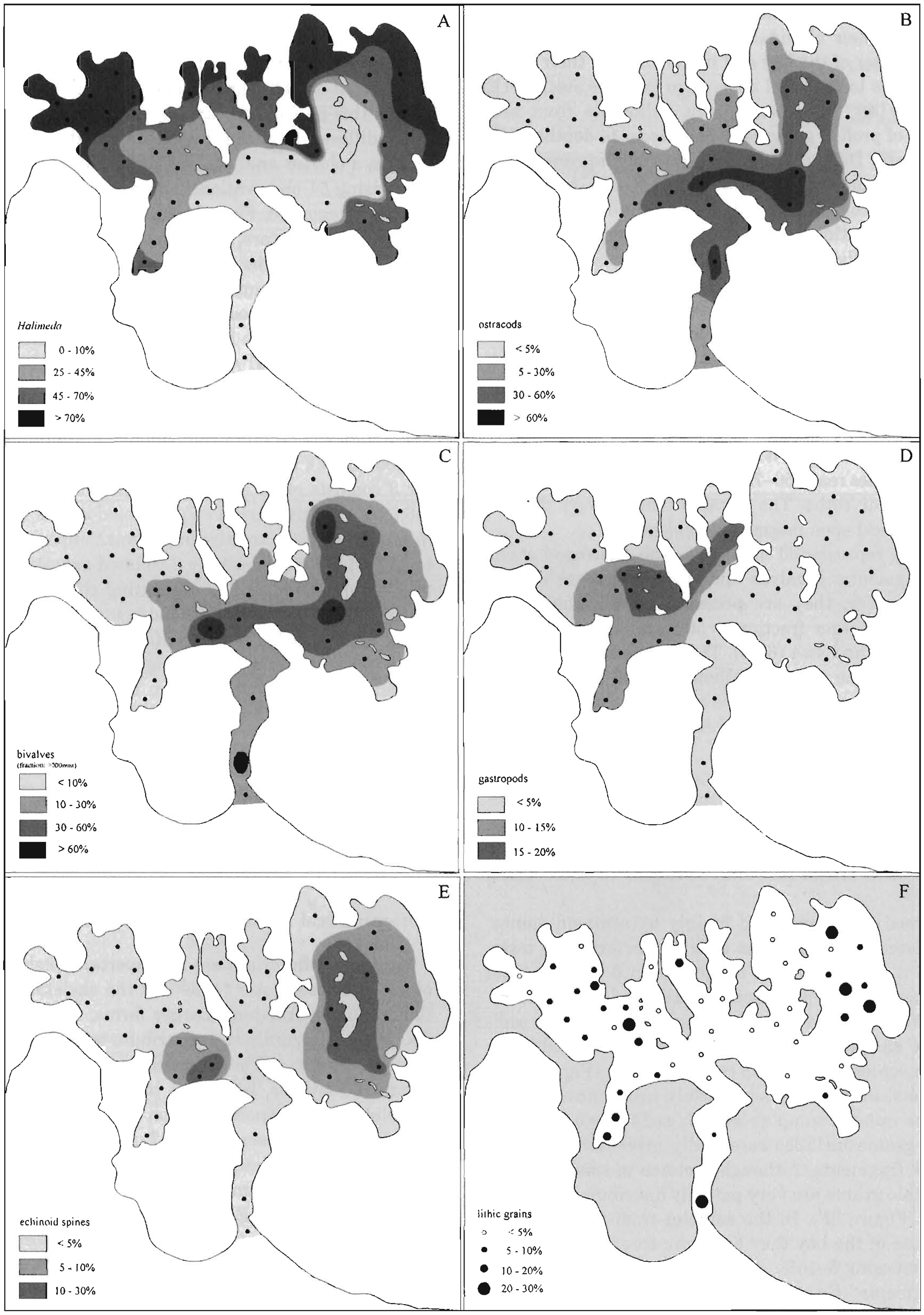

Figure 3. Frequency distribution of selected sediment componets (>125 μm).

more are restricted to the northern coastal parts of the bay, especially in the northeast and northwest. Also in the west part of the bay their abundances remain high, up to 50%. Towards the center of the bay and in the channel their abundance diminishes to practical absence in samples sw4, sw11, sw126 and sw148. In general, only sediments from and around areas of prolific growths of *Halimeda,* to depths of 5–6m (KUENEN and DEBROT, 1995), are rich in the remains of this alga. Calcareous algae are also represented, to a much lesser extend, by coralline red algae. Coralline algae show a very patchy distribution and are only locally important in the sediments. Generally, the frequency of coralline algae is less than 5%, with the exception of samples sw124 and sw12 (outer channel), containing 34% and 25% respectively. A larger continuous area, which contains percentages >15% is located to the east and to the west of Isla Grandi, as well as a few isolated samples (sw117, sw129, sw134).

Ostracods are present throughout the bay. The average amount makes this group the second most abundant of all particle categories (Figure 3B). Whereas generally about 10%, the maximal frequencies reach 50–75% in the channel, central basin and around Isla di Yerba. The ostracod fauna is very diverse, consisting of typical open marine assemblages.

Mollusca are represented by bivalve and gastropod shells and their fragments. Bivalves and their fragments remain below 3%, however, they are present in remarkably high quantities in the larger fraction (>500 μm) of samples sw2 (95%), sw5 (77%) and sw4 (67%). These samples are located in the vicinity of the islands Willemberg and Isla di Yerba (Figure 3C). Very low values were registered in areas characterized by high percentages of *Halimeda, i.e.,* along the coasts and in the west parts.

The frequencies of gastropods in most areas are low. However, in areas around Isla Grandi they become more significant, constituting up to 20% of the sediment. The distribution of worm tubes closely follows that of gastropods; worm remnants make up to 3% of the total sediment in those areas (Figure 3D).

Echinoderms are represented mainly by echinoid spines, rarely by plates and fragments of irregular echinoid tests. The amount is highly variable ranging from 0 to 28% of the >125 μm fraction. The distribution pattern of this group resembles that of bivalves and ostracods. Generally, the sediments of the eastern part of the bay and the central basin are richer in echinoids than the rest of the bay (Figure 3E).

Fecal pellets, although quantitatively insignificant, reach 7–8% in some isolated samples (sw127, sw147, sw5). The category lithic grains includes essentially green and greenish volcanic rock fragments. Although common in some samples (20–30%), lithic grains are very patchily distributed throughout the bay (Figure 3F). In the samples from the northeast and west parts of the bay they are more frequently present, generally composing 5–15%.

Coral fragments, Bryozoa, sponges, pteropods, crab and fish fragments (in the form of fish teeth) constitute a very small fraction of the sediments and their general distribution is not discussed.

The skeletal components of most of the samples are very fresh. In the samples from the central-west part of the bay (to the north and the south of Isla Grandi), however, the grains show some abrasion of sharp edges and are dark grey rather than white (samples: sw6, sw107, sw108, sw110, sw111, sw112, sw116, sw118, sw145, sw146), which may be interpreted as relict grains and suggest very low accumulation in this part of the bay.

To differentiate the initial raw data into meaningful groups, a cluster analysis was performed from a data matrix comprising 51 observations (samples) and 11 variables (component categories). Five clusters were distinguished (Figure 4A). Of these clusters, only three have a high number of samples and thus are the most important. The largest, cluster 1, (20 samples), is characterized by *Halimeda* (70%). Foraminifera, lithic grains, coralline algae and ostracods amount to only 5% to 8%, while none of the others reach 2% of the investigated fractions. Although *Halimeda* debris (38%) is by far the most abundant component of cluster 2 (12 samples), the cluster is distinctly characterized by relatively large amount of several other components: foraminifers (17%), gastropods (20%), coralline algae (10%), worm tubes (3%). Cluster 3 consists of 11 samples and is dominated by ostracods (46.5%). Foraminifers (17%), echinoid spines (11%) and *Halimeda* debris (8%) are also important components of this cluster. Cluster 4 includes only 3 isolated samples and is clearly related to cluster 2. The separating character is the occurrence of bivalves (5%), echinoid spines (4.5%) and ostracods (18%) in slightly higher percentages. The 3 samples of cluster 5 are separated due to the highest coralline algae (32.5%) content. The other important components are: ostracods (27%), *Halimeda* fragments (14%), foraminifers (12%) and lithic grains (6.5%).

A distribution map of these clusters (Figure 4B) reveals that cluster 1 dominates the northern and eastern coastal areas of the bay, cluster 2 is restricted to the western part of the bay and cluster 3 covers the central basin, central-eastern part of the bay and most of the channel.

Foraminiferal Fauna

Benthic foraminifera are an important skeletal component of the Spaanse Water (4–30% of the skeletal components of the >125 μm fraction). Larger forms, in the fraction above 500 μm, can significantly contribute to the production of sediment in the bay. The foraminiferal assemblage consists of about 100 species, belonging to some 50 genera (Table 2). Miliolids are the most common group (15–60% of the total population), represented by *Triloculina, Quinqueloculina, Spiroloculina* and less frequently *Hauerina* and *Miliolinella.* Other abundant foraminifers belong to the following families and/or species: Elphidiidae (*Elphidium poeyanum* (d'Orbigny), *E. discoidale* (d'Orb.)), *Ammonia tepida* (Cushman), *Ammonia parckinsoniana* (d'Orb.), Peneroplidae (*Peneroplis proteus* d'Orb., *P. planatus* (Fichtel and Moll), *P. pertusus* (Forskål)), Soritidae (*Archaias angulatus* (Fichtel and Moll), *Cyclorbiculina compressa* (d'Orb.)), *Amphistegina lessoni* d'Orb., *Nonion grateloupii* (d'Orb.) and *Textularia agglutinans* d'Orb. The rare or only locally more significant forms include *Reussella simplex* (Cushman), *Discorbis mira* Cush-

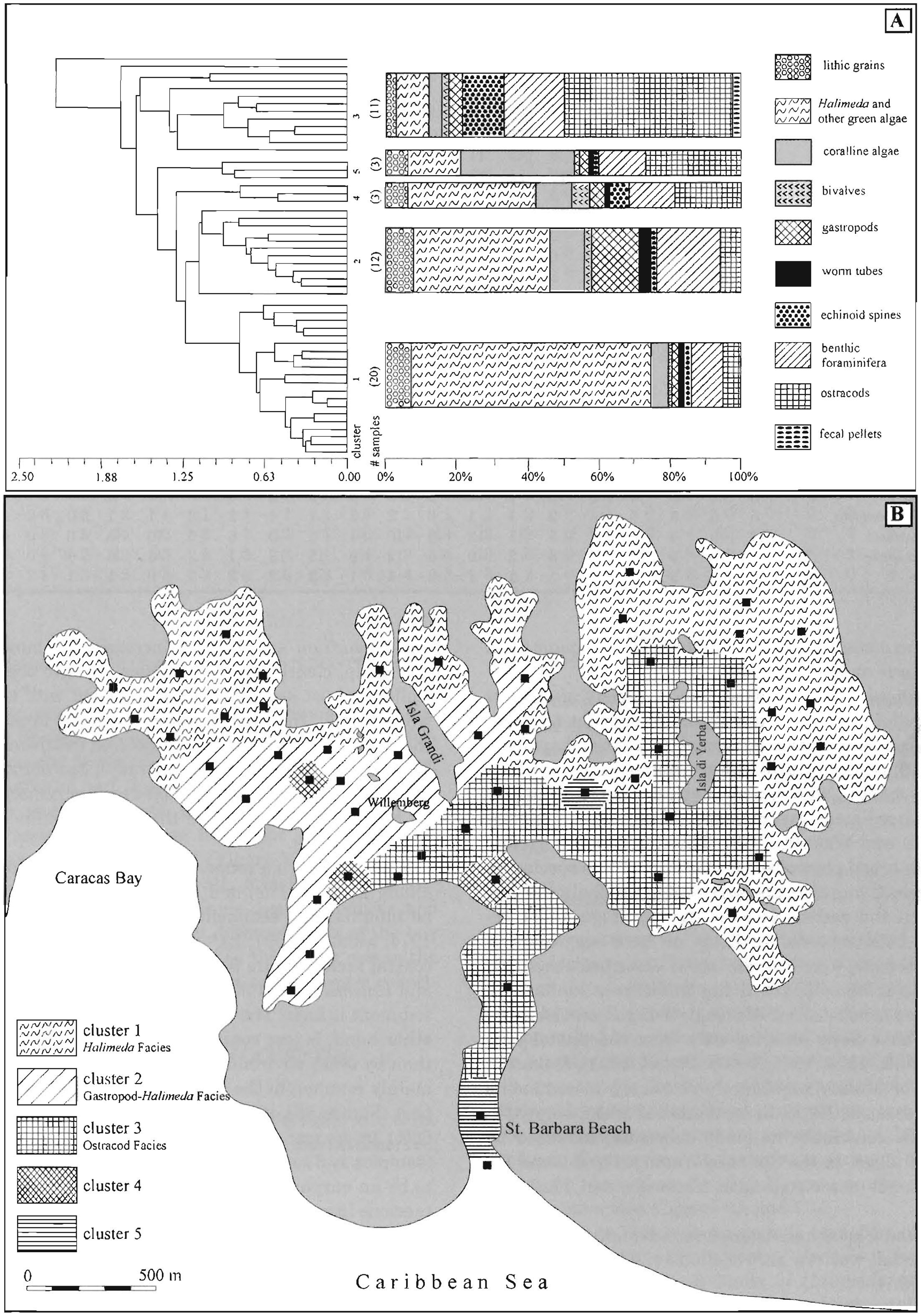

Figure 4. A. Dendrogram of a hierarchical cluster analysis of components combined with their frequency distribution in each cluster. B. Distribution of the clusters of the cluster analysis performed on components.

Table 2. *Relative abundance (%) of selected species, genera and species groups of benthic foraminifera from the Spaanse Water bay.*

Species	sw101	sw102	sw103	sw104	sw105	sw107	sw108	sw110	sw111	sw112	sw113	sw115	sw116	sw117	sw118	sw119	sw120	sw122	sw124	sw126	sw127	sw128
arenaceous	7	3	1	1	1	6	1	6	9	21	6	24	10	22	7	21	14	10	8	3	20	5
Spiroloculina spp.	0	0	0	1	0	0	0	0	0	2	3	0	0	0	0	3	4	3	7	5	2	5
Hauerina sp.	2	1	5	1	3	1	1	2	2	0	2	0	4	1	2	1	0	2	1	0	4	0
Quinqueloculina spp.	2	7	5	2	7	5	10	8	11	2	3	3	11	7	4	4	5	10	11	10	4	5
Miliolinella sp.	2	0	1	4	1	0	1	1	0	1	2	0	1	1	0	0	1	10	8	0	1	1
Triloculina spp.	6	8	12	8	11	6	12	11	12	3	7	3	15	9	6	5	6	21	19	10	6	5
Penoroplis proteus	6	9	10	12	9	13	14	12	11	5	6	2	13	10	23	5	2	2	0	0	10	1
Peneroplis planatus	3	2	3	6	2	5	1	2	2	1	1	0	2	0	3	0	0	0	0	0	1	0
Archaias angulatus	7	7	1	3	6	13	13	7	6	0	0	0	1	0	3	1	0	0	0	0	1	0
Bolivina spp.	0	2	0	0	1	0	1	0	0	0	2	0	0	0	0	1	1	1	5	1	1	2
Reussella simplex	0	0	0	0	0	0	1	0	0	2	0	2	0	0	0	2	4	0	1	0	1	4
Cancris	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	0
Discorbis mira	2	3	5	18	8	0	0	0	0	0	2	0	0	0	0	0	0	2	1	0	0	1
Discorbis rosea	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Rosalina globularis	0	3	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	1	0	0	0	1
Cibicides refulgens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Cibicides	2	0	0	0	0	1	1	1	0	0	5	0	0	1	0	1	0	3	1	1	0	0
Cymbaloporetta squammosa	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
homotrematiids and acervulinids	1	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0
Amphistegina lessoni	1	1	19	4	4	7	10	2	1	0	4	0	6	0	0	0	0	0	0	0	0	0
Asterigerina carinata	0	1	8	0	3	0	1	0	0	0	1	0	4	0	0	1	0	0	0	0	0	0
Nonion grateloupi	2	0	0	1	2	1	1	0	3	1	3	4	1	1	1	5	5	3	2	7	2	4
Ammonia tepida	9	3	5	4	8	3	4	2	2	2	3	2	3	4	8	2	8	2	1	16	4	13
Ammonia parckinsoniana	5	5	3	0	1	2	1	1	0	2	3	1	1	2	3	1	1	0	2	5	0	4
Elphidium poeyanum	12	9	4	6	8	5	11	13	9	10	4	5	3	6	5	10	5	0	0	1	3	5
Elphidium discoidale	6	13	0	2	2	5	2	9	5	12	2	15	3	1	2	3	6	0	0	0	8	4
Elphidium spp.	4	7	2	3	1	1	1	1	2	4	1	3	2	8	7	0	1	1	2	1	5	10

man, *Rosalina globularis* d'Orb., *Cymbaloporetta squammosa* (d'Orb.), *Cancris* and *Bolivinidae.*

Archaias angulatus is reported from a variety of shallow water reef habitats. It is a prominent component of quiet, back reef assemblages and restricted marine embayments (MARTIN, 1986; BRASIER, 1975). A large number of empty tests occur also in shallow, high-energy environments and fore-reef foraminiferal sediment assemblages (MARTIN and LIDDELL, 1988; MARTIN and WRIGHT, 1988). The widespread distribution indicates broad physiological tolerance of this species. In the study area, *A. angulatus* is restricted to the shallow, nearshore western and eastern parts of the bay (Figure 5B). *Peneroplis* has been reported as living on both seagrass and sediment substrate; *e.g.*, LANGER (1993) described *Peneroplis* as a motile, grazing epiphyte, living on different kinds of algal and seagrass substrates. Although living *P. pertusus* and *P. planatus* have been reported only from the phytal substrates (BRASIER, 1974, 1975; VÉNEC-PEYRÉ, 1991), *P. proteus* in the Gulf of Mexico was largely restricted to sediments (POAG and TRESSLAR, 1981). In most studied areas, empty *Peneroplis* shells contribute to sandy substrate, colonized by seagrass and algae. In the Spaanse Water we also found *Peneroplis* in sands associated with *Halimeda* and *Thalassia* (Figure 5C).

Amphistegina lessoni and *Asterigerina carinata* are restricted to the coastal, western part of the bay, where both reach 10% (Figure 5A).

Miliolids generally form 10–60% of the total foraminiferal assemblage of the bay (Figure 5D). Maximum values occur in the areas associated with fine sediments. The proportion tends to decrease from the channel, south and central basin towards the coastal areas where *A. angulatus,* peneroplids and *Elphidium* spp. become increasingly abundant. Within the group, clearly defined changes are also observed. Thick walled, robust specimens are associated with coastal areas, while fragile, thin-walled, often elongated forms increase to the center and the channel. *Triloculina tricarinata* d'Orbigny, *T. oblonga* d'Orb., *T. cultrata* (Brady), *Spiroloculina communis* Cushman and Todd, *Quinqueloculina poeyana* d'Orbigny, *Q. bradyana* Cushman are the common miliolids from the finer sediments.

Elphidiids with a rounded periphery (here *Elphidium poeyanum, E. discoidale*) and *Ammonia tepida* are considered to be infaunal and sediment dwellers (BANDY, 1964; FRENKEL, 1974; MURRAY, 1991; LANGER, 1993). We found *Elphidium* in coastal areas (Figure 5E) characterized by coarser sediments and *Halimeda.* It is absent in deeper parts of the bay where sediment is finer. The distribution of *Ammonia tepida,* on the other hand, is less controlled by the nature of the substrate than by other environmental factors. Although the species is mainly common in the finer sediments of the central-eastern part (Figure 5F), it reaches highest abundances (as much as 50%) in coarser sediment near areas of mangrove growth (samples sw3 and sw8; Figure 1C). *Ammonia tepida* is known to be an euryhaline indicator, which tolerates seasonal fluctuations in salinity. As the measured salinity in Spaanse Water was constant our observations confirm SEIGLIE and BERMUDEZ (1963) and SEIGLIE (1968) who similarly recorded abundant *Ammonia tepida* from normally saline areas with mangroves, where sediments contain vegetable matter.

Nonion grateloupii, Reussella simplex and *Cancris* show increasing abundance with higher amounts of finer sediments (Figures 5H, I). This is in agreement with the worldwide distribution of these species that are often characteristic of finer

Table 2. *Extended.*

sw129	sw130	sw131	sw132	sw133	sw134	sw135	sw136	sw139	sw140	sw141	sw142	sw143	sw145	sw146	sw147	sw148	sw151	sw1	sw2	sw3	sw4	sw5	sw6	sw8	sw9	sw10	sw12
	8	7	7	4	4	7	3	4	15	8	9	13	17	15	12	5	5	2	0	2	1	12	4	1	4	1	12
11	1	1	0	0	0	0	0	2	1	5	3	0	1	1	5	4	1	1	1	0	6	2	1	0	0	1	1
1	1	0	1	0	1	1	6	0	1	4	2	0	1	1	1	0	4	2	0	1	0	0	5	0	5	0	1
3	1	5	3	5	7	3	7	7	7	8	9	7	5	6	5	5	4	8	8	4	14	5	9	1	9	2	10
2	0	1	0	0	0	0	4	0	2	6	1	0	3	0	12	6	4	2	0	4	0	1	1	0	0	5	7
5	3	6	4	5	7	4	17	7	10	17	12	8	9	7	18	11	13	11	8	9	14	5	14	2	14	6	18
9	15	12	17	3	8	10	2	1	15	1	4	9	4	9	1	0	9	0	0	0	0	0	0	0	0	0	0
0	1	0	1	0	1	1	2	0	1	0	1	0	1	2	1	0	3	0	0	0	0	0	0	0	0	0	0
10	3	8	16	0	12	3	0	0	2	0	0	0	4	1	0	0	2	0	0	1	0	0	3	0	5	0	1
1	0	1	0	5	1	0	2	1	0	1	0	0	0	0	1	0	1	2	2	2	3	1	1	2	0	1	0
3	1	4	1	3	1	1	0	2	2	0	0	0	0	0	0	0	0	0	3	0	2	5	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0
0	0	0	1	0	0	1	6	0	1	4	3	0	0	0	0	0	1	3	0	0	0	0	0	0	3	29	0
0	0	0	0	0	1	0	2	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	0	0	2	2	1	1	0	1	1	0	0	1	1	0	1	1	0	0	2	0	0	2
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	1	0	2	2	0	2	1	0	0	0	3	1	0	0	1	0	1	1	1	0	0	4	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	6
0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	1	5
0	0	1	3	0	1	0	0	0	0	0	0	0	0	11	2	1	2	0	0	2	0	0	6	4	2	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	1	0	0	1	0	0	6	3	1	0	0
2	1	2	0	9	4	3	2	5	2	3	3	1	2	1	5	2	1	2	8	4	4	5	1	3	0	0	2
5	4	6	9	15	10	7	17	14	4	4	9	5	3	1	3	9	10	23	38	57	22	9	6	50	6	0	2
1	3	1	6	13	2	4	1	4	2	1	5	2	1	1	2	0	1	0	0	3	0	0	0	5	0	1	0
4	5	6	9	5	11	10	3	7	13	1	6	14	14	2	2	0	4	0	4	28	2	8	5	0	7	0	0
16	19	10	6	2	13	25	2	3	2	1	4	9	4	10	0	0	3	0	0	0	0	0	1	0	3	0	0
2	8	5	3	3	2	3	2	2	0	2	5	4	3	3	2	0	1	20	2	10	1	0	0	3	1	2	0

substrate (SEIGLIE, 1969; SEN GUPTA and SCHAFTER, 1973; FRENKEL, 1974).

Bolivinidae constitute a persistent but minor faunal element in the Spaanse Water and show no substrate preference. Arenaceaous foraminifera, mainly represented by *Textularia agglutinans* and *Bigenerina irregularis* Phleger and Parker, show no preference for a particular substrate either. They mostly constitute less than 10% of the total assemblages, but locally, may reach 20–30% (Figure 5G).

Foraminifera that are permanently attached to hard substrate or phytal surfaces (cibicidinids, homotrematiids and acervulinids) were rarely found in different parts of the bay but probably are under-represented in this study due to the sampling method (only loose sediment samples were collected).

DISCUSSION AND CONCLUSIONS

The sediments of Spaanse Water can be divided into three facies (Figure 4) and the following patterns can be observed:

(1) Halimeda Facies

In the shallowest (approx. <6 m) coastal areas, the dominating sediment component is *Halimeda* debris (70%); no other component reaches an average of 10%. The grain size is sand-dominated, with more than 60% of coarse sand. The silt and clay content is generally below 20% (Figure 6A). The foraminiferal assemblage consists essentially of *Archaias angulatus, Amphistegina lessoni, Asterigerina carinata,* peneroplids, *Elphidium poeyanum, E. discoidale* and some miliolids.

(2) Ostracod Facies

The deeper parts of the bay have fine sediment (>90% of silt and clay in the central basin and inner channel (Figure 6B)), rich in ostracods (average 46%), foraminifers (17%), echinoid spines (11%). Small miliolids dominate the foraminiferal assemblage and species such as *Nonion grateloupii, Reussella simplex, Cancris* are largely restricted to samples of this facies.

(3) Gastropod-Halimeda Facies

The western part of the bay is characterized by an impoverished *Halimeda* Facies composition with a relatively high percentage of sturdy gastropods (20%). At 38% *Halimeda* is still the most abundant element. The grain size distribution is dominated by sand (mainly coarse sand; Figure 6C), except for samples sw115 and sw117, which have 54% and 63% of silt, respectively. Particles of most samples of this facies are dark-stained, rounded, which suggest low- to non-accumulation/-production and constant movement (higher energy conditions). We interpret the relative scarcity of the finest material, *i.e.,* finer than 6 phi (0.16 mm), as the result of winnowing (compare Figures 6A and C).

In Spaanse Water no large-scale transport of the biogenic components across the bay takes place; it is for instance apparent that the lateral limits of *Halimeda* debris coincide with the limits of its growth areas. Horizontal water movements in the deeper parts of the bay are impeded by a coralline sill at 6 m depth at the entrance of the bay (KUENEN and DEBROT, 1995).

The grain size distribution of carbonate sediments is well

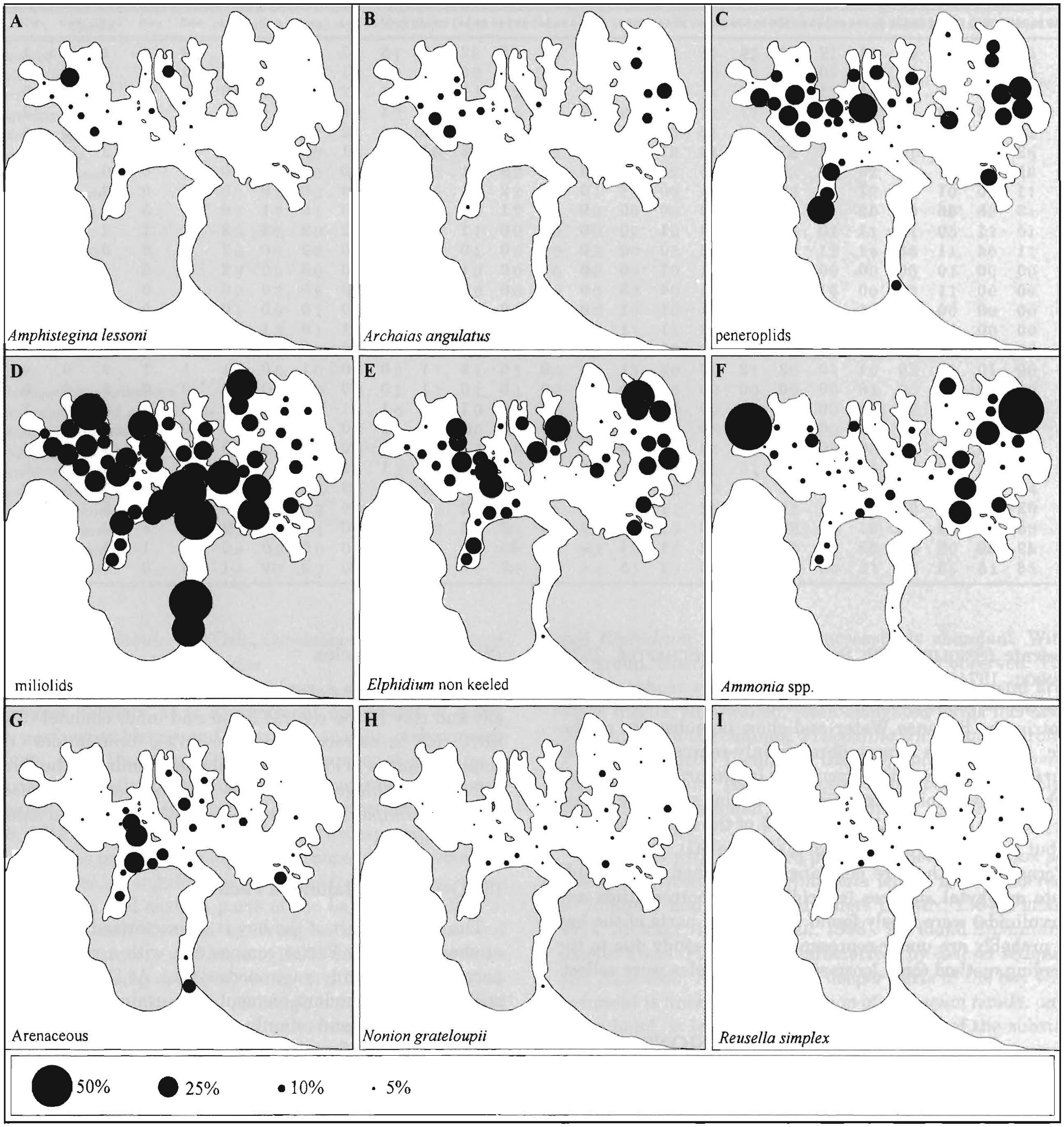

Figure 5. Frequency distribution of some foraminifera species and species groups (>125 μm).

known to be controlled by the initial size of individual skeletons, their variable resistance to disintegration agents, and water energy (FOLK and ROBLES, 1964). In the study area, grain size is governed by biological rather than physical processes, since most sediments are poorly sorted and tests are well preserved. The western part of the bay with the Gastropod-*Halimeda* Facies forms a notable exception. Although physical conditions like water depth and the absence of currents are similar to the Halimeda Facies area, the biota have drastically diminished their carbonate production. The obvious difference with the rest of the bay is the fact that this part of the bay, with its small islands and peninsulas, is the most intensively urbanized and used as an anchorage by numerous boats and yachts, as well as a place for various water

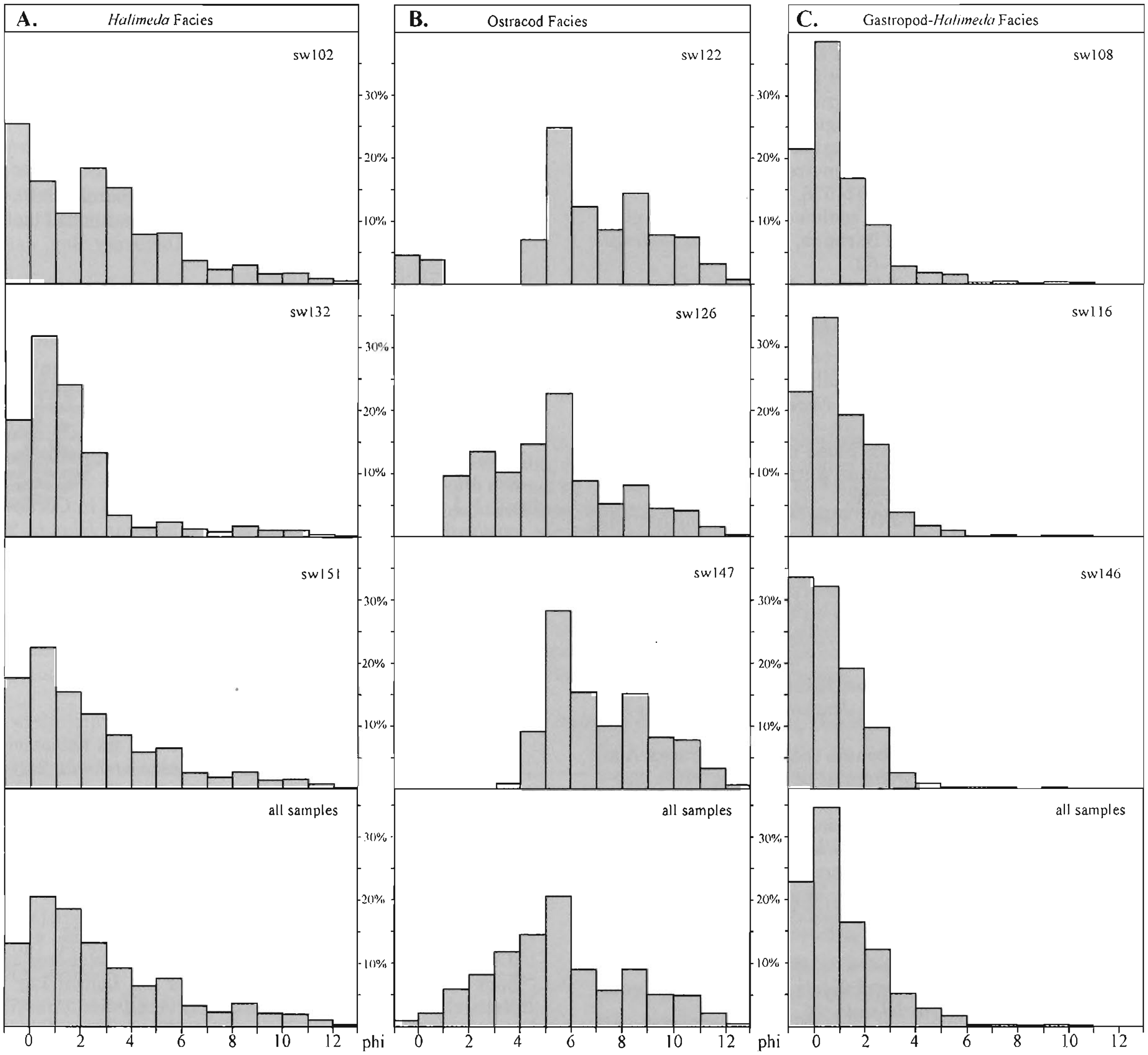

Figure 6. Grain size frequency distribution of selected samples from the three recognized facies and mean frequency distribution of those facies.

sports. We therefore conclude that human activities might have a detrimental effect on the natural environment of this part of the bay.

The depth range of Spaanse Water is limited to 15 m, yet its waters are generally well mixed in terms of salinity and temperature. Occasional fluctuations as a result of heavy rainfall or evaporation are too brief to influence the distribution of the biota. Water column turbidity differs between the various areas of the bay, being relatively low in the channel and the western and central basin (light extinction coefficient: 0.332–0.421), and higher in the eastern basin (light extinction coefficient: 0.514) (KUENEN and DEBROT, 1995). Therefore, the substrate type and light penetration (turbidity) are expected to be the most important factors determining the distribution of biota and benthic foraminifera in the bay.

Sediment size and composition, indeed, do show a relationship with foraminiferal faunas, as is seen by their difference in fine-grained and in coarse-grained sediments. Large algal symbiont-bearing foraminifera (soritiids, peneroplids) together with *Elphidium* spp., *Discorbis mira* and *Amphistegina lessoni* are restricted to shallow, coastal areas and the western part of the bay, associated with the *Halimeda* and *Thalassia* pattern. The central basin and the channel, with the finest sediments of the bay, are dominated by miscellaneous smaller miliolids alone. The relation of the *Ammonia tepida* distribution with the presence of mangroves is an exception.

ACKNOWLEDGEMENTS

We are most obliged to the CARMABI Institute on Curaçao for the use of their facilities and especially thank Brian Leysner for his assistance to B. Klosowska during her 1999 fieldwork. Martin Konert is thanked for his generous help with the grain size analysis. This research is funded by the Netherlands Institute of Applied Geosciences (NITG-TNO).

LITERATURE CITED

Bak, R.P.M., 1975. Ecological aspects of the distribution of reef corals in the Netherlands Antilles. *Bijdrage tot Dierkunde,* 45, 181–190.

Bandy, O.L., 1964. Foraminiferal biofacies in sediments of Gulf of Batabano, Cuba, and other geologic significance. *Bulletin of the American Association of Petroleum Geologists,* 48(10), 1666–1679.

Brasier, M.D., 1974. Morphology and habitat of living benthonic foraminiferids from Caribbean carbonate environments. *Revista Espanola de Micropaleontologia,* 7(3), 567–578.

Brasier, M.D., 1975. Ecology of Recent sediment-dwelling and phytal foraminifera from the lagoons of Barbuda, West Indies. *Journal of Foraminiferal Research,* 5(1), 42–62.

Debrot, A.O.; Kuenen, M.C.E., and Dekker, K., 1998. Recent declines in the coral fauna of the Spaanse Water, Curaçao, Netherlands Antilles. *Bulletin of Marine Science,* 63(3), 571–580.

de Buisonjé, P.H., 1974. Neogene and Quarternary geology of Aruba, Curaçao and Bonaire (Netherlands Antilles). *Natuurwetenschappelijke Studiekring voor Suriname en de Nederlandse Antillen,* 78, 1–293.

de Haan, D. and Zaneveld, J.S., 1959. Some notes on tides in Annabaai Harbour, Curaçao, Netherlands Antilles. *Bulletin of Marine Sciences.* Gulf Caribb., 9, 224–236.

de Kock, W.C. and de Wilde, W.J.J.O., 1964. Verslag over het onderzoek naar de fertiliteit van enige Curaçaose binnenbaaien. CARMABI, (unpublished) 14p.

Djohani, R.H. and Klok, C., 1988. Een onderzoek naar de waterkwaliteit van enkele baaien van Curaçao op basis van biologische en abiotische parameters. CARMABI/University of Amsterdam, (unpublished), 55p.

Folk, R.L. and Ward, W.C., 1957. Brazos River Bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology,* 27(1), 3–26.

Folk, R.L. and Robles, R., 1964. Carbonate sands of Isla Perez, Alacran Reef complex, Yucatan. *The Journal of Geology,* 72(3): 225–292.

Fransen, C.H.J.M., 1986. Caribbean Bryozoa: Anasca and Ascophora imperfecta of the inner bays of Curaçao and Bonaire. *Studies on the fauna of Curaçao and other Caribbean Islands,* 68, 1–119.

Frenkel, H., 1974. Observations on some shallow benthonic foraminifera in the Gulf of Elat, Israel. *Israel Journal of Earth Sciences,* 23, 63–67.

Hofker, J., 1964. Foraminifera from the tidal zone in the Netherlands Antilles and other West Indian Islands. *Studies on the fauna of Curaçao and other Caribbean Islands,* 21, 1–119.

Hofker, J., 1971. The Foraminifera of Piscadera Bay, Curaçao. *Studies on the fauna of Curaçao and other Caribbean Islands,* 35, 1–57.

Hofker, J., 1976. Further studies on Caribbean Foraminifera. *Studies on the fauna of Curaçao and other Caribbean Islands,* 49, 1–156.

Konert, M. and Vandenberghe, J., 1997. Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. *Sedimentology,* 44, 523–535.

Kuenen, M.M.C.E. and Debrot, A.O., 1995. A quantitative study of the seagrass and algal meadows of the Spaanse Water, Curaçao, The Netherlands Antilles. *Aquatic botany,* 51, 291–310.

Langer, M.R., 1993. Epiphytic foraminifera. *Marine Micropaleontology,* 20, 235–265.

Martin, R.E., 1986. Habitat and distribution of the foraminifer *Archaias angulatus* (Fichtel and Moll)(Miliolina, Soritidae), Northern Florida Keys. *Journal of Foraminiferal Research,* 16(3), 201–206.

Martin, R.E. and Liddell, W.D., 1988. Foraminiferal biofacies on a north coast fringing reef (1–75 m), Discovery Bay, Jamaica. *Palaios,* 3, 298–314.

Martin, R.E. and Wright, R.C., 1988. Information loss in the transistion from life to death assemblages of foraminifera in back reef environments, Key Largo, Florida. *Journal of Paleontology,* 62, 399–410.

Murray, J.W., 1991. *Ecology and paleoecology of benthic foraminifera.* Longman, Harlow, 397p.

Poag, C.W. and Tresslar, R.Ch., 1981. Living foraminifers of West Flower Garden Bank, northernmost coral reef in the Gulf of Mexico. *Micropaleontology,* 27(1), 31–70.

Ross, P.J., 1964. The distribution of reef corals in Curaçao. *Studies on the fauna of Curaçao and other Caribbean Islands,* 20, 1–51.

Ross, P.J., 1971. The shallow-water stony corals of the Netherlands Antilles. *Studies on the fauna of Curaçao and other Caribbean Islands,* 37, 1–108.

Seiglie, G.A., 1968. Foraminiferal assemblages as indicators of high organic carbon content in sediments and of polluted waters. *The American Association of Petroleum Geologists Bulletin,* 52(11), 2231–2241.

Seiglie, G.A., 1969. The distribution of the foraminifers in the Jabucoa Bay, Southeastern Puerto Rico and its paleoecological significance. *Revista Española de Micropaleontología,* 2(2), 183–208.

Seiglie, G.A. and Bermúdez, P.J., 1963. Distribución de los Foraminiferos del Golfo de Cariaco: *Inst.Oceanogr. Univ. Oriente Bol.,* 2(1), 1–97.

Sen Gupta, B.K. and Schafer, C.T., 1973. Holocene benthonic foraminifera in leeward bays of St.Lucia, West Indies. *Micropaleontology,* 19(3), 341–365.

van den Hoek, C.; Colijn, F.; Cortel-Breeman, A.M., and Wanders, J.B.W., 1972. Algal vegetation types along the shores of the inner bays and lagoons of Curaçao and of the lagoon Lac (Bonaire), Netherlands Antilles. *Verh. Kon. Ned. Akad. Wet.,* Afd. Natuurkunde, (2), 61(2), 1–72.

van der Horst, C.J., 1927. Resultaten eener reis van Dr. J.C. van der Horst in 1920, in bijdragen tot de kennis der fauna van Curaçao. *Bijdrage tot Dierkunde,* 25, 1–164.

Vénec-Peyré, M.-T., 1991. Distribution of living benthic Foraminifera on the back-reef and outer slopes of a high island (Moorea, French Polynesia). *Coral Reefs,* 9, 193–203.