Reefal Sediments of the Northern Great Barrier Reef

P. G. Flood and T. P. Scoffin

Phil. Trans. R. Soc. Lond. A 1978 **291**, 55-68
doi: 10.1098/rsta.1978.0089

Phil. Trans. R. Soc. Lond. A. **291**, 55–71 (1978) [55]
Printed in Great Britain

Reefal sediments of the northern Great Barrier Reef

By P. G. Flood† and T. P. Scoffin‡
†*Department of Geology and Mineralogy, University of Queensland, St Lucia, Queensland*, 4067, *Australia*
‡*Grant Institute of Geology, University of Edinburgh, West Mains Road, Edinburgh EH*9 3*JW, U.K.*

with an appendix by A. B. Cribb

[Plates 1 and 2]

Skeletal carbonate sediments collected from nine reef flats have been analysed by using multivariate statistical techiques to determine the inter- and intra-reefal variations of sediment texture and composition. Q-mode cluster analysis of granulometric analysis data allows the combined collection of approximately 200 samples to be grouped into four sediment types. The same data were re-analysed by using Q-mode factor analysis techniques which showed that three factors will explain more than 90% of the variations exhibited by the sediments. The factor scores illustrate the relative influence that individual particle sizes have on each factor. R-mode cluster analysis shows three distinct grouping of sizes which are interpreted as the individual population of sizes that are subjected to differing modes of transportation (traction, saltation and suspension load) which form in response to the prevailing hydrodynamic régime. The distribution of particle size within these three populations is modified by the presence of six skeletal modes within the sand size range. The organic group contributing to each skeletal mode has been identified with the aid of a scanning electron microscope.

1. Introduction

This paper describes the unconsolidated sedimentary deposits associated with reefs in the northern region of the Great Barrier Reef (figure 1). A subjective account of the sediment bodies and a statistical account of their component and grain size compositional variability is provided. Eight of the reefs display the range of variation characteristic of the inner shelf reefs. They are:

low wooded island type: (cf. Maxwell's (1968) high reef of inner shelf)	Low Isles, Three Isles, Pipon, Watson, and Ingram–Beanley Reefs
platform type:	Mid and Megaera Reefs
lagoonal platform type:	Stapleton Reef

One shelf edge platform reef immediately to the south of Waterwitch Passage was visited. More than 200 sediment samples were examined.

Steers (1929, 1930), Stephenson, Stephenson, Tandy & Spender (1931) and Stoddart, McLean & Hopley (1978, part B of this Discussion) provide detailed accounts of the morphological features and ecological zonation characteristic of reefs in this region (figure 2, plate 1).

2. Prevailing physical conditions

The reader is referred to Maxwell (1968) for details of the physical environment and hydrographic setting of the Northern Province of the Great Barrier Reef.

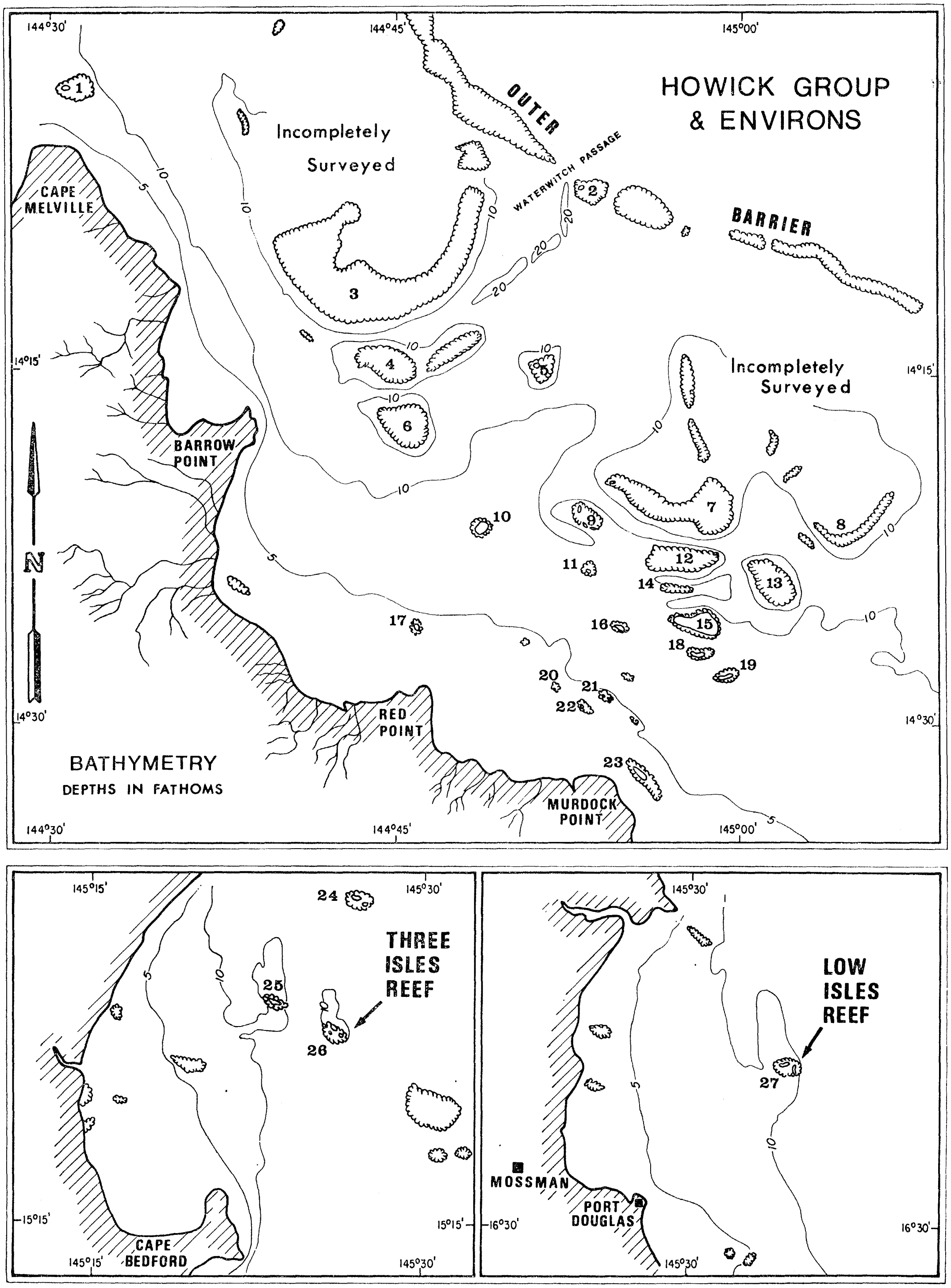


Figure 1. Location of the nine reefs studied: 1, Pipon; 2, 'Waterwitch'; 5, Stapleton; 9, Ingram–Beanley; 11, Watson; 12, Mid; 14, Megaera; 26, Three Isles; 27, Low Isles.

During the expedition (July–November 1973) the trade winds blew steadily from the south-east. Only four calm days were recorded. The wind, normally 15–40 km/h, produced swells of 1–3 m amplitude in the inner shelf seas and plunging breakers on the windward sides of patch reefs up to 2 m in height. All the reefs under study had emergent reef flats at low water and even at high water, waves did not break on the central parts of reef tops.

Three main types of currents influence the reef-top sediments. Tidal currents seldom exceed 2 km/h even though there is a 3 m tidal range. The drainage on a falling tide is crudely radial though the impervious ramparts at the windward and flanking rims of the reef tend to channel the water approximately parallel to the reef edge for some distance until it can escade over a sill or through a gap. The bulk of the reef flat water drains to leeward during low tide simply because the leeward side of the reef is lower than the windward.

The wind usually blows the surface water to lee, and during low tide the water level on the reef flat is sufficiently shallow for the effect of this surface current to reach the bottom and agitate sand grains.

The waves impinging on the windward front of the reef refract in various patterns according to reef shape, proximity of neighbouring reefs, orientation of the reef front with respect to the wind, and the surface morphology (particularly of emergent features such as ramparts, platforms or mangroves). Generally there is a consistent refraction around the margins of the reef flats which results in a long-shore transport of grains from windward to leeward. Where the two lateral sets of waves converge at the leeward edge the current energy is lost and sediment is deposited.

3. REEFAL SEDIMENT BODIES

There are several distinct unconsolidated sediment bodies occurring on the tops of most of the inner shelf reefs. They are: (*a*) rim deposits of shingle ramparts and boulder tracts; (*b*) blanket sands of reef flat or lagoon; and (*c*) leeward sand cay.

(*a*) *Rim deposits*

At the perimeter there is normally a rim of broken coral. On the windward side the dominant components of this rim are *Acropora* branches which are piled up by waves to form large asymmetric ridges (often also called ramparts) 50–100 m in wavelength and 0.5–3 m in amplitude. The seaward slope is usually less than 5° and slopes towards the reef centre about 60°. These ramparts have a crescent-shaped outer margin paralleling the reef edge and a cuspate inner margin from which tongues of steeply banked shingle project on the reef flat. Commonly several sets of ramparts occur on one reef and seawater is ponded between adjacent sets forming moats at low tide. Thickets of branching *Acropora* corals living in shallow water on the windward side of the reef are the source of the gravel to boulder sized coral fragments of the ramparts.

Towards the leeward flanks of the reef the shingle ramparts give way to a linear pile of massive boulders. Each boulder is normally one massive coral colony (predominantly *Porites*) which formerly grew on the leeward flanks of the reef in shallow water as coral heads or ‘bommies’. A few isolated boulders are irregularly scattered along the leeward rim of the reef or they may be so numerous that they form a continuous coarse conglomerate deposit: the boulder tract.

These rim sediments are produced by wave action which removes skeletal debris and deposits them at the margins of the shallow reefs when the wave loses its energy. The grains are too coarse to be moved by wind or tidal currents and these sediments remain as intertidal lag deposits.

The very large boulders on the reef are not deposited by normal wave action but during cyclones, as are the ramparts. The occurrence of distinct sets of ramparts and boulder tracts on any one reef flat and the analysis of their spatial distributions over the years (Stoddart *et al.* 1978, part B of this Discussion) suggest that the main movement of reef rim deposits is during storms.

(*b*) *Blanket sands*

The reef flat sediment cover is normally only a few centimetres thick. The thickest deposits occur in hollows on the underlying solid reef top. Those parts of the reef flat that do not dry completely at each low tide commonly have a sparse cover of soft vegetation. *Thalassia* grass and some algae species occur only where the sediment thickness is greater than 5 cm. The typical concentric variation in sediment thickness across the reef flats plays a part in producing the marked concentric zones of vegetation on the margin of reefs (algal specimens collected along a radial transect across Ingram–Beanley Reef were kindly identified by Dr Alan Cribb of the Botany Department, University of Queensland, Brisbane; see the appendix).

The sediments on the reef flats and in shallow lagoons consist essentially of sand sized grains of corals, benthonic Foraminifera, and green and red calcareous algae. The coral sand is supplied by the mechanical and biological breakdown of corals growing mainly on the reef front (though a few corals grow on the reef flat). The benthonic Foraminifera are attached to the soft plants on the reef flat. *Marginopora* is particularly abundant on the *Thalassia* grass and *Baculogypsina* and *Calcarina* occur in vast quantities attached to the short fronds of *Laurencia* algae on the windward margin of the reef top just seaward of the ramparts. In this region the intertidal zone is the area of maximum biological corrosion of carbonate. Here, boring activities of *Lithophaga* bivalves, sponges and filamentous algae are important in the breakdown of coarse coral and mollusc skeletons.

The distribution of silt and clay sizes is governed by the distribution of stabilizing networks such as mangrove roots, grass blades, algal fronds, porous shingle ramparts, all of which act as baffles, locally lowering the current velocities and allowing fine sediment to settle.

The sediments on the reef flats are moderately to poorly sorted. The grains can be whole or broken, subangular to subrounded. Organisms play a part in influencing texture; for example, grass thickets produce poor sorting with finer sediment whereas burrowing crustaceans and worms mix and sometimes separate grain sizes. On the bare areas of reef flats, the sediments are mobile and shallow asymmetric ripples with well sorted, well rounded grains occur. Experiments using dyed sand on Ingram–Beanley Reef flat showed that the net movement of sand over several tidal cycles was to leeward.

(*c*) *Leeward sand cays*

Wave refraction around the reefs allows the deposition of sand towards the leeward edge. These deposits include the cays, bars and spits. Wind removes the sand and finer sizes from a beach at low tide to develop a cay that is emergent above the high water mark. The cay is commonly stabilized by freshwater vegetation, whereas the intertidal rim deposits, particularly the inner portions of ramparts, are colonized by mangroves. Both types of intertidal deposit are fairly readily cemented (see Scoffin & McLean 1978, this volume). The components of the cay sands are essentially similar to those of the mobile parts of the reef flat consisting of coral,

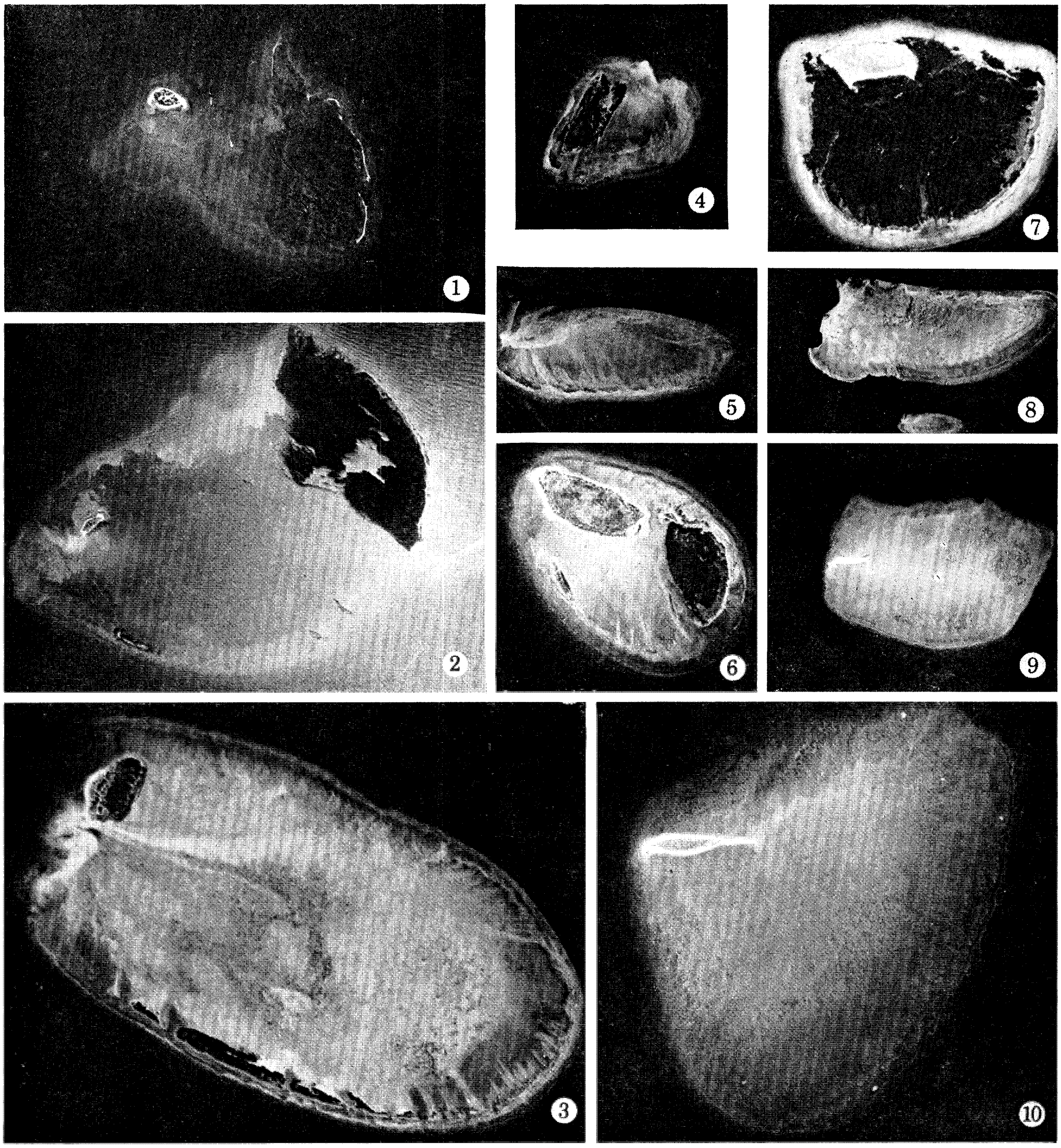


FIGURE 2. Vertical aerial photographs of the reef tops. 1, Low Isles; 2, Pipon; 3, Ingram–Beanley; 4, Watson; 5, Megaera; 6, Three Isles; 7, Bewick (site of diamond drill hole: Thom, Orme & Polach 1978, this volume); 8, Mid; 9, 'Waterwitch'; 10, Stapleton (site of diamond drill hole). For a comparison of sizes see figure 3. Published with permission of the Director of National Mapping, Australia.

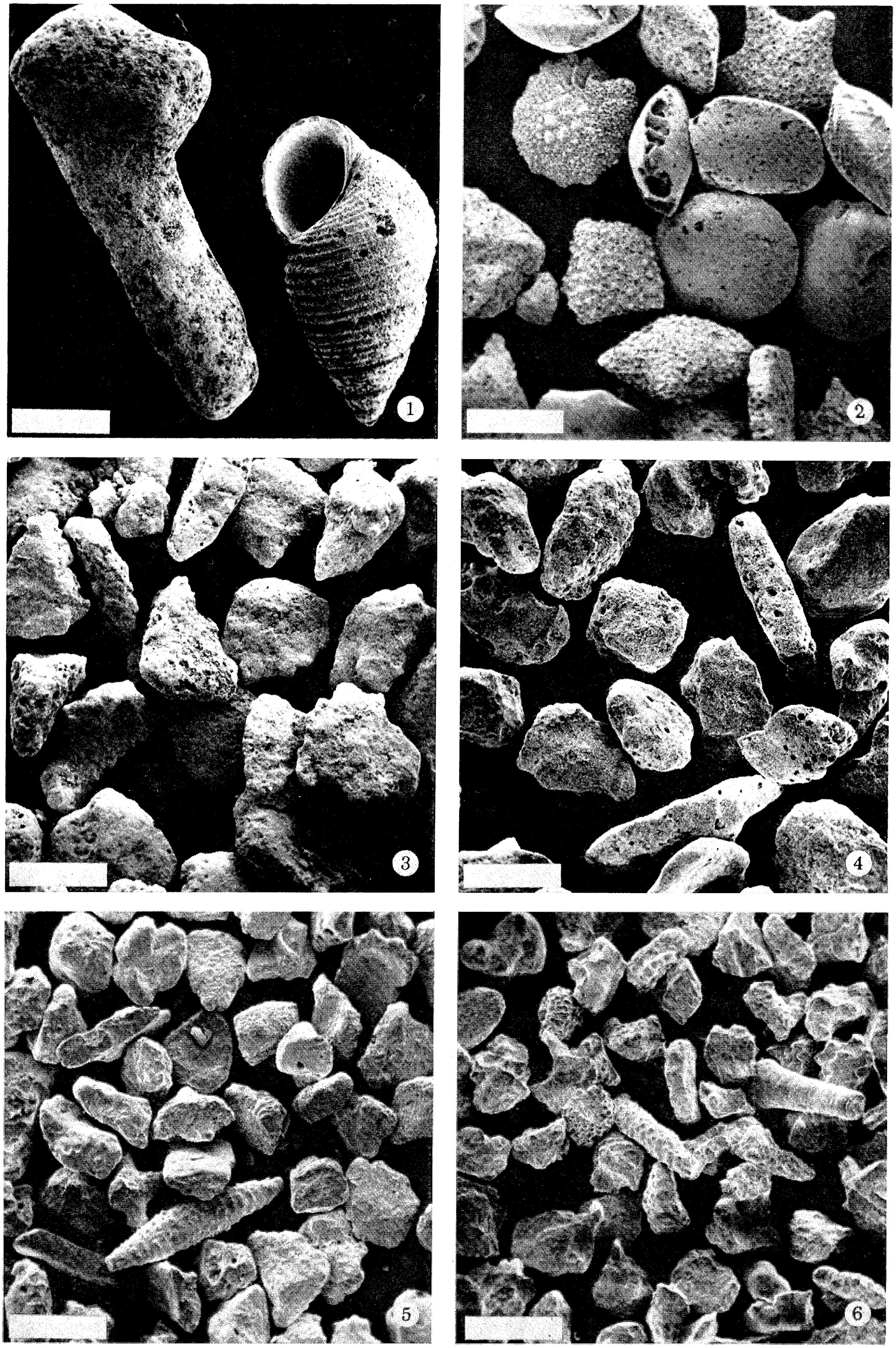


FIGURE 9. Scanning electron microphotographs of selected $\frac{1}{4}\ \phi$ fractions: (1) coral and shell, size $-0.25\ \phi$, bar scale 1 mm; (2) benthonic Foraminifera, size $0.25\ \phi$, bar scale 0.8 mm; (3) coral, *Halimeda* and others, size $1\ \phi$, bar scale 0.8 mm; (4) size $2\ \phi$, bar scale 0.5 mm; (5) size $2.75\ \phi$, bar scale 0.5 mm; (6) size $3.25\ \phi$, bar scale 0.2 mm.

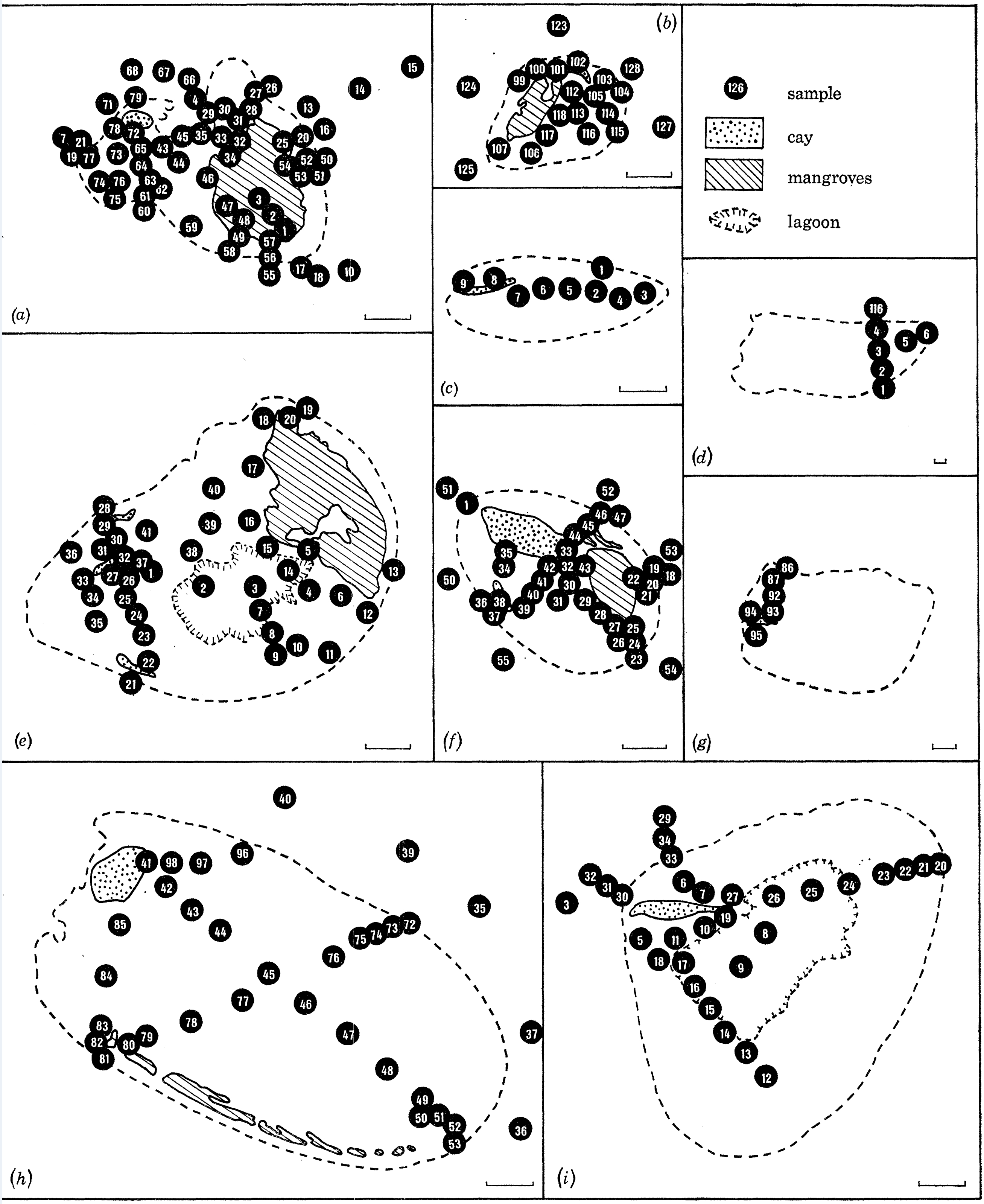


FIGURE 3. Location of sediment samples. (*a*) Low Isles; (*b*) Watson; (*c*) Megaera; (*d*) Mid; (*e*) Pipon; (*f*) Three; (*g*) 'Waterwitch'; (*h*) Ingram–Beanley; (*i*) Stapleton. The bar scales represent 0.5 km.

Foraminifera and coralline algae. These grains have been under the influence of wave action on the beaches of the leeward sand cay and therefore normally show improved rounding, sorting and polishing (see McLean & Stoddart 1978, this volume).

4. The sediments

Sampling of the reef flats (figure 3) was accomplished by traversing on foot during periods of low tide. Tidal conditions and the Expedition programme generally dictated that any one reef flat could be examined for only a few hours and on one occasion only. The sediments were collected by hand and placed into plastic bags. Later each sample was split into two equal parts: one was treated with 10% hydrogen peroxide to remove organic material, the other with alcohol to preserve it. A representative fraction of the treated sample was sieved to determine the particle size distribution. Another representative fraction was impregnated with epoxy resin for making a thin section for point counting to determine the component composition. Multivariate statistical programs have been used to analyse the sediment data and to provide objective groupings of the samples, components and grain size variables. Component and grain size data were analysed using Davis's (1973) cluster and Klovan & Imbrie's (1971) factor programs.

Representative samples are housed at the University of Queensland, Australia and at the University of Edinburgh, Scotland.

(a) *Components*

Coral, Foraminifera, *Halimeda*, molluscs and coralline algae are quantitatively the most important skeletal components present in the sediments. The component analysis data obtained from the Low Isles and Three Isles sediments was processed in a manner similar to that used by Imbrie & Purdy (1962). The Q-mode cluster analysis dendrogram shows five distinct groupings (cf. reaction groups) which represent discrete sediment types (see figure 4).

The mean and standard deviation of each component present within the types 1–5 are shown in table 1.

Table 1. Reef flat sediments: compositional statistics for Low Isles and Three Isles reefs only

(Mean ($\bar{x}$) and standard deviation (s); value in parentheses indicates number of samples; * denotes dominant compositional group.)

	coral		molluscs		coralline algae		*Halimeda*		benthonic Foraminifera		*Marginopora*		others	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
type 1 (10)	27.7*	4.1	9.7	2.7	7.6	3.4	11.0	5.0	29.6*	6.7	1.3	1.3	12.7	4.3
type 2 (15)	40.0*	14.2	11.4	3.9	6.3	4.1	12.3	4.3	11.7	4.7	2.7	2.0	12.8	4.9
type 3 (15)	29.1*	4.0	10.5	2.7	7.0	2.9	21.2*	4.4	15.0	4.1	3.8	2.1	13.4	4.9
type 4 (5)	14.8	5.5	5.8	3.2	4.8	2.9	11.6	5.8	52.0*	7.9	2.2	1.7	9.2	5.7
type 5 (10)	18.5	5.2	11.3	2.6	4.0	2.2	34.2*	6.0	21.5	6.1	2.2	1.3	12.4	3.2

Q-mode factor analysis, which conveniently bypasses the problem of closure of data, showed that 97% of the component variation could be explained by three factors. The relative component contribution with respect to each factor (i.e. the factor score) is shown in figure 5. The normalized varimax triangular plot shows the relation of the samples with respect to the factors I, II and III (39, 26 and 31% variance respectively) and illustrates the approximate fields occupied by the five cluster groupings. The results indicate that the variation exhibited by the majority of sediments can be expressed in terms of three components: coral (and to a lesser extent coralline algae), benthonic Foraminifera and *Halimeda*. Combinations of these components produce the five sediment types.

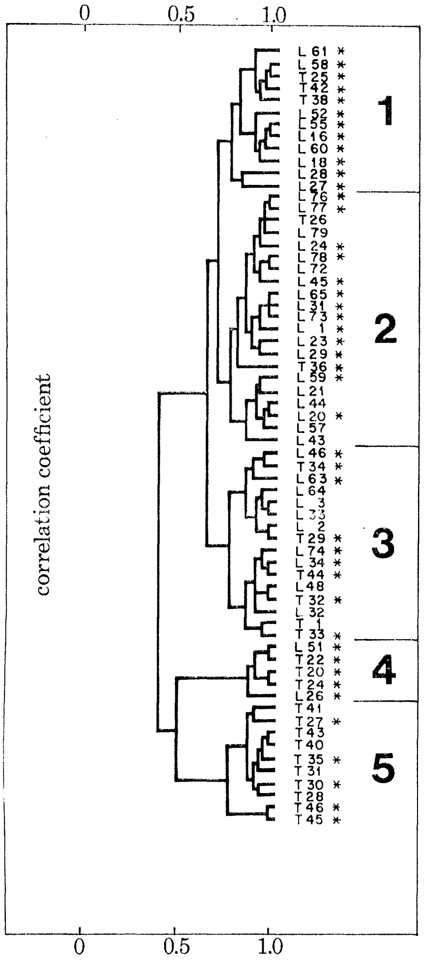


FIGURE 4. Q-mode cluster dendrogram of component analysis of reef flat sediments from Low and Three Isles Reefs. Five groups (1–5) are recognizable. Asterisk denotes that the sample is common to the component and textural analyses.

(*b*) *Texture*

Grain size analyses were made using a Ro-Tap shaker, U.S. standard sieves and a sieving time of 15 min. The results, expressed as percentages by mass in each $\frac{1}{4}$ ϕ ($-\log_2$ millimetre transformation) interval of the sand size range, were processed by using the same programs as used for the component analyses. Because the number of samples exceeded the maximum that could be processed by the cluster program, analysis was performed on two subgroups: the Low Isles and Three Isles samples, and samples from the reefs of the Howick Group respectively.

The Q-mode cluster dendrograms (figure 6) show three distinct groupings (1–3). Statistics of the grain size relations within the three groups are given in table 2. Typical textural parameter values expressed in verbal terms are:

Type 1: usually coarse or very coarse sands and gravel; moderately to poorly sorted; strongly fine skewed or fine skewed; kurtosis variable.

Type 2: usually very coarse sand or coarse sand, with minor gravel; moderately to moderately well sorted, occasionally well sorted; strongly fine skewed, fine skewed or near symmetrical; kurtosis variable.

Type 3: usually coarse and medium sands; moderately to poorly sorted; fine skewed, kurtosis variable.

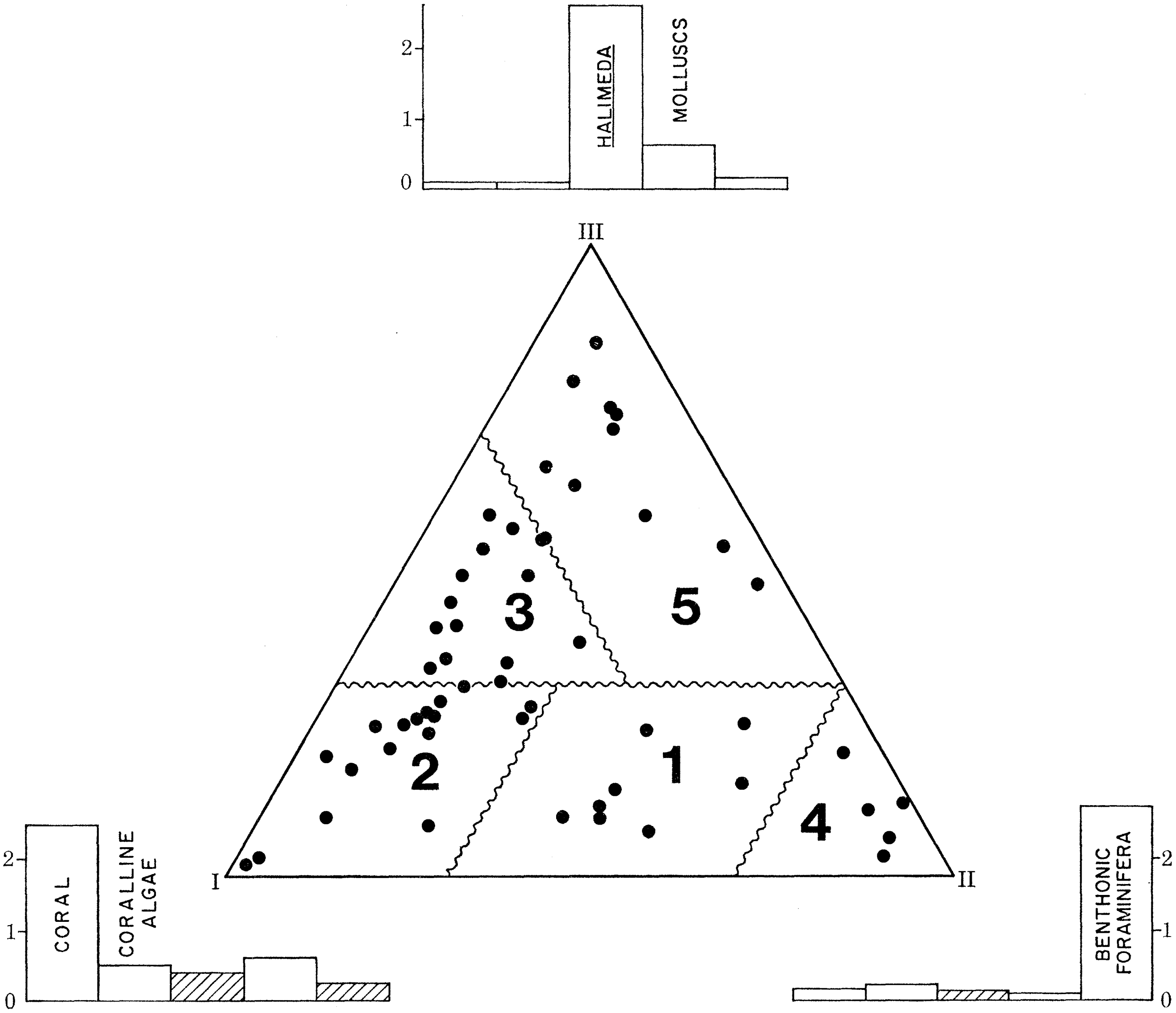


Figure 5. Plot of sediments in terms of three normalized varimax factors. The areas occupied by component groupings (1–5) are indicated. The relative influence of components to each factor is shown as the plot of factor scores. Hatched areas are those showing negative influence.

Q-mode factor analysis (figure 7) indicates that 95 % of the grain-size variation can be explained by three factors. The normalized varimax triangular plot shows the relation of the samples with respect to factors 1, 2 and 3 (40, 40, and 15 % variance respectively) and illustrates the fields occupied by the three cluster groupings. The relative grain size contribution with respect to each factor is shown by the factor score.

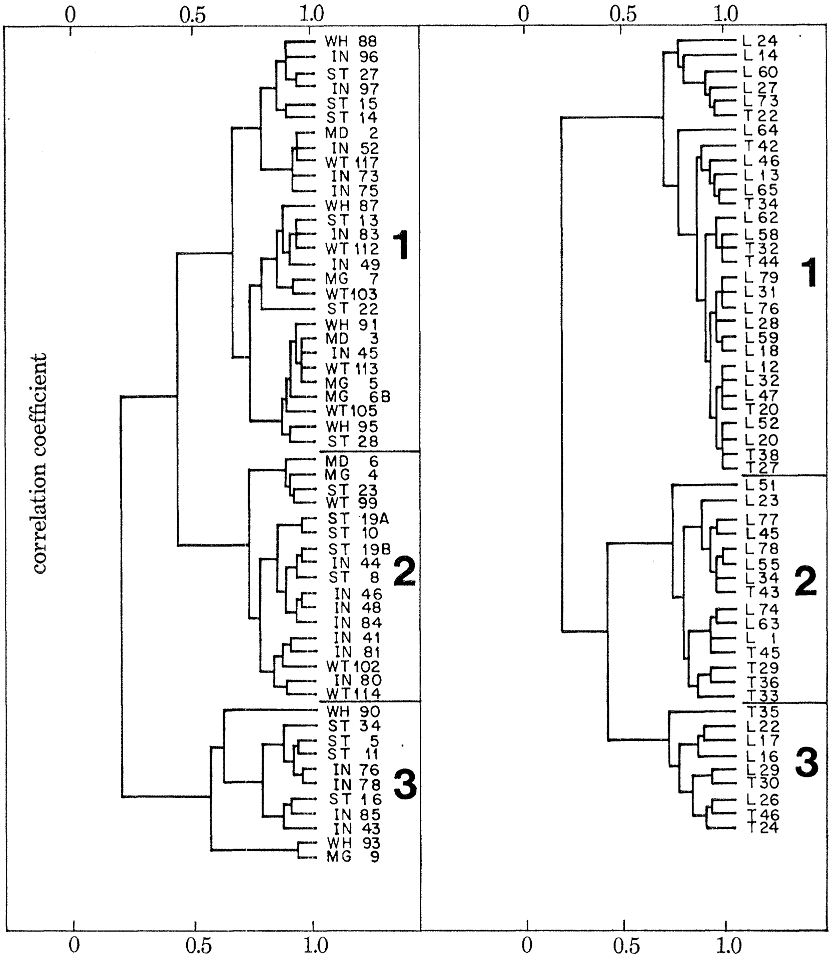


FIGURE 6. Q-mode cluster dendrograms of grain size analysis of the reef flat sediments. Three clusters (1–3) are recognizable. The other cluster relates to sediments from the mangrove area or from the inter-reef area.

TABLE 2. REEF FLAT SEDIMENTS: GRAIN SIZE STATISTICS

Percentage by mass retained at $\frac{1}{4}$ ϕ intervals (22 values)

					type 1 (55)							
$\bar{x}$	26.2*	6.0	7.3	7.9	7.0	9.6	6.4	5.0	4.7	4.0	2.9	(*a*)
s	11.1	3.1	3.3	2.7	2.6	3.9	2.1	1.8	2.1	2.1	1.9	
size (ϕ)	gravel	−0.75	−0.50	−0.25	0.00	0.25	0.50	0.75	1.00	1.25	1.50	
$\bar{x}$	2.5	2.2	1.3	1.7	1.3	0.8	0.6	0.4	0.2	0.3	0.9	(*b*)
s	1.8	1.7	1.1	1.5	1.3	0.8	0.6	0.4	0.2	0.4	1.5	
size (ϕ)	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	mud	
					type 2 (24)							
$\bar{x}$	7.5	3.6	5.9	9.2	10.7*	17.2*	11.9*	8.7	7.3	5.2	3.2	(*a*)
s	3.4	1.6	2.7	3.1	4.1	6.9	3.5	2.4	2.9	3.0	2.1	
$\bar{x}$	2.0	1.3	1.0	1.4	1.0	0.7	0.4	0.3	0.1	0.1	0.6	(*b*)
s	1.7	1.5	1.2	1.7	1.3	1.0	0.6	0.4	0.1	0.2	0.6	
					type 3 (17)							
$\bar{x}$	4.5	2.1	3.2	4.7	4.7	7.8	7.3	7.5	9.2*	9.9*	8.3*	(*a*)
s	4.2	1.5	2.1	2.1	1.8	2.7	2.1	1.8	3.7	4.9	4.0	
size/mm	gravel	1.68	1.41	1.19	1.00	0.84	0.71	0.59	0.50	0.42	0.35	
$\bar{x}$	6.2*	5.7*	4.7*	4.6*	3.1*	1.9	1.3	0.7	0.3	0.3	0.9	(*b*)
s	2.5	3.0	2.1	1.9	1.8	1.5	1.1	0.7	0.3	0.3	0.6	
size/mm	0.30	0.25	0.21	0.17	0.15	0.125	0.105	0.088	0.074	0.062	mud	

$\bar{x}$, mean; *s*, standard deviation; * denotes dominant grain size. (n), number of samples.

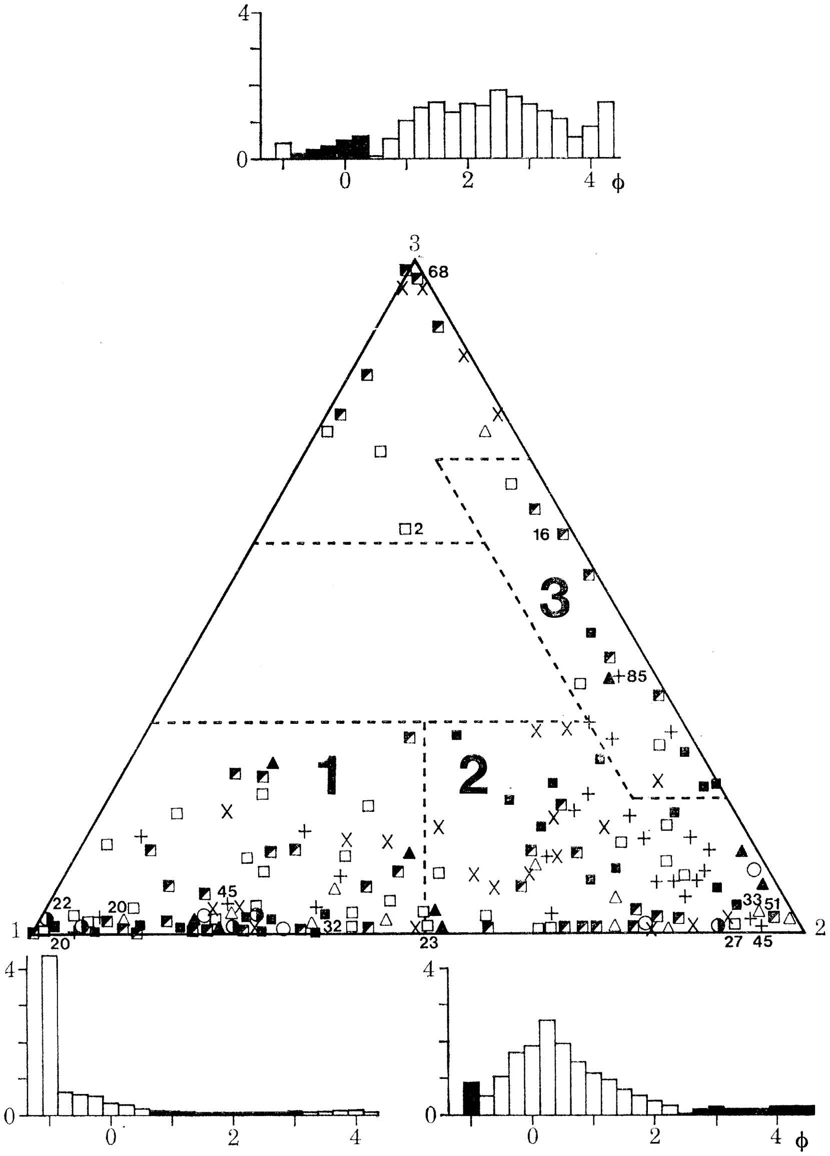


FIGURE 7. Plot of sediments in terms of three normalized varimax factors. The areas occupied by each grain size group (1–3) are indicated. The relative influence (black for negative score) of each $\frac{1}{4}$ ϕ interval is shown on the plot of the factor scores ($-1\ \phi = 2$ mm; $0\ \phi = 1$ mm; $1\ \phi = 0.5$ mm; $2\ \phi = 0.25$ mm; $3\ \phi = 0.125$ mm; $4\ \phi = 0.062$ mm). ■, Three Isles; ◩, Low Isles, +, Ingram; ×, Stapleton; □, Pipon; △, Watson; ○, Mid; ◑, Megaera; ▲, 'Waterwitch'.

(c) *Relations between component and grain size*

The complex relation between organic components and grain size, produced by the irregular nature of the disintegration of individual skeletons (Sorby Principle: Folk & Robles 1964), has been investigated in two ways. The component and grain size data of each sediment sample were combined, and R-mode cluster analysis performed; representative fractions of each of the distinct modes indicated on the grain size frequency histograms were examined using the scanning electron microscope. The following associations are indicated within the sand size range:

coral: sizes -0.75 to $-0.25\ \phi$ (1.68–1.19 mm) and 3.25–4.00 ϕ (0.105–0.062 mm);

benthonic Foraminifera: sizes 0.00–0.75 ϕ (1–0.59 mm) (larger species) and 2.75–3.00 ϕ (0.149–0.125 mm) (smaller species);

coralline algae: sizes −1.00 to −0.25 ϕ (2–1.19 mm);

Halimeda: sizes 0.00–3.00 ϕ (1.0–0.125 mm);

molluscs: sizes −0.75 to −0.25 ϕ (1.68–1.19 mm) and 2.25–2.50 ϕ (0.210–0.177 mm).

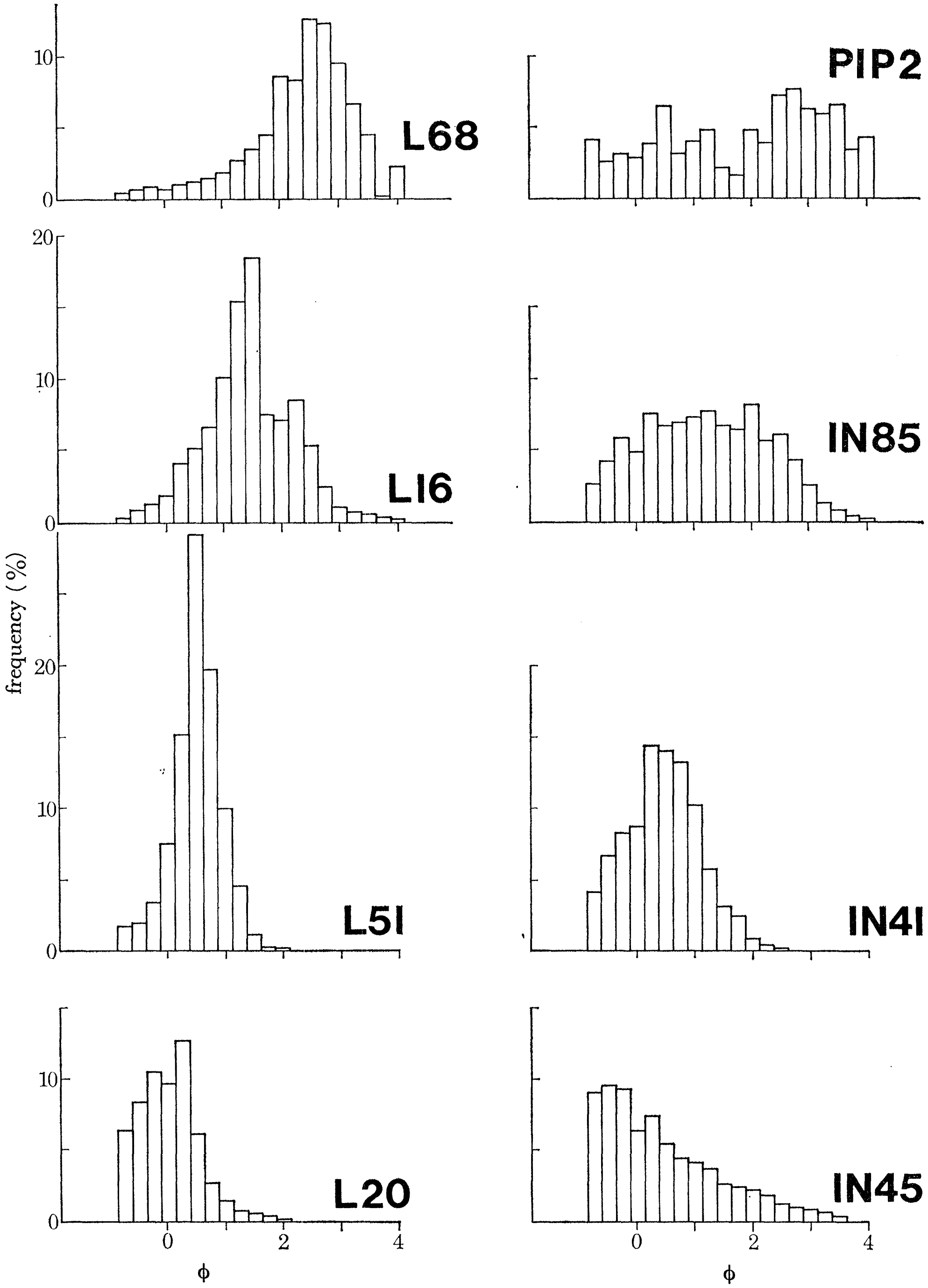


FIGURE 8. Grain size histograms for selected sediments. Several skeletal modes are obvious. Samples L16 and L68 are from the reef slope area and PIP2 is from a lagoonal area (conversions from ϕ to millimetres are given with figure 7).

(The range of sizes mentioned for each component group does not preclude the possible occurrence of the component in any other size.)

(*d*) *Distribution of the sediment types*

The sediments represent individual skeletons or the finer sediment derived from their breakdown. The distribution patterns of the component and textural types are controlled both by the location of the living organisms and by the movement of their detritus from the growth areas to areas of deposition. The following patterns were observed:

Reefal component type 1 (high percentage content of coral and benthonic Foraminifera), occurs at the windward outer margins of the reef flat and reef rim. It represents mixing of types 2 and 4.

Reefal component type 2 (high percentage content of coral) occurs toward the leeward part of the reef flat or forming the coral shingle ramparts. It can occur in pools adjacent to areas of prolific coral growth and characteristically represents any shallow lagoonal area.

Reefal component type 3 (high percentage of coral and *Halimeda*) occurs in the more protected areas of the reef flat, usually on a rocky substrate. The coral component is in the process of moving across the reef flat from windward to leeward and the *Halimeda* component is produced by the breakdown *in situ* of that organism. It represents mixing of types 2 and 5.

Reefal component type 4 (high percentage of benthonic Foraminifera) occurs at the seaward extremities of the reef flat and reef rim on the windward side.

Reefal component type 5 (high percentage of *Halimeda*) occurs in the more protected environments such as the lee of mangroves where contamination by other skeletal components is minimal. This sediment type appears to be restricted to reefs of low wooded island type.

Reefal textural type 1 (high percentage of particles coarser than sand size and varying percentages of other particle sizes) occurs towards the outer windward margin of the reef flat and on the reef rim. It represents lag deposits remaining after fine particles have been removed to the off-reef area or leeward across the reef flat.

Reefal textural type 2 (high percentage of particles of coarse to medium sand size and varying percentage of other particle sizes) occurs either on the windward side of the shingle ramparts and ridges or towards the central and leeward parts of the reef flat. It is characteristic of the sand flat areas.

Reefal textural type 3 (no gravel, varying percentages of coarse, medium, or fine sand) occurs towards the leeward parts of the reef flat in places where the tidal currents are reworking the medium and fine sand sizes. Particles finer than 3 ϕ (i.e. very fine sand and smaller) are characteristically absent on the exposed parts of the reef flats.

There is no obvious correlation between the component and textural types, individual skeletal particles not being restricted to any one size.

(*e*) *Synthesis*

The organic skeletal components provide an almost continuous spectrum of particle sizes which are modified into distinct size populations by the hydrodynamic conditions (waves and tides) prevailing on individual reefs. Irrespective of the individual skeletal modes, the distribution of sand size particles (figure 10) shows several log-normal populations similar to those recognized in clastic sediments (Moss 1962, 1963; Visher 1969) suggesting that the size populations present in the sand-sized carbonate sediments may be explained in a similar manner regardless of inherent differences in shape, relative density, etc. (cf. Folk & Robles 1964; Force 1969).

Reefal sediments would therefore be considered to consist of any of the following:

A coarse population (approximately 1 ϕ (0.5 mm) and coarser), representing either lag deposits of particles too large to be removed from the outer part of the reef, where it was deposited by wave action, or particles that can be moved as a traction load by translatory wave action or tidal currents.

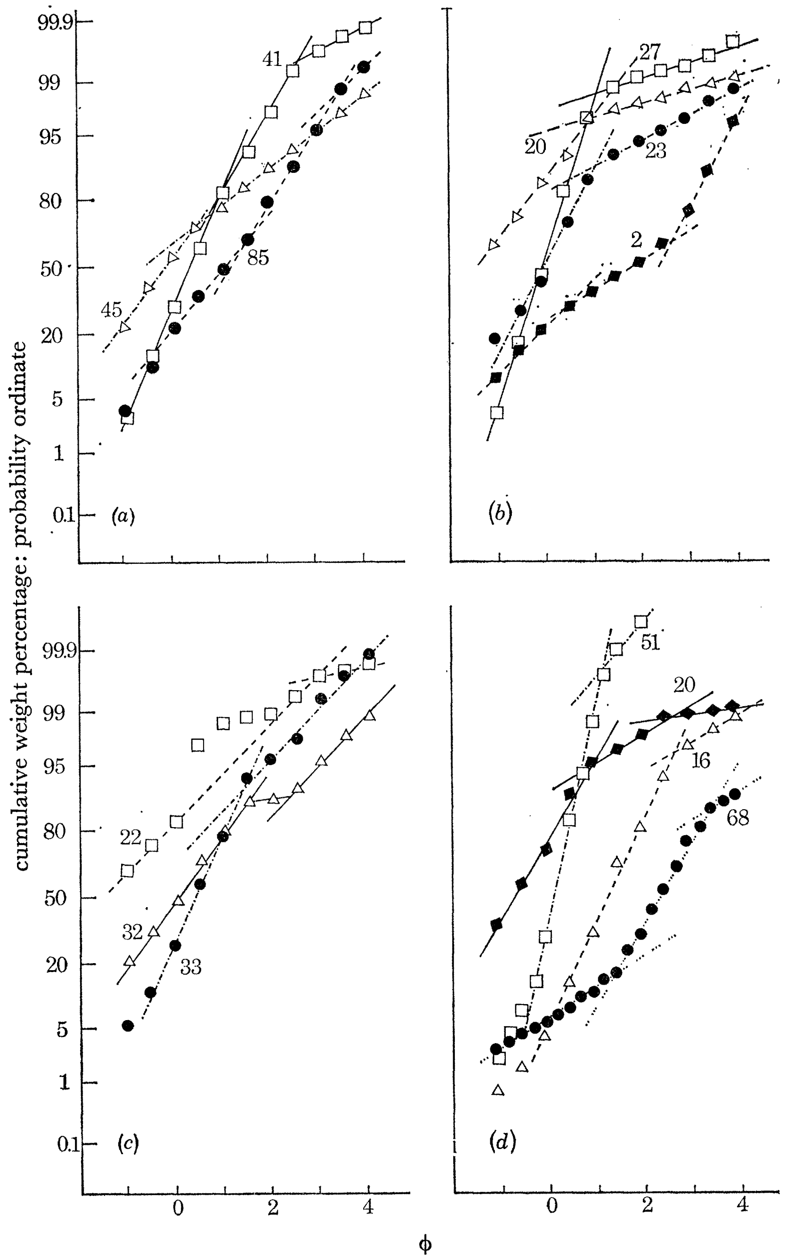


FIGURE 10. Cumulative curves of selected sediments illustrating the presence of distinct log-normal population (cf. Visher 1969). (*a*) Ingram–Beanley; (*b*) Pipon; (*c*) Three Isles; (*d*) Low Isles (conversions from ϕ to millimetres are giveh witn figure 7).

A medium to fine (1–3 ϕ; 0.5–0.125 mm) population representing material eroded from the lag deposit and which is being deposited as the energy of the eroding agent (currents or waves) decreases.

A very fine population (3 ϕ (0.125 mm) and smaller) capable of being removed as suspension load from the reef to be deposited in the lagoonal or inter-reef areas.

Several populations representing material being moved by a combination of one or more of the modes of transportation (traction, saltation, or suspension). The particular size at which the mode of transportation changes depends upon the prevailing energy conditions of the waves and/or tidal currents.

These results are in harmony with Marshall & Orr's (1931) finding relating to the movement of sediment on the reef flat at Low Isles.

6. Conclusion

The occurrence and stability of sediment bodies is primarily related to the prevailing energy conditions (wave and tidal currents) and only secondarily are they related to biological factors (availability of skeletal particles).

The statistical analyses have shown that 95% of the variation displayed by the reefal sediments can be explained either in terms of three skeletal component groups: coral plus coralline algae, *Halimeda*, and benthonic Foraminifera; or alternatively in terms of three grain size populations: 1 ϕ (0.5 mm) and coarser, 1–3 ϕ, and 3 ϕ (0.125 mm) and finer. A textural gradient is displayed as follows: gravel and coarser sand on the windward part of the reef, medium sand on the central part of the reef flat and fine sand on the leeward part of the reef. Such gradients from windward to leeward are a direct response to diminishing amounts of the wave energy available to transport skeletal material from the areas of maximum productivity (the windward sector) to leeward. Tidal current can modify these textural differences.

The numerical results confirm the visual observations.

References (Flood & Scoffin)

Davis, J. C. 1973 *Statistics and data analysis in geology*. New York: John Wiley.

Folk, R. L. & Robles, R. 1964 *J. Geol.* **72**, 255–292.

Force, L. M. 1969 *J. sedim. Petrol.* **39**, 902–904.

Imbrie, J. & Purdy, E. G. 1962 In *Classification of carbonate rocks*. (ed. W. E. Ham), pp. 253–272. (American Association of Petroleum Geologists, Mem. 1.)

Klovan, J. E. & Imbrie, J. 1971 *Math. Geol.* **3**, 61–77.

McLean, R. F. & Stoddart, D. R. 1978 *Phil. Trans. R. Soc. Lond.* A **291**, 101–117 (this volume).

Marshall, S. M. & Orr, A. P. 1931 *Scient. Rep. Gt Barrier Reef Exped. 1928–29* **1**, 93–133.

Maxwell, W. G. H. 1968 *Atlas of the Great Barrier Reef*. Amsterdam: Elsevier.

Moss, A. J. 1962 *Am. J. Sci.* **260**, 337–373.

Moss, A. J. 1963 *Am. J. Sci.* **261**, 297–343.

Scoffin, T. P. & McLean, R. F. 1978 *Phil. Trans. R. Soc. Lond.* A **291**, 119–138 (this volume).

Steers, J. A. 1929 *Geogrl J.* **74**, 232–257, 341–367.

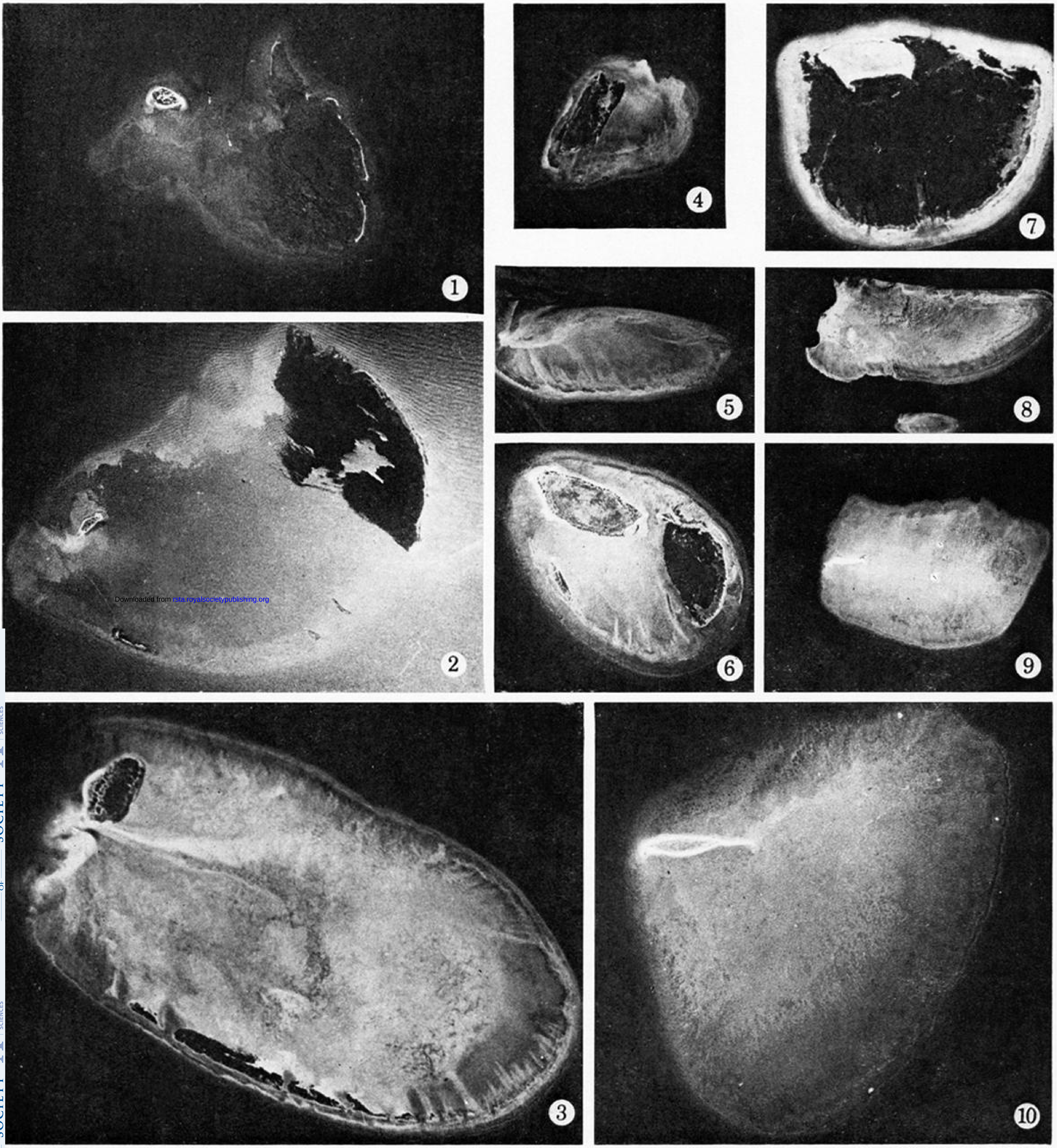
Steers, J. A. 1930 *Scient. Rep. Gt Barrier Reef Exped. 1928–29* **3**, 1–15.

Stephenson, T. A., Stephenson, A., Tandy, G. & Spender, M. A. 1931 *Scient. Rep. Gt Barrier Reef Exped. 1928–29* **3**, 17–112.

Stoddart, D. R., McLean, R. F. & Hopley, D. 1978 *Phil. Trans. R. Soc. Lond.* B **284**, 39–61 (part B of this Discussion).

Thom, B. G., Orme, G. R. & Polach, H. A. 1978 *Phil. Trans. R. Soc. Lond.* A **291**, 37–54 (this volume).

Visher, G. S. 1969 *J. sedim. Petrol.* **39**, 1074–1106.



IGURE 2. Vertical aerial photographs of the reef tops. 1, Low Isles; 2, Pipon; 3, Ingram–Beanley; 4, Watson; 5, Megaera; 6, Three Isles; 7, Bewick (site of diamond drill hole: Thom, Orme & Polach 1978, this volume); 8, Mid; 9, 'Waterwitch'; 10, Stapleton (site of diamond drill hole). For a comparison of sizes see figure 3. Published with permission of the Director of National Mapping, Australia.

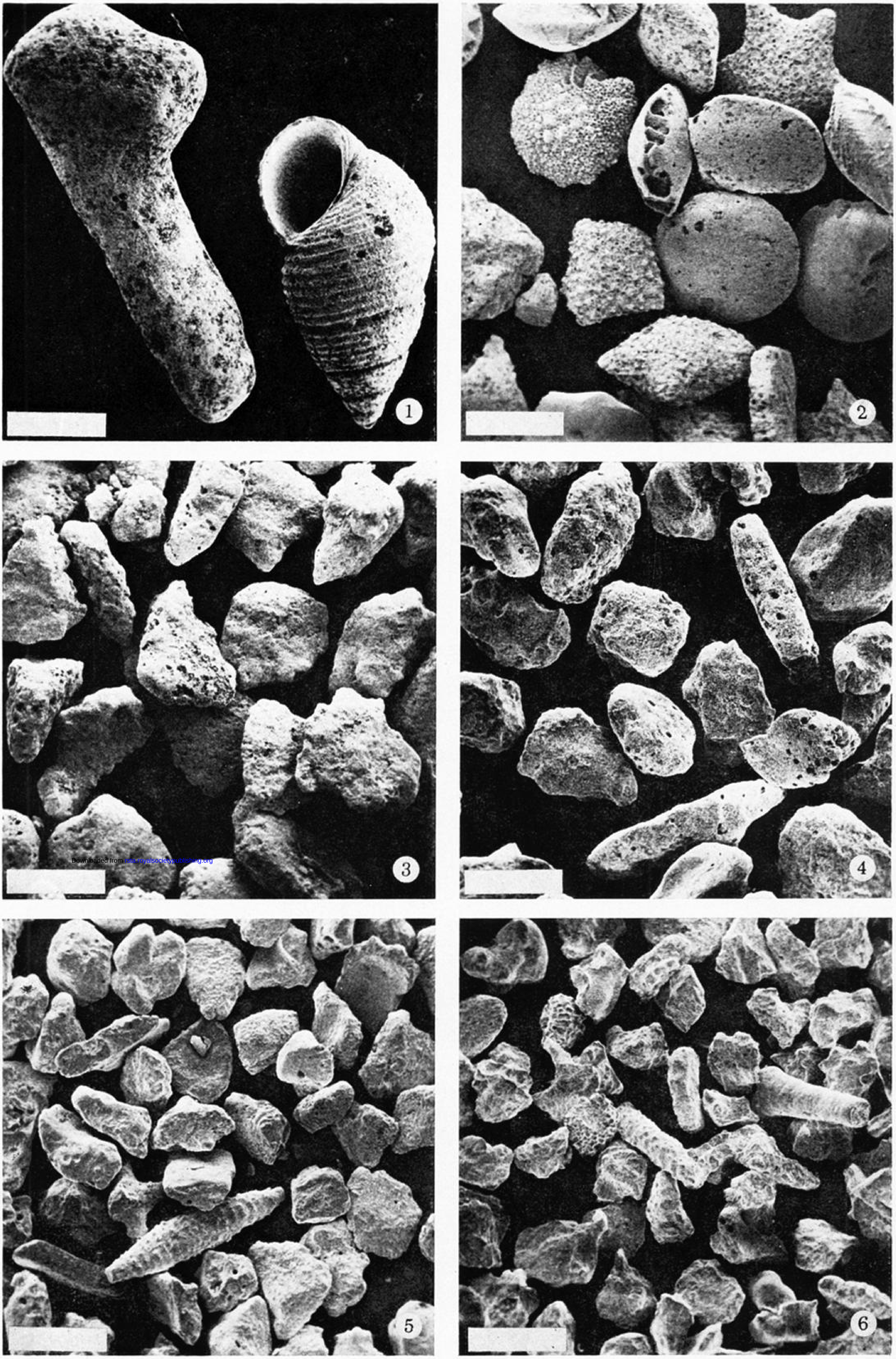


Figure 9. Scanning electron microphotographs of selected $\frac{1}{4}$ ϕ fractions: (1) coral and shell, size -0.25 ϕ, bar scale 1 mm; (2) benthonic Foraminifera, size 0.25 ϕ, bar scale 0.8 mm; (3) coral, *Halimeda* and others, size 1 ϕ, bar scale 0.8 mm; (4) size 2 ϕ, bar scale 0.5 mm; (5) size 2.75 ϕ, bar scale 0.5 mm; (6) size 3.25 ϕ, bar scale 0.2 mm.