PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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An analysis of the textural variability displayed by inter-reef sediments of the Impure Carbonate Facies in the vicinity of the Howick Group

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[Plates 1 and 2]

Recent surface sediments from the continental shelf in the vicinity of the Howick Group have been analysed to determine their textural, chemical and skeletal composition. There is a decrease in terrigenous particle size from quartz sand in the nearshore area to mud offshore. Carbonate particle size decreases from gravel to mud moving away from the reef. Multivariate statistical analysis of grain size data has determined the influence of various sources. Q-mode cluster and factor analysis distinguished four sediment types and indicated that three factors are responsible for 94% of the textural variation. R-mode cluster analysis showed three distinct size populations. They result from intermixing of material from different sources and do not necessarily reflect distinct modes of transportation. The distribution of the textural sediment types displays concentric elliptical patterns around each platform reef in a zone approximately 2 km wide, within which there is a size gradient from coarse sand and gravel near the windward reef edge to fine sand near the leeward margin.

1. Introduction

The apparent homogeneity of the inter-reef sediments (most of which belong to the Impure Carbonate Facies) which were collected in the vicinity of the Howick Group highlights the lack of sensitivity on a local scale of the criteria used by previous researchers (Maxwell & Maiklam 1964; Maxwell 1968, 1973; Maxwell & Swinchatt 1970) for regional facies differentiation within the Great Barrier Reef Province. An account of the textural variations exhibited by these sediments is presented. This investigation supplements Maiklem's (1970) study of sediments of the High Carbonate Facies from the Capricorn Group, and Frankel's (1974) investigation of sediments of the Transitional and Terrigenous Facies within Princess Charlotte Bay. Together, they provide a more comprehensive understanding of the complex interplay of the terrigenous, *in situ*, and reefal sources which determine the regional facies pattern throughout the province.

2. The regional facies pattern

Maxwell (1968, 1973) has outlined a dual classificatory scheme for shelf sediments from the Great Barrier Reef Province based upon the carbonate:non-carbonate ratio or the mud:sand ratio. This scheme is useful on a regional scale for delineating areas where the sediments reflect the dominance of either the mainland terrigenous source or the reefal carbonate sources. Some, however, display variable influence from multiple sources and the Howick Group is one such area. In the present study the carbonate content is used for distinguishing facies. The mud content (terrigenous plus carbonate) used to differentiate subfacies. The resultant pattern

Table 1. Inter-reef sediments of the Howick Group and neighbouring area: data

sample no.	position S lat.	position E long.	depth	gravel	mud	sand	acid insoluble gravel + sand (%)	acid insoluble mud (%)	acid insoluble total (%)	median size (φ)	textural classification
1	14° 29′	144° 55′	16	5	29	66	21	85	39	1.9	slightly gravelly muddy sand
2	14° 29′	144° 58′	24	10	6	84	25	69	28	1.3	gravelly sand
3	14° 19′	144° 51′	10	12	0	88	0	0	0	1.3	gravelly sand
4	14° 20′	144° 50′	20	7	48	45	10	60	34	4.3	slightly gravelly sandy mud
29	14° 18′	144° 51′	6	0	3	97	2	36	3	2.3	sand (moderately sorted)
35	14° 25′	144° 53′	28	15	17	68	14	75	24	0.5	gravelly muddy sand
36	14° 26′	144° 54′	28	12	20	68	10	62	20	0.8	gravelly muddy sand
37	14° 25′	144° 54′	26	11	20	69	11	59	21	1.1	gravelly muddy sand
38	14° 24′	144° 54′	25	12	5	83	5	44	7	0.7	gravelly sand
39	14° 24′	144° 53′	17	11	24	65	10	56	21	2.3	gravelly muddy sand
40	14° 24′	144° 53′	18	12	36	62	2	64	25	2.8	gravelly muddy sand
56	14° 25′	144° 52′	8	6	1	93	1	1	1	0.2	gravelly sand
57	14° 25′	144° 51′	26	10	18	72	11	67	22	1.7	gravelly muddy sand
59	14° 24′	144° 54′	10	9	7	84	3	36	5	1.3	gravelly sand
60	14° 26′	144° 48′	11	7	11	82	1	60	2	2.1	gravelly muddy sand
61	14° 27′	144° 48′	14	6	0	94	1	0	1	0.6	gravelly sand
62	14° 27′	144° 49′	16	8	24	68	20	72	33	2.3	gravelly muddy sand
63	14° 28′	144° 50′	14	10	25	65	18	75	33	2.3	gravelly muddy sand
64	14° 28′	144° 51′	13	6	31	63	22	77	39	2.6	gravelly muddy sand
65	14° 29′	144° 52′	13	9	24	67	21	65	31	2.2	gravelly muddy sand
66	14° 30′	144° 53′	13	11	28	61	23	96	43	2.3	gravelly muddy sand
67	14° 30′	144° 54′	18	7	31	62	24	77	40	2.6	gravelly muddy sand
68	14° 31′	144° 54′	10	8	14	78	25	77	33	2.1	gravelly muddy sand
69	14° 31′	144° 55′	20	8	18	74	25	77	34	1.5	gravelly muddy sand
70	14° 31′	144° 56′	15	10	17	73	23	73	32	1.1	gravelly muddy sand
71	14° 30′	144° 57′	14	7	34	59	4	73	28	2.7	gravelly muddy sand
112	14° 26′	144° 55′	20	7	36	57	11	52	26	3.0	gravelly muddy sand
113	14° 26′	144° 57′	25	11	9	80	27	59	30	1.6	gravelly muddy sand
114	14° 26′	144° 59′	30	7	29	64	22	82	39	2.3	gravelly muddy sand
115	14° 26′	145° 00′	22	6	32	62	14	74	33	2.6	gravelly muddy sand
116	14° 27′	144° 59′	12	0	2	98	2	40	3	1.4	sand (moderately sorted)
117	14° 31′	144° 58′	24	10	24	66	57	74	60	1.8	gravelly muddy sand
120	14° 30′	145° 02′	25	15	13	72	11	80	20	0.3	gravelly muddy sand
121	14° 29′	144° 58′	15	8	16	76	43	59	46	1.8	gravelly muddy sand
122	14° 29′	144° 57′	10	1	6	93	1	50	4	2.4	sand (moderately sorted)
123	14° 27′	144° 53′	10	6	5	89	1	61	4	0.2	gravelly sand
124	14° 28′	144° 53′	14	12	23	65	8	80	25	1.2	gravelly muddy sand
125	14° 29′	144° 53′	20	6	14	80	21	67	27	1.8	gravelly muddy sand
126	14° 28′	144° 54′	13	6	29	65	19	89	39	2.8	gravelly muddy sand
127	14° 28′	144° 54′	22	12	19	69	13	84	26	1.8	gravelly muddy sand
128	14° 27′	144° 53′	20	3	17	80	1	75	13	0.6	slightly gravelly muddy sand
130	14° 25′	144° 47′	14	7	41	52	10	89	42	3.0	gravelly muddy sand
131	14° 25′	144° 46′	15	4	47	49	12	75	42	4.0	slightly gravelly muddy sand
132	14° 25′	144° 45′	15	2	60	38	27	85	61	—	slightly gravelly sandy mud
133	14° 25′	144° 43′	14	0	75	25	25	80	66	7.0	sandy mud
135	14° 25′	144° 41′	13	1	64	35	19	79	57	6.0	slightly gravelly sandy mud
136	14° 25′	144° 39′	10	0	86	14	—	80	—	9.0	sandy mud
137	14° 25′	145° 01′	26	4	18	78	53	64	54	2.2	slightly gravelly muddy sand
138	14° 27′	145° 02′	22	8	7	85	28	69	31	1.8	gravelly sand
139	14° 29′	144° 57′	10	12	14	74	13	62	20	0.9	gravelly muddy sand
140	14° 25′	144° 47′	13	15	36	49	5	64	26	2.0	gravelly muddy sand
141	14° 25′	144° 48′	14	13	31	56	12	67	29	1.1	gravelly muddy sand
142	14° 25′	144° 50′	18	9	44	47	18	65	39	3.2	gravelly muddy sand
143	14° 27′	144° 54′	19	10	29	61	19	72	34	1.7	gravelly muddy sand
144	14° 29′	144° 55′	16	7	23	70	6	50	16	3.3	gravelly muddy sand

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TABLE 1 (*cont.*)

ple	position						acid insoluble			median	
o.	S lat.	E long.	depth	gravel	mud	sand	gravel + sand (%)	mud (%)	total (%)	size (ϕ)	textural classification
45	14° 29′	144° 57′	25	9	6	85	32	67	34	1.6	gravelly sand
46	14° 23′	144° 50′	22	42	2	56	6	4	7	−0.7	sandy gravel
47	14° 22′	144° 54′	17	6	53	41	5	59	34	6.0	gravelly mud
48	14° 18′	144° 53′	25	4	38	58	7	82	35	5.0	slightly gravelly muddy sand
49	14° 15′	144° 53′	27	25	8	67	0	32	3	−0.3	gravelly muddy sand
50	14° 16′	144° 51′	30	1	49	50	3	43	23	4.5	slightly gravelly muddy sand
51	14° 23′	144° 50′	17	10	50	40	5	74	40	4.5	gravelly mud
52	14° 32′	144° 53′	8	6	10	84	44	85	48	5.0	gravelly muddy sand
53	14° 34′	144° 51′	5	7	1	92	66	37	67	1.7	gravelly sand
54	14° 34′	144° 50′	4	12	8	80	46	2	43	0.3	gravelly sand
55	14° 32′	144° 50′	6	11	3	86	28	63	29	0.9	gravelly sand

es:
Positioning of all samples given to nearest minute.
All percentages quoted to nearest whole number.
Median size is measured in ϕ units and based on sieve analyses at $\frac{1}{4}$ ϕ intervals.
Textural classification after Folk (1954, *J. Geol.* **62**, 345–351).
Depths are stated in metres below i.s.l.w. (chart datum, Marine Chart AUS 823).
Sample nos 1–128, grab samples collected July–August 1973.
Sample nos 130–139, grab samples collected October 1973.
Sample nos 140–156, dredge samples collected July–August 1973.
Samples were split, one treated with hydrogen peroxide, the other preserved in alcohol.
Representative samples are housed at the University of Queensland and the University of Edinburgh.

obtained from analyses of inter-reef sediments collected from the Howick Group (see figure 1) is shown in figure 2. It consists of:

1. High carbonate (greater than 80 % carbonate) facies
2. Impure carbonate (60–80 % carbonate) facies
   (*a*) Very high mud (40–60 % mud) subfacies
   (*b*) High to moderate mud (10–40 % mud) subfacies
3. Transitional (40–60 % carbonate) facies
   (*a*) Low mud (less than 10 % mud) subfacies
   (*b*) High to moderate mud (10–40 % mud) subfacies
4. Terrigenous (less than 40 % carbonate) facies.

3. Inter-reef sediments of the Howick Group

The bathymetric character of the area of the continental shelf around the Howick Group is illustrated in figure 4.

The Impure Carbonate Facies consist of material derived from at least three sources:

(1) Terrigenous material (predominately mud) derived from a variety of igneous and sedimentary rock types which occur on the mainland and from the igneous rocks on Howick Island.

(2) Carbonate material representing the calcareous skeletons of *in situ* organisms such as: *Halimeda*, molluscs, bryozoans, echinoderms, ostracods, corals, benthonic foraminiferans, etc. The Foraminifera *Marginopora vertebralis* and *Alveolinella quoyi* are ubiquitous (and frequently blackened) in sediments of this facies and together with the planktonic foraminiferal species they are unquestionable indicators of the inter-reef shelf environment.

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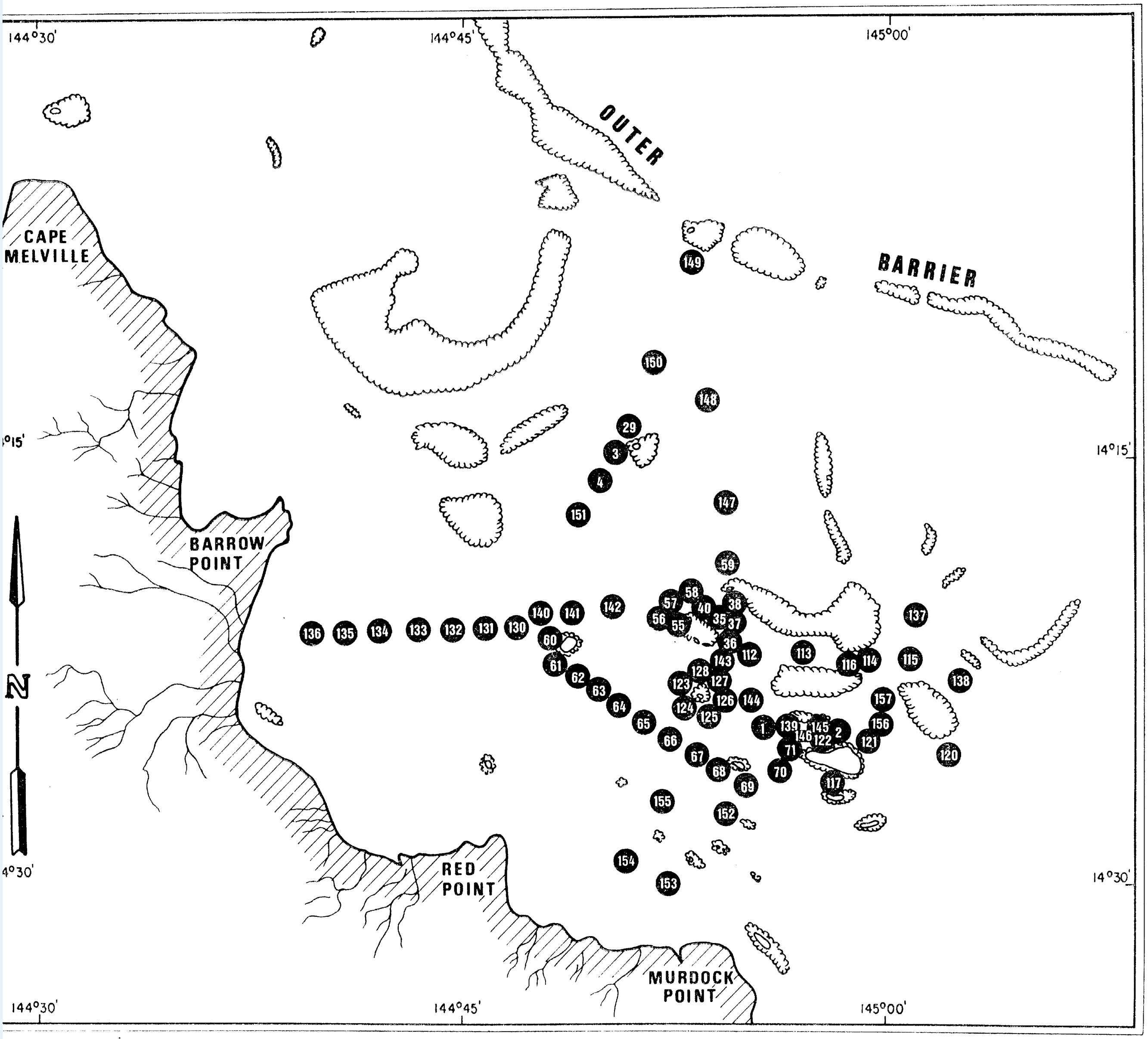

FIGURE 1. Location of the continental shelf sediment samples.

(3) The reef derived material includes significant contributions from corals, molluscs, *Halimeda* spp., and the benthonic foraminiferans *Calcarina hispida* and *Baculogypsina sphaerulata*. The reefal material is often distinguishable from *in situ* skeletal material by its abraded appearance.

(*a*) *Texture*

Q-mode (i.e. samples) cluster analysis (Davis 1973) of the grain size data (sieve analyses) shows four textural groupings (see figure 5) and Q-mode factor analysis (Klovan & Imbrie 1971) shows the 95% of the variation is explained by three factors only. The triangular plot of the normalized varimax factors (factors 1, 2, and 3 explains 22, 24, and 49% variance respectively) and the plot of the relative contribution of each $\frac{1}{4}\phi$ interval to the factors (i.e. factor score) is shown in figure 6. (Conversions from ϕ to millimetres are included in the legend to figure 6.)

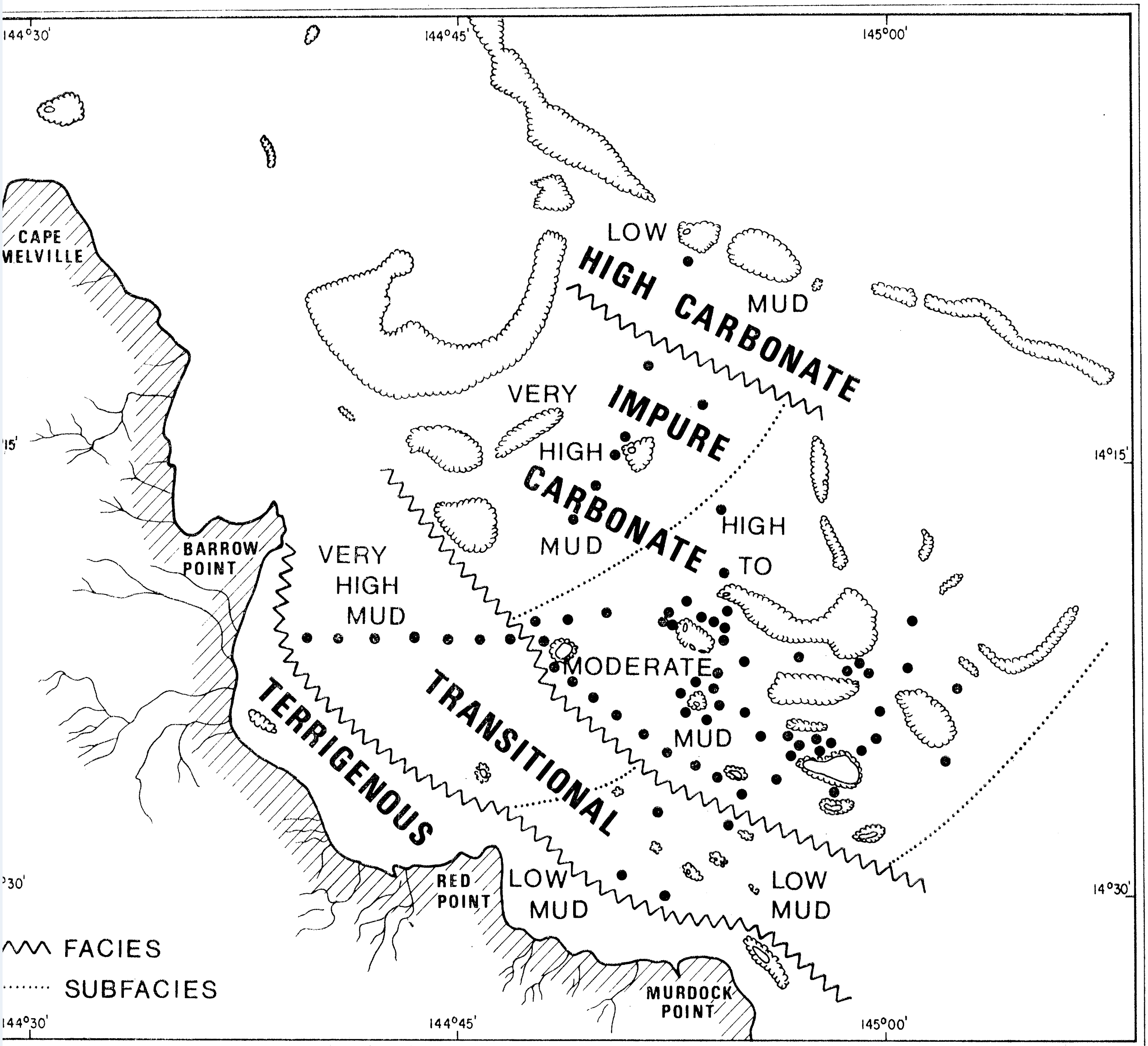

Figure 2. Regional facies pattern on the continental shelf, based on the results of the present investigation.

Textural type 1: greater than 50% by mass coarser than 1 ϕ; less than 10% finer than 4 ϕ; less than 20% finer than 3 ϕ; consists of coarse sand with a varying percentage of gravel; moderately to poorly sorted; strongly fine skewed; variable kurtosis.

Textural type 2: greater than 50% by mass in the range 1–4 ϕ; less than 10% finer than 4 ϕ; less than 40% finer than 3 ϕ; consists of medium sand; poorly sorted; near symmetrical to coarse skewed; commonly leptokurtic.

Textural type 3: 10–30% finer than 4 ϕ, 20–40% finer than 3 ϕ; less than 40% of 1–3 ϕ range; consists of medium sand with a varying percentage of gravel or finer sand and mud; poorly to very poorly sorted; fine skewed; very leptokurtic.

Textural type 4: 30–60% finer than 4 ϕ; 40–60% finer than 3 ϕ; variable percentage gravel

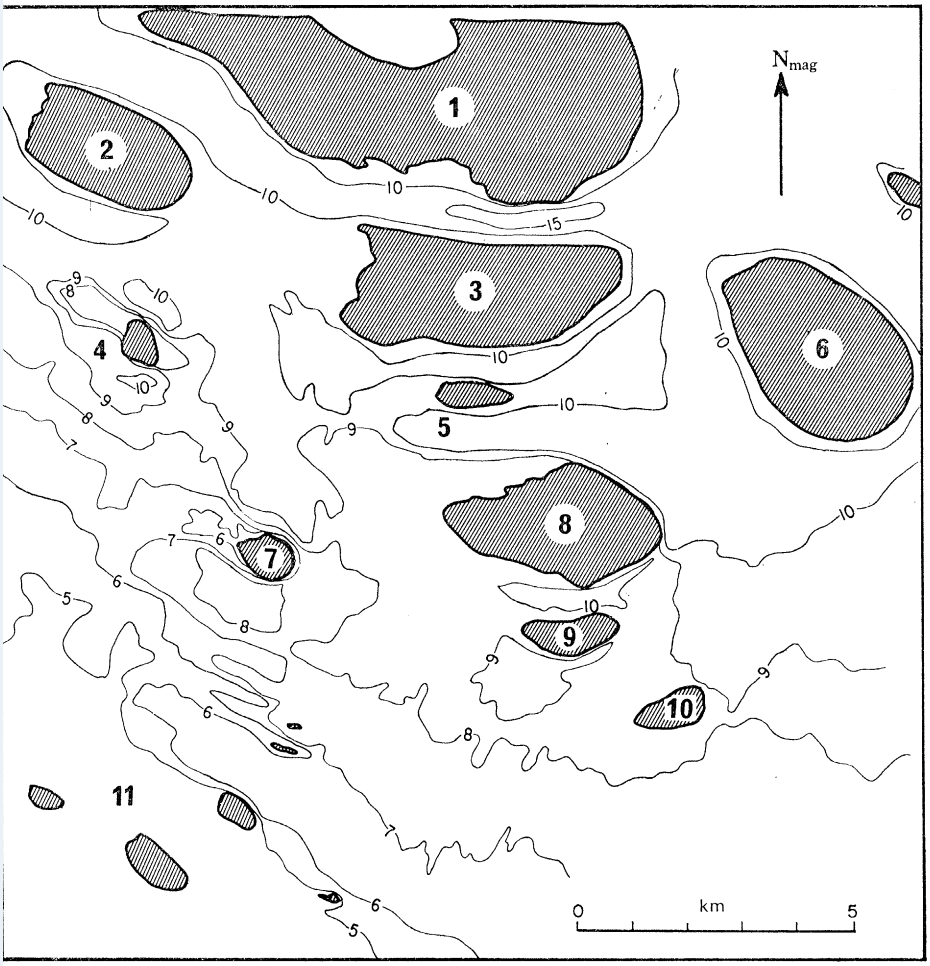

FIGURE 3.

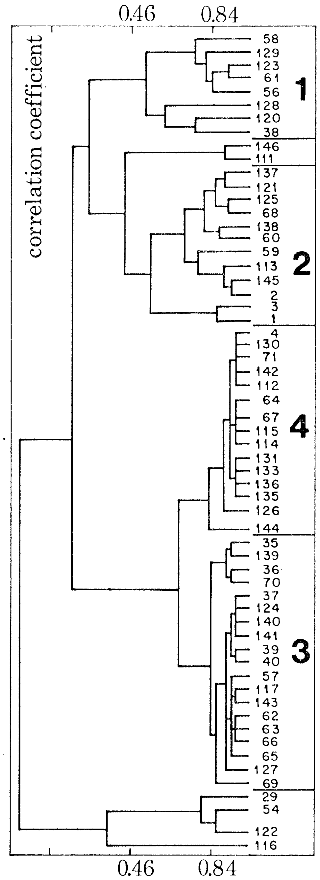

FIGURE 4.

FIGURE 3. Bathymetric character of the continental shelf in the vicinity of the Howick Group. Based on survey by H.M.A. Survey Ship *Paluma* in 1965; Marine Chart AUS 832, 1971; and echo soundings made during the Expedition. Reef names: 1, Combe; 2, Ingram–Beanley; 3, Mid; 4, Watson; 5, Megaera; 6, Snake; 7, Newton; 8, Howick; 9, Houghton; 10, Coquet; 11, Cole Islands. Contours in fathoms (1 fathom ≈ 1.83 m).

FIGURE 4. Q-mode cluster dendrogram of grain size analysis of the inter-reef sediments. Four groups are recognizable. The four negatively correlated samples are reef slope sediments.

or sand; consists of fine to very fine sand with a high percentage of mud sizes; poorly to very poorly sorted; strongly coarse skewed; very leptokurtic.

The R-mode (i.e. variables) cluster analysis dendrogram (figure 6) displays the behavioural relation between each $\frac{1}{4}$ ϕ size interval, the gravel (G) and the mud (M). Three grain size populations are present: I, gravel and coarse sand (1 ϕ and coarser); II, medium to find sand; and III, very fine sand and mud (3 ϕ and smaller). Individual sediments may consist of any combination of the three populations (see figure 7). For example, sample 29 consists predominantly of the medium to fine sand population; sample 61 the coarse sand and gravel population; sample 2 the coarser populations; sample 37 a combination of the three populations; sample 135 the very fine sand and mud population.

The relative proportions of each population with respect to the textural types are as follows: type 1: I $\gg$ II > III, type 2: II $\gg$ III > I, type 3: III > II > I, type 4: III $\gg$ II > I.

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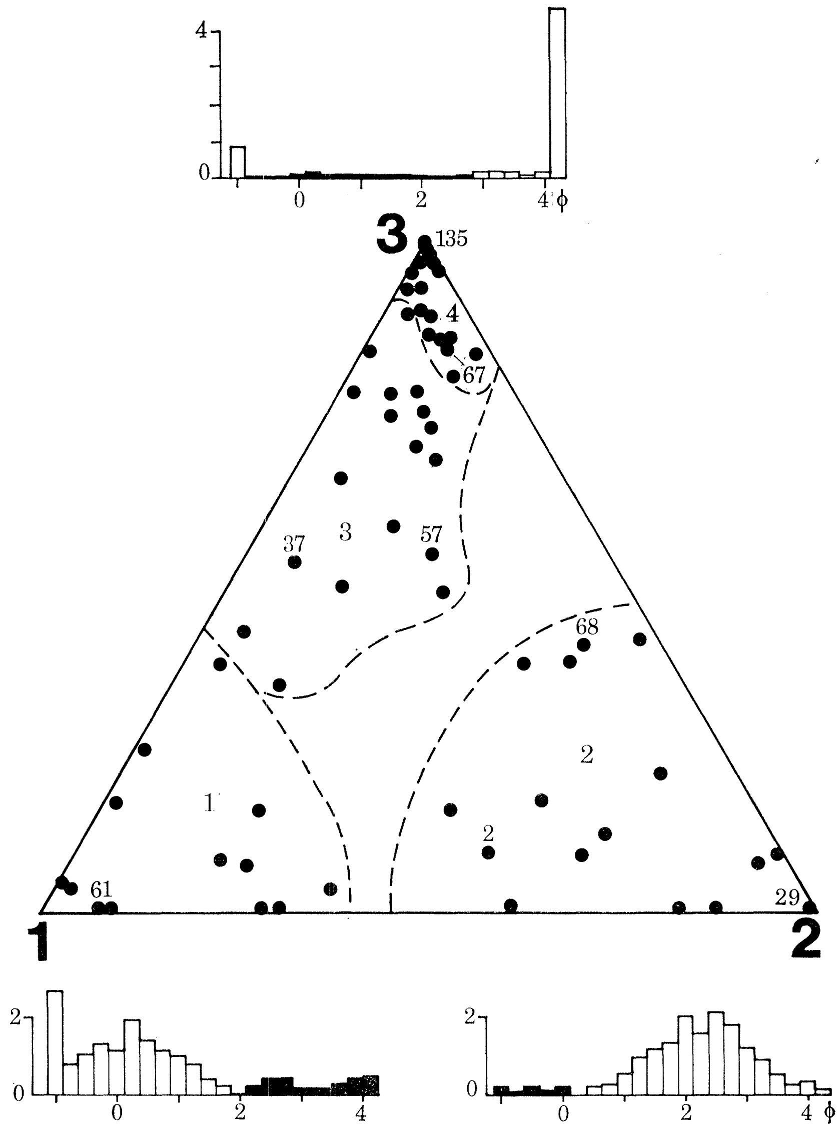

FIGURE 5. Plot of sediments in terms of three normalized varimax factors. The areas occupied by the grain size groupings (1–4) are indicated. The relative influence (black for negative) of each $\frac{1}{4}$ ϕ interval is shown on the plot of the factor scores (−1 ϕ = 2 mm, 0 ϕ = 1.0 mm, 1 ϕ = 0.5 mm, 2 ϕ = 0.25 mm, 3 ϕ = 0.125 mm, 4 ϕ = 0.062 mm).

These populations do not necessarily reflect distinct modes of transportation (traction, saltation or suspension; cf. Visher 1969) nor do they represent depositional populations (designated A ≡ framework, B ≡ interstitial, and C ≡ contact; cf. Moss 1972). They result from intermixing of material from the different sources. The gravel fraction represents either the *in situ* fauna which is usually coarser than 2 mm (−1 ϕ) and which compares with the size of the *in situ* fauna in other reefal provinces (see Swinchatt 1965; Milliman 1973, 1974), or the coarse carbonate detritus (usually coral) derived from the reef proper. The coarse sand (coarser than 1 ϕ) represents either particles formed by the breakdown of the *in situ* organisms (see figure 8*b*, plate 1), or the inter-reef and reefal contribution made by benthonic foraminiferans (see figures 9*a*, plate 2 and 8*a*). The medium to fine sand (see figure 8*c* and *d*) represents a compositionally

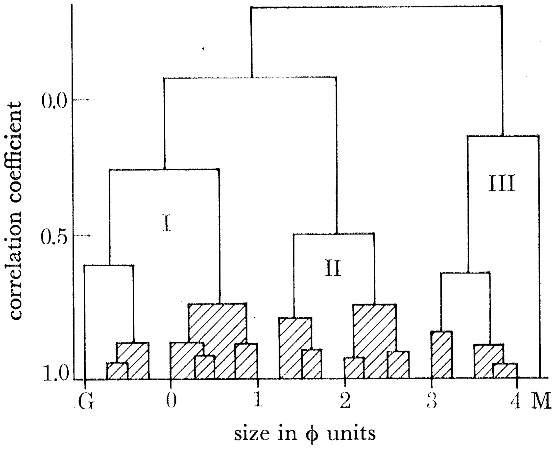

Figure 6. R-mode cluster dendrogram showing the presence of three distinct size populations. The gravel (G) fraction is correlated with the coarse sand sizes, and the mud (M) content is correlated with the fine sand fraction (conversions from ϕ to millimetres are given with figure 5).

complex population consisting of reef-derived skeletal debris, terrigenous quartz particles, *in situ* skeletal breakdown material, and *in situ* organisms such as ostracods, benthonic foraminiferans, molluscs, etc. The very fine sand (see figure 8*e* and *f*) represents an exceptionally heterogeneous admixture, consisting of the finer particles which are removed in suspension from the reef flat (Flood & Scoffin 1978, this volume), the *in situ* contribution, and the calcareous and siliceous tests of a variety of planktonic organisms. The mud fraction is predominantly terrigenous in origin; the carbonate contribution rarely exceeds 30%.

Figure 9 represents stereoscopic pictures of randomly selected sediments (mud fraction removed) representative of the four textural types of sediments present within the Impure Carbonate Facies.

(*b*) *Distribution of the textural types*

The relatively uniform terrigenous and *in situ* carbonate contribution throughout the area is overshadowed in the vicinity of individual reefs by a series of concentric zones characterized by higher carbonate content, increasingly coarser grain size and improved sorting (reflecting the predominance of one source). This pattern is further complicated in areas of dense reef development where overlapping of the concentric arrangement occurs. A somewhat idealized presentation of the distribution of the textural types is shown in figure 10.

Type 1 surrounds each reef and resembles either of the reefal textural types 1 or 2 (Flood & Scoffin 1978, this volume). It consists of a predominance of coarse coral detritus to the windward and benthonic foraminiferans to leeward and represents a talus slope type of accumulation of reef-derived skeletal debris at the base of the reef slope.

Type 2 is restricted to the sediment cone which is developed to the leeward of the platform reefs. It resembles reefal textural type 3 and consists of the finer sizes (1–4 ϕ) of skeletal detritus that may be moved across the reef flat to be deposited in the deeper water.

Type 3 surrounds each reef and represents an admixing of material derived from either the reef mass (finer than 3 ϕ), the *in situ* organisms (coarser than −1 ϕ) and the terrigenous mud component (finer than 4 ϕ). In general the reefal contribution is restricted to particle sizes smaller than 3 ϕ capable of being removed in suspension by wave or tidal currents from the reef flat to the inter-reef area.

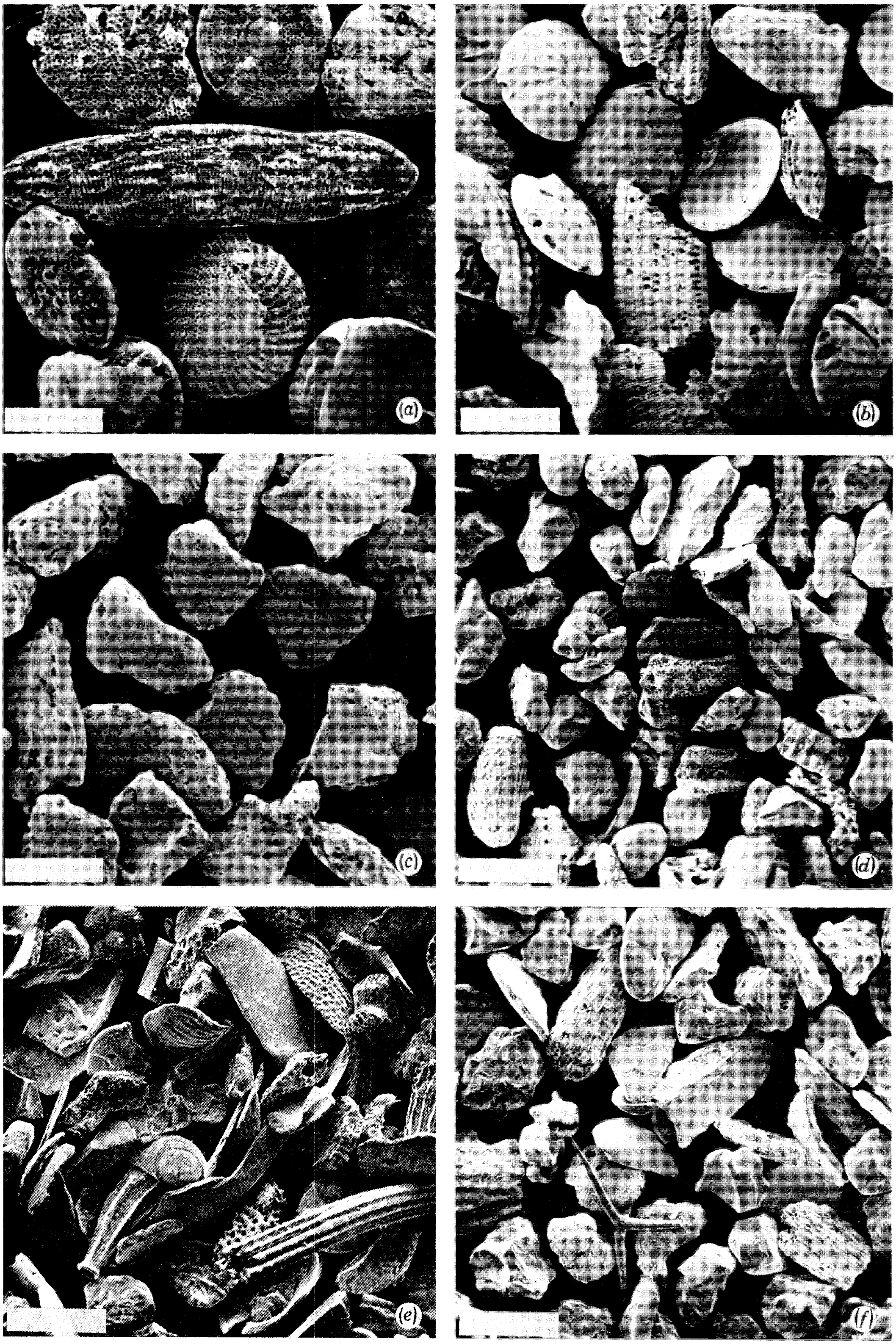

FIGURE 8. Scanning electron micrographs of various grain sizes showing the complex contribution of skeletal components: (*a*) size −0.25 ϕ, scale 1.3 mm, various benthonic Foraminifera; (*b*) size 1.0 ϕ, scale 0.6 mm, benthonic Foraminifera and molluscans; (*c*) size 1.5 ϕ, scale 0.5 mm, *Halimeda* and coral fragments; (*d*) size 2.75 ϕ, scale 0.5 mm, quartz particles, ostracods, molluscans, bryozoans, Foraminifera, etc; (*e*) size 3.0 ϕ, scale 0.5 mm, benthonic and planktonic Foraminifera, molluscan fragments, bryozoans, etc.; (*f*) size 3.5 ϕ, scale 0.5 mm, quartz particles, Foraminifera, siliceous sponge spicules, and a variety of other skeletal particles.

(*Facing p.* 80)

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FIGURE 9. Stereoscopic views of scanning electron micrographs of randomly selected sediments (mud removed) representing the textural types: (a) 4 (sample 67); (b) 3 (57); (c) 2 (2); (d) 1 (61). Bar scale in (d) is 1 mm and applies to all micrographs.

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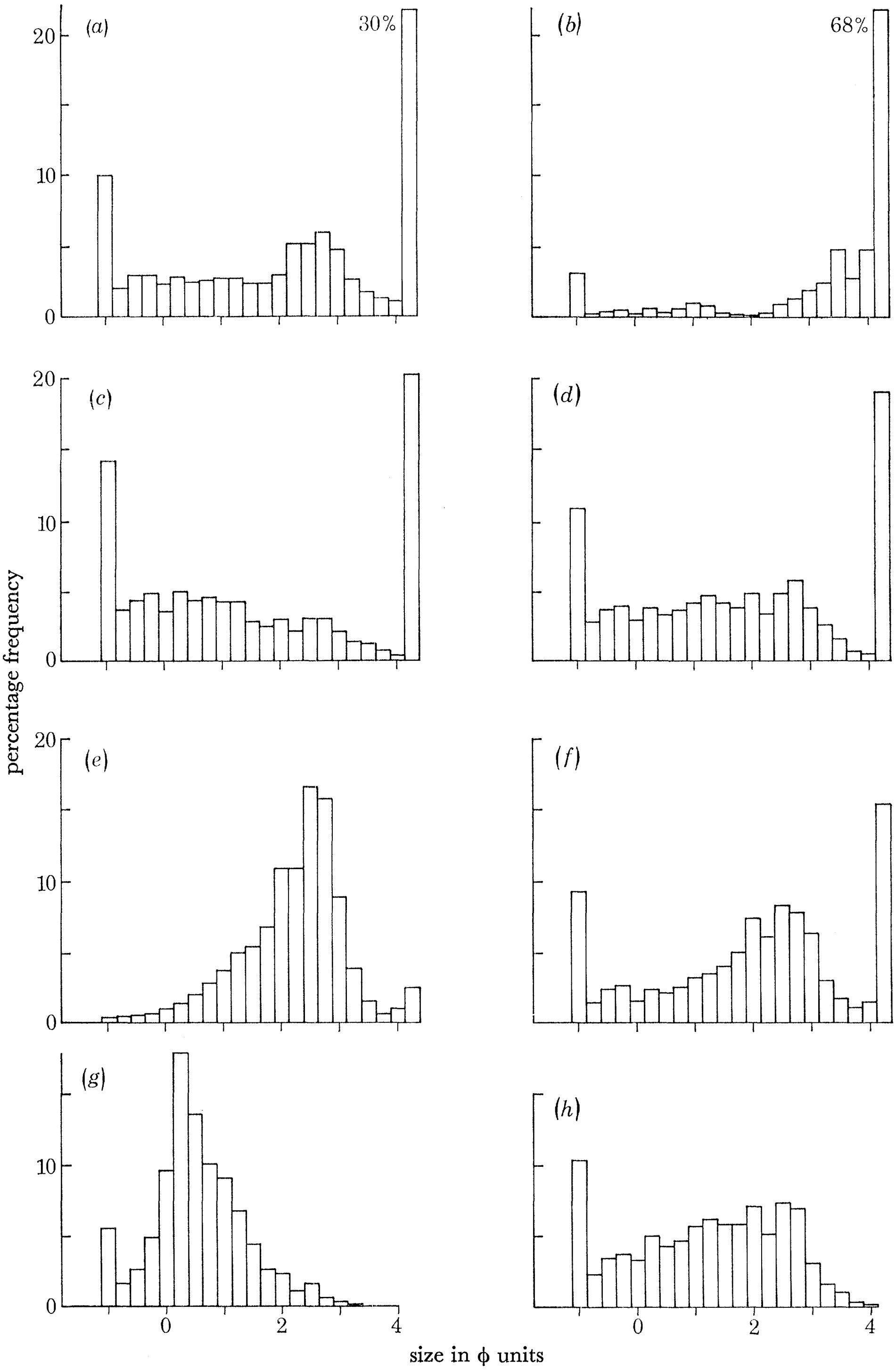

FIGURE 7. Frequency histograms of selected sediments illustrating the presence of distinct sand size modes (conversions from ϕ to millimetres are given with figure 5). (*a*) Sample 67; (*b*) 135; (*c*) 37; (*d*) 57; (*e*) 29; (*f*) 68; (*g*) 61; (*h*) 2.

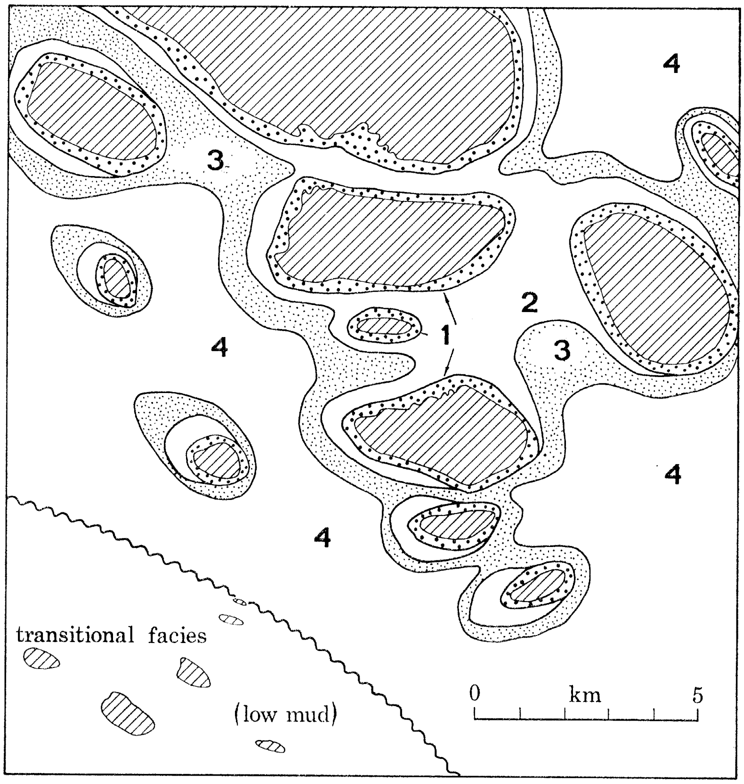

FIGURE 10. Idealized distribution of the textural types in the area of the Howick Group. The influence of the reefs is restricted to within 2 km of individual reef masses. Type 1 circumscribes the entire reef; 2 is restricted to the lee; 3 occurs in the inter-reef areas; 4 characterizes the remaining part of the shelf in the vicinity of the Howick Group.

Type 4 represents the textural type present on the shelf in areas which received a relatively significant contribution of terrigenous mud and material of coarse gravel sizes representing the skeletons of *in situ* organisms. Subordinate amounts of medium to very fine sand and mud sizes are derived from the reef masses. The distance of reefal influence rarely exceeds 2 km from any reef.

To summarize: the textural relation within the Impure Carbonate Facies can be qualitatively expressed in terms of the varying influence of the sediment sources.

Type 1: reefal (R) $\gg$ *in situ* (IS) > terrigenous (T) (R size is coarser than 1 ϕ).
Type 2: R > IS > T (R size ranges from 1 to 3 ϕ).
Type 3: IS > T > R (R size is smaller than 3 ϕ).
Type 4: T > IS $\gg$ R.

4. Conclusion

This study has shown that the Impure Carbonate Facies is divisible into four textural types that reflect the varying influence of reefal, *in situ*, and terrigenous sources. The distribution of the textural types displays concentric elliptical patterns around each platform reef in a zone approximately 2 km wide, within which there is a size gradient from coarse sand and gravel near the windward edge of the reef to fine sand near its leeward margin. More complex textural patterns are produced in areas of the shelf which have a denser pattern of reef development.

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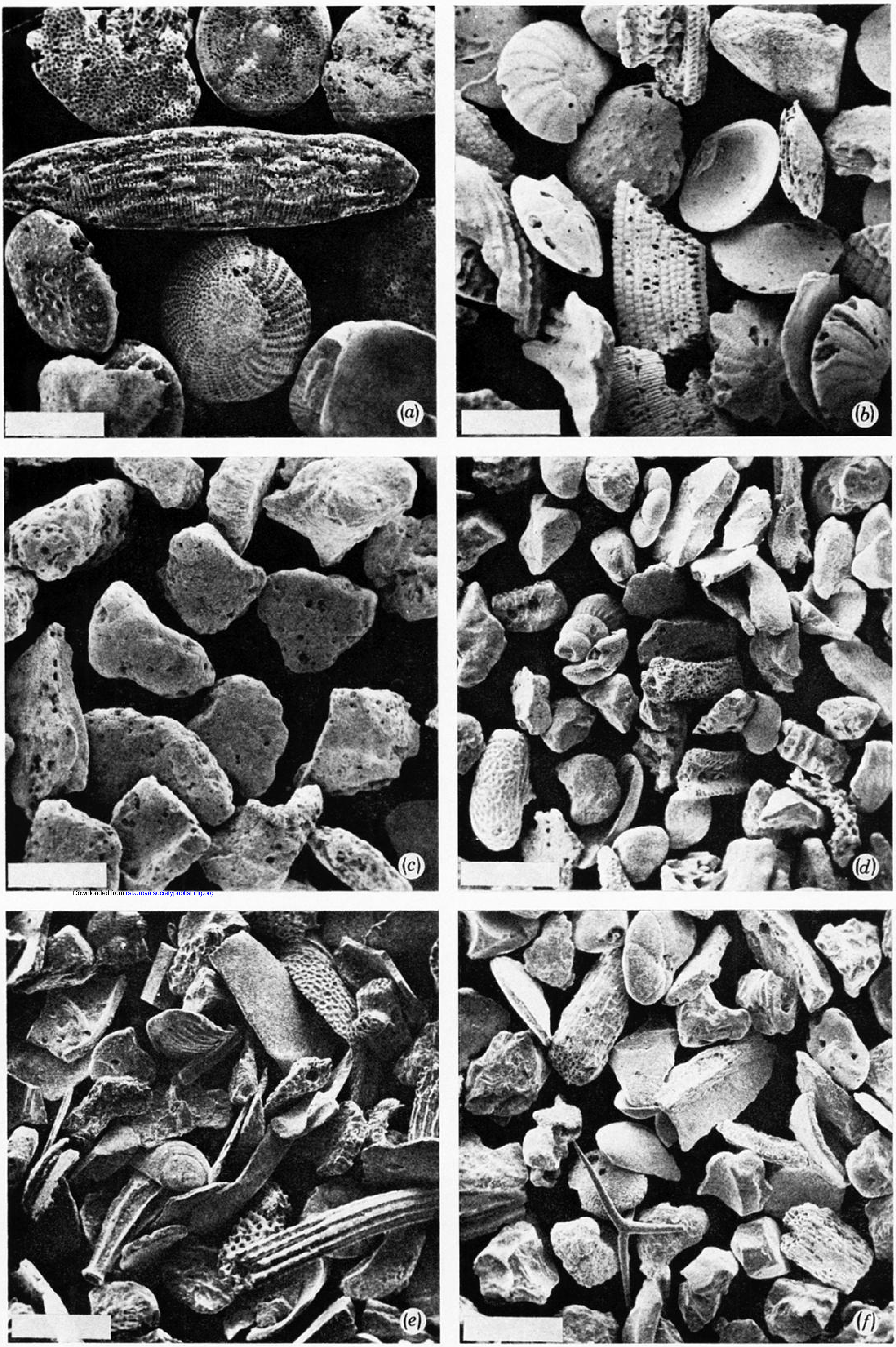

FIGURE 8. Scanning electron micrographs of various grain sizes showing the complex contribution of skeletal components: (*a*) size −0.25 ϕ, scale 1.3 mm, various benthonic Foraminifera; (*b*) size 1.0 ϕ, scale 0.6 mm, benthonic Foraminifera and molluscans; (*c*) size 1.5 ϕ, scale 0.5 mm, *Halimeda* and coral fragments; (*d*) size 2.75 ϕ, scale 0.5 mm, quartz particles, ostracods, molluscans, bryozoans, Foraminifera, etc; (*e*) size 3.0 ϕ, scale 0.5 mm, benthonic and planktonic Foraminifera, molluscan fragments, bryozoans, etc.; (*f*) size 3.5 ϕ, scale 0.5 mm, quartz particles, Foraminifera, siliceous sponge spicules, and a variety of other skeletal particles.

FIGURE 9. Stereoscopic views of scanning electron micrographs of randomly selected sediments (mud removed) representing the textural types: (*a*) 4 (sample 67); (*b*) 3 (57); (*c*) 2 (2); (*d*) 1 (61). Bar scale in (*d*) is 1 mm and applies to all micrographs.