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Geomorphology of reef islands, northern Great Barrier Reef

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During the 1973 Great Barrier Reef Expedition, 67 reef islands were mapped between latitudes 11° 30′ S and 17° S on the Great Barrier Reef. During the mapping, the major topographic, lithological, sedimentological and vegetational features of the islands were distinguished, and their elevations relative to a sea level datum established. The islands themselves were categorized in terms of topographic and vegetational complexity. Previous classifications by Steers, Spender, Fairbridge and others are reviewed in the light of these findings. Some of the islands had been previously mapped by Steers in 1928–29 or 1936; on others, changes could be identified from the evidence of shoreline advance or retreat and from vegetation patterns. The floristics and vegetation units of the islands are briefly described, on the basis of the field mapping and a large collection of flowering plants. Vegetation is influenced by stage in island development, latitudinal variation in rainfall, effects of ground-nesting seabirds, and probably also by disturbance by aboriginal man. Development of mangroves on reef flats is related to stage of reef flat and island development, and relation to tidal levels. This study of the geomorphology of the islands raises questions over the nature, origin and history of specific features (ramparts, beach ridges, boulder tracts, exposed limestones) which the Expedition attempted both to define and to answer.

Introduction

Islands, in spite of their limited size, provide a key to Holocene geomorphic history in the coral reef seas. The information they contain is a function of their topographic complexity, and no reef islands in the world approach those of the northern Great Barrier Reef in this respect. Hence much of the effort of the 1973 Expedition was devoted to investigating reef islands between 17° and 12° S. This paper is concerned with describing the main types of islands and their geomorphic features; later papers investigate these in more detail and present conclusions on their evolution.

The islands were mapped by Stoddart using compass-and-pacing methods; maps were constructed at scales of 1:1000 to 1:5000, with paces converted to metres. Low Isles was mapped with compass and metric tape. The accuracy of linear measures on most islands is thus constrained by the method used, but closure errors were generally small. Dimensions can be compared within and between reefs, since the error attached to the measuring method is likely to be uniform throughout. Most of the maps were constructed during day-time low spring tides. The maps have been supplemented by monochrome vertical aerial photographs made available by the Division of National Mapping, Canberra, and by vertical and oblique monochrome and colour aerial photographs subsequently taken by Hopley. Levelling traverses were carried out mainly by Stoddart and McLean during the first part of the Expedition, and by

Hopley and A. L. Bloom during the second. Heights are referred to the Queensland datum of mean lower low water springs; tide tables were used to predict tidal heights at the time of survey, and local water levels were then used to relate the profiles to datum. Uncertainties in such determinations are discussed by Scoffin & Stoddart (1978) and by McLean, Stoddart, Hopley & Polach (1978, part A of this Discussion). During this investigation, McLean was mainly concerned with island sediments, McLean and T. P. Scoffin with platform conglomerates, Hopley with beach-rock, Scoffin and P. G. Flood with reef-top sediments, and P. E. Gibbs with soft-bottom communities. B. G. Thom and others assisted with problems of interpretation during the early phase of the Expedition, as did J. E. N. Veron during phases I and III. Stoddart also collected about 5000 sheets of vascular plants, representing over 1100 numbers, from many of the islands mapped. Some of these additional studies are reported elsewhere in this volume, but is should be emphasized that the island studies were largely cooperative projects in which the above and other members of the Expedition all participated.

Table 1. Islands examined in the Northern Province of the Great Barrier Reef in 1973 and on previous occasions

island	1770[1]	1819–21[2]	1843[3]	1848[4]	1910[5]	1929[6]	1936[7]	1973[8]
Arlington	—	—	—	—	—	—	×	×
Ashmore	—	—	—	—	—	—	—	×
Beesley	—	—	—	—	—	—	—	×
Bewick	—	—	—	×	—	—	×	×
Binstead	—	—	—	—	—	—	×	×
Bird	×	—	—	×	×	—	—	×
Burkitt	—	—	—	—	—	—	×	—
Chapman	—	×	—	×	—	—	×	×
Combe	—	—	—	—	—	×	—	×
Coquet	—	—	—	—	—	—	×	×
Eagle	×	—	—	×	—	—	—	×
Ellis	—	—	—	—	—	—	—	×
Fife	—	—	—	×	×	—	×	×
Green	×	—	—	—	—	×	—	×
Hampton	—	—	—	—	—	—	—	×
Hope, East	×	—	—	—	—	—	×	×
Hope, West	×	—	—	—	—	—	×	×
Houghton	—	—	—	—	—	×	×	×
Howick	—	—	—	—	—	—	×	×
Ingram–Beanley	—	—	—	—	—	—	×	×
Kay	—	—	—	—	—	—	—	×
King	—	—	—	—	—	—	×	—
Leggatt	—	—	—	—	—	—	—	×
Low	×	×	—	×	—	×	×	×
Low Wooded	—	—	—	—	—	—	×	×
Lowrie	—	—	—	—	—	—	×	×
Mackay	—	—	—	—	—	×	×	×
Magra	—	—	—	—	—	—	—	×
Michaelmas	—	—	—	—	—	×	×	×
Morris	—	—	—	×	×	—	—	×
Newton	—	—	—	—	—	—	×	×
Night	—	—	—	—	—	—	×	—
Nymph (= Enn)	—	—	—	—	—	—	×	×
Pelican	—	×	—	×	×	—	×	×
Pethebridge (= Kew), East	—	—	—	—	—	—	—	×
Pethebridge (= Kew), West	—	—	—	—	—	—	×	×
Pickard	—	—	—	—	—	—	—	×
Pickersgill, North	—	—	—	—	—	—	×	×

Table 1 (*cont.*)

island	1770[1]	1819–21[2]	1843[3]	1848[4]	1910[5]	1929[6]	1936[7]	1973[8]
Pickersgill, South	—	—	—	—	—	—	×	×
Piper (Farmer–Fisher)	—	—	—	×	×	—	—	×
Pipon	—	—	—	—	—	—	×	×
Raine	—	—	×	×	×	—	—	×
Sand	—	—	—	—	—	—	—	×
Saunders	—	—	—	—	—	—	—	×
Sherrard	—	—	—	—	—	—	×	×
Sinclair–Morris	—	—	—	—	—	—	—	×
Stainer	—	—	—	—	—	—	—	×
Stapleton	—	—	—	—	—	×	—	×
Sudbury	—	—	—	—	—	×	×	×
Three	×	—	—	×	—	×	×	×
Turtle I	—	—	—	—	—	×	×	×
Turtle II	—	—	—	—	—	—	×	×
Turtle III	—	—	—	—	—	—	×	×
Turtle IV	—	—	—	—	—	—	×	×
Turtle V	—	—	—	—	—	—	×	×
Turtle VI	—	—	—	—	—	—	×	×
Turtle Mid-reef	—	—	—	—	—	—	×	×
Two	—	—	—	×	—	—	×	×
Undine	—	—	—	—	—	—	×	×
Upolu	—	—	—	—	—	—	—	×
Waterwitch	—	—	—	—	—	—	—	×
Watson	—	—	—	—	—	—	—	×
Wilkie	—	—	—	—	—	—	×	—

References: (1) Cook, in Beaglehole (1955); (2) King (1827); (3) Jukes (1847); (4) MacGillivray (1852); (5) MacGillivray (1910); (6) Steers (1929); (7) Steers (1938); (8) this expedition.

Island types

The reef islands of the Great Barrier Reef were first extensively studied by Steers (1929, 1937, 1938), who distinguished sand cays, shingle cays, and what he termed 'low wooded islands' (1929, pp. 20–27), comprising an assemblage of windward shingle rampart, leeward sand cay, and intervening shallow reef flat with mangrove swamp, characteristically developed on small reefs of the inner shelf north of about 16° S. Two of these low wooded islands, Low Isles and Three Isles, were mapped in great detail by Spender (1930; T. A. Stephenson, Stephenson, Tandy & Spender 1931) during the 1928–29 Expedition, and Steers (1938) later mapped a further 16, proposing Bewick and Nymph (= Enn) Islands as type examples. Spender (1930, pp. 277, 285–286) preferred the term 'island-reef' to low wooded island, and Fairbridge & Teichert (1947) compromised with 'low wooded island-reef'. None of these terms is perfect, but Steers's 'low wooded island' is now well established in the literature and is used here. Umbgrove (1928) described rather similar islands from Djakarta Bay, Java, Steers (1940, pp. 32–35) comparable forms in the Pigeon and Salt Cays, Jamaica, and Stoddart (1965) analogous islands in the British Honduras barrier reef lagoon. None of these examples, however, exhibits the topographic complexity of the Queensland low wooded islands, and all of them are, moreover, in areas of low tidal range.

These low wooded islands and the other types recognized by Steers (1929) were incorporated in a general classification of reefs based on the nature and distribution of superficial sediments by Spender (1930). Fairbridge (1950, pp. 347–349) revised the classification to include unvegetated sand cays, vegetated sand cays, shingle cays, sand cays with separate shingle ramparts (= low wooded islands), and islands with a core of older reef material. While this scheme needs to be extended to serve as a general classification of reef islands of the world (Stoddart & Steers 1977), it serves as a useful framework for discussion of the islands of the northern Great Barrier Reef.

Table 1 lists all the islands surveyed during the 1973 Expedition, with notes on previous surveys. Detailed accounts of individual islands will be given in other publications.

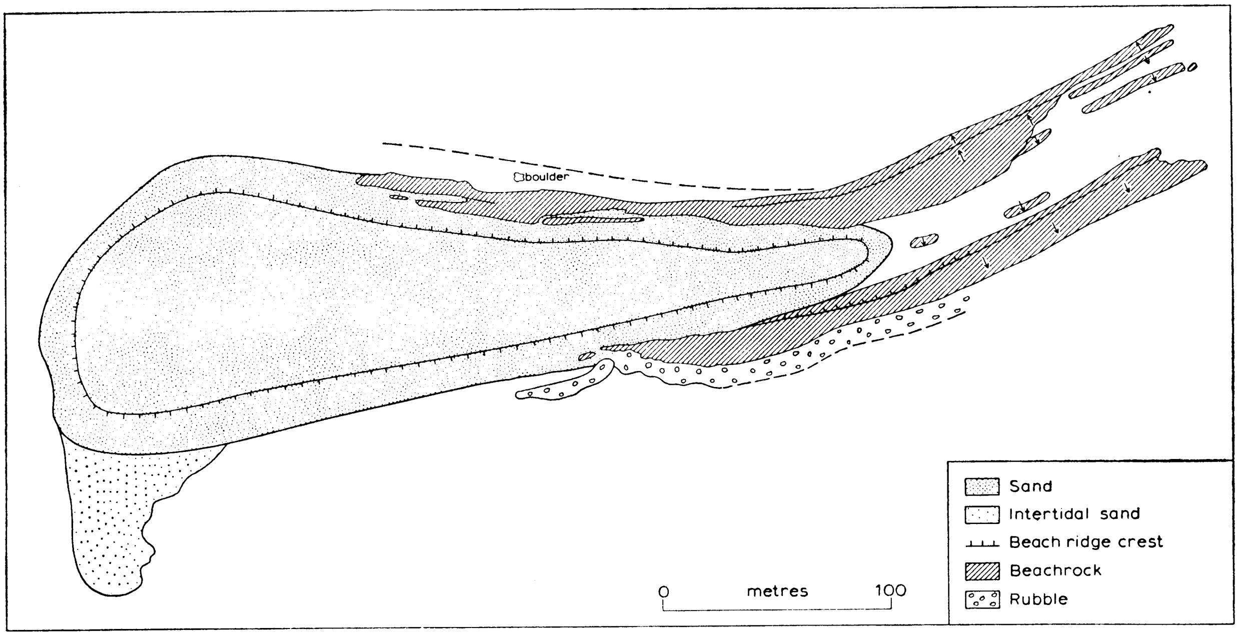

FIGURE 1. A sand cay with relict beachrock: Waterwitch, 1973.

UNVEGETATED SAND CAYS

These are usually located on the leeward sides of reef tops; their location and size are controlled by patterns of wave refraction. Three types may be distinguished:

(*a*) Small ephemeral cays. These are either intertidal sandbores less than 0.1 ha in area, or steeper, rather larger islands which are not overtopped by swash at all high tides. The former group includes the sand cays of several low wooded islands (Binstead, Chapman, Turtle II. Turtle IV, Watson), and the latter such islands as North and South Pickersgill, Pickard and Undine. None of these cays possesses beach-rock.

(*b*) Large, generally oval-shaped islands up to 300 m long and 100 m wide, with areas of 1.0–1.4 ha. These have steep marginal beaches and pronounced swash ridges; some have central depressions. Arlington, Mackay, Sudbury and Upolu fall in this class. Beach-rock was not found in the examples mapped.

(*c*) Other cays of variable dimensions (up to 400 m long and 120 m wide) which are surrounded by extensive relict beach-rock. The present form and size of the cay may differ from that outlined by the beach rock. Presumably in these cases an earlier phase of cay development has been terminated by storm activity, and a new cay has re-formed. Examples are Ashmore, Ellis and Waterwitch (figure 1).

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Unvegetated cays are generally small (for 19 examples mapped, mean length is 140 m, mean width 40 m, and mean area 0.5 ha), and also variable in form and size over time. Five of those surveyed in 1973 were also mapped by Steers in 1936: table 3 gives comparable dimensions and shows substantial changes. In all cases the islands have decreased in size: Arlington in 1973 was 0.2 of its size in 1936, Sudbury 0.8, Undine 0.4, Mackay 0.4, North Pickersgill 0.3, and South Pickersgill 0.15.

TABLE 2. DIMENSIONS OF UNVEGETATED SAND CAYS

island	latitude S	longitude E	cay area m²	maximum length m	maximum width m	intertidal sand and rubble area m²	beach-rock area m²	conglomerate platform area m²
Arlington	16° 39½′	145° 59½′	4600	120	50	—	—	—
Ashmore	11° 53′	143° 37′	12400	325	60	—	1400	—
Binstead West Cay	13° 13′	149° 34′	920	60	22	—	—	—
Chapman West Cay 1	12° 53′	143° 36′	140	17	12	—	—	—
Chapman West Cay 2	12° 53′	143° 36′	350	32	19	—	—	—
Ellis	13° 22′	143° 41½′	4000	175	30	5500	—	1960
Mackay	16° 03′	145° 39′	9350	190	63	—	—	—
North Pickersgill	15° 51′	154° 33½′	3800	120	40	310	—	—
Pickard	12° 14′	143° 09′	4450	250	30	—	—	—
Sand	14° 31′	144° 51′	1290	115	27	—	—	—
South Pickersgill	15° 51′	154° 33½′	490	53	12	340	—	—
Sudbury	16° 57′	146° 09′	13950	205	105	480	—	—
Turtle II Cay	14° 44′	145° 12′	940	70	20	—	—	—
Turtle IV Cay	14° 43½′	145° 12′	3280	110	40	—	1205	—
Turtle Midreef Islet	14° 43′	145° 11′	450	65	18	7200	—	—
Turtle Reef Cay	14° 43′	145° 10′	210	19	10	570	—	—
Undine	16° 07′	145° 38½′	4610	220	26	—	—	—
Waterwitch	14° 12′	144° 53′	27800	380	120	—	8600	—
Watson North Cay	14° 28′	144° 49′	2570	120	35	—	85	—

TABLE 3. CHANGES IN UNVEGETATED CAYS 1936–1973

island	year	total area ha	area above high tide level ha	area above high tide as percentage of total area	vegetated area ha	vegetated area as percentage of total area	maximum length m	maximum width m
Arlington	1936	2.05	0.97	39	0.05	2.6	295	90
	1973	0.46	0.13	27	0	0	120	50
Sudbury	1936	1.72	—	—	0	0	230	105
	1973	1.40	0.73	52	0	0	205	105
Undine	1936†	1.12	0.13	11	0	0	275	50
	1973	0.46	0.03	7	0	0	220	26
Mackay	1936†	2.39	0.82	34	0.18	7.4	385	105
	1973	0.93	0.28	29	0	0	190	63
North Pickersgill	1936†	1.51	0.33	22	0	0	170	140
	1973	0.41	0.01	2	0	0	120	40
South Pickersgill	1936†	0.53	0.10	18	0	0	75	38
	1973	0.08	0.05	59	0	0	53	13

Source of data: calculated from maps given by Steers (1938) and from 1973 maps.
† Original measurements given in paces, converted at 1 pace = 1.2 m.

What governs the transition between cays of type (*a*) and larger islands of type (*b*) is not immediately apparent, nor what governs the transition of type (*b*) islands to vegetated sand cays. Some of the larger islands here termed unvegetated do in fact possess vascular plants, though only as scattered individuals which are clearly ephemeral. Thus in 1929 on Sudbury, Steers (1929, p. 257) noted 'seven small seedlings, one of *Ipomoea* (?) and six of *Sesuvium portulacastrum*'; in 1936 there were no plants at all (Steers 1938, pp. 67 and 68); and in 1973 there were three coconut seedlings and a small patch of *Sesuvium*. Similarly Mackay in 1929 'was well covered in its higher parts by grasses and creeping plants' (Steers 1929, p. 257); by 1936 (following a cyclone in 1934) the continuous vegetation had disappeared, being replaced by two or three clumps of grass, a single *Ipomoea* and a few other plants (Steers 1938, p. 70); and in 1973 there were four drift coconut seedlings, but no other plants present. In June 1936 Arlington had a vegetated area of 0.05 ha, of grasses and creepers, which was being eroded on all sides (Steers 1938, p. 68); in 1973 it had neither plants nor drift seeds. Spender (1930, p. 285) also noted that Pickersgill, which had previously been described as slightly vegetated, had no plants on it in 1929, and this was also the case in 1973.

Table 4. Characteristics of vegetated sand cays

island	latitude S	longitude E	cay area m²	maximum length m	maximum width m	vegetated area m²	vegetated area as percentage total area	number of species of vascular plants	beach-rock area m²	intertidal sand and rubble area m²
Beesley	12° 11½′	143° 12′	6950	420	30	720	10	11†	7250	—
Combe	14° 24′	144° 54′	45700	545	155	27190	59	24	6840	—
Eagle	14° 42′	145° 23′	12530	430	150	8230	66	34	4630	—
East Hope	15° 44′	145° 28′	35530	270	240	21900	62	40	1445	—
Fife	13° 39′	143° 43′	71650	580	230	58130	81	31	6610	—
Green	16° 45½′	145° 58½′	139100	690	300	117420	84	114	8540	—
Kay	12° 14′	143° 16′	4300	185	43	285	7	3	2680	5430
Magra	11° 51½′	143° 17′	33470	450	130	20950	63	16†	3060	—
Michaelmas	16° 36½′	145° 59′	29030	385	70	7580	26	5	910	2412
Morris	13° 30′	143° 43′	65380	595	170	47350	72	29	980	—
Pelican	13° 55′	143° 50′	80530	430	250	57100	71	17	1840	—
Raine	11° 36′	144° 01′	273000	860	420	163300	60	12	6800	—
Saunders	11° 42′	143° 11′	97200	610	215	64115	66	30	470	—
Stainer	13° 57′	143° 50′	15336	235	115	5130	33	8	860	6150
Stapleton	14° 19′	144° 51′	46800	620	125	26820	57	12	5520	—
Turtle III	14° 44′	145° 11′	14610	200	150	6350‡	44	32	13230	9400
Upolu	16° 41′	145° 56′	13800	300	65	735	5	2	0	—

† Collection not complete. ‡ Excludes 620 m² mangrove.

Vegetated sand cays

Vegetated sand cays (excluding the discrete sand cays of low wooded islands) mapped in 1973 are listed in table 4. The mean length of 17 such islands is 460 m and the mean width 170 m; the mean area (5.8 ha) is ten times that of unvegetated cays. As a class, however, these islands are highly diverse: Upolu with two species of vascular plants is scarcely distinguishable from Sudbury with none, whereas Green Island is ten times larger and has over 100 species of plants. However, all the vegetated cays mapped possess beach-rock, with the single exception of Upolu, an association noted also by Steers (1929, p. 20; 1937, p. 16).

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Vegetated cays may be further distinguished by topography and vegetation type. One group comprises elongate, narrow islands, with steep beaches often surmounted by dunes which reach maximum altitudes of 7 m. These islands include Beesley, Combe, Eagle, Kay, Stapleton and Upolu, with areas ranging from 0.7 to 4.7 ha. Three of them have vegetated areas less than 10 % of the total, the others from 57 to 66 %. Numbers of plant species range from 2 to 11 in the first group and from 12 to 34 in the second. The vegetation consists of herbs, grasses and low scrub.

A second group comprises larger oval-shaped islands, averaging 530 m in length, 200 m in width, and 9.3 ha in area. Most of these islands are rather flat topped and featureless, though levelling within the woodland on Green Island showed terraces at 3.5–4.0 and at 4.3 m. The vegetation varies from the dense broadleaf woodland of Green Island, to scrub on Morris, dwarf scrub, herbs and grasses on Magra, Michaelmas, Raine, Saunders and Stainer (all of which have large seabird populations). The vegetated areas are more than 60 % of the total on all islands except Michaelmas and Stainer. Beach-rock is extensive at each island, including Michaelmas where it was not mapped by Steers; in all cases it is fairly closely associated with modern beaches and usually records retreats of 10–30 m. Raine Island has extensive phosphorites forming low cliffs round much of the island; Green and Bird Islands have superficial broken phosphorites under woodland in their centres.

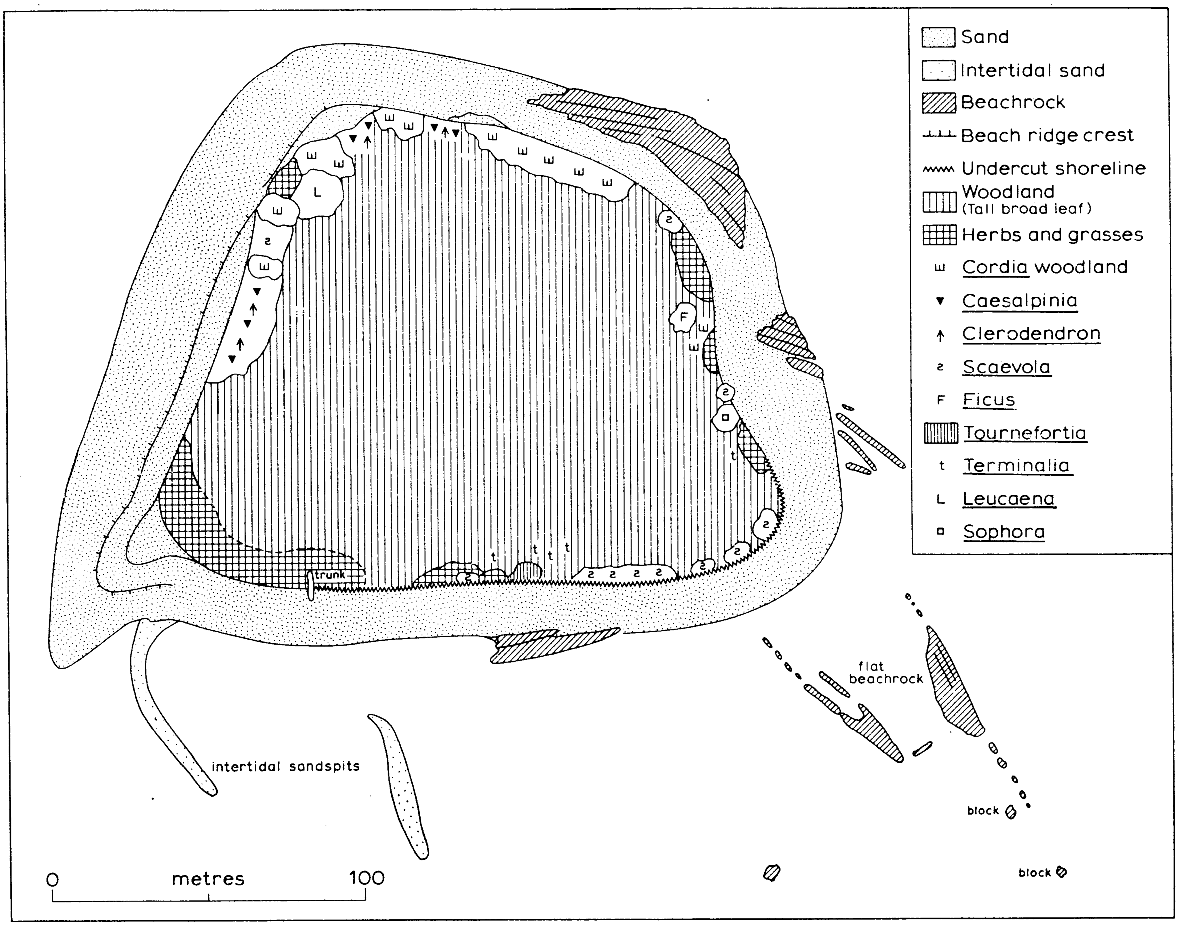

FIGURE 2. A vegetated sand cay: East Hope, 1973.

A third group consists of more equidimensional islands such as East Hope (figure 2), Fife and Pelican, 270–580 m long, 200–250 m wide, and 3.5–8.0 ha in area. The smallest of these, East Hope, is densely wooded, but the others are seabird islands with low scrub, herbs and grasses. In size, character of vegetation, and extent of beach-rock, these islands lie within the range of variation of the oval group. As at Green, East Hope has two distinct surface levels: a lower terrace at 3.4–4.4 m, and a higher at 4.9–5.5 m.

The orientation of the vegetated cays is more variable than Steers (1929, p. 19) supposed. Taking all islands together (unvegetated, vegetated, and cays of low wooded islands), the modal 30° orientation class is 080–110°, with 40 %. South of Cape Melville, orientation tends to be more nearly E–W, and north of that point NW–SE.

The vegetated cays of the northern Barrier Reef may be compared with the Bunker and Capricorn Groups in the south (Steers 1929, 1938; Flood 1977). The Bunker and Capricorn cays are substantially larger than those in the north. They range in length from 510 to 1880 m (mean 1020 m), in width from 130 to 960 m (mean 365 m), and in area from 5.3 to 116.7 ha (mean 28.0 ha). This mean area is more than three times greater than the mean area of vegetated cays in the northern province. Several of the southern islands are very densely wooded with *Pisonia* and *Pandanus* forest of very different aspect to that of the north, but in spite of their greater size their floristic diversity is no greater than on the northern islands.

TABLE 5. CHANGES IN VEGETATED SAND CAYS

island	year	total area ha	vegetated area ha	vegetated area as percentage of total area	beach-rock area ha	maximum length m	maximum width m
Combe	1929	4.93	3.92	79.5	0.41	530	155
	1973	4.57	2.72	59	0.68	545	155
Michaelmas	1936	3.13	1.46	47	n.r.	415	95
	1973	2.90	0.76	26	0.09	385	70
Stapleton	1929	3.96	1.69	43	0.40	810	96
	1973	4.67	2.68	57	0.55	620	125

Source of data: calculated from maps given by Steers (1929, 1938) and from 1973 maps.

Detailed comparisons of change over time can only be made for three islands (Combe, Michaelmas, Stapleton), by using Steers's maps of 1929 or 1936 (table 5). Combe shows a decrease in total area and in vegetated area, and a corresponding increase in area of exposed beach-rock; Michaelmas has also decreased in size; but Stapleton has increased and its vegetation cover expanded.

Low wooded islands

This group, comprising types III–V of Spender's classification of reefs (1930, pp. 285 and 286) and type 4 of Fairbridge (1950, pp. 347–349), is, through the complexity of forms represented, the most informative but in many respects ambiguous of Great Barrier Reef island types. As previous workers have recognized, it includes islands of differing characteristics, and it is perhaps unfortunate that the best known member of the class, Low Isles (which is also the southernmost), lacks many of the typical features common to the rest.

Low Isles and Three Isles are known in detail from the maps of Spender (1930), and Low Isles in particular from the ecological surveys of T. A. Stephenson *et al.* (1931), W. Stephenson, Endean & Bennett (1958), and the geomorphological observations of Moorhouse (1933, 1936)

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and Fairbridge & Teichert (1947, 1948). Both islands were re-surveyed in detail in 1973, and form the basis of a separate discussion (Stoddart, McLean, Scoffin & Gibbs 1978, this volume). In addition to Low Isles and Three Isles, Steers (1938) also mapped 16 more islands which could be included in the class of low wooded island. All of these except King, Burkitt, Wilkie and Night were remapped in 1973, when a further sixteen low wooded islands were also mapped for the first time. We therefore now have geomorphic information on 34 such islands, including comparative data over the last 37–45 years on 14 of them. Table 6 lists the main attributes of the low wooded islands mapped in 1973.

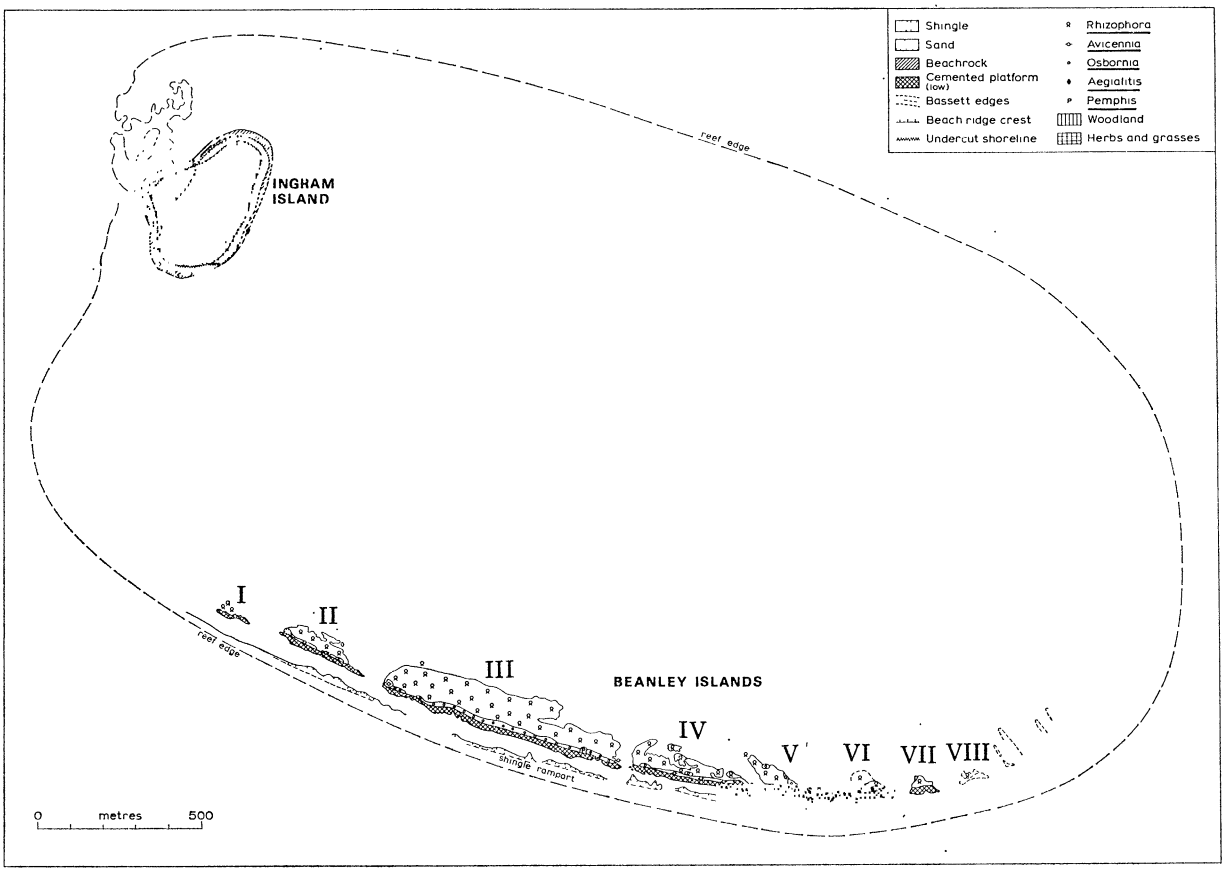

FIGURE 3. Ingram–Beanley Islands, 1973.

These extend over more than 4° of latitude, and are located on reef tops varying in extent from less than 10 to more than 500 ha. The total land area (including mangrove swamps) exposed at low water varies from 1.1 to nearly 150 ha. It is not surprising, therefore, that there is considerable variety in form, nor that many features are not matched by the idealized forms suggested from the Low Isles type example.

In this section we first consider some of the characteristic features of low wooded islands, and then categorize the islands themselves in terms of the occurrence of these features.

Characteristic features

These are discussed as they occur in transverse section from the seaward (windward) to leeward sides of the reef.

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Table 6. Characteristics of low wooded islands

island	lat. S	long. E	area of reef top (ha)	total land area (ha)	total land as percentage of reef top	cay area (ha)	promenade and old shingle ridge area (ha)	mangrove area (ha)	enclosed pool area (ha)	new rampart area (ha)	number of species of vascular plants
Bewick	14° 26′	144° 49′	185.2	147.3	79.5	10.46	11.42	125.44	0	—	30†
Binstead	13° 13′	149° 34′	29.6	0.9	2.9	0.09	0.87	0	0	0	20
Chapman	12° 53′	143° 36′	n.d.	2.2	n.d.	0.05	1.76	0.34	0	0	17
Coquet	14° 32½′	144° 59′	61.8	26.3	42.6	12.07	8.45	5.79	4.20	—	11†
Hampton	14° 34′	144° 53′	90.5	29.4	32.4	0.43	0	28.92	0	—	2†
Houghton	14° 31½′	144° 58′	135.8	50.0	36.8	12.46	11.54	26.00	5.25	—	13½
Ingram–Beanley	14° 25′	145° 53′	540.0	26.2	4.8	11.09	4.27	8.90	0	1.92	47
Leggatt	14° 33′	144° 40′	54.9	8.5	15.5	2.08	0.23	2.86	0	3.34	12†
Low	16° 23′	145° 34′	136.2	37.5	27.5	2.25	2.94	32.29	0	—	58
Low Wooded	15° 05′	145° 23′	87.9	51.8	58.9	4.16	12.01	31.96	0	3.65	62
Lowrie	13° 17′	143° 36′	n.d.	3.4	n.d.	0.24	—	2.37	0	0.75	13
Newton	14° 30′	144° 55′	72.3	31.3	43.3	2.58	3.05	25.70	0	—	33†
Nymph	14° 39½′	145° 15′	135.3	35.8	26.5	—	24.17	7.62	21.29	4.00	25†
Piper (Farmer–Fisher)	12° 14½′	143° 13½′	n.d.	8.8	n.d.	6.16	1.21	1.43	0	—	18†
Pipon	14° 07½′	144° 31′	334.0	72.0	21.6	0.74	4.86	62.12	—	4.29	37
Sherrard	12° 59′	143° 34′	n.d.	1.8	n.d.	1.39	0.36	0	0	—	17
Sinclair–Morris	14° 33′	144° 54′	31.7	8.1	25.6	2.23	0.95	1.77	0	3.18	30†
Three	15° 07′	145° 17′	133.5	47.1	35.2	15.81	11.50	8.18	0	11.56	59
Turtle I	14° 44′	145° 11′	42.3	18.2	43.1	—	9.32	5.36	0	3.55	53
Turtle II	14° 44′	145° 12′	61.0	23.0	37.8	—	8.82	12.00	3.57	2.21	15†
Turtle IV	14° 43½′	145° 12′	29.0	3.8	13.1	0.33	1.63	—	0	1.83	16†
Turtle V	14° 42′	145° 12′	14.8	4.7	31.8	—	4.68	0	0	0.02	14†
Turtle VI	14° 43′	145° 10½′	9.0	1.1	12.3	—	0.59	0.20	0	0.32	20†
Two	15° 01′	145° 27′	128.7	33.1	25.7	19.46	4.79	1.48	0	7.39	65
Watson	14° 28′	144° 49′	57.2	10.3	18.0	0.26	3.55	5.33	—	1.14	26†
West Hope	15° 45′	145° 27′	315.0	31.3	9.9	0	7.90	17.49	—	0.55	47

† Collection not complete.

(*a*) *Reef flat*

The reef flat forms a rocky platform, drying at low water springs, round the windward margins of reefs. It is laterally continuous, usually 60–100 m wide, and encloses the central reef top which on small reefs may resemble the reef flat or on large reefs may form an enclosed depression (called a pseudolagoon by Hedley & Taylor (1907) and Steers (1929), though this term was rejected by Spender (1930) and Steers (1937, p. 254)). The nature of these enclosed reef tops and their sediment covers is discussed by Flood & Scoffin (1978, part A of this Discussion). Generally the reef flats are covered with a felt of green and brown algae and corals are uncommon. At Three Isles in particular the surface of the flat consists of lineations of low relief a few metres apart and parallel with the reef edge (the 'honeycomb rock' of Stephenson *et al.* 1931), apparently the result of erosional planing of reef flat structures. The surface of the flat slopes gradually seawards (average slope 1 : 80 or 0° 40′), to levels at which corals can survive tidal exposure. The highest level of living reef flat corals appears to be 1.0 m (mean low water springs (m.l.w.s.) 0.5 m), but is frequently lower. Seaward of this point the slope increases rapidly and emersion becomes less frequent and coral cover greater. No algal ridges *sensu stricto* were found on low wooded island reefs, even in the most exposed situations, but shallow algal-rimmed pools and terraces do occur near the reef edge on some flats. Steers found them at Night, Houghton, Bewick, Pipon and Beanley (1937, pp. 122–124; 1938 pp. 85 and 86), and we also found them at West Hope and Leggatt.

(*b*) *Rampart*

Ramparts are asymmetric ridges of coral shingle with a steep inward face, locally reaching 80°, and a gentle seaward slope of less than 10°. Their outer margin is a feather edge of shingle on the reef flat and is often too indistinct to map; in plan it roughly parallels the edge of the reef. The inner edge is arcuate, with occasional shingle tongues which on the windward side are at right angles to the reef edge but elsewhere are at an angle to it. Though the term rampart is used by many American workers as synonymous with beach ridge, it is useful to retain it for these shingle accumulations of the reef flat which are wholly or almost wholly submerged at high water (Teichert 1947, pp. 154 and 155).

The mean maximum width of ramparts on the low wooded islands mapped is 45 m; the widest reach 65 m. The mean maximum elevation of the rampart crest is 1.8 m (mean high water springs (m.h.w.s.) 2.3 m), but the highest found, at Watson, reached 3.12 m. The mean maximum elevation of the rampart crest above the reef flat or moat floor immediately to landward is 0.8 m (maximum 2.9 m).

Shingle tongues are common round the entire inner perimeters of ramparts but are particularly well developed at the windward point, where, as Spender (1930, 206) showed, they suggest a basic homology of form between different reefs. Not all are recent. At Low Isles a shingle tongue extends far into the mangrove, and at Three Isles the main tongue is lithified and vegetated. Fresher tongues on other islands are often more than 100 m long, and at Houghton one reaches 340 m; these may have invaded pre-existing mangrove woodland during storm events.

In general, ramparts consist of clean white shingle, dominantly composed of *Acropora* sticks, and these are the components usually exposed in the landward face. On some islands with mangroves, close to the mainland, however, shingle on the backslope is embedded in a muddy matrix which inhibits mobility and reduces permeability; this is well seen at Leggatt and Sinclair–Morris.

Bassett edges form a particular and distinctive feature of eroding older ramparts. These are lithified foreset beds forming projecting steeply dipping ridges, straight or more often arcuate in plan, recording former locations of the inner edges of unconsolidated ramparts (Steers 1937, p. 26). Patches of bassett edges on otherwise bare reef flats indicate where ramparts formerly existed. Their elevations at Low Isles and West Hope range from 1.1 to 1.9 m (range at neaps 1.2–1.6 m).

Spender (1930) in his survey of Low Isles drew attention to the existence of inner and outer ramparts. The inner consisted of old, blackened, partially compacted shingle, the outer of fresh, white, loose shingle. Fairbridge & Teichert (1947, 1948) identified an older innermost rampart at Low Isles, and a more recent new rampart, formed since 1929. Most low wooded islands have multiple ramparts, though only the outer has the simple form described above; they are distinguished by colour, degree of weathering of the clasts, extent of colonization by vegetation, and relative location. In particular the older ridges coalesce and overlap to form shingle islands, margined at their outer edge by a ridge or breastwork of fresh white shingle (Moorhouse 1933, 1936). At Low Isles in 1973 new breastworks were found in places where the 1929 ramparts had disappeared.

Ramparts may be colonized by a low scrub of *Aegialitis annulata* and *Avicennia marina*. Older shingle sheets characteristically carry succulent mats of *Sesuvium portulacastrum*, *Salicornia quinqueflora*, *Arthrocnemum* spp., and *Suaeda australis*.

(*c*) *Moat*

Shingle ramparts may enclose shallow ponds on inner reef flats, which fail to drain at low water. These are ephemeral features subject to rapid changes in extent and water level with changes in the size and location of the enclosing ramparts. Corals grow in these moats at levels well above those of the outer reef flat, commonly reaching 0.9–1.0 m and expectionally 1.8 m (mean low water neaps (m.l.w.n.) 1.2 m). The corals include carpets of *Montipora* in shallow moats, and large microatolls and giant clams in deeper moats. Fairbridge & Teichert (1947, p. 4) noted that growth of corals in such ponded situations could lead to difficulties in the use of corals to reconstruct past sea levels.

Elsewhere, these shallow water bodies are colonized by mangroves, notably *Aegialitis annulata*, *Avicennia marina* and *Rhizophora stylosa*, and these in their turn serve as a baffle limiting the inward migration of shingle ramparts.

(*d*) *Platforms or promenades*

Conglomerate platforms often fringe the inner margins of moats and form the seaward edge of the larger land bodies of low wooded islands. They are usually confined to the seaward side of the mangrove–shingle islands, but are occasionally also found on the sand cays (e.g. Leggatt). Platforms are absent at Low Isles, but were mapped at Three Isles by Spender and interpreted as 'a cemented and conglomerated inner rampart now being eroded' (1930, pp. 207–210), an explanation followed by Steers (1930, p. 5). Spender observed that the level of the platform at Three Isles (2.1 m) was less than that of the highest ramparts at Low Isles (2.3 m) so that relative elevation of the platform was not necessarily implied; he also drew attention to the apparent absence of corals in growth position in the material of the platforms.

In his map of Three Isles, Spender (1930) clearly identified an upper and a lower platform, but he did not make this distinction in his discussion. Subsequently, Steers (1937, pp. 16–28) emphasized the existence of two discrete features, and equated them with benches on mainland and high-island coasts. The lower platform he stated was 'awash at high water springs' (m.h.w.s. 2.3 m), the upper (and less widespread) 'never exceeds' 3.3 m. Steers (1938, pp. 75 and 78) argued from their topography, structure, location and composition that both platforms were lithified shingle ramparts truncated and cliffed on their seaward sides by erosion. Fairbridge & Teichert, who worked only at Low Isles where these features do not exist, added nothing to Steers's account, and interpretation of the platforms plays little part in their model of low wooded island evolution. Steers himself (1931) favoured a eustatic explanation for the difference in elevation of the two platforms, and he also (1938) clearly felt that the lower as well as the higher had been slightly raised with respect to present sea level. At Turtle I and Nymph (= Enn) he estimated the level of the lower platform at 1.0–1.2 m above the reef flat, and of the high platform at 1.0 m above this (Steers 1938, pp. 77, 79 and 81).

Platforms were identified on most low wooded islands mapped in 1973. In some cases they could be clearly assigned to 'upper' or 'lower' categories, but often their relative position was unclear, and frequently the morphological distinction between platform and beach-rock was ambiguous. The use of terms such as 'upper' and 'lower', therefore, while carrying a precise connotation on individual reefs, does not necessarily imply accordance in height or similarity of origin and history between reefs.

Lower platforms on 14 reefs have a mean width of 30 m and a maximum width of 68 m (on Watson). Often, however, particularly beneath *Aegialitis* and *Avicennia* scrub, the outer edge of the lower platform is difficult to distinguish for irregular basset edges of eroding ramparts, with which they are indeed probably genetically linked. Mean maximum elevations of lower platforms on eight reefs (18 profiles) is 2.3 m, identical to the level of m.h.w.s. (as Steers observed); several examples reach between 2.6 and 3.0 m.

Upper platforms are less widespread. Mean maximum width on seven islands is 30 m, and the greatest width (on Coquet) is 40 m. Mean maximum elevation on nine islands (19 profiles) is 2.9 m, 0.6 m above m.h.w.s. and the mean maximum elevation of the lower platform. This level approximates to that of extreme h.w.s. However, several cases have maximum elevations of 3.2–3.5 m. The upper platform usually has an abrupt vertical or undercut seaward slope. Its surface is highly variable. In many cases the outermost few metres consists of jagged basset edges, similar to but higher than those of the reef flat. Elsewhere the surface may be dissected by large circular potholes 1 m or more deep; usually, however, where basset edges are absent the surface is horizontal in transverse profile, and in at least some cases this horizontality results from the presence of superficial flat-bedded shingle deposits on top of the main conglomerate, a feature first noted by Steers (1929, p. 255) at Houghton. Frequently, lower platform deposits lap up against and cover pinnacles of upper platform, and residuals of the latter can be found protruding through the former. Small pocket beaches may occur in gaps eroded in the face of the upper platform, and these generally have extensive beach-rock.

At several localities, platform conglomerate was found to overlie fossil microatolls in the position of growth (e.g. at Turtle I and Three Isles). These are interpreted as having grown in a former moat ponded by a shingle rampart. The rampart then advanced, overriding and killing the corals, was lithified, and subsequently eroded to form the present platform. The mechanism is described in more detail by Scoffin & Stoddart (1978, this volume). The genetic link between modern ramparts and the platforms is considered so close by Scoffin & McLean (1978, part A of this Discussion) that they term the platform conglomerate 'rampart rock'. Nevertheless, the platforms raise important questions, as Steers and Spender realized. Are there really two discrete levels? Are they accordant between reefs? If so, do they have time-significance? What external events (such as sea level change or storm activity) led to their formation?

(*e*) *Shingle island*

Platforms are usually surmounted by a series of old shingle ridges, now stabilized and vegetated. In plan these resemble modern breastworks and probably had a similar origin. There are usually two or three such ridges, but in places there are much wider sequences of ridges of variable width and height. These are well seen on West Hope, Watson, Low Wooded Island, and several of the Turtle group. Their maximum elevation varies from 3.5 to 4.9 m. Some of these ridges are misleadingly called dunes in the older literature. Thus Green Ant Island at Low Isles is described as an 'accumulation of shingle, sand and pumice forming a dune-like bank about 50 yds [45.7 m] wide and probably as much as 20 ft [6.1 m] above datum at the summit' (Stephenson *et al.* 1931, p. 28; also Spender 1930, p. 207). The term dune here refers to morphology and not to composition or origin; true dunes are found on some sand cays, but they are absent from the windward sides of low wooded islands.

(*f*) *Mangrove swamp*

The mangrove swamp at Low Isles was studied in some detail in 1928–29, and has been re-examined by Macnae (1966). Mangroves on low wooded islands are clearly opportunistic in the sense that their distribution depends on the location and dynamics of shingle ramparts, platforms and ridges, and also on variations in reef-top topography. Steers (1937, p. 133), however, considered that the extent of mangrove could be used to place the low wooded islands in a sequence of development, from initial colonization to a stage where most of the reef top is covered by mangroves and the sand cay partly surrounded (as at Bewick and Nymph). This view was accepted by Fairbridge & Teichert (1948, p. 85) and Stephenson *et al.* (1958, p. 309), who found evidence of rapid mangrove colonization at Low Isles since 1929; Macnae (1966, p. 88), on the other hand, found no such evidence. The general characteristics of low wooded island mangroves will be considered elsewhere and the detailed record of change at Low Isles and Three Isles is discussed by Stoddart *et al.* (1978, this volume). Here we simply note the main attributes of the mangrove zone.

Mangrove areas vary from less than 1 ha to a maximum of 125 ha (on Bewick); the mean mangrove area on 22 low wooded islands is 19 ha. There is no relation between reef-top area and percentage covered by mangroves: some large reefs have very small areas of mangrove (Two, Three, Pipon), others, such as Bewick, a large proportion.

Aegialitis annulata and *Avicennia marina* are characteristic of shingle ramparts, often in very exposed situations, and moats. *Rhizophora stylosa* is the main colonizer of reef tops, with occasional tall trees of *Sonneratia alba*. At higher levels, *Rhizophora* is replaced by *Ceriops tagal*, several species of *Bruguiera* and *Xylocarpus*, and at the highest levels by *Osbornia octodonta* (especially on shingle substrates) and *Excoecaria agallocha*. The mean maximum elevation reached by mangroves, usually in the lee of windward shingle ridges, based on 40 profiles from 15 islands, is 2.0 m, with some examples reaching 2.4 m (m.h.w.s. 2.3 m).

A key to the history of low wooded island mangroves is given by the discovery, first at Houghton and later elsewhere, of fields of fossil microatolls in the position of growth within mangrove woodland. Such corals had been noted at Low Isles and Two Isles by Spender (1930, p. 207) but their significance had not been realized. On both Houghton and Leggatt these microatolls reach elevations of 1.35 m (m.l.w.n. 1.2 m); this may be compared with elevations of up to 2.0 m for fossil microatolls beneath conglomerate platforms, and of 0.9–1.0 m for living corals in rampart-ponded moats. On Houghton the microatolls form an extensive field, fortuitously revealed by hurricane damage, and similar microatolls have also been found within the swamps at Hampton and Bewick. Their interpretation in the context of sea level change and island history is discussed by Scoffin & Stoddart (1978, this volume) and McLean *et al.* (1978, part A of this Discussion).

(*g*) *Sand cay*

Leeward dry-land sediment accumulations are characteristic of most low wooded islands, but they differ in nature even more widely than ordinary sand cays (table 7). In a first group, the sand cay is discrete and separate, and may be compared with an ordinary sand cay. Some are unvegetated ephemeral islets of small size (Binstead, Chapman, Sand, Turtle II, Watson: mean area 0.1 ha). Others are larger vegetated cays (Bird, Farmer, Ingram, Low, Lowrie, Pipon, Sherrard, Sinclair, Three, Two: mean area 6.3 ha). Most of these are covered with woodland or scrub, and the number of species of vascular plants on each is generally higher than on the simple sand cays.

A second group consists of recognizably discrete cays partly or largely surrounded by mangrove, in some cases forming a single land unit with the windward shingle ridges and platforms. These include Bewick, Howick, Leggatt and Newton (mean area 4.9 ha). Of these, Howick and Newton are partly wooded, but the others are covered with grassland.

Taken together, the vegetated discrete cays of low wooded islands have a mean length of 420 m, a mean width of 185 m, and a mean area of 12.0 ha. They are, as a group, almost exactly twice the area of ordinary vegetated sand cays, but still less than half as large as the vegetated cays of the Bunker and Capricorn Groups.

In one important respect the vegetated sand cays of low wooded islands are more complex than most simple vegetated sand cays. This is in the presence of a low terrace round a central higher and more extensive core, a situation similar to that noted by Steers (1929, p. 347), following Stanley, on Middle Island. Sample terrace levels are given in table 8. Terraces at comparable levels, with similar vertical separation, have already been noted on Green Island. The two levels are distinguished not only by elevation but also by soil development and sedimentological characteristics (McLean & Stoddart 1978, part A of this Discussion) and vegetation: the higher terrace usually carries woodland or dense scrub, the lower a more open community of shrubs and herbs. Where the lower terrace is absent, cay beaches are steep and may have extensive arrays of well cemented beach-rock; where it is present the beaches are lower and beach-rock is patchily developed, often at lower intertidal levels, and less well cemented. There is no doubt that the lower terrace is an aggradation feature formed after the main formation of the cay; in two cases (Two Isles and Three Isles) it can be shown that part at least of its development has taken place over the last few decades (Stoddart *et al.* 1978, this volume).

The widespread existence of the two terrace levels on the cays has not previously been recognized, but it clearly needs to be discussed in the same context as the existence of upper and

TABLE 7. DISCRETE SAND CAYS OF LOW WOODED ISLANDS

island	lat. S	long. E	cay area m²	cay area as percentage of reef top	maximum length m	maximum width m	vegetated area m²	vegetated area as percentage of cay area	number of species of vascular plants	beach-rock area m²	mangrove area m²
Bewick	14° 26′	144° 49′	104580	5.5	600	300	104580	100	18	6176	0
Binstead	13° 13′	149° 34′	920	3.1	60	22	0	0	0	0	0
Bird	11° 46′	143° 05′	40310	n.d.	380	150	29250	73	8†	9030	0
Chapman 1 and 2	12° 53′	143° 36′	490	n.d.	17; 19	12; 19	0	0	0	0	0
Farmer (Piper)	12° 14½′	143° 13½′	61590	n.d.	535	201	39965	65	6†	9565	0
Howick	14° 30′	144° 58′	45715	n.d.	695	230	28720	63	27	8280	0
Ingram	14° 25′	145° 53′	110910	2.1	490	350	89810	81	44	13780	0
Leggatt	14° 33′	144° 40′	20840	3.8	320	125	14220	68	8†	2312	0
Low	16° 23′	145° 34′	22500	1.7	240	130	14060	63	34	6015	0
Lowrie	13° 17′	143° 36′	2380	n.d.	78	42	266	11	4	0	0
Newton	14° 30′	144° 55′	25760	3.6	395	120	13998	54	27	2898	0
Pipon	14° 07½′	144° 31′	7400	0.2	240	65	3850	52	32	5124	0
Sand	14° 31′	144° 51′	1290	n.d.	115	27	0	0	0	0	0
Sherrard	12° 59′	143° 34′	13870	n.d.	220	110	7104	51	10	2468	0
Sinclair	14° 33′	144° 54′	19260	6.1	300	112	11570	60	24	0	3010
Three	15° 07′	145° 17′	158130	11.8	715	285	131400	83	46	16210	0
Turtle II	14° 44′	145° 12′	940	0.2	70	20	0	0	0	0	0
Two	15° 01′	145° 27′	194600	15.1	720	350	164450	85	48	20140	0
Watson	14° 28′	144° 29′	2570	0.4	120	35	0	0	0	85	0

† Collection not complete.

lower platforms and of sequences of shingle ridges. The difference in nature of beach-rock outcrops is also of interest. The mean maximum width of the older beach-rock is 2.4 m; in all cases it is associated with modern beaches, except at Sherrard, where relict beach-rock indicates a bodily translocation of the whole cay a distance of 150 m to the northwest. The average range of elevation on low wooded island cays is 1.2–2.4 m (m.l.w.n. 1.2 m; m.h.w.s. 2.3 m),

Table 8. Elevations of terraces on sand cays of low wooded islands

island	height of lower terrace m	height of higher terrace m	height difference m	maximum elevation m
Leggatt	3.4–3.6	4.6–4.9	1.2–1.3	4.9
Two	3.4–3.7	6.0–6.3	2.6	6.6
Three	3.0–3.8	4.8–5.9	1.8–2.1	6.0
Howick	3.4–3.5	4.4–4.9	1.0–1.4	4.9
Ingram	2.7–4.0	5.0–6.2	2.2–3.3	6.9

Table 9. Summary of significant elevation data derived from profiles

feature	mean elevation m	number of measurements	maximum elevation m	minimum elevation m
highest living corals	0.47	11	0.94	0.09
highest ramparts	1.77	14	3.12	0.80
living moat corals	1.04	24	1.78	0.42
highest lower platform	2.31	23	3.27	1.40
highest upper platform	2.87	19	3.53	2.08
highest mangrove	2.01	38	2.86	0.71
dead microatolls	1.47	18	2.30	0.98
height range of sand cay lower terrace	3.34–3.89	10	4.0–4.4	2.7–3.5
height range of sand cay higher terrace	5.01–5.63	10	6.0–7.2	4.3–4.9
highest land	5.74	17	8.99	4.41
top of beach-rock	2.29	21	3.30	1.25
bottom of beach-rock	1.09	21	2.20	0.40

Extreme h.w.s. 2.9; m.h.w.s. 2.3; m.h.w.n. 1.6; m.l.w.n. 1.2; m.l.w.s. 0.5; extreme l.w.s. 0.

but the highest examples reach 2.7–3.0 m (extreme h.w.s. 2.9 m). Erosion of the windward extremities of islands revealing complex arcuate bands of beach-rock, as at Three Isles and Newton, is quite common, even where the shore is now protected by mangroves; some of these beach-rock arrays are unusually high, and some are even vegetated. Steers (1938, pp. 78–86) also noted the existence of possibly raised beach-rock on low wooded islands, apparently associated with the lower platform at Bewick, Pipon and King, and with the higher platform at Nymph and Ingram. The higher more massive beach-rock consists either of inclined ledges with 10–15° seaward dip, often showing complex patterns of overlap, or horizontal platforms, often covered with *Sesuvium* and other succulent herbs. The less massive beach-rock on the shores of lower terraces stands at lower elevations; the height range is commonly 1.1–2.0 m.

(*h*) *Boulder zone*

This was defined on the northwest (leeward) side of Low Isles by Steers (1929) and Spender (1930, p. 201). It is a recurrent feature on low wooded islands, and occurs either close to the leeward reef edge (as at Low and Watson) or near the island shore (as at Bewick). The zone is up to 200 m long, with boulders reaching 3–4 m in greatest dimension. The constituents are mainly individual coral colonies, undoubtedly storm-deposited. Similar deposits have been found, also in leeward situations, cemented into platform rocks, forming a coarse boulder conglomerate, as at Howick.

Types of low wooded island

Taken together, the rather heterogeneous group of low wooded islands here described have a mean total land area at low tide of 28.5 ha (25 cases). Of this total, dry land (i.e. cay, shingle ridges and platforms) comprises a mean area of 9.8 ha, the mangrove zone 16.5 ha, and the fresh shingle ramparts 2.1 ha. However, these figures conceal wide variations, and it is helpful to distinguish four subgroups of low wooded islands, differentiated by location and nature of sedimentary deposits and the extent of mangroves on the reef top. Characteristics of individual islands have already been given in table 6.

(*a*) *Mangroves of limited extent, sand cay separate*

Low Isles forms the classic example of this type. The reef top is large; the cay and the mangrove–shingle island are well separated; and there are well defined fresh shingle ramparts on the windward reef. These features are repeated on Lowrie, Two Isles, Three Isles and Pipon; Sinclair–Morris is somewhat comparable but smaller. On some reefs the sand cay is embryonic (Chapman, Binstead, Watson, Turtle IV) or almost non-existent (West Hope). In others it is substantially larger than the mangrove–shingle island (Ingram–Beanley, Sherrard, Piper). Mangroves may be limited to a few seedlings on fresh shingle tongues (e.g. East Hope, which has therefore here been treated as a simple sand cay), or are restricted to species characteristic of higher levels (*Excoecaria*, *Osbornia*, *Xylocarpus*) on the shingle cay, with only a narrow fringe of *Rhizophora* (Chapman, Binstead, Sherrard). It is possible to speculate on the reasons for these differences, but here we simply draw attention to them.

(*b*) *Mangroves extensive, joining the shingle and sand cays*

Of all the islands, Bewick (figure 4) has the most continuous mangrove cover, though the outline of the sand cay is quite distinct. Both Newton and Nymph also have extensive reef-top cover, though with large enclosed lagoons. The sand cay at Newton is well defined, but the boundary between mangrove and dry-land vegetation at Nymph is much less distinct. Sinclair–Morris is an example of a smaller reef with cay, mangrove and rampart forming a continuous unit.

Three islands on more elongate reefs have rather different characteristics. Houghton and Coquet have large distinct sand cays and extensive mangroves, but the windward shingle area is linked to the cay by a continuous belt of conglomerate platform and shingle ridges; Low Wooded Island is similar, except that the sand cay has less well defined boundaries.

(*c*) *Turtle-type islands*

Steers (1929, p. 25) drew attention to the islands of the Turtle Group as representing an ‘intermediate stage between the simple sand cay and the complex cay’, lacking a central open flat, and with the mangrove–shingle cay ‘closely wrapped round the sand cay’. Later (1937, pp. 128–130) he emphasized the lack of sharp boundaries of the ‘cay-like area’, the extensive high shingle ridges forming most of the dry-land area, and the ‘old aspect’ of the terrain by comparison with other islands. Vegetated shingle ridges, with pronounced surface topography, dominate the reef top; on Turtle VI (figure 5) there is a distinction, similar to that on some sand cays, between a higher central area and a lower surrounding terrace, with slabs of old beach-rock on the slope between the two. The sediments of these islands also differ from those of other low wooded islands (McLean & Stoddart 1978, part A of this Discussion).

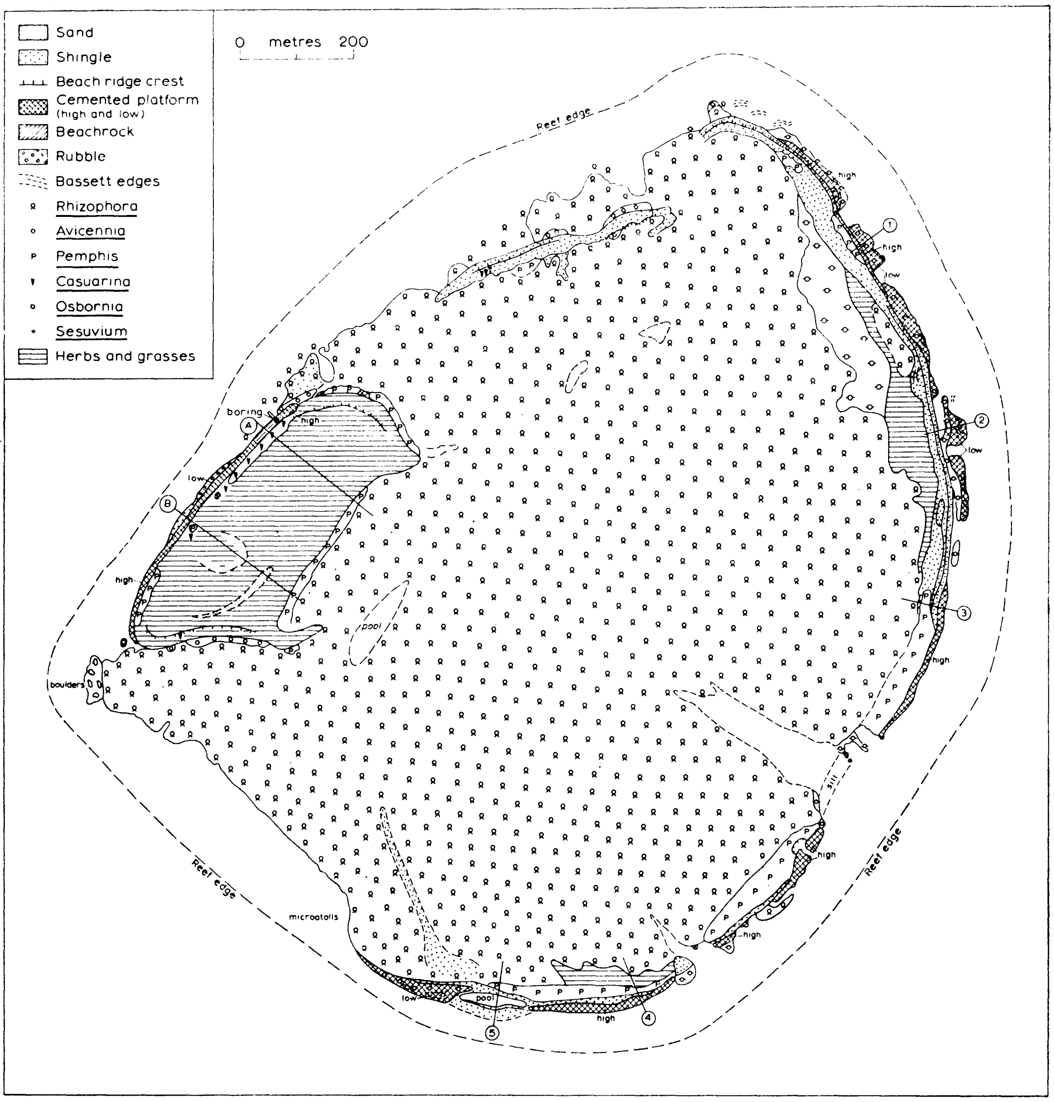

FIGURE 4. Bewick Island, 1973.

(*d*) *Miscellaneous*

Several islands of very variable characteristics were also mapped and cannot be assigned to the above categories. Hampton could be considered as wholly a mangrove island, but there are small low remnants of conglomerate platform near the windward reef edge and a dry cay area within the mangrove. Steers (1937, p. 128) similarly found a completely mangrove-encircled sand cay at Hannah. Sand Island has an embryonic sand cay, patches of conglomerate platform and much rubble, with mangrove scrub of *Avicennia* and *Aegialitis*; it was undoubtedly larger in the past. The two Pethebridge (= Kew) Islands consist of a dry shingle island, conglomerate platforms and rubble sheets to windward, with to leeward intertidal sand spits, ephemeral cays, and only embryonic mangroves.

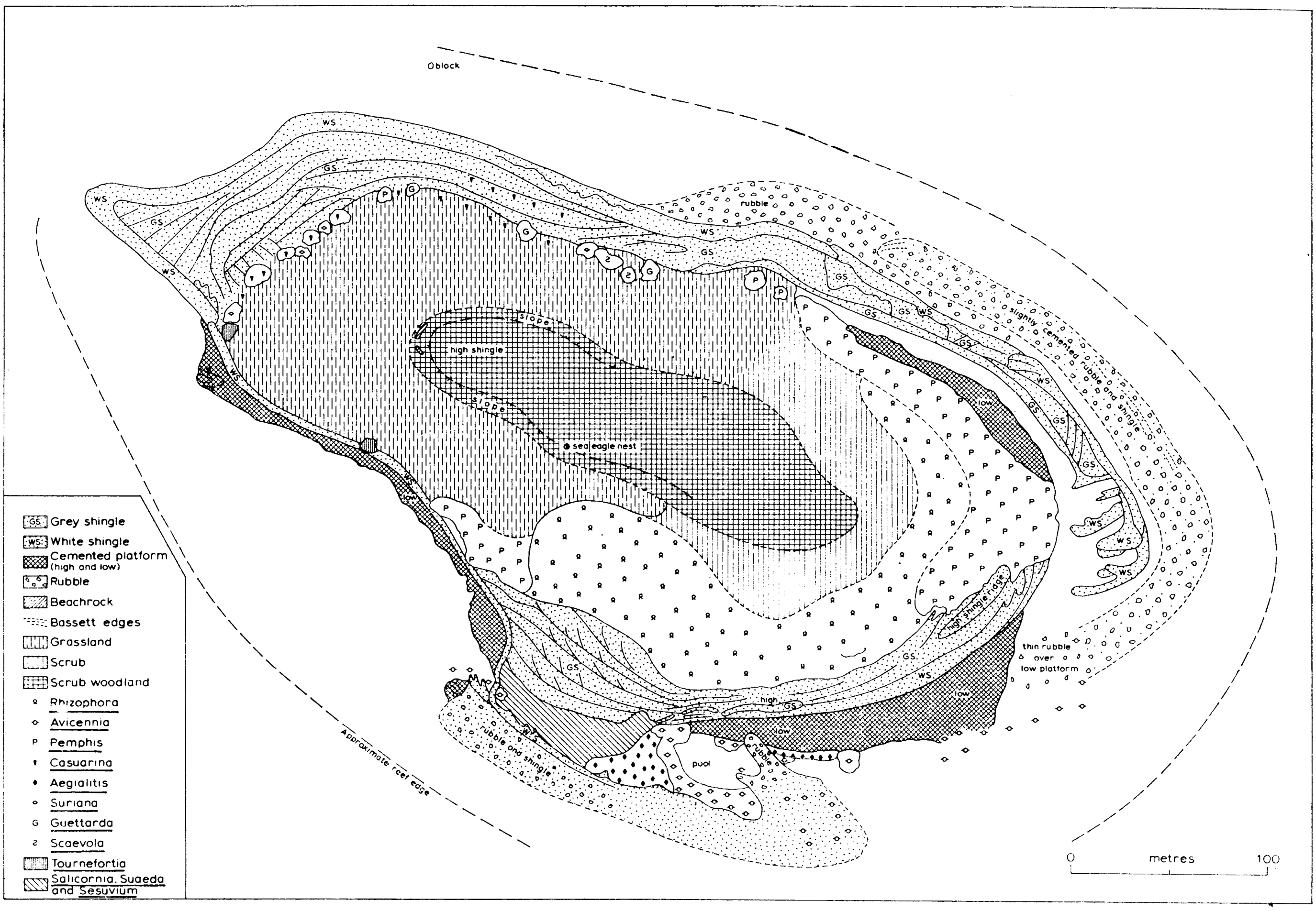

Figure 5. Turtle VI Cay, 1973.

Problems of interpretation

Two main sets of problems arise from this consideration of the geomorphology of reef islands of the northern Great Barrier Reef.

(a) *Spatial distribution*

Both Steers (1929) and Spender (1930) emphasized differences in the distribution of islands on the reefs. The outer ribbon reefs have almost no islands at all. The Admiralty charts mark six between Cairns and Cape York, all sandbanks except for Waterwitch (shown by relict beach-rock to have formerly been larger) and Raine (which is on a detached reef, not a ribbon reef). The large platform reefs of the outer shelf, within the ribbon reefs, in general also lack islands, except for a few intertidal sand banks. Near the centre of the shelf, some large reefs carry simple sand cays (Eagle, Pickersgill, Sudbury, Combe, Stapleton, East Hope). Most of the islands, however, are concentrated on smaller reefs of the inner shelf. These are either simple sand cays formed by refraction round the reefs (Green, Michaelmas, Fife, Kay, Magra, Morris, Pelican, Saunders, Stainer), or, especially near the mainland coast, they are low wooded islands of varied size and form. Of the islands mapped in 1973, the mean distance of sand cays from the mainland was 24.5 km and from the shelf edge 36 km, and of low wooded islands 14 and 38 km respectively. Sand cays are found across the whole width of the shelf (minimum distance from mainland 4.5 km, maximum 104 km), whereas 94 % of low wooded islands are within 20 km and 26 % within 10 km of the mainland.

Spender (1930) suggested that this distribution resulted from a systematic difference in level of the reef tops, the outer reefs being too low for permanent sediment bodies to accumulate, and the inner reefs being progressively higher towards the mainland with sediment accumulations forming more readily on their tops. Steers (1930, 1931, 1937) maintained that exposure to wave action was a more important control of sediment accumulation. The outer reefs, exposed to ocean swell, were swept clear of debris. The outer platform reefs immediately in the lee of the ribbon reefs and intersected only by narrow channels are too protected for shingle ridges to form. The smaller, more widely separated inner shelf reefs, rising from shelf levels of 20–30 m, are exposed to the Southeast Trades blowing longitudinally along the shelf, affecting not only the growth direction of the reefs and the reef morphology but also patterns of wave refraction and storm-deposition of debris. The implications of these two general models for reef-island distribution in other parts of the world have been discussed by Stoddart (1965). Most workers have supported Steers's general view, but Spender's postulate of systematic variation in reef-top levels transverse to the mainland coast has received some support from theoretical considerations of hydroisostasy (Thom & Chappell 1978, part A of this Discussion).

(*b*) *Temporal development*

Crucial to the interpretation of the record of the reef-top features is the calibration of their response to relative sea level changes in the Holocene. Previous workers, lacking radiometric dating techniques, have relied on geological interpretations of topographic features, many of which were themselves ambiguous in origin. Steers (1929, 1937) used the presence of upper and lower platforms, the fairly consistent height difference between them, the possible existence of raised beach-rock on the cays, and the presence of high and low erosional benches (though at rather different levels) on high-island and mainland shores to suggest that sea level may have fallen eustatically and episodically during the period of reef-island formation. Spender (1930) argued from the accordance in the maximum elevations of platforms and modern ramparts that there was no necessary argument for such falls; he did not, however, discuss the problem presented by the presence of platforms at two distinct levels.

In addition to the platforms, the present investigation has introduced additional evidence: (*a*) the existence of upper and lower terraces on cays, which can be correlated between islands with fairly consistent vertical separation, and (*b*) the widespread identification of reef-top microatolls, either beneath platform deposits or within mangrove swamps, at intertidal levels which are unusually high by comparison with modern growing corals. Our investigation has therefore focused on relating these different features to each other (figure 6) and to an independent radiometric time scale.

The presence of the microatolls on many low wooded islands also has implications for a question raised by Steers (1937, pp. 135 and 136), denied by Spender (1930, p. 290), and discussed by Fairbridge & Teichert (1948): how far do the relative extents of shingle ridges. sand cays and especially mangrove swamps on low wooded islands record a temporal succession from a stage with no mangroves at all on the flat to one, like Bewick, where the cover is complete, and if so, what controls the rate and timing of stages in the developmental sequence (Fairbridge & Teichert 1948, p. 85)?

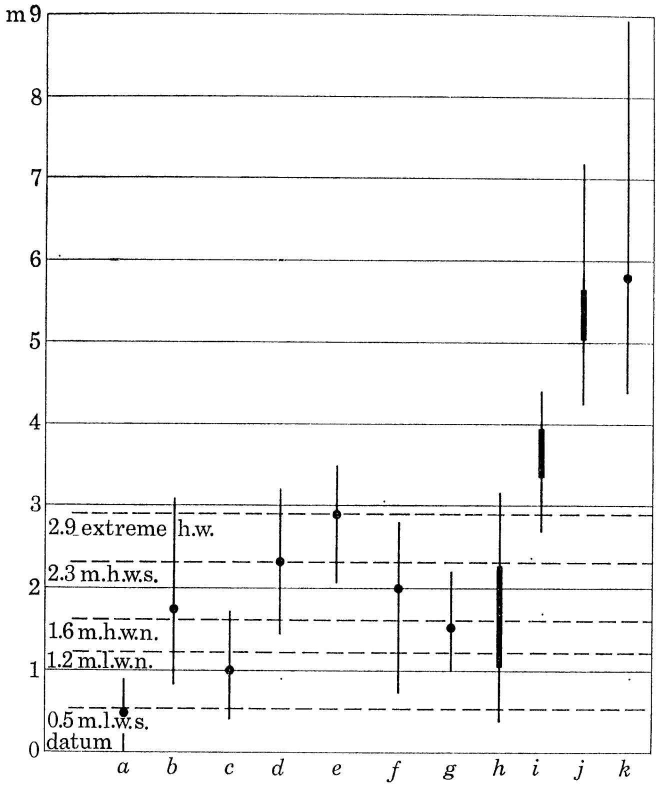

FIGURE 6. Elevations of significant topographic features of low wooded islands: (*a*) living corals; (*b*) ramparts; (*c*) moat corals; (*d*) lower platform; (*e*) upper platform; (*f*) highest platform; (*g*) dead microatolls; (*h*) beach-rock; (*i*) lower shelf; (*j*) upper shelf; (*k*) highest point.

Steers (1937, pp. 135 and 136) and Fairbridge & Teichert (1948, p. 85) thought that extent of mangrove on the reef top was the main indicator of stage or age of low wooded islands. Spender (1930, p. 290) considered that at any one time the relative extent of reef-top features was determined by reef level and environmental conditions, rather than stage of development. He even suggested that mangroves might be decreasing rather than increasing in area at Low and Three Isles (Spender 1937, p. 142), largely because of the removal by erosion of protecting ramparts and platforms or by the chemical erosion of reef-top substrates by the mangroves themselves. Steers (1937, p. 145) suggested that perhaps the number and size of the shingle ridges would be a better index of topographic development than the extent of mangroves. Detailed surveys over nearly 50 years have shown extensive spread of mangroves at Low Isles, and no spread at all at Three Isles (Stoddart *et al.* 1978, this volume); and in general over this period of time there appears to have been remarkably little geomorphic change. There is, however, considerable evidence of catastrophic damage to mangroves as a result of cyclones. This was noted by Steers (1938) at Houghton, Wilkie and Night Islands, and again at Houghton and Newton by us. These effects seem to be local rather than regional in their incidence. If there is a progressive extension of mangroves in the manner suggested by Steers and Fairbridge & Teichert, it clearly takes place at different rates on different reefs and with frequent random interruptions because of storms.

The morphological evidence alone, therefore, though suggestive, is ultimately ambiguous in terms of origin and genesis, and reliance on this evidence alone would place severe constraints on our reconstruction of Holocene reef history in the northern Great Barrier Reef area. As other papers in this Discussion will show, however, the purely morphological evidence can be supplemented by detailed sedimentological, lithological and ecological studies, and calibrated by reference to a radiometric time scale, so that the area of speculation in the choice of alternative models of the development of islands can be reduced.

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