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Reef island sediments of the northern Great Barrier Reef

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[Plate 1]

The reef islands are composed almost exclusively of bioclastic materials locally supplied from adjacent reef flats and reef crests. No sediment of terrigenous origin was encountered on the islands investigated (except drift pumice). Islands are built either of sand or of gravel, and only rarely mixtures of both sand and gravel. The *sands* are typically well sorted with a prominent size mode within the medium–coarse size range (0.25–1.00 mm). Major skeletal components include corals, Foraminifera, molluscs and crustose coralline algal fragments, either whole or broken. Most grains show signs of considerable abrasion. The *gravels* are more homogeneous in composition (mainly corals) but reveal a great range of size, shape and surface characteristics. Elongated clasts, derived from branching corals, provide the main components but corals of other growth forms are present. The sand deposits and gravel deposits are normally spatially discrete on any one reef but mixtures of these two size grades do occur, notably on the Turtles. Reasons for the presence or absence of spatial discrimination are discussed.

1. Introduction

Reef islands are morphologically coherent accumulations of bioclastic materials standing on reef tops and exposed above the level of the sea at high tide. During the 1973 Great Barrier Reef Expedition, island sediments were examined on 31 reefs between Low Isles in the south and Waterwitch in the north (figure 1). It was found that single islands were built (i) predominantly of sand, (ii) predominantly of gravel, or (iii) of mixtures of sand and gravel (either sandy-gravels or gravelly-sands depending on the dominant size grade), or (iv) parts of the same island comprised a combination of the above grades. In reef areas 'shingle' rather than 'gravel' is commonly used to describe the coarser sediments and this usage is adopted here. Thus, in terms of sediment calibre reef islands in the area can be classified as sand cays, shingle cays, mixed sand–shingle cays, composite cays.

Certain characteristics of the reefs and islands visited are summarized in table 1. On 21 of the reefs only one island was present although most possessed additional surficial sediment bodies which were not emergent at high water. The other ten reefs contained two or more islands which in the case of Ingram–Beanley and Sinclair–Morris are identified by different names. In general the reef islands occupy only a small proportion of the reef top on which they stand and rise but a few metres above low water level. In addition to unconsolidated sediments, many of the islands possess consolidated deposits, particularly beach-rock and rampart-rock. These exposed limestones are described elsewhere (Scoffin & McLean 1978, this volume).

The purpose of the present paper is to describe the nature of unconsolidated reef island sediments in terms of particle size, mineralogy and composition, and discuss the source and supply of sediments, local and regional distribution of sediment types and history of island sedimentation.

The account is a general one. Conclusions are based on data from some 200 sediment samples. Detailed results will be presented elsewhere. The foregoing division of island types based on sediment calibre will be followed.

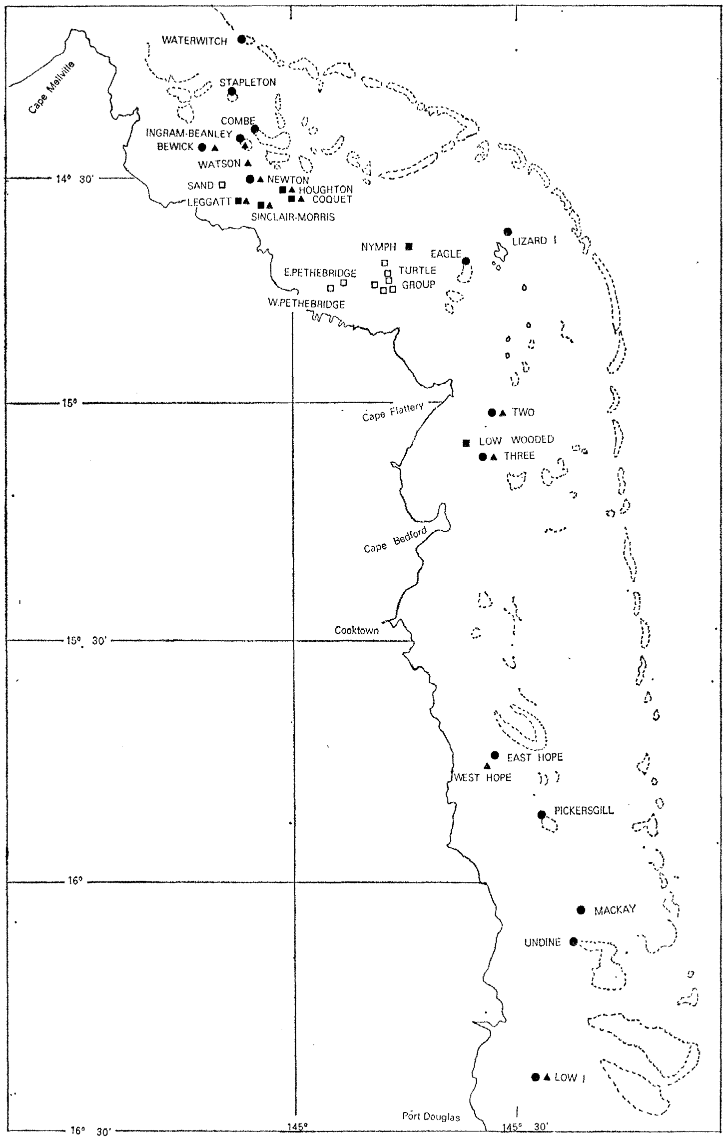

FIGURE 1. Location of reef islands on the northern Great Barrier Reef classified in terms of sediment type: ●, sand cay; ▲, shingle island; □, mixed sand–shingle island; ■, composite island.

2. SAND CAYS

The sand cays investigated can be divided into three types on the basis of the number of islands on the reef and the complexity of the sand cay itself.

(A) Single island on reef top
  I. Sand cay, unvegetated
    (i) Without beach-rock: Pickersgill, Undine, Mackay
    (ii) With beach-rock: Waterwitch

II. Sand cay, vegetated, with beach-rock
Combe, Stapleton, Eagle, East Hope

(B) More than one island on reef top

III. Sand cay of type II, plus shingle island and mangroves on same reef flat, i.e. the sand cay of a 'low wooded island' (Steers 1929): Ingram, Two Isles, Three Isles, Newton, Bewick

Table 1. Reef island characteristics

reef	percentage of reef occupied by island†	distance from coast km	distance from barrier km	reef type‡	island type			
					sand	shingle	mixed	composite
Undine	< 1	20	23	L	X	—	—	—
Mackay	2	22	23	L	X	—	—	—
Pickersgill	< 1	20	28	L	X	—	—	—
East Hope	2	13	39	H	X	—	—	—
Eagle	1	28	29	L	X	—	—	—
Combe	< 1	24	23	L	X	—	—	—
Stapleton	1	26	16	L	X	—	—	—
Waterwitch	2	35	1	L	X	—	—	—
Watson	9	18	31	H	—	X	—	—
West Hope	5	11	41	H	—	X	—	—
Turtle I	38	15	45	H	—	—	X	—
Turtle II	33	15	44	H	—	—	X	—
Turtle III	15	16	46	H	—	—	X	—
Turtle IV	4	17	43	H	—	—	X	—
Turtle V	32	17	42	H	—	—	X	—
Turtle VI	37	19	40	H	—	—	X	—
E. Pethebridge	6	9	48	H	—	—	X	—
W. Pethebridge	9	7	49	H	—	—	X	—
Sand	20	9	37	H	—	—	X	—
Nymph	52	22	33	H	—	—	—	X§
Low Wooded	59	15	36	H	—	—	—	X§
Low	4	18	36	H	X	X	—	—
Three	19	18	32	H	X	X	—	—
Two	18	17	29	H	X	X	—	—
Newton	8	15	34	H	X	X	—	—
Ingram	3	22	26	H	X	X	—	—
Bewick	16	18	29	H	X	X	—	—
Leggatt	8	7	41	H	—	X	—	X‖
Houghton	20	16	33	H	—	X	—	X‖
Sinclair	10	9	39	H	—	X	—	X‖
Coquet	32	15	34	H	—	X	—	X‖

† Includes island-enclosed ponds.
‡ Reef type after Maxwell (1968, fig. 72): L, lagoonal platform or platform reef; H, high reef.
§ Mainly shingle.
‖ Mainly sand.

The essential features of these sand cays have been well described by Steers (1929, 1937) and need not be repeated here. They are all located on the leeward (west) side of their respective reefs. In plan they possess flask, teardrop or ovate shapes with shape and long-axis orientation depending on the geometry of the surrounding reef in relation to prevailing southeasterly seas. Cays of type I and II are situated on large reefs with shallow lagoons. They are small islands with areas ranging from *ca.* 4000 m² (Undine and Pickersgill) to 45000 m² (Combe and Stapleton), which cover no more than 2% of the total reef area (table 1). In contrast, cays of type III are located on high lagoonless reef tops. Excluding Ingram, the reefs are small and the cays cover a proportionally greater area of the reef top, up to 15% in the case of Two Isles. Two Isles, with an area of some 195000 m², is the largest sand cay in the whole region. However, in spite of differences in island size, reef size and type, as well as the presence or absence of vegetation, beach-rock or other islands on the same reef, the sand cays possess a surprisingly homogeneous sediment population. Data from over 100 samples from these cays indicate that variation between cay sediments on different reefs is less than variation between reef flat and cay sediments on the same reef. Nevertheless, differences do exist and these are elucidated below.

2.1. *Constituent composition, mineralogy and morphology*

Apart from drift pumice, sand cay sediments are made up almost exclusively of skeletal reef materials. In order of abundance, Foraminifera, coral, *Halimeda*, molluscs and coralline algae are the most important constituents. Bryozoa, crustacea, echinoid and other fragments are rare and together account for less than 5% of components. Typically, taxonomically unrecognizable coral fragments provide 20–25% of the sands, Foraminifera 25–30% and molluscs 10–15%. Values for coralline algae and *Halimeda* are more variable, although the latter makes up more than 10% of each sample. Proportions of the various skeletal types differ on different islands suggesting that each reef possesses a unique biota and set of environments. Sediments from Low Isles and Ingram are particularly rich in coral (30%) and coralline algae (25%) and poor in Foraminifera (8%), while Bewick, Newton and Two Isles have a high percentage of forams (30%) and are low in coralline algae (5%). Sediments from Waterwitch cay on the outer ribbon reef are unusual in that they have both the highest percentage of molluscs and lowest percentage of forams in the sample suite.

There are also indications, as yet unquantified (1) that the relative abundance of constituents changes from reef flat to reef island, e.g. the proportion of *Halimeda* declines; (2) that the cays of high reefs possess a different suite of components than those of reefs with lagoons, e.g. the latter are especially poor in coralline algae; and (3) that contemporary beach materials differ in composition from older adjacent sands on the same cay, e.g. there is more coralline algae and less *Halimeda* in the modern sands. These suggest that the nature of skeletal production and reef-top environments have changed through time.

Bulk mineralogical determinations indicate the sands contain mixtures of aragonite and high magnesium calcite, although low magnesium calcite was present in a number of samples. Percentages of aragonite range from 20 to 70% and calcite from 20 to 80% depending on the relative proportions of the various skeletal types.

Grain morphology is also dependent on constituents. Foraminifera are either discoidal (e.g. *Marginopora*) or spherical (e.g. *Calcarina*), *Halimeda* leaf-like, calcareous algae elongate while coral fragments and molluscs have highly irregular shapes. All grains show signs of wear and abrasion and many are broken fragments. Nevertheless there is great variation in grain surface texture depending on skeletal type and grain size, though most are edge rounded and polished.

2.2. *Grain size and sorting*

In spite of variations in constituent components, the entire suite of cay samples are surprisingly uniform in terms of size grading (figure 2) irrespective of whether they were collected from vegetated or unvegetated cays, windward or leeward beaches, berms, soil horizons or island surfaces or subsurfaces.

It became apparent during plotting of cumulative curves that the division between sand and silt sizes in the Wentworth scale (4 ϕ) was a less appropriate break between sand and fines than 3 ϕ. None of the beach, and very few of the cay sands, possessed material finer than 3 ϕ, although it was detected in some soils. This implies that fines are rarely transported to and deposited on sand cays. Their presence is indicative of post-accumulation weathering and soil development. Also, plots of individual samples showed that grain size distributions are typically unimodal. Those possessing bimodal or polymodal distributions were few in number and commonly resulted from the occurrence of a few coarser coral or shell fragments. Mean sizes all fall within a range of less than 2 units (−0.3 to 1.6 ϕ) (figure 3*a*). Within this range, 75% have means in the coarse sand category (0–1 ϕ), 11% in the very coarse sand and 14% in the medium sand grades. In terms of sorting, the majority of samples 54% fall into Folk's moderately well sorted category (0.5–0.71 ϕ) with 17% and 19% being better or poorer sorted respectively. Thus, as a generalization, the cay sediments can be classified as moderately well sorted coarse sand.

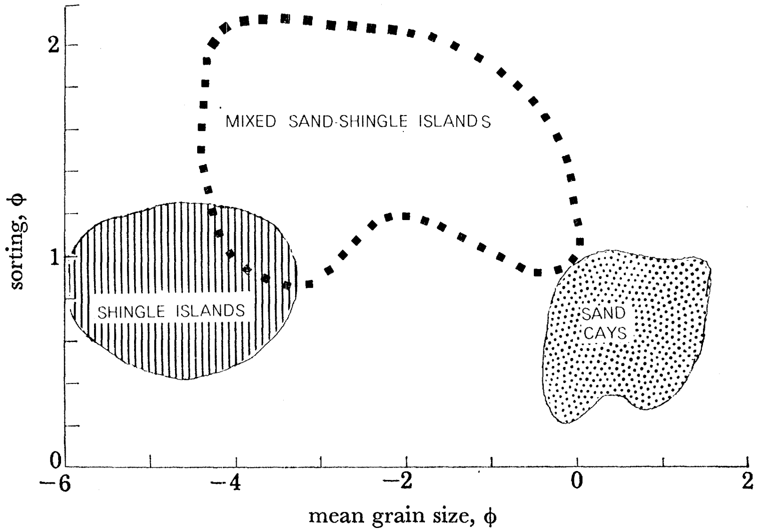

Figure 2. Fields of sorting versus mean grain size for three sediment types.

There are, however, fairly systematic differences in texture depending on whether samples were collected from contemporary beach, cay surface and subsurface or soil horizons (figure 3). Beach sands include the coarsest cay sediments. Figure 3*b* shows a sinusoidal trend which is accounted for by the difference between windward reef flat facing beaches of vegetated cays which possess larger sizes than sands of lee beaches and unvegetated cays. Unmodified clean cay sands, that is, those that do not have clear indications of soil development, commonly possess means between 0.3 and 1.0. Presently developing soils and buried soil horizons provide the finest cay sediments (figure 3*d*). Sample means show a prominent mode around 1 ϕ and a minor mode at 1.5 ϕ, the first being slightly offset from that of parent cay sands. This suggests that the soils are composed basically of parent sand with the addition of finer organic matter. This addition of fines accounts for the poorer sorting in those samples.

Earlier it was noted that the size–sorting distributions for the suite of basic cay sands were relatively uniform. However, it is clear from figure 3*c* that there are subtle differences between cays such that each cay has its own distinctive sediment population. For instance, Bewick sands are fine and moderately sorted whereas Ingram sands, although equally fine, are somewhat better sorted. Low Isles sands are generally coarser than both Bewick and Ingram samples and possess a greater range of sorting values. Three Isles sands, although within the combined size range of Low, Bewick and Ingram samples are well sorted and this better sorting distinguishes them from the three others. Sands from the other cays all fall within the fields set by Low, Bewick, Ingram and Three Isles but again subtle differences can be recognized (figure 3*c*). Reasons postulated to account for the differences in sediment size and sorting between cays include: (1) variations in proportions of different constituent components in areas of sediment production; (2) differences in distances, modes and rates of transport from source area to cay sinks and the degree of sorting and abrasion during transport; and (3) variations in residence-time since deposition.

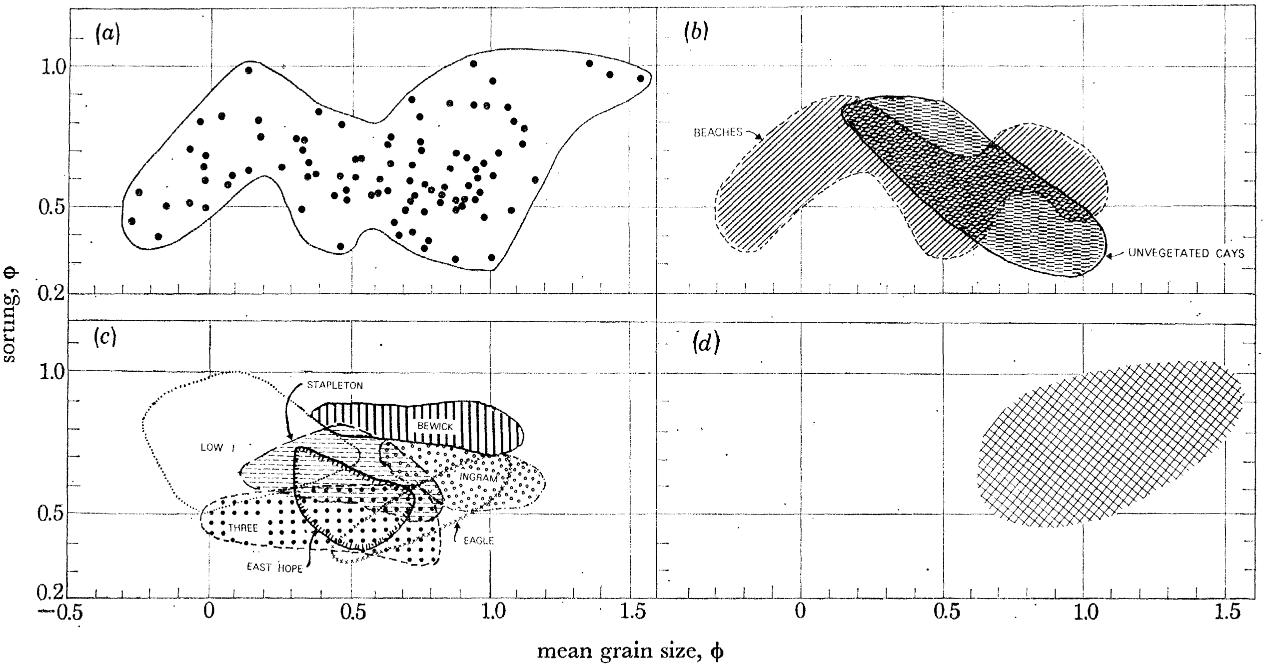

FIGURE 3. Sorting versus mean size of sand cay sediments. (*a*) All samples; (*b*) fields of beach and unvegetated cay samples; (*c*) fields of particular sand cays; (*d*) fields of samples from contemporary and buried soil horizons.

2.3. *Source of sand cay sediments*

The sediments which ultimately go into cay building originate mainly from the reef flat with a small proportion coming from biota (mainly molluscs) living within the beaches and beach-rock around the cay's margin. Sand cays develop on the lee corner of the reef platform at the zone of convergence of refracted southeast swell that wraps around the reef and crosses the reef flat at high tide. Their location is a relatively stable one and is dependent on reef configuration and orientation in relation to predominant swell direction. Ramparts, shingle islands, mangroves and other features on reef tops cause obstructions to wave fronts and create secondary zones of wave convergence and divergence which may influence the incidence and direction of wave attack on the cay. Thus cay shapes may change in detail through time depending on the number, size, location and time of development of other features on the reef top.

The nature of reef flat sediments for a number of the reefs in this area are described by Flood & Scoffin (1978, this volume). A comparison between reef flat and cay sediments for Three

Isles, Stapleton, Ingram and Low Isles samples is made in terms of size–sorting plots (figure 4). It is clear from these plots, for the first three reefs at least, that there are two sediment populations. However, the populations are not discriminated on grounds of mean size, but on the basis of their sorting values: the cays sands are uniformly better sorted than reef flat materials. Thus in the interval between production of skeletal debris on the reef flat and its accumulation on the cay, changes in one but not both sediment parameters takes place. The high sorting values in the reef flat sediments is the result of the presence of both coarse and fine tails in the size distributions: their frequency curves are lower and more spread out than the cay samples which possess much steeper unimodal curves. The finest reef flat material does not reach the sand cays and the coarsest is broken down during transport. Thus wave agitation during passage from reef flat to the cay selectively sorts the sediments, bringing the basic array of reef flat sizes (excluding finest and coarsest) to the cay in a graded state. The greater the distance between reef flat source and cay sink, the greater the degree of grading. Thus, for the Low Isles samples the cay sands fall within the field of the reef flat sediments presumably because the distance of travel and/or frequency of particle movements is less than on the other three reefs. Another reason for the good discrimination between the reef flat and cay sediments of Three Isles, Stapleton and Ingram reefs could be that the older cay samples were derived from reef flats in the past which possessed material different from that currently forming.

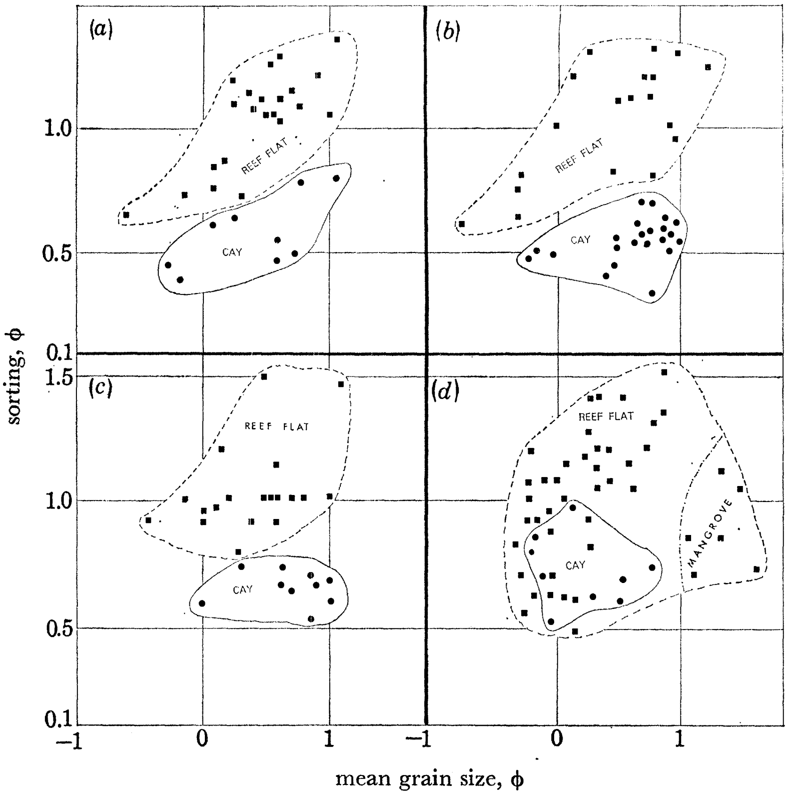

FIGURE 4. Comparison of reef flat and cay sands in terms of sorting versus mean size for four reefs: (*a*) Stapleton; (*b*) Three; (*c*) Ingram–Beanley; (*d*) Low Is.

2.4. *Age of sand cay sediments*

Sixteen radiocarbon dates of bulk sand samples from ten sand cays which included a small unvegetated cay (Pickersgill), simple cays (Eagle, Stapleton, East Hope), and sand cays of low wooded islands (Bewick, Ingram, Leggatt, Low Isles, Two Isles and Three Isles) were obtained. In spite of this range of cay types and in spite of the great range of sample locations and elevations nine of the samples fell within a 500-year time span from 2900–3400 a B.P. which indicates considerable clustering in the age of sand cay bioclastics. The youngest age was 2190 ± 70 a B.P. (ANU-1641) and oldest 4380 ± 80 a B.P. (ANU-1559). Pickersgill sands were dated at 2230 ± 70 a B.P. (ANU-1606), a surprisingly great age considering the cay is unvegetated and only just emergent at high water. These data which are presented in detail elsewhere (see McLean, Stoddart, Hopley & Polach 1978, this volume) point to a period of high reef-top productivity some 3000 years ago, and suggest that sand cays, rather than being ephemeral features, are relatively stable deposits.

3. CORAL SHINGLE ISLANDS

In the northern Great Barrier Reef, reef islands made up predominantly of gravel sized clasts have been variously called mangrove–shingle cays (Steers 1929), mangrove islets, shingle islands, shingle and mangrove islets (Steers 1937), vegetated ramparts (Spender 1930) and at Low Isles rampart systems (Fairbridge & Teichert 1948). On a reef top a shingle island may be the only deposit emergent at high water (as in the case of Watson, West Hope and Sand reefs), or there may be more than one island present, either a sand cay (such as at Low, Two, Three, Bewick, Newton and Ingram) or a composite cay (as at Coquet, Leggatt, Sinclair–Morris and Houghton), in addition to the shingle island. Coral shingle islands are all located on high reefs (Maxwell 1968) of the inner shelf some 30–40 km in from the outer ribbon reefs (figure 1, table 1). They typically occupy 5–10 % of the area of the reef top. On individual reefs shingle islands are generally located on the windward (SE) side of the reef top where they form continuous or discontinuous linear deposits which commonly mimic the plan geometry of the peripheral reef edge. Islands are frequently quite narrow, their width being dependent on the number and nature of ramparts, ridges and swales. Mangroves colonize the sheltered leeside reef top while to windward the exposed island beach frequently overlies or is fronted by a consolidated platform or shallow moat. In some cases, such as Watson, the loose shingle deposits which make up the island surmount cemented platforms rather than directly overlie the reef flat. The variable morphology of shingle islands and rampart systems in this area have been described by Steers (1929, 1937), Fairbridge & Teichert (1948), Stoddart, McLean & Hopley (1978, part B of this Discussion) and others. However, sediments making up the islands have not been described in such detail, although most authors have commented on the fact that fragments of branching corals (*Acropora*) make up a very large percentage of the shingle.

3.1. *Particle size and sorting*

Because coarse materials cannot be easily measured by using sieving techniques, tri-axes measurements were made on 100 clasts from each sample. Mean size and sorting were therefore computed on a number rather than mass frequency basis (Folk 1962). Field inspection suggested that the shingle deposits were relatively uniform in terms of size grading (figure 5, plate 1) and results from five samples indicate that this is the case (table 2).

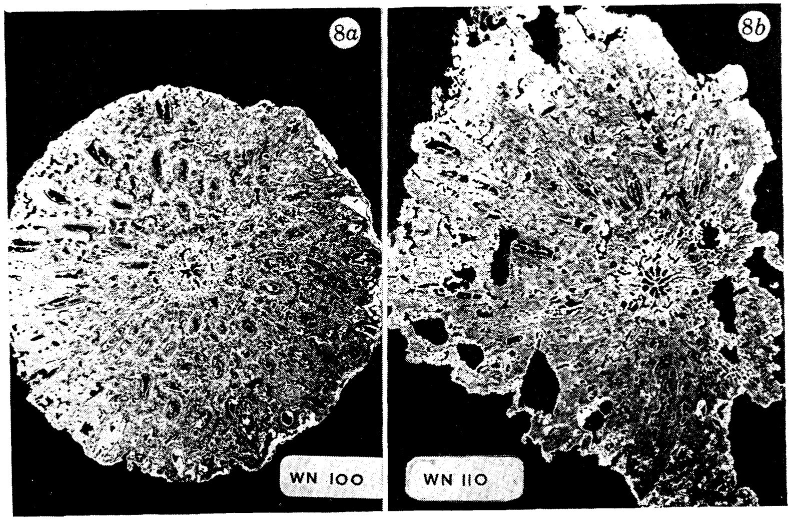

FIGURE 5. Coral shingle deposit at Two Isles. Scale bar is 30 cm long.

FIGURE 6. Abraded, cleaned and imbricated branching coral fragments on shingle beach at Turtle Island.

FIGURE 7. Contrast between exposed surface and subsurface shingle island deposits at Low Wooded Island.

FIGURE 8. Transverse sections of *Acropora* branching coral fragments from Watson Island showing contrast between smooth outline of beach clast (WN 100) and micro-karstic outline of island surface clast (WN 110). Note reduced size of WN 110 and presence of partly and completely filled primary and secondary voids. Both corals are 2 cm in diameter.

Mean size for the intermediate *b*-axis falls around $-4\ \phi$ (16 mm), which is the typical diameter of living reef edge corals of branching growth form. While the extreme range of clast diameters covered up to 8 ϕ units (2–512 mm), all samples possessed relatively normal frequency distributions. Particle length of *a*-axis medians registered about 1.5 ϕ greater than *b*-axis means. Cumulative curves of particle diameter and length indicate a regular relation such that the length of smaller particles is about 0.7 ϕ greater than their diameter, while for larger particles it reaches over 2 ϕ. In terms of size grading, island deposits can be described as moderate to moderately well sorted medium sized pebbles. Typically, shingle clasts have lengths of some 50–60 mm and diameters of 15–20 mm. These sizes result from breakage of branching corals in the original coral thickets.

TABLE 2. SHINGLE SIZE AND SORTING (ϕ UNITS)

reef	mean size, *b*-axis	sorting	maximum size	minimum size	median size, *a*-axis	remarks
Watson	−4.3	0.55	−6.0	−2.0	−5.5	beach
Watson	−4.3	0.61	−6.0	−1.0	−5.6	third rampart
Watson	−4.3	0.61	−9.0	−2.0	−5.8	innermost ridge
Two	−3.8	1.06	−9.0	−1.0	−5.2	outer rampart
Low	−4.1	0.96	−6.0	−2.0	−5.7	inner rampart

3.2 *Particle shape*

Particle shapes derived from the three-axes measurements clearly show the dominance of rod-shaped clasts. Plots on Folk form triangular graphs indicate that 65% of clasts possess elongate (20%) or very elongate (45%) shapes. Blades are the next most abundant group followed by those of compact (spherical) shapes. Less than 5% of particles fit into the platy (discoidal) class, which is perhaps the most common particle form on shingle islands of Pacific atolls.

The visual ubiquity of elongate pebbles on shingle islands of the northern Great Barrier Reef is confirmed, the obvious ultimate source of this sediment being the thickets of branching corals so characteristic of the windward periphery of reefs in the area. During storms, colonies and individual branching corals are broken down to finger-like or Y-shaped segments (coral sticks) which are readily transported across the reef top, built into ramparts and ultimately islands.

Nevertheless, while stick corals of pebble size do make up the major proportion of shingle island deposits, the contribution of both larger and smaller particles, as well as fragments possessing non-rod-like shapes, may be underestimated. First, the use of mean size values tends to obscure the fact that maximum dimensions of measured individual particles ranged from 5 to 500 mm. Secondly, 35% of particle shapes are not rod-like, and these invariably comprise the largest and smallest particles. Thirdly, our observations have been predominantly of surface deposits rather than sections. They are thus biased to the zone in which sediments have accumulated at maximum swash limit and storm washover levels, that is, above the reach of normal high water. Thus, where sections are available on eroding island shores or beaches, stratified deposits are frequently observed. In some, the surface deposit continues down to a distinctive basal layer, while in others it is separated from the basal layer by a zone of smaller coral fragments and sand which accumulate in the swash zone under normal wave conditions. The basal unit is most distinctive. Typically it consists of larger cobble-sized hemispherical and highly irregularly shaped corals, plus occasional massive clam valves. This lag gravel rarely reaches above mean sea level, although storm-tossed individual components are found scattered on island surfaces. Sections also reveal the loose packing of constituents which results in highly unstable erosional cliff faces, except in cases where stick corals are preferentially orientated and imbricated. Interclast voids are rarely occupied by sand or mud sized sediment above mean sea level.

3.3. *Constituent composition*

In common with sand cays, the shingle islands are made up exclusively of bioclastic carbonates (excluding drift pumice). However, fewer taxa are represented in the shingle deposits. Scleractinian corals are clearly dominant and perhaps account for 95% of the constituent components. Mollusca, hydrozoan corals (*Millepora*), Octocorallia (*Heliopora* and *Tubipora*) and crustose coralline algae are subordinate contributors. Lithoskels reworked from cemented rampart-rocks are also locally present.

Of the corals, the prolific genus *Acropora* dominates the shingle rampart and island deposits as it does most living reefs in the area. Staghorn and bushy forms are the most abundant of the various acroporid growth forms. Other branching forms include *Porites*, *Seriatopora* and particularly *Pocillopora*. Rounded and hemispherical corals, especially various members of the family Faviidae also occur, notably in the basal layer. Fragments of tabular, foliaceous, and encrusting corals as well as solitary free corals are also found in island deposits.

The richness of the coral suite of the shingle deposits is illustrated by the fact that J. E. N. Veron (personal communication) observed a similar number of coral genera in the windward shingle deposits of Bewick reef as were presently living on the reef edge between depths of 0 and 12 m. Moreover, surface collections of easily recognizable clasts of different growth forms were made at about 40 localities on all the shingle islands visited and it was possible to collect quickly at least two branching corals (*Acropora*, *Pocillopora*), one foliaceous or encrusting coral (commonly *Turbinaria* or *Echinopora*), one solitary coral (*Fungia*), one hemispherical coral (Faviidae) and the rounded spiky *Galaxea*, as well as one clam, either *Tridacna* or *Hippopus*, from each site. Thus, despite the visual dominance of branching *Acropora*, the suite of corals (and probably molluscs) present in shingle deposits appears to include most windward reef flat and reef edge species.

3.4. *Particle surface characteristics*

In the field a major visual contrast is between the dull grey of island surface shingle and white brilliance of windward beach shingle. This contrast differentiates stabilized from active deposits. Wave action in the harsh windward beach zone abrades particles and ensures that most surface epibionts, obtained during post-death reef flat residence, are cleaned from the clasts before they reach their final sites of deposition. Windward beach clast surfaces are typically smooth and edge rounded (figure 6, plate 1), although original skeletal architecture is frequently maintained in taxonomically recognizable, although subdued, form. Particle surface textures obtained in the beach environment appear relatively unchanged in subsurface island deposits, but those exposed on the surface obtain a micro-phytokarstic architecture of tiny jagged spongy pinnacles and pits (figure 7, plate 1), which result from colonization by boring filamentous algae. The extent and intensity of pitting varies systematically across a shingle ridge or rampart system, being dependent principally on the age of the deposit and length of time of exposure. Old surfaces are more intensely pitted than young surfaces. Porous corals and massive clam valves are equally subjected to post-depositional pitting in the subaerial environment.

Thus, as a result of both abrasion and corrosion, shingle island surface clasts are smaller than their living or broken reef flat counterparts. Reconstruction of original skeleton circumferences from transverse thin sections of branching *Acropora* clasts allows the magnitude of change from source area to final site of deposition to be evaluated. Clasts from shingle beaches at Low Isles, Bewick and Watson possessed 90–98 % of their original cross sectional areas, while those from the surfaces of adjacent islands were only some 51–67 % of their original size. These figures indicate the severity of *in situ* degradation of exposed island surface shingle (figure 8, plate 1).

3.5. *Mineralogy, porosity and diagenesis*

Unlike sand cays which are composed of bioclastic components of both calcitic and aragonitic organisms, shingle islands are made up almost exclusively of corals which build skeletons of aragonite. However, bulk mineralogical determinations of over 70 clasts from shingle islands on ten reefs in the area show that high magnesium calcite is present in almost all samples. Commonly the percentage is between 3 and 10 but values up to 52 % were registered. Large sample to sample variation exists and adjacent coral sticks from the same locality have given up to tenfold differences in calcite values. The presence of calcite in individual shingle clasts is indicative of early diagenesis, and can result either from recrystallization of the original skeleton or the presence of secondary calcitic cement or sediment. Thin section analysis favours the second alternative, with the percentage of high magnesium calcite being a function of the amount of adhering and intraskeletal void sediment and cement.

Corals are porous structures and porosity measurements of live branching *Acropora* from the area average 25 %. Post-death occupation by boring organisms creates secondary voids such that there is an increase in the total void space. For island shingle clasts this averages 45–65 %, an increase of no less than 20 % on primary pores. However, voids serve as sediment traps and loci for intraskeletal cementation and are partially filled or completely filled synchronously. Thus it is unlikely that the magnitude of primary porosity is greatly exceeded at any one time during the passage of an individual clast from live source area to its island site of final deposition. Measurements of thin sections of *Acropora* sticks from shingle islands and ramparts in the area show that on average between 25 and 40 % of clast volume is occupied by cement and sediment. The lack of a significant difference between beach or rampart clasts and those in island deposits suggests that both intraskeletal void creation and void filling is accomplished primarily during the particle's residence in the reef flat environment. Rapid diagenesis of particles is indicated in the intertidal zone. Subsequent changes which take place on the beach and post-island deposition (abrasion and corrosion) are essentially size reducing and void enlarging.

3.6. *Age of shingle clasts*

Components of shingle islands, either corals or tridacnids from both consolidated and unconsolidated shingle deposits, have been radiometrically dated. The oldest dated bioclasts are from the cemented rampart-rocks of the upper platform and these give a mean age, for eight determinations, of 3500 a B.P. (Scoffin & McLean 1978, this volume). Bioclasts from the consolidated lower platforms and unconsolidated shingle rampart and island deposits are significantly younger, with one group (three determinations) averaging 1500 a B.P. and another (five determinations) averaging 750 a B.P., there being no difference between loose and cemented shingle. These data which are presented elsewhere in detail (McLean *et al.* 1978, this volume) suggest two major phases of shingle island development, one pre-dating 3000 a B.P., the second post-dating 1500 a B.P., with the latter being subdivisible into earlier and later minor phases.

While the difference of approximately 2000 years between the major episodes may be an artefact of sampling, the general consistency of ages of equivalent deposits between different reefs is striking and suggests that the development of shingle islands has been episodic with periods of accumulation being separated by phases of stability or erosion. These episodes may reflect variations in relative sea level, storminess or reef productivity, or possibly a combination of all three.

TABLE 3. PARTICLE SIZE AND SORTING OF SAMPLES FROM TURTLE I ISLAND (ϕ units)

sample no.	mean size	sorting	sand (%)	gravel (%)	sand fraction median	gravel fraction median
TON-104	−1.69	1.37	21	79	+0.6	−2.4
TON-105	−3.26	1.36	9	91	+0.5	−3.5
TON-106	−3.33	1.73	10	90	+1.0	−3.7
TON-107	−1.48	1.93	41	59	+1.0	−3.2
TON-110	−0.30	1.57	75	25	+0.3	−2.5
TON-111	−4.16	2.02	13	87	+0.9	−4.7

4. MIXED SAND–SHINGLE ISLANDS

Sand cays and gravel islands when they occur on the same reef are generally geographically discrete sediment bodies. While small quantities of shingle are found on sand cays and sand on shingle islands, proportions of the secondary size components are insignificant and may be ignored. However, on some islands sediments consist of sandy-gravel or gravelly-sand such that the two size components are thoroughly mixed. Islands of the Turtle Group particularly fall into this category, as do the two Pethebridge islands and Sand Island (figure 1). It is notable that in all cases these reefs possess only one island, which in sediment terms can be described as a mixed sand–shingle cay. Reefs occupied by mixed sand–shingle cays are generally small high reefs located close to the mainland and the cay covers a large proportion of the reef top, up to 40% (table 1). These features distinguish mixed sand–shingle cays from other reef islands in the area. Steers (1937) recognized that islands of the Turtle Group 'are examples of a kind of intermediate stage between the simple sand cay and the complex cay' but he did not explicitly relate this to differences in sediment type. While island surface sediments appear to be either sandy or shingly, and recently formed ramparts possess sediment characteristics similar to the shingle islands described above, pits dug in the older parts of the islands show that the two size components are mixed and have been deposited together.

4.1. *Mean size and sorting*

Sediment samples were sieved and weighed and grain size curves plotted by using mass frequency. Because the sediments comprise mixtures of sand and shingle in variable proportions, the range of sample mean sizes has a wide ϕ spread, from 0 to $-5\ \phi$, and sorting values are high, commonly between 1 and 2 ϕ units (figure 2). In textural terms the sediments can be classified as poorly sorted sandy-shingle. Some poorly sorted shingly-sands are also present. Results from analyses of six soil pit samples from Turtle I Island cover the range of values found on mixed sand–shingle islands (table 3).

Grain size curves are typically bimodal, the strength of the sand and shingle modes being variable. Mean sizes fall between the sand and shingle end-members with some overlap into the latter's range. Each of the two modal fractions is relatively well sorted. Size parameters calculated for the sand fraction and shingle fraction of the mixed sediments are quite similar to those described earlier for sand cay and shingle cay sediments respectively (table 3). Thus, the unique granulometric feature of these deposits is that the two sizes are thoroughly mixed and not geographically separated or sorted as elsewhere.

4.2. *Particle shape and surface features*

Axes measurements of shingle sized clasts from the mixed deposits of Turtle I Island plotted on Folk form triangular graphs show that blade shapes are the dominant group (43 %) followed by platy (23 %) and elongate (22 %) particles. Compact shapes account for 12 % of the clasts. Only the last value is similar to those from pure shingle islands. These data show that the shingle component of the mixed deposits is not dominated by elongate stick coral fragments and that there is a more equable distribution of the various shape categories. Part of this is the result of the presence of a large number of *Acropora* joints as well as the presence of corals of different growth forms. Moreover, clasts are more thoroughly edge rounded and polished such that distinct primary skeletal surface markings of corals are only recognizable on about 10 % of the particles. While the shape characteristics do reflect different proportions of constituents, particularly growth form constituents, surface features also suggest that the clasts of mixed deposits have been more severely abraded than their shingle island counterparts.

4.3. *Constituent composition and mineralogy*

The sand fraction of the mixed deposits contains a similar suite of skeletal components as the pure sand cays, but the proportions of the various constituents are markedly different. Sands from the Turtle islands are particularly rich in coral fragments, which account for over 50 % of constituents, and also molluscan fragments (20–25 %). Equivalent values for sand cay sediments are 20–25 % and 10–15 %. Coralline algae is the third most important component (10 %) while Foraminifera and *Halimeda* make up 7 % and 5 % of the sands respectively, compared with 25–30 % and 10 % for cay sediments. Thus, the sand fraction of mixed sand–shingle island sediments is clearly distinguished from those of pure sand cays.

Similarly the shingle fraction of mixed deposits can be distinguished from sediments of pure shingle islands. While *Acropora* continues to dominate the coarse fraction, the proportion of encrusting or foliaceous corals such as *Turbinaria*, stalky corals such as *Lobophyllia*, and smaller hemispherical faviid corals appear more abundant in the Turtle Island deposits. Two other features can be noted. First, there is a large number of lithoskels present. These clasts, which were noted only rarely in pure shingle island deposits, are characterized by a hard brown micrite streaky coating on the skeletal surface, the micrite also being present in intraskeletal voids. For the most part the original coral skeletons are taxonomically unrecognizable. The similarity between the adhering micritic cement of lithoskels and the high magnesium calcite cements of rampart-rocks (Scoffin & McLean 1978, this volume) strongly suggests that they have been reworked from these exposed limestones. Secondly, both the range of species and absolute numbers of molluscs appears to be greater. While clams and larger molluscs are present in roughly similar proportions to pure shingle deposits, smaller molluscs, particularly gastropods (e.g. *Nerita*, *Melaraphe*) and the oyster *Crassostrea*, are present in significantly greater numbers. Both whole and broken shell fragments are evident.

Bulk mineralogy of the sand and coral shingle fractions of the mixed deposits fall within the ranges of the sand cay sediments and shingle island sediments respectively. However, the sands possess a greater than average proportion of aragonite, and stick corals a greater than average proportion of high magnesium calcite, the former resulting from the larger number of aragonite building organisms and the latter from the presence of void infills and adhering surface cement.

4.4. *Age of sand–shingle deposits*

The only radiocarbon dates available for materials from mixed sand–shingle islands relate to one island of the Turtle Group, Turtle I. Coral from a loose coral and shell deposit beneath mangrove mud in the centre of the island dated 4910 ± 90 a B.P. (ANU-1479) while a *Tridacna* from rampart-rock of the upper platform gave an age of 4420 ± 90 a B.P. (ANU-1478). These dates suggest that island sediments began accumulating at least 4000 years ago. Bulk determinations of unconsolidated sandy-gravels from soil pits on the upper and lower levels towards the northwestern end of the island range over 3320 ± 80 a B.P. (ANU-1388) for the upper level to 2760 ± 80 a B.P. (ANU-1598) and 2480 ± 70 a B.P. (ANU-1597) for the lower level. The presence of lithoskels from rampart-rocks, intertidal rock-dwelling molluscs and highly abraded clasts in the shingle, plus the high coral and mollusc and low *Halimeda* and Foraminifera content of the sands, suggests that there was continual reworking and local redistribution of reef top materials in the interval 4000–2000 years ago. The mixed nature of the sediments comprising these deposits also supports this view. These data and geomorphological evidence additionally suggest that the island has been basically stable during the last 2000 years, although fresh material in the form of narrow shingle ramparts has been added to the island's periphery in this period. A *Tridacna* from one of these deposits dated 1430 ± 70 a B.P. (ANU-1477).

Regrettably, there are no radiocarbon dates from other mixed sand–shingle islands upon which to base an absolute chronology for comparison with Turtle I. Nevertheless, the relative size (in relation to reef-top area), location and nature of deposits of some other islands in the Turtle Group, notably Turtle II, V and VI, suggests that these at least may have had a similar history of sedimentation. Other islands in this group, Turtle III and IV, together with Sand Island, East Pethebridge and West Pethebridge which occupy less than 10% of the available reef top on elongate reefs, may well have a different history.

5. COMPOSITE ISLANDS

Composite islands are those that contain areas of at least two of the three sediment types described above (table 1). None of the islands possess large areas of mixed deposits, the main components being either sand or shingle. Frequently these sediment types are zonally arranged and although there may be a narrow swale between the two, more usually they abut or overlap one another with little obvious morphological break.

The simplest composite islands consist of a large sand deposit with a narrow band of shingle (frequently cemented) on one side. Examples of this type are the leeward islands on Leggatt, Sinclair–Morris and Houghton reefs, while Coquet has a broader loose shingle deposit backed against the 'sand cay' in addition to a cemented shingle shore. These reefs also have another island (shingle) on the windward side, or, in the case of Leggatt, residuals of cemented shingle, rampart-rock. Nymph and Low Wooded Island are more complex islands. They consist of a single island which encircles a large central pond or mangrove swamp. The islands are highly variable in width and their morphology suggests that there were formerly a number of discontinuous deposits which have since become united. On the leeside both islands possess what Steers called a 'sandy cay-like area' which passes rather indefinitely into mixed sand–shingle or shingle ridges and ramparts which make up the bulk of the islands. Nymph and Low Wooded Island are the largest reef islands in the region. They both cover an area of some 450000 m^2 (including enclosed ponds and mangrove swamp), and occupy 50–60 % of the available reef top space.

5.1. *Sediment characteristics*

Composite islands have been distinguished as a separate category in this paper only because the geographical arrangement of sediment types, but not the nature of those sediments, is different from other islands. Analysis of seven sand samples from the main island of Leggatt and the cay-like area of Nymph show they fall within the size-sorting and compositional fields of the other sand cays. The sediments from both sites can be described as Foraminifera and coral-rich moderately well sorted coarse sands. Likewise, the shingle deposits of composite islands are similar to those of pure shingle islands, being composed predominantly of moderately sorted medium pebble sized stick coral fragments.

5.2. *Age of composite island sediments*

It is believed that the majority of the sand and shingle deposits of composite islands accumulated around 3000 a B.P., though there are insufficient radiocarbon dates to substantiate this conclusion. A bulk calcarenite from Houghton Island was dated 2670 ± 70 a B.P. (ANU-1596). This sample included secondary aragonite as a cementing medium, the presence of which postdates the age of the bioclastic components. Overlying the calcarenite was a coral shingle veneer, one component of which dated 3550 ± 80 a B.P. (ANU-1413). At Nymph and Low Wooded Island tridacnids from rampart-rock of the upper platform aged 3540 ± 80 (ANU-1383) and 3320 ± 70 (ANU-1604) a B.P. respectively. These data suggest an early phase of island building and that island cores were established by about 3000 a B.P. More recent peripheral accumulation is indicated by samples of loose shingle and cemented shingle from Coquet and Nymph which have been dated at 1070 ± 60 (ANU-1411) and 520 ± 70 (ANU-1476) a B.P.

All these ages are similar to those from equivalent deposits on pure sand cays and shingle islands in the region and it is likely that composite islands have similar chronologies. The essential difference is that the windward shingle deposit has extended leeward to encompass, partly or wholly, the sand cay to form what here is called a composite island. In other words spatially disjunct islands on the same reef have joined to form a single island processing two or more contrasting sediment populations.

6. Conclusions

1. Three distinct sediment types exists on the islands of the northern Great Barrier Reef. These sediment types are discrete populations, distinctive in textural properties, composition and geographic occurrence, and allow single reef islands in the region to be classified as either sand or shingle or mixed sand–shingle islands. A fourth type, composite islands, is included to cater for those instances where two of the foregoing sediment types have been morphologically united. Size and geometry of the reef, relative exposure to prevailing and catastrophic waves, as well as reef-top morphology govern in large measure the nature and distribution of reef organisms and local sediment types.

2. Sand cay sediments can be described as moderately well sorted coarse sands composed predominantly of worn foraminiferal, coral and molluscan fragments. Subtle differences in texture and constituent composition exist between cays and between beach, basic cay and soil horizons on the same cay. Cay sands are derived from reef flat bioclasts. Sediments of the two environments are discriminated on textural grounds, particularly sorting.

3. Shingle island sediments can be described as moderately sorted medium sized pebbles composed predominantly of elongate shaped corals. Fragments of branching corals, particularly *Acropora*, account for the major constituents though deposits include the range of coral growth forms and species present on windward reef flats and edges. Coral thickets and colonies are broken down during storms and built into shingle ramparts, and ultimately islands. Boring organisms increase skeletal porosity, and voids are partly or completely filled with sediment or cement while particles are on the reef flat. Wave action on beaches abrades, cleans and smooths bioclasts. Beach shingle surface textures are unchanged in subsurface island deposits, but exposed bioclasts develop a micro-phytokarstic architecture.

4. Mixed sand–shingle island sediments can be described as poorly sorted sandy-gravels or gravelly-sands. The two modal populations, sand and shingle, are moderately well sorted but vary considerably in relative abundance. Both fractions possess similar textural characteristics as the pure sand and shingle deposits, though there are some distinguishing features. Mixed sands have a significantly higher percentage of coral and molluscan constituents and lower percentage of Foraminifera and *Halimeda* than pure sand deposits. Likewise, the shingle components differ in that the mixed shingle has a more equable distribution of particle shapes, contains a greater percentage of molluscan fragments and lithoskels, and all clasts are well worn and some polished. The two size populations are thoroughly mixed indicating contemporaneous deposition, and considerable reworking of original materials.

5. Composite islands do not possess a unique sediment type. Instead they are made up of two or more of the foregoing types, commonly pure sand and pure shingle.

6. An essentially zonal pattern of island sediment types exists across the shelf from the mainland to outer ribbon reefs. Sand cays (types I and II) occur in the outer zone where they are the only islands on the reefs. In the central zone, both sand cays and shingle islands are present on the same reef. Composite islands also occur in this region. Nearer the mainland, sole shingle islands and mixed sand–shingle islands are present. This zonal pattern mainly reflects variations in energy conditions in the manner outlined by Stoddart (1965).

7. At the local reef level, sand deposits occur on the leeward side and shingle deposits on the windward side of the reef top. Occasionally the latter extend leeward to partly or completely surround the sand cay. Mixed sand–shingle deposits are more centrally located on a reef. An idealized distribution of sediment types on reefs of the area has been described and explained by Steers (1929, 1930).

8. Radiocarbon dates indicate that some reef islands in the Northern Province of the Great Barrier Reef were formed at least 4000 years ago. However, the major period of both sand cay and shingle island building took place around 3000 a B.P. The basic outlines of islands established at this time have since become modified to a greater or lesser degree through subsequent erosion and redistribution of island materials and additions of fresh reef flat and reef edge detritus. Considerable enlargement, particularly of shingle islands, has taken place in the last 1500 years and some new islands may have been created. Nevertheless, the basic pattern of islands, both at regional and local scales, pre-dates this more recent period. As a consequence of

reef tops becoming more packed with emergent sedimentary deposits, the available space for production of primary sediment has been reduced such that some islands, for example Turtle I, V, VI, Nymph and Low Wooded Island, may well have now reached their maximum size.

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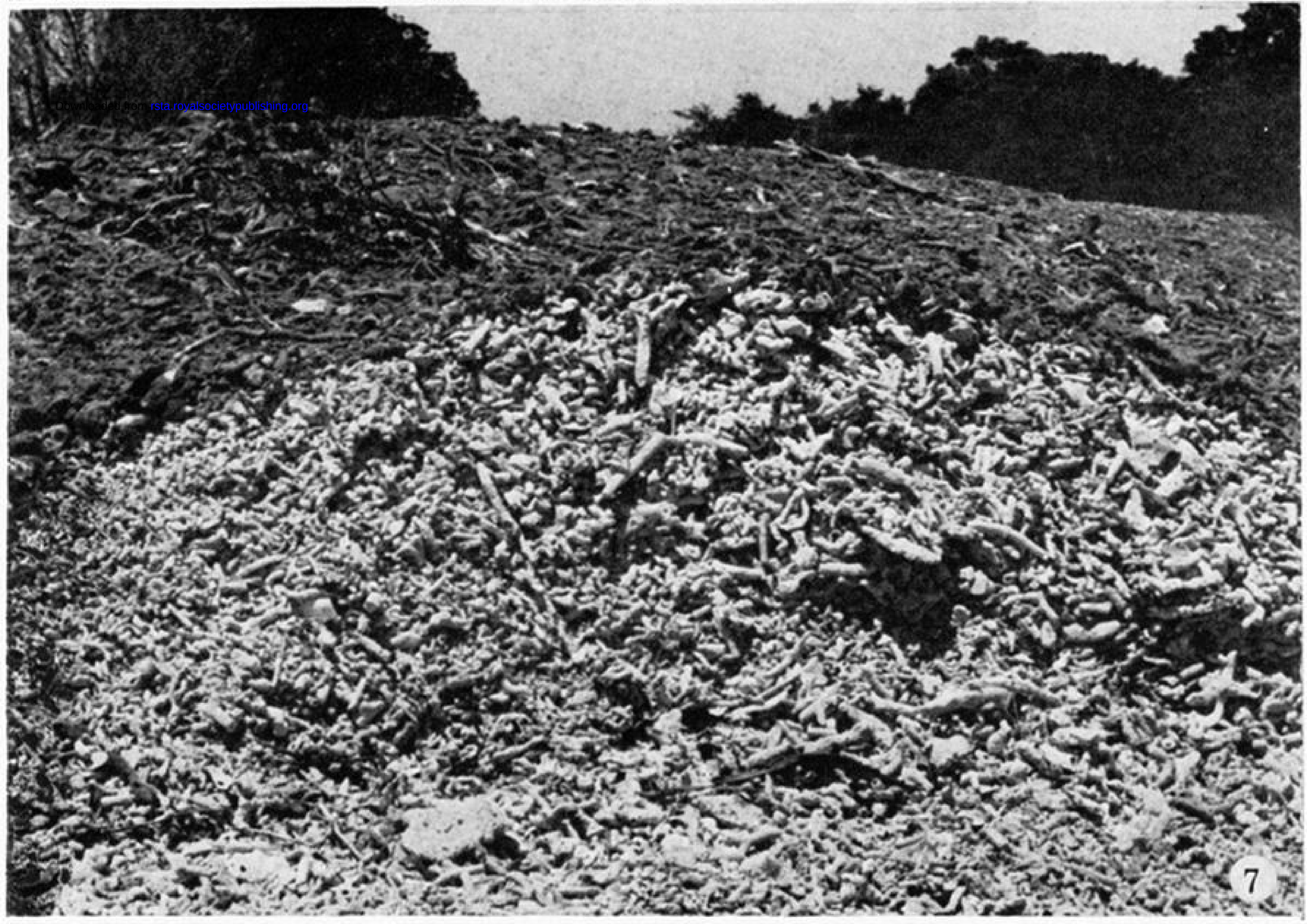

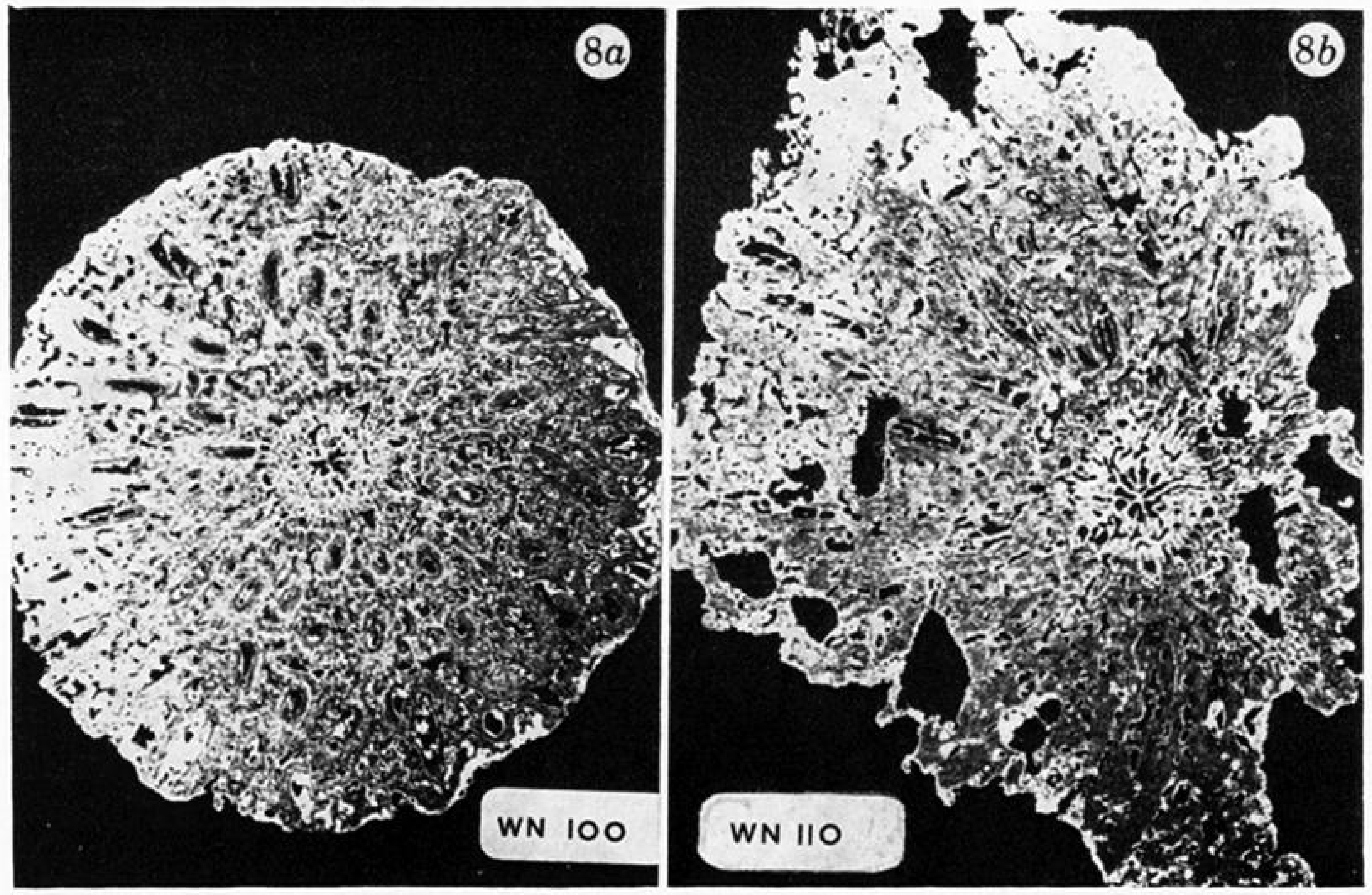

FIGURE 5. Coral shingle deposit at Two Isles. Scale bar is 30 cm long.

FIGURE 6. Abraded, cleaned and imbricated branching coral fragments on shingle beach at Turtle Island.

FIGURE 7. Contrast between exposed surface and subsurface shingle island deposits at Low Wooded Island.

FIGURE 8. Transverse sections of *Acropora* branching coral fragments from Watson Island showing contrast between smooth outline of beach clast (WN 100) and micro-karstic outline of island surface clast (WN 110). Note reduced size of WN 110 and presence of partly and completely filled primary and secondary voids. Both corals are 2 cm in diameter.