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Carbonate sediments of Half Moon Cay, British Honduras

by

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The reef islands of the British Honduras barrier reef and atolls have been the subject of a series of reports (Stoddart 1962, 1963), to which the present paper is essentially supplementary. Earlier papers were concerned with the distribution and areal variation of the reef islands, about which little was previously known. Mapping of topography, sediment distribution, and gross vegetation patterns involved the approximate delimitation of "ecologic field units" (Cloud 1952) for use in constructing field maps. As in other reef studies, a primary distinction was made in sediment distribution between fine ("sand") and coarse ("shingle") sediments, which with qualifying adjectives ("fine", "medium", "coarse") became the basis of sediment mapping.

The data reported here result from an attempt to define the limits of these sediment units in quantitative terms, and the results are of interest primarily in terms of the original field reports. They are not intended as a contribution to the study of carbonate sediments as such. Because of the limited time available no specific sampling design was set up, and samples were simply collected along the course of levelling traverses. Generally these were oriented normal to the beach, and hence parallel to the greatest sediment gradients. The great variability in sediment pattern on most foreshore areas presents a major problem, which in any subsequent design would require stratified random sampling (Krumbein 1954, Krumbein and Slack 1956). The density of sampling points also varied inversely with vegetation cover: at Half Moon Cay few samples were taken from the dense *Cordia*-*Bursera* bush at the west end of the island. Because of this variability and the absence of design, no attempt is made to draw any conclusions from these data on, for example, the relative importance of contributing organisms in above-water sediments. The aim is to demonstrate the quantitative significance of the terms "sand" and "shingle" as applied to British Honduras cays, and to explore the relationship between sediment calibre and organic constituents in the collected samples.

When this work was in progress, few papers had been published on reef-island sediments, with the notable exception of the Bikini reports (Emery, Tracey and Ladd 1954, pp. 35-43). Tracey, Abbott and Arnow (1961, pp. 58-67) have reported on the sediments of Ifaluk Atoll. The paucity of the literature is in strong contrast to that on underwater carbonate sediments. A major advance in the study of above-water carbonate sediments has resulted from the work of Robert L. Folk and associates in the southern Gulf of Mexico. Folk, Hayes and Shoji (1962) have described carbonate sediments from Isla Mujeres, east coast of Yucatan; Charles Hoskin (1963) has included beach sediments in his comprehensive study of Alacran Reef sediments; and Folk himself (1962) has treated the relations of size and sorting in carbonate beach sediments at several Gulf of Mexico beach locations. The fundamental study of Caribbean reef island sediments is that of Folk and Robles (1964) on the sediments of Isla Perez, Alacran Reef; Professor Folk kindly allowed me to read the manuscript of this paper while in the field in 1961 and some of the data reported here supplement his conclusions. Folk and his associates are working on further studies of other Alacran island sediments.

Procedure

Most of the samples described were collected in 1961 by the writer and Stephen P. Murray at Half Moon Cay, Lighthouse Reef. Half Moon Cay lies on the eastern (windward) reef flat of the Lighthouse Reef atoll, at a point where the reef front curves sharply westwards (Figure 1). Tidal range is small, and the dominant waves are easterly and northeasterly, refracting round the reef angle to approach the south side of the island from the southeast. The island itself is 1100 yards long. It is highest along the south and southeast shores, where in 1961 it reached a maximum height of 10 feet above sea level. The island falls naturally into two parts. The eastern sector, built of sand except for shingle ridges at the eastern point, is arcuate in shape, with a steep ridge 10 feet high facing the southeast bay, the surface falling quite steeply to the northern shore. This part of the cay is covered with coconuts, with little ground vegetation. The western sector of the cay is still covered with a dense thicket of vegetation, mainly _Cordia sebestena_ and _Bursera simaruba_. The south shore is formed by a shingle ridge, decreasing in height (in 1961) from 8 feet at the east end to 3 feet at the west. The cay surface falls gently from this ridge crest toward the north shore, and is built of sand and rotten coral fragments. The north shore is sandy and subject to wave action only during winter "northers"; the offshore area is covered with _Thalassia_, with only a few scattered coral patches. Off the south shores, steep waves enter the southeast bay, which is floored with strongly rippled sand with little living reef. Further west, off the south shingle shore, living reef approaches within a few feet of the shore itself. Cemented beach sands are widespread in the intertidal area, but are not treated in this paper; for a full account of the island, with contoured topographic maps, see Stoddart 1962, pp. 64-77, Figures 30-34, and Stoddard 1963, pp. 94-98, Figures 58-61.

In addition to the Half Moon Cay samples, samples were also taken from shoal water areas (less than 2 fathoms) on the atolls and barrier reefs, and in the Turneffe lagoon, and from a number of other islands, chiefly Rendezvous Cay and Cay Glory (barrier reef), Northern Cay (Lighthouse Reef), Southwest Cays (Glover's Reef), some of the central barrier reef lagoon cays, and a few mainland and barrier beach stations. All the sediments consisted of carbonates, except for quartz sands from the mainland and barrier beach stations. The samples taken in 1961 at Rendezvous and Half Moon Cays were repeated as far as possible in 1962, following major changes to cay sediments and topography during Hurricane Hattie in October 1961. In all 202 samples were studied, of which 155 are from Half Moon Cay.

Different techniques were necessarily adopted for sand and shingle size material. For sand size sediments, surface scoop samples of approximately 750 grams were collected, and taken to Cambridge for sieving with a nest of British Standard sieves, and for microscopic inspection to determine approximate organic constitution. Approximate organic constitution was noted during this inspection, but no more refined analysis was carried out. Cumulative frequency curves were constructed from the sieving data, and mean size and sorting values computed, using the methods recommended by McCammon (1962):

$$\text{Ø Mean size} = \frac{Ø16 + Ø50 + Ø84}{3}$$

$$\text{Ø Sorting} = \frac{Ø85 + Ø95 - Ø5 - Ø15}{5.4}$$

Size values are given in phi (Ø) units ($Ø = -\log_2 D$, where D is particle diameter in millimeters) for ease of handling (Krumbein and Pettijohn 1938, p. 84). Zero Ø is equivalent to a particle size of 1 mm ; smaller particle sizes are indicated by positive and larger by negative Ø values. Ø percentiles were read from the cumulative curves.

Only sand size sediments and small shingle up to -6Ø could be taken to Cambridge; larger shingle and boulder size sediments evade standardised sieving treatment. For coarse sediments, the technique adopted was to measure the long axis of not less than 50 particles in the field, to construct cumulative frequency curves from this data, and to calculate mean size and sorting values. Since the cumulative frequency curves of sand samples express the quantity of sand by weight in each class interval rather than the number of particles retained by each sieve, it was decided in the case of measured long axes to sum the lengths of particles within each class interval rather than the numbers of particles, as do Folk and Robles for Isla Perez shingle. Folk and Robles constructed frequency curves by numbers, and converted these to weight frequency distributions by adding approximately 0.5Ø to the number value (Folk 1962, p. 232). In this case Folk was dealing mainly with Acropora cervicornis shingle, in which particle volume and shape bear some stable relationship to long axis measurement. Different relationships obtain, however, when dealing with other organisms, such as globular or hemispherical corals. For this reason the sums of lengths method is used, since it is probably more directly comparable over the whole shingle range to the weight measurements of sands. This technique for handling coarse material is extremely unsophisticated: its chief merits are speed and ease of execution under conditions of discomfort. Owing to the inherent qualities of reef-derived organic carbonate material, there is usually no question of deriving simple shape parameters such as those of Zingg (1935) or Sneed and Folk (1958), using three-dimensional and other measurements. The problem of the quantitative description of highly irregular particles such as reef-derived sediments has yet to be investigated in detail, and is not dealt with here.

Size Characteristics and Origin

The dominant characteristic of reef island sediments, taken as a single population, is bimodality. Figure 2 includes cumulative frequency curves for 115 samples from Half Moon Cay, collected in 1961. The samples divide themselves quite clearly into two families: one with a mean size ranging from about -0.30 to +1.00, fairly tightly grouped; the other, with a rather wider range, from about -5 to -100, but strongly clustered round -80. These correspond, respectively, with the "sand" and "shingle and boulders" of the cay descriptions. There is no apparent gradation in size between the two. Some sand samples contain larger shingle fragments, accounting for the open ended curves on the right of Figure 2, but the distinction between the two families is otherwise abrupt. To an undetermined extent this distinction may be due to the two methods of measuring sediments used, but this is unlikely to be very significant. The curves show that sediments larger than -100, between -5 and -10, and finer than +20 are uncommon on sand and shingle cays. Fine sediments are probably important on mangrove islands, but no samples were taken. This sharp distinction between two types of sediment is primary evidence of (a) the diverse origin of cay sediments, and (b) the particular breakdown patterns of sediments of organic origin on cays. At the same time, the distinction hides other finer variations within each of the major sediment families, variations which, though expressed topographically and in sediment calibre, can be understood only by reference to the organisms from which the sediments derive. In this, cay sediments differ fundamentally from most beach materials, such as the Placencia quartz sands on the mainland coast.

Composition

Cay sediments are derived from the wide and complex range of organisms of many shapes and sizes forming and inhabiting the living reef and near-reef environments, and subject to sorting and modification by marine action. Theoretically, the size and shape of sediment particles on cays may be initially as varied as those of any reef organism, within the range of the transporting capacity of the waves. Attrition by waves, subaerial weathering, or biological means may produce further changes in both size and shape, the products of which may be selectively transported and deposited by waves and currents. While generalization is, therefore, difficult, it is soon recognized in the field that sediments of certain sizes tend to consist largely or even exclusively of single organisms. Thus boulder material (larger than -90) consists of whole hemispherical coral colonies, often deposited by storm waves beyond the reach of normal wave action and exposed to chemical weathering only; intermediate shingle (-80) consists of fragmented *Acropora* colonies, smaller corals and shells; coarse sand (00) of algal fragments; and medium sand (+0.50) of fragmented coral particles and colonial foraminifera.

In most of these cases, the characteristics of the sediment reflect directly the characteristics of the dominant constituent organism. Since each organism usually has fairly sharply defined size and shape characteristics, sediments which consist largely of a single organism have similar size and shape characteristics. Thus reef-flat colonies of _Siderastrea_ and _Diploria_, growing to diameters of 2-3 feet, when piled up by waves form a sediment in the size range -9 to -10ø, with rounded and hemispherical particles. _Acropora cervicornis_, which when growing forms tangled thickets with narrow cylindrical stems and branches, may be broken down by waves into cylindrical fragments up to -7ø (5 inches) long and -3.5 to -4.5ø diameter, closely following the original growth dimensions. _Halimeda_ is a bushy green alga with abundant plate-like segments up to 8 mm (-3ø) in diameter, but extremely thin; when the segments are detached by wave action and accumulate they form a sediment with a mean size of 0 to -2ø. These groups of organisms are among the most abundant; other organisms also have characteristic shapes and sizes, but are not usually present in sufficient quantity to dominate the characteristics of a sediment population.

Constituent organic materials control not only the size characteristics of a sediment, but also the sorting, or measure of the spread of grain sizes present. In sediments derived from a single organic constituent, the mean size will closely reflect the size of the original organism, and the sorting will reflect the range of sizes present in the living population. In general, sizes of living reef organisms tend to cluster fairly tightly round a mean value, and the derived sediment shows small scatter about the mean size, or is well sorted. This applies to most sediments composed of a single type of organic constituent. Selective transportation by waves imposes a secondary sorting effect, but this is apparently less important than the primary composition of the sediment. When a sediment is composed of more than one organic constituent, each will influence the sediment characteristics in proportion to its abundance. Hence samples composed of coral grit and _Halimeda_, or _Acropora_ sticks and smaller corals, will have a bimodal frequency distribution, with poorer sorting as the dominance of a single organism decreases. In some samples, particularly underwater samples, as on the Turneffe lagoon floor, many organisms are present and the sorting is extremely poor. On cays, however, most sediments are formed from one or two main constituents, are moderately or well sorted, and closely reflect the size and shape of the original contributing organisms.

In British Honduras, the main sediment sources and sediment-contributing organisms, in order of decreasing size, are as follows:

1. Conglomerate beachrock blocks, dislodged from beachrock pavements by wave action. Except for some massive corals these form the largest particles, up to -10ø in longest dimension. Their shape is plate-like, and probably because fracture is conditioned by inherent joint weaknesses in the beachrock, the fragments tend to be of closely similar size: the sediment is thus extremely well sorted.

2. Large hemispheric corals of the genera _Montastrea_, _Diploria_, _Siderastrea_, etc. These vary from -8 to -10ø, but the larger specimens are very rare.

3. *Acropora palmata*: a massive branched coral (elkhorn), in which the branches break down into slabs which exceptionally are up to -9Ø (20 inches) long, but are more usually -7 to -8Ø (5-10 inches) in length and up to 2 inches thick. This is more widespread in rough water areas, particularly as a shingle ridge constituent on the atoll islands.

4. Gastropod shells, particularly massive specimens of *Strombus gigas*, which are locally very abundant. They are generally found whole, with greatest dimensions of about -7Ø, but may break down under severe wave action into curved and disc-shaped fragments.

5. *Acropora cervicornis*, one of the most important sediment producers and perhaps the most widespread constituent of shingle ridges. Dimensions of the original colony vary considerably with depth and degree of exposure to wave action. In exposed locations the branches are stubby, massive and tightly clustered; in calm water the colonies are open-branched and taller. The diameter of branches is normally greater in deeper and rougher water, and is least in protected barrier reef areas. For data on growth form at Alacran, see Kornicker and Boyd 1962, pp. 667-668. In most shingle ridges *A. cervicornis* branches vary from -5 to -7Ø in length, but on protected barrier reef cays such as Robinson Point and Wild Cane Cay they rarely exceed -5Ø.

6. Medium hemispheric corals, a group which includes such small corals as *Siderastrea radians*, *Dichocoenia*, *Isophyllastrea*, *Porites astreoides*, small *Montastrea*, etc., varying in size from -6.5 to -8Ø. These colonies are generally mixed with *Acropora* fragments in shingle ridges.

7. Small corals such as *Porites*, *Favia* and *Siderastrea*, in the size range -5 to -6Ø: these are not individually important sediment sources.

8. Nodular algae, particularly *Goniolithon boergesenii*. *Goniolithon* forms loose nodules, cylindrical in shape with a smooth or mammillate surface, up to -6.5Ø in length. *Goniolithon* is found living on the east reefs of Lighthouse and Glover's Reef cays, where it forms a prominent minor constituent of shingle ridges. It is possible that fragmented *Goniolithon* is important in the sand fraction, where it has not yet been identified.

9. Branching algae, including the massively branched *Goniolithon strictum* and the more delicate *Lithothamnium calcareum*. These are found in all reef provinces, but are quantitatively unimportant as sediment sources.

10. *Halimeda* fronds, which are the main constituent of coarse sands. The segments are easily distinguished by their shape and dead white, chalky appearance. They are mainly retained by the Nos. 5 and 10 sieves, have a maximum diameter of about -2Ø, and form sediments with median diameter approximately 0Ø. Individual segments break into two or three fragments which are easily identified by shape and structure. In the Pacific *Halimeda* is more important as a source of lagoon floor sediments than as a beach constituent (see, for example, Tracey, Abbott and Arnow 1961, p. 65).

11. Coral grit, fragments of corals no longer identifiable, consisting of equant, greyish particles, highly polished in areas of high wave action but dull on protected beaches, and invariably mixed with small amounts of red Homotrema as a secondary constituent. Coral grit is largely retained by the Nos. 22 and 30 sieves, with mean sizes of 0.5 to +10, extending down to +20. Coral grit is the dominant constituent of medium and fine sands.

12. Small organic debris found in most sand samples, but individually and collectively of small importance. The group includes echinoderm spines and tests, peneroplid foraminifera, gastropod and pelecypod tests, sponge spicules and fish bones. Foraminifera as a group are not important in cay sands, by contrast to most Pacific atolls.

13. Very fine sediments, +20 and finer, of unidentified origin and quantitatively insignificant, found in many samples of fine sand.

14. Finally, the remains of many other reef-dwelling organisms which are thrown up on beaches and contribute in some way to cay sediments. These include the remains of numerous gorgonians, sponges and crustaceans.

Breakdown

Field observation and sediment samples show that of these groups, three are dominant in the formation of cay sediments:

1. Acropora cervicornis sticks and similar size corals in the shingle class;

2. Halimeda segments in the coarse sand class; and

3. Coral grit with Homotrema in the sand class.

The correspondence between organism and sediment characteristics is best seen in the coarser materials: in sediments finer than Halimeda sand whole organisms become relatively scarcer and detrital fragments more important. However, organisms directly influence the characteristics not only of "primary" sediments (those formed by simple skeletal accumulation), but also of "secondary" sediments formed by the breakdown of whole skeletons and the accumulation of detrital fragments.

Many reef organisms do not break down gradually, giving a continuous sequence of sizes, but sharply and suddenly, in a manner determined less by the mechanisms of erosion than by the inherent structure and weaknesses of the skeleton (Wentworth and Ladd 1931, pp. 9-12). Thus, large coral heads do not become smaller and smaller under the influence of mechanical or chemical weathering, but after subaerial exposure are observed to fall apart by radial fracture into a number of pyramidal blocks, which in turn disintegrate into cuboidal fragments one inch across. These then break down directly into grit.

The process has been seen in *Montastrea annularis*, *M. cavernosa*, *Diploria clivosa*, and on one occasion in *Colpophyllia natans*. In the case of *Acropora cervicornis* the individual branches first lose their calices by mechanical weathering, then break down directly into grit. *Halimeda* segments apparently break into two or three fragments, and then directly into fine-sand or silt-size aragonite particles (though at Ifaluk in lagoon sediments Tracey and others found evidence of gradual breakdown: Tracey, Abbott and Arnow 1961, p. 65). Each of these breakdown stages is controlled by factors inherent in each particular organism, and this controls the resulting sediment characteristics to a degree second only to that of the original whole skeletons. The process of breakdown is also important, and is largely influenced by the point of lodgment of the particles in question: large particles lodged near the top of the beach will only be affected by chemical breakdown, whereas those of the foreshore will be affected by wave abrasion also. Discontinuous breakdown in cay sediments is explored in greater detail for *A. cervicornis* and *Halimeda* by Folk and Robles, but there is much scope for detailed investigation in the precise mode of breakdown in other reef organisms on islands.

Major Sediment Types

This section deals with the size, sorting and composition characteristics of six main types of sediments found on the British Honduras cays, particularly on Half Moon and Rendezvous Cays.

Beach sands

Beach sands are of two main types: coral grit sand, and *Halimeda* sand. These are composed of different organisms, have different size characteristics, and are found in different environments. Coral grit sand consists of equant, rounded, sometimes polished particles of coral, no longer specifically identifiable, and mollusc material, and subordinate amounts of red *Homotrema* which give a pinkish cast to the sand. Hoskin has stressed the usefulness of *Homotrema* as an environmental indicator, since it occurs in living-reef areas (Hoskin 1963). Echinoid spines and other materials are present in small quantity, with very small amounts of foraminifera. This sand concentrates in the No. 22 sieve (0.5φ); at Half Moon Cay (Figure 3) 16 coral grit beach sands had a mean size of 0.09φ, and mean sorting of 0.77φ. Coral grit sands are found on more exposed cays, particularly on the atolls and southern barrier reef. The grit seems to represent a stable stage in the breakdown of larger coral colonies. *Halimeda* sands are of small importance in these more exposed cays.

Halimeda sands, which may consist of up to 100% *Halimeda* segments, are chiefly found on more protected cays, particularly on the north-central barrier reef between English and South Water Cays, where sand consists of both coral grit and *Halimeda*, and pure *Halimeda* beaches also occur. Patches of pure *Halimeda*, often in unsegmented clumps, are usually found high on the foreshore, where they are lodged by a selective sorting process. Figure 4 shows cumulative frequency curves for eight Halimeda sands at Cay Glory, and Figure 5a curves for 11 Halimeda sands for Rendezvous Cay. In Figure 6, size is plotted against sorting for both groups. The sands tend to cluster round a mean size of 0φ, with a sorting value of 0.6φ (moderately good to good). Mean values (unweighted arithmetic means) for each group of sediments are:

	No. of samples	Mean size	Mean sorting
Cay Glory	6	-0.12φ	0.64φ
Rendezvous Cay 1961	11	+0.04	0.74
Rendezvous Cay 1962	7	-0.25	0.60

Halimeda segments appear more abundant in nearshore sands than in interior sands, possibly as the result of the greater mobility of flat, platey segments under wave action, and their selective concentration in the nearshore zone. The importance of Halimeda has been noted elsewhere on Caribbean beaches (Puerto Rico: Van Overbeek and Crist 1947; Jamaica: Steers and others 1940), and Folk and Robles (1964) estimate that this alga forms 50-70% of the sands of Isla Perez, Alacran. In the Pacific, however, Halimeda is most important as a sediment contributor on lagoon floors and is not important on beaches (Funafuti: David and Sweet 1904; Marshall Islands: Emery, Tracey and Ladd 1954; Kapingamarangi: McKee, Chronic and Leopold 1959).

Many sand-size constituents of cay sands are ill-adapted to sieve analysis because of their departure from spherical or equant form. Well-rounded coral grit appears to approach closest to "normal" quartz sands in shape, but other constituents, such as Halimeda plates, echinoid spines, spindle-shaped spicules, mollusc fragments and foraminiferal tests depart considerably from equant form. Plate-like algal segments, for example, bear no relation in weight or settling velocity to quartz spheres of comparable "diameter", and are lighter than many "finer" coral grits. This is explored in some detail by Folk and Robles: the limitations of the use of simple cumulative frequency curves derived from sieve analysis are thus apparent.

Beach shingle

All the data on beach shingle come from Half Moon Cay, where sediments up to -10φ diameter are found, the coarsest formed by broken conglomerate-pavement blocks. The term "shingle", not used in the Wentworth scale, is commonly used by English writers for cobbles and gravel and is imprecisely defined; it here refers to coarse, highly permeable, interlocking coral fragments, derived with a minimum of breakage from colonies of living coral and other organisms, which are still specifically recognizable.

Of 53 samples for which cumulative frequency curves are given in Figure 2, the mean size is -7.46φ and mean sorting 0.59φ. Such figures cover much variation, and in particular the differentiation at Half Moon Cay of beach shingle into zones distinguished by size and color variation. The foot of a shingle beach is often formed by a discontinuous zone of coarse, rotted, yellow coral blocks; the foreshore itself by a low but continuous ridge of fresh, white, small calibre shingle; and the beach crest by a zone of large, blackened coral blocks. The following table gives mean size of sediments in each zone at four transects across the beach on the south shore of Half Moon Cay; cumulative frequency curves for the same stations are given in Figure 7. For location of sampling stations, see Figure 14.

Black zone	(91)	7.420	(85)	7.810	(80)	8.100	(75)	7.960
White zone	(90)	6.37	(84)	6.46	(79)	6.75	(74)	6.93
Yellow zone	(89)	8.01	(83)	8.34	(78)	8.05	(73)	8.40

Figures in brackets are sample numbers

The fresh corals of the white zone are clearly being continually deposited by day-to-day wave action: wave competence is small, and therefore only small material is transported beachward. Mechanical abrasion is important in this zone. The larger blocks of the ridge crest must date from major storms: mostly they consist of little-damaged whole corals picked from the bottom and deposited on the beach crest: here they are exposed only to chemical and biological breakdown, and not to mechanical action. The ridge-foot blocks probably accumulate by transport across the reef flat during bad weather periods. Between the easternmost most exposed stations (73, 74, 75) and the more protected western stations (89, 90, 91), there is little lateral variation in calibre in either black or yellow zones, indicating approximately equal wave competence along the whole shore during storms; but calibre in the white zone decreases continuously from east to west, away from the seaward reefs, in response to decreasing wave energy as waves are refracted round the eastern point and travel westwards.

In addition to corals, large gastropods such as *Strombus gigas* are locally important. At two stations, HMC 21 and HMC 54, *Strombus* shells were separately measured.

Station	Number	Length	Breadth	
HMC 21	40	6.25	3.9	inches
HMC 54	25	7.2	4.7	inches

At HMC 54, of 100 measured pebbles and cobbles, 37 were whole *Strombus* shells. Pumice occurs in smaller quantities in Half Moon Cay shingle ridges, and is of finer calibre: at HMC 91a, the mean diameter of 100 pumice pebbles was 0.98 inches, and the largest cobble seen had maximum dimensions of 4 inches. No data are available on the breakdown of pumice pebbles, which probably proceeds by attrition of the pebbles and production of grit; but collection of *Strombus* fragments in an area of strong wave activity suggests that breakdown is gradual, producing a wide range of particle sizes and shapes.

Interior sands

Away from the beaches the character of cay sediments changes, color changing with humus formation, and calibre with the breakdown of particles and accumulation of fines during the soil-forming process. At Half Moon Cay soil-formation has proceeded furthest where the vegetation cover is densest. Almost all the beach sediments contain a negligible silt fraction (i.e., finer than +3.750). Under the eastern coconut plantation at Half Moon, silt content varies from 0.1 to 0.6%; while under the Cordia-Bursera woodland this rises to 1.0-3%. The maximum silt fraction of 4.95% is found at HMC 113 (Figure 14). The silt fraction consists of brown material which does not dissolve in dilute HCl; it generally appears in sieve No. 22 and increases in relative quantity through No. 200; at all stages it is quite distinct from the white carbonate grains. The larger coral grit grains can be seen to be pitted and infilled with this material.

Figure 3 compares cumulative frequency curves for 16 beach and 26 interior sands at Half Moon Cay, and Figure 8 plots size against sorting for both these sets of data. Size and sorting means for the two groups are as follows:

	Number	Mean size	Mean sorting
Beach sands	16	+0.090	0.770
Interior sands	26	+0.44	0.78

There is no difference in sorting between the two groups, but the interior sands are considerably finer than the beach sands. This is probably the result of breakdown of sand particles by soil forming processes under a vegetation cover. On small cays without a vegetation cover, such as Cay Glory, these differences between beach and interior sands are not found.

Dune sands

Dune sands are a special type of interior sands, characterised by fineness, but consisting, like beach and interior sands, of coral grit, Homotrema and mollusc fragments. Figure 9 gives cumulative frequency curves for dune sands from Half Moon Cay (HMC 55), Ambergris Cay (three samples), and Northern Cay (Lighthouse Reef). These sands are all finer than normal interior or beach sands (compare Figure 3), but the samples at Northern Cay, where the dunes are most extensive, is also exceptionally well sorted (mean size +1.590; mean sorting 0.350). The position of the cumulative frequency curves compared with normal beach and interior sand curves suggest that there is a real difference between the two groups, which may be diagnostic of origin in cases where this is uncertain, as at Ambergris Cay. However, the number of samples collected is too small to reach any conclusion: dune areas are uncommon on the British Honduras reef islands.

Hurricane deposits

Qualitative data on hurricane deposits have already been presented for a large number of islands (Stoddart 1963). In 1962, following Hurricane Hattie, sand samples were taken on Rendezvous and Half Moon Cays at locations sampled in 1961 before the hurricane. It was not possible in 1962 to carry out any measurements of shingle deposits, and where, as a result of the storm, sand was overlaid with shingle, and vice versa, no comparison is possible. Sand-size hurricane deposits were less well sorted than normal beach deposits, and microscopic examination showed the presence of many organisms, mainly gastropods, pelecypods and foraminifera, not normally seen in beach sands. These fairly uniform sands were spread over large areas of cay surfaces, and were not confined to foreshore areas. They probably originated in reef-flat sand deposits, which were transported landward and roughly sorted by the storm waves. The following table summarizes changes at Rendezvous and Half Moon Cays 1961-2, and the Rendezvous Cay frequency curves for 1961 and 1962 are given in Figure 4. Figure 10 plots mean size and sorting of pre- and post-hurricane sands at Half Moon Cay.

	Year	Number	Mean size	Mean sorting
Rendezvous Cay	1961	11	+0.04ø	0.74ø
	1962	7	-0.25	0.60
Half Moon Cay	1961	16	+0.09	0.77
	1962	28	+0.69	0.92

The apparent anomaly, that Rendezvous sands in a protected situation are coarser than the Half Moon sands on an exposed cay, is explained by the fact that the former are *Halimeda* sands and the latter coral grits.

Underwater sands

By contrast to beach sands, underwater sands consist of a large range of grain sizes corresponding to local organic production, and in the absence of wave action are poorly sorted. In general, sorting will be poorer in more protected locations. Figure 11 gives cumulative frequency curves for sediments from the leeward reef flat, Glover's Reef, from southern lagoon, Turneffe Islands, and from the anchorage at Rendezvous Cay, for which size and sorting are summarized in the following table:

	Mean size	Sorting
Glover's Reef (Bushy Spot)	+0.88ø	0.92ø
Turneffe (southern lagoon)	+0.65	2.18
Rendezvous Cay A1	-0.80	0.70
Rendezvous Cay A2	+0.29	1.03

Samples are quite insufficient in number to make any detailed comparison of above and underwater sedimentation on the reefs; for a very detailed study of mainly underwater sedimentation at Alacran, see Hoskin (1963).

Sediments of Half Moon Cay

Data for 155 samples at Half Moon Cay are sufficient to map the distribution of sediment characteristics (Figure 12); the samples are well distributed except in the Cordia- Bursera woodland (Figure 13). At the east end of the cay, close to the seaward reefs, and again along the south shore, the beach is built of shingle coarser than -6ø but generally less coarse than -8ø. These are both areas of high wave energy, and high coral productivity close inshore. In both areas there is a well-marked zonation into yellow, white and black zones, with distinctive calibre. In the yellow and black zones calibre tends to be uniform irrespective of location along the beach, but gradation is found in the white zone in response to changes in wave energy. Two patches of -9 to -10ø sediment on the southeast beach are formed by accumulations of broken beach conglomerate slabs.

Beach sands are generally fairly coarse (1ø or 0.5 mm), though finer than the Halimeda sands of Rendezvous Cay. Over most of the cay surface, sands under coconuts are coarser (0.5 to 1ø) than those under dense woodland (0 to 0.5ø). This probably results from wind-winnowing of fines in the former area, leaving a fairly coarse surface lag, and from increased breakdown by chemical and biomechanical means in the woodland. Within the woodland the surface is littered with old, blackened and rotted coral blocks in the size range -5 to -8ø.

Sorting varies less regularly. The coarser material on the beaches is in general best sorted, with values along the south shore and at the east point of less than 0.5ø. Excellent sorting is found in some shingle along the south shore (0.29 to 0.3ø), in dune sands at the south point (0.26ø), and in conglomerate block accumulations (0.21ø). Bare sand under coconuts is moderately sorted, with values ranging from 0.7 to 0.85ø, in contrast to beach sands, which have a fairly uniform sorting value of 0.5 to 0.6ø. Under the dense woodland, where the sand is often mixed with coral blocks and the sediments are bimodal, sorting is poor, with values in excess of 1.0ø. The sand alone in these areas is as well sorted as under the coconuts.

The variation in silt content has already been noted. Silt (finer than +3.75ø) is only appreciable (more than 1%) under the Cordia-Bursera woodland, reaching a maximum of nearly 5%: elsewhere it is negligible.

For notes on such erratic sediments as brown limestone and pumice, see Stoddart (1962, pp. 105-106); the same paper also describes consolidated sediments on Half Moon Cay.

Size and Sorting

When all values of size and sorting at Half Moon Cay are plotted against each other in Figure 15, certain broad relationships are seen. The best sorted sediments are the coarsest and the finest. This is very well seen in the shingle sector, where sorting gets progressively better as size increases from -5 to -10Ø. The best sorted sediments (sorting less than 0.5Ø) are those grouped near a mean size of -8Ø. This trend is probably partly due to the narrowing range of organisms as size increases: the -8Ø sediments consist largely of small brain corals and Acropora palmata slabs. In the sand-size sector the scatter of size and sorting is greater, but there is a tendency for sorting to improve with decreasing calibre from -1Ø to +2Ø. It has already been seen that Halimeda sands at Rendezvous Cay, with a mean size of 0Ø, have a sorting value of 0.6Ø (Figure 5).

At Isla Perez, Alacran, Folk (1962) has demonstrated a sinusoidal relationship between size and sorting in the size range -3Ø to +2.5Ø, with best-sorting peaks at mean sizes of -3Ø, 0Ø and +2Ø. Each peak corresponds with the modal size of a particular organic constituent: the -3 to -4Ø peak with Acropora cervicornis branches, the 0Ø peak with Halimeda sand, and the 2Ø peak with coral grit. At Isla Perez, sediments with mean sizes between those which correspond to peaks for each particular organic group have been shown to contain more than one type of sediment, with correspondingly poorer sorting. In general, Folk's hypothesis is fully confirmed by the British Honduras data, though details vary. The absence in Honduras of sediments in the -1 to -5Ø range rules out direct comparison with Folk's curves, and in the Honduras data sorting values are less good for both Halimeda sand and coral grit than at Alacran. The Half Moon coral grit (mean size +1Ø) is considerably coarser than the dominantly +2Ø grit at Isla Perez.

Sorting values for both sand and shingle at Half Moon Cay have been plotted as cumulative frequency curves in Figure 16, which may be compared with Folk's similar figure for Gulf of Mexico carbonate sands (Folk, 1962, p. 241). Shingle is consistently better sorted than sand (0.53Ø against 0.74Ø) and the mean sorting of all sediments is 0.61Ø. This compares with 0.47Ø for Folk's carbonate beach sands. It is interesting that sorting is so closely comparable on adjacent beaches where calibre may vary over the range from +2Ø to -10Ø (¼ to 1024 mm). Submarine deposits appear to be very much more poorly sorted.

Conclusion

The data reported here are sufficient to add some definition to the concept of ecological field units suggested by Cloud, insofar as these have been used as a field survey technique in British Honduras. Sediments of diffent calibres are shown to have sharply defined size and sorting characteristics, and also to be characterized by regular organic derivation. Hence, the field units can be readily defined in terms both of size and composition, the two attributes together being directly related. Future field mapping can thus use terms such as cervicornis shingle, Halimeda sand, and coral grit sand, with the knowledge that the attributes of each group are fairly stable in terms of size, sorting and composition, and are mutually distinct. Because this survey was not designed specifically to study the sediments, this analysis is carried no further: a sampling plan could readily be devised to test these points and establish their significance.

The results also in large measure confirm the original work by Folk at Alacran and Isla Mujeres, where he showed that size and sorting depend less on wave energy than on organic composition. Wave energy controls mean size (i.e. the type of organism present), and the type of organism then controls sorting.

There is clearly further scope for (a) specific design for further sediment study both above and below water on the British Honduras cays, to test the relationships of size, sorting and other sediment characteristics to organic composition and wave energy, and the nature of the interlocks between them; (b) for experimental studies on breakdown under wave action of different types of organic carbonate skeletons; and (c) for studies of the effect of diverse size and shape characteristics on mobility under water and on the foreshore. To a large extent, the solution of these problems involves a fourth, (d) the derivation of meaningful measures of size and shape for reef-derived carbonate particles.

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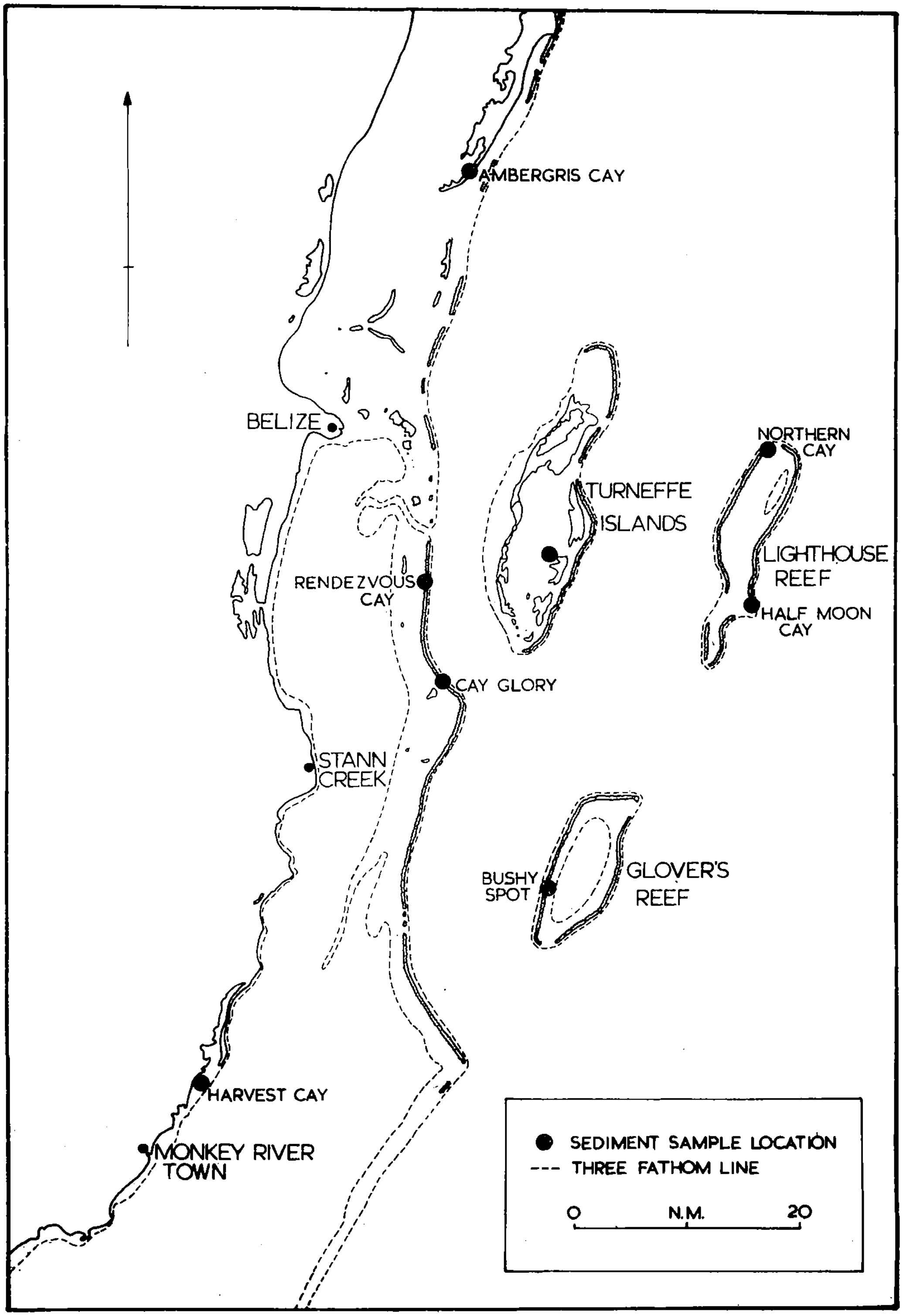


Figure 1. British Honduras: location of areas sampled

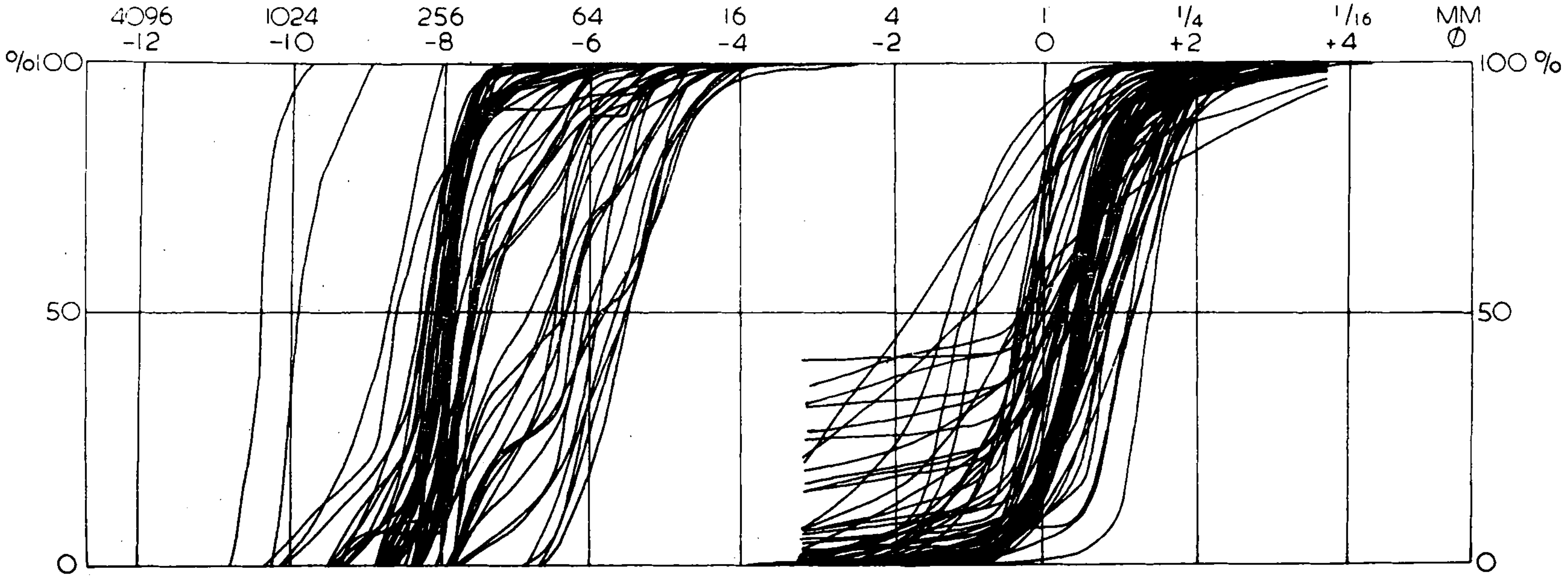


Figure 2. Cumulative frequency curves for 115 Half Moon Cay sediment samples

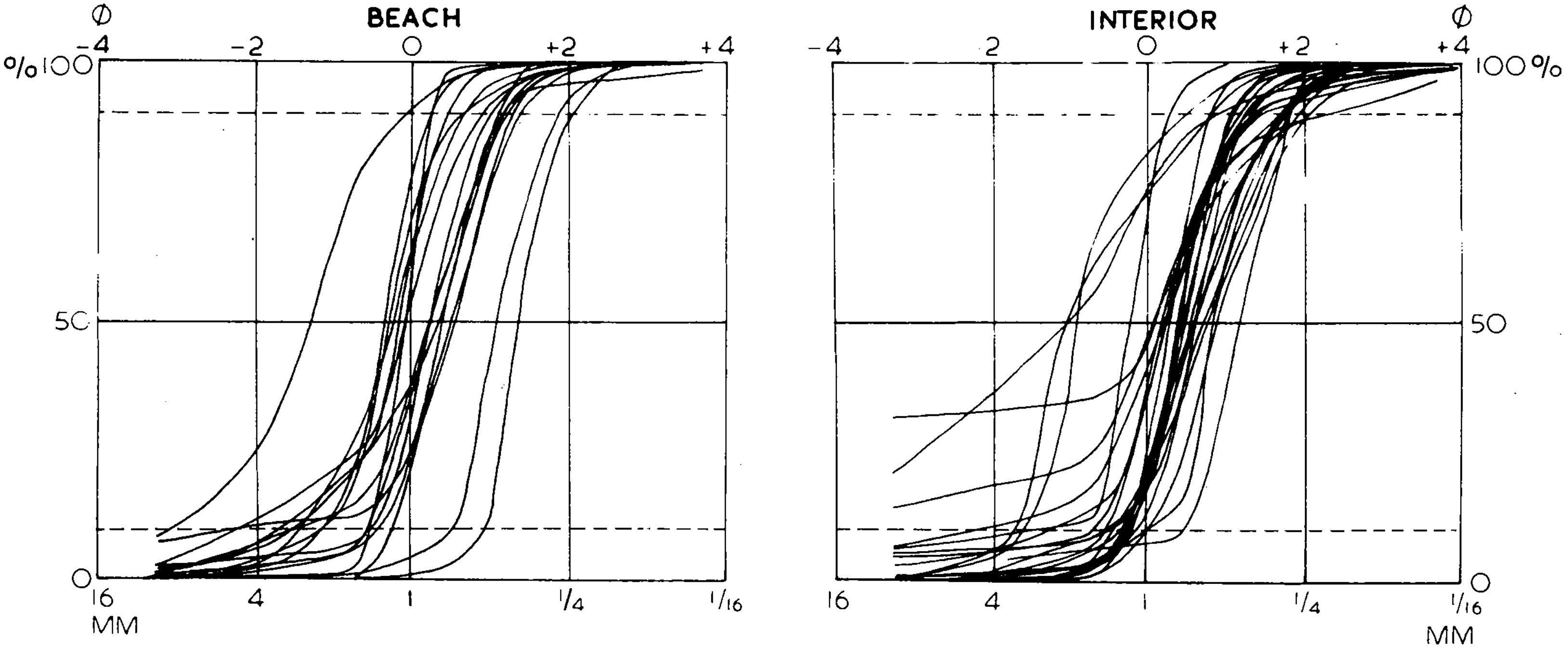


Figure 3. Cumulative frequency curves for 16 beach and 26 interior sands at Half Moon Cay

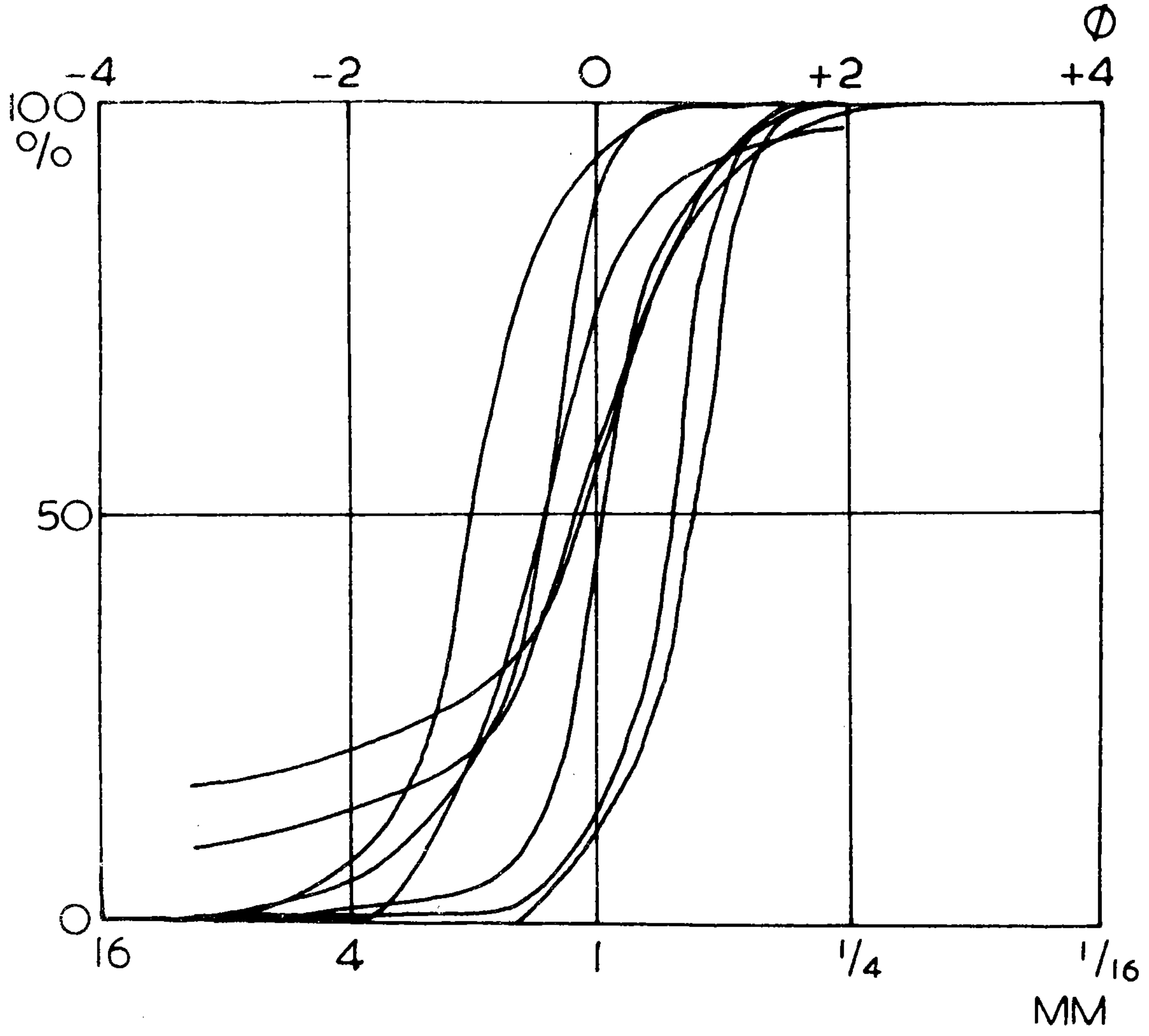


Figure 4. Cumulative frequency curves for 8 Cay Glory *Halimeda* sands

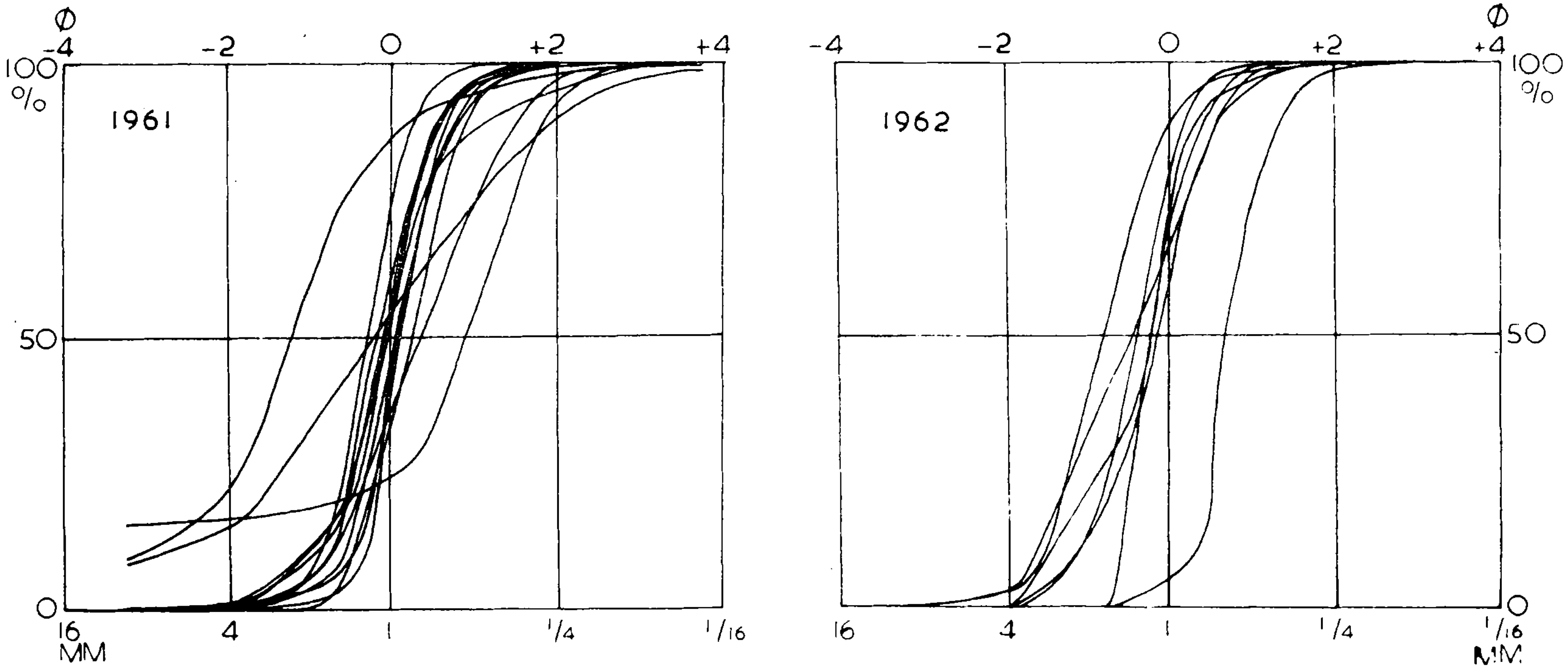


Figure 5. Cumulative frequency curves for 13 *Halimeda* sands in 1961 and 7 in 1962 from Rendezvous Cay

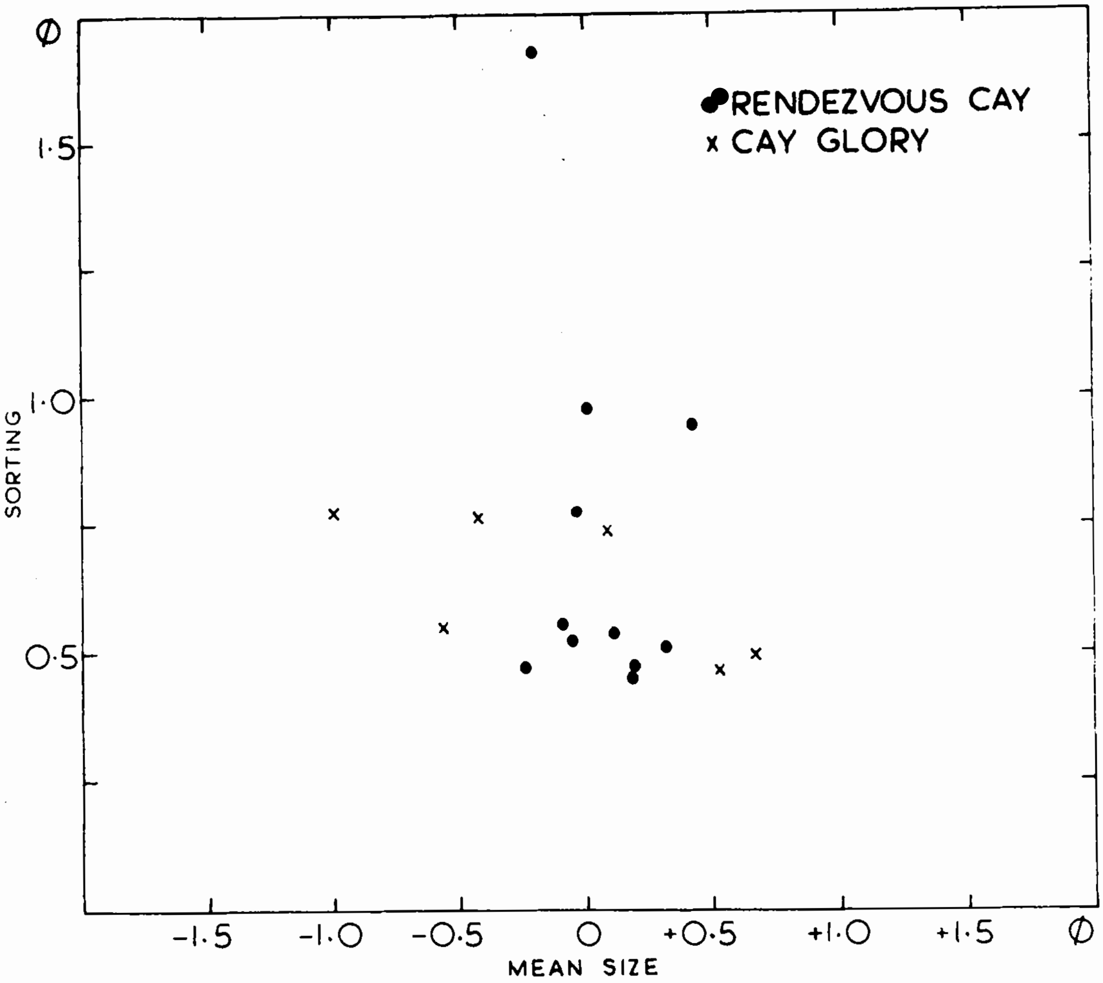


Figure 6. Mean size and sorting of Rendezvous Cay and Cay Glory beach sands

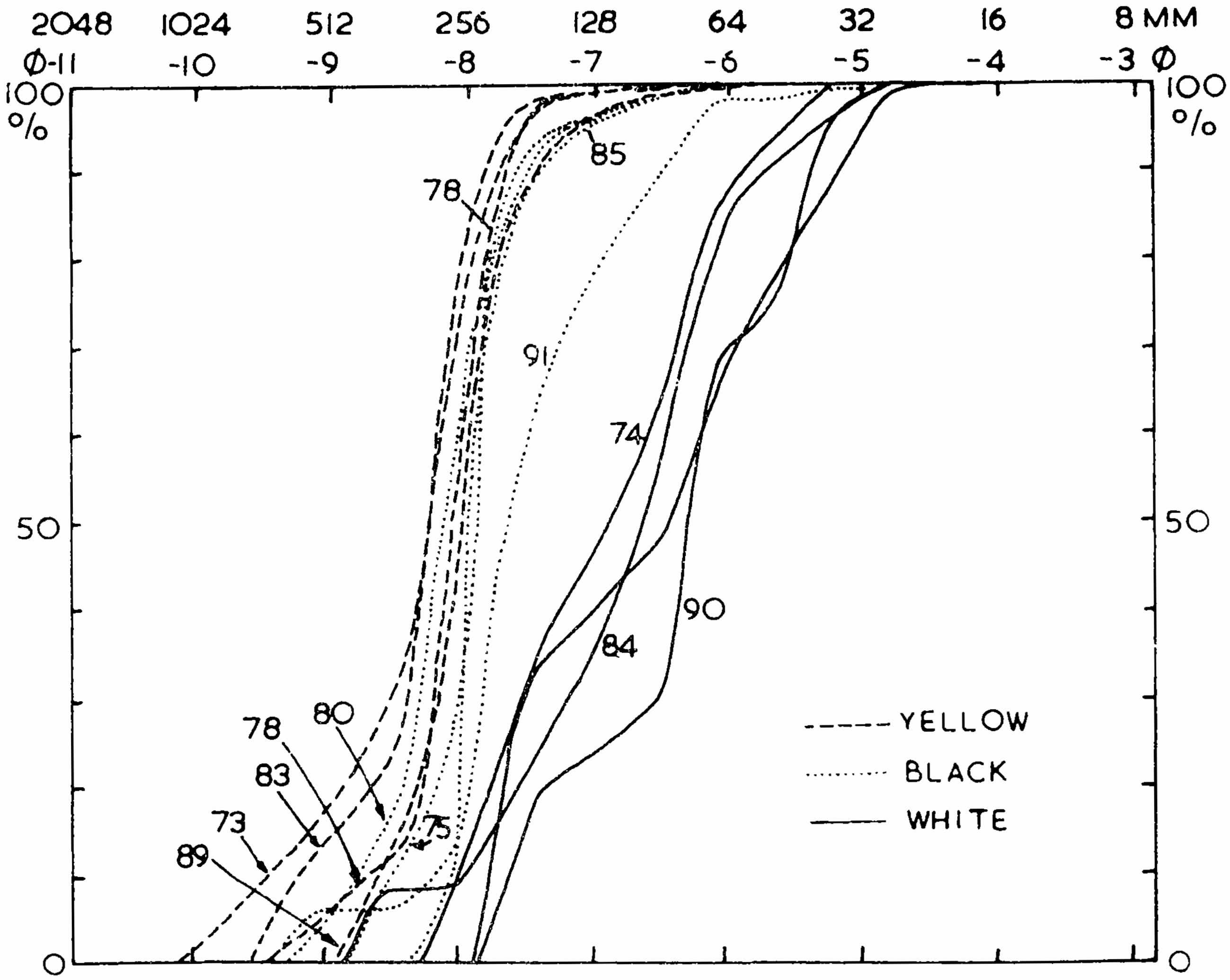


Figure 7. Cumulative frequency curves for yellow, white and black shingle zones, south shore of Half Moon Cay

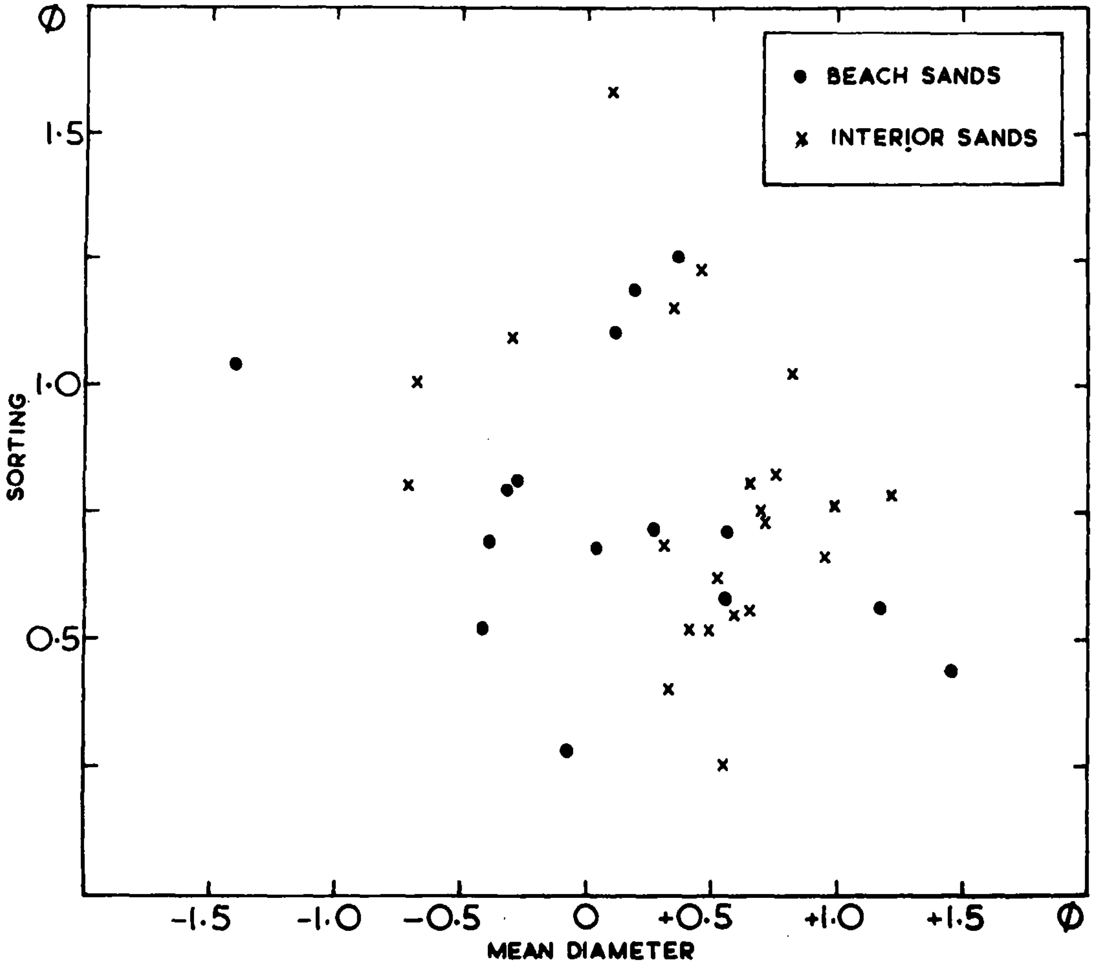


Figure 8. Mean size and sorting of Half Moon Cay beach and interior sands

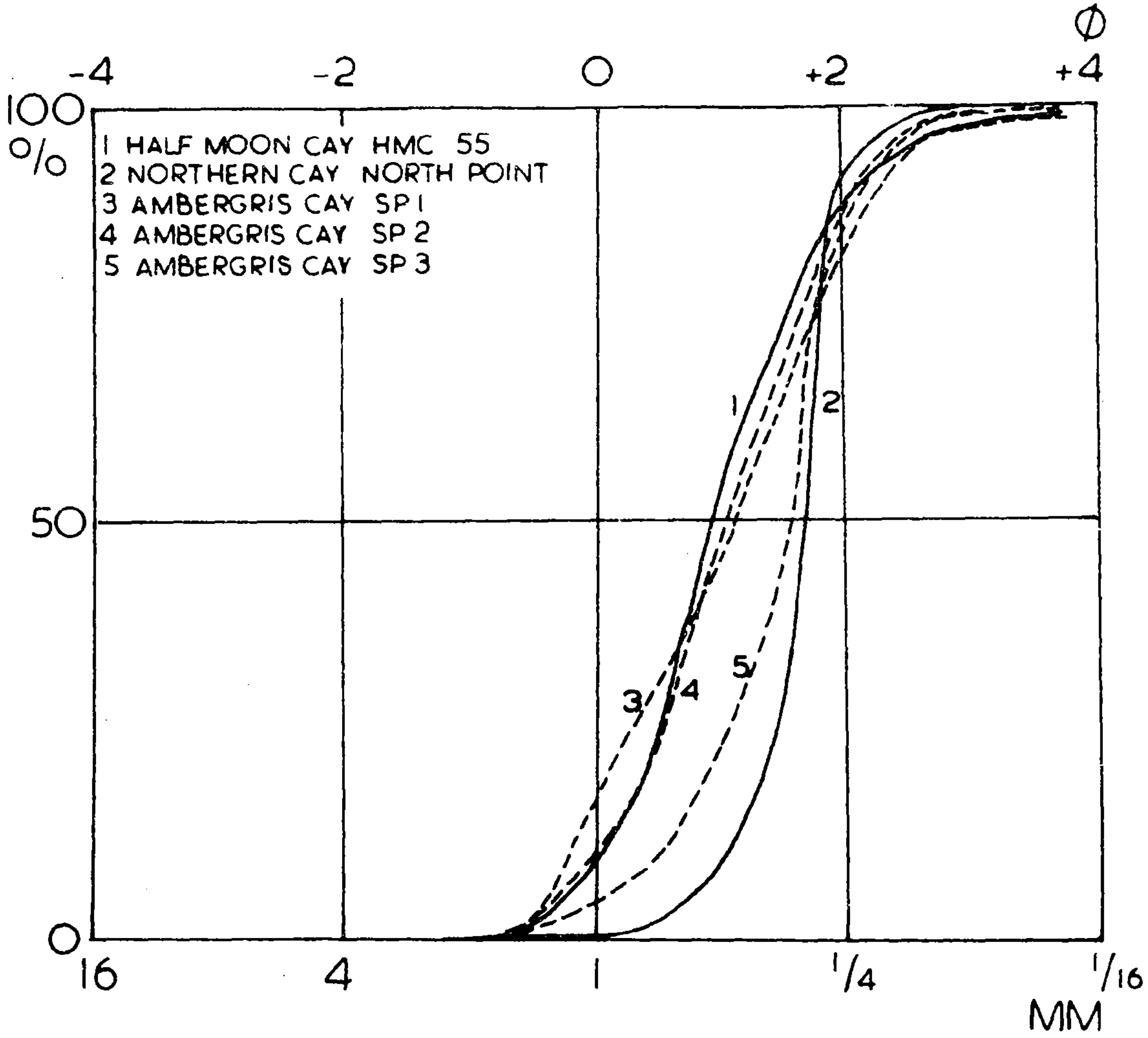


Figure 9. Cumulative frequency curves for dune sands

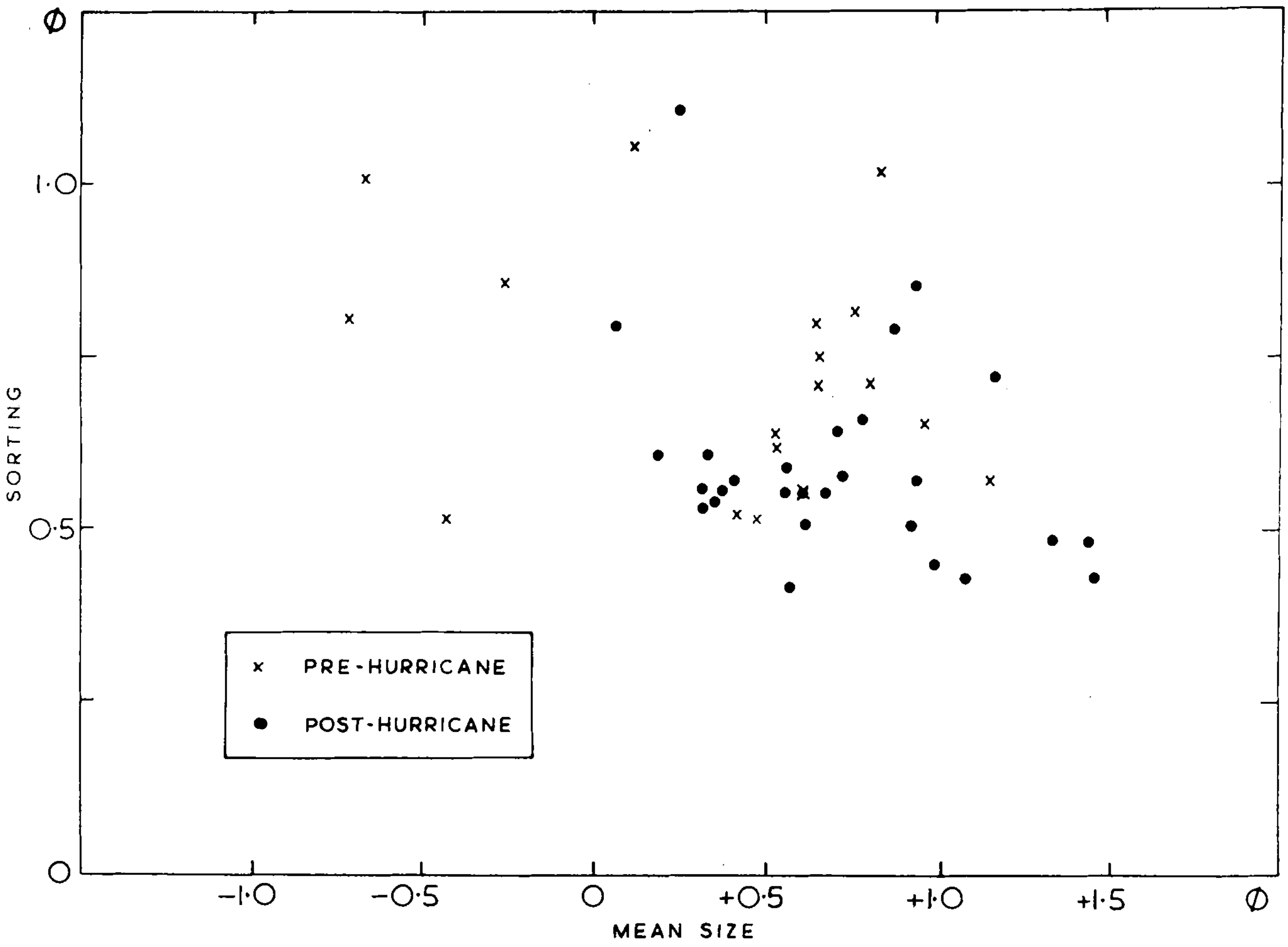


Figure 10. Mean size and sorting of pre- and post-hurricane sands at Half Moon Cay

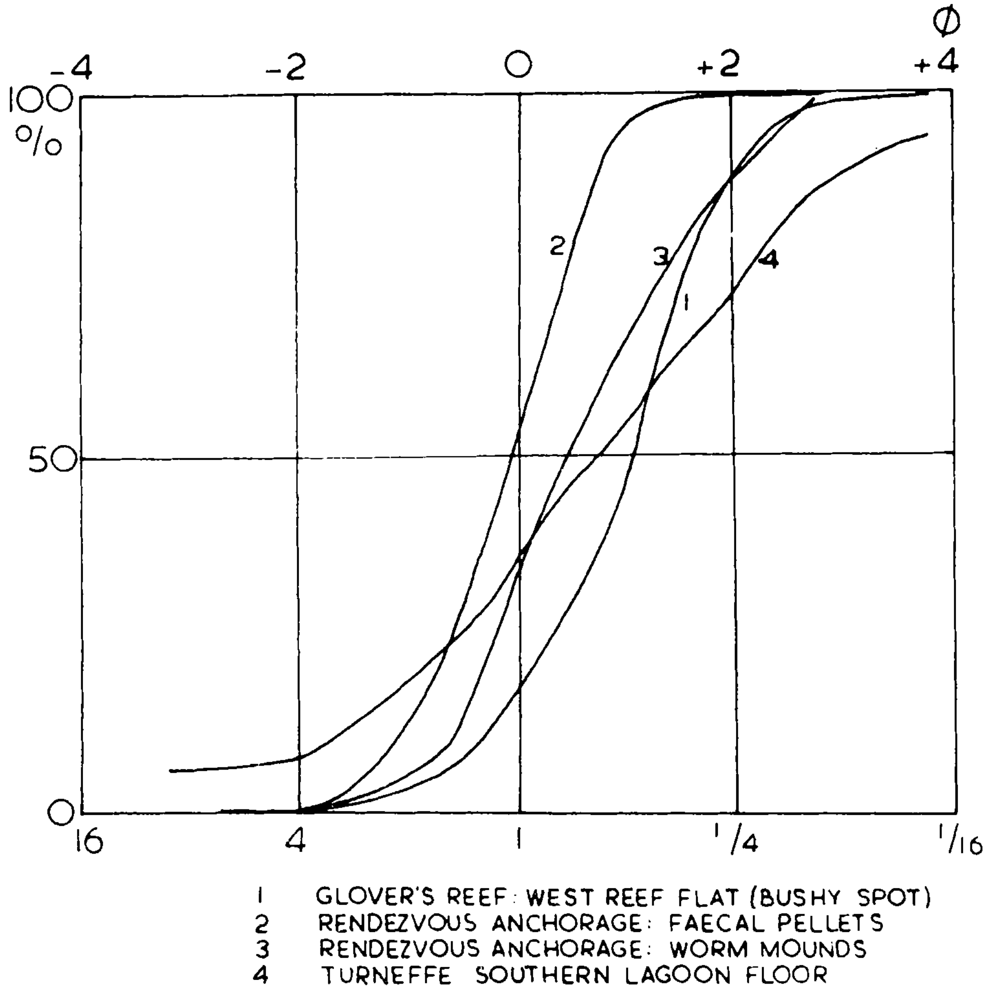


Figure 11. Cumulative frequency curves for underwater sediments

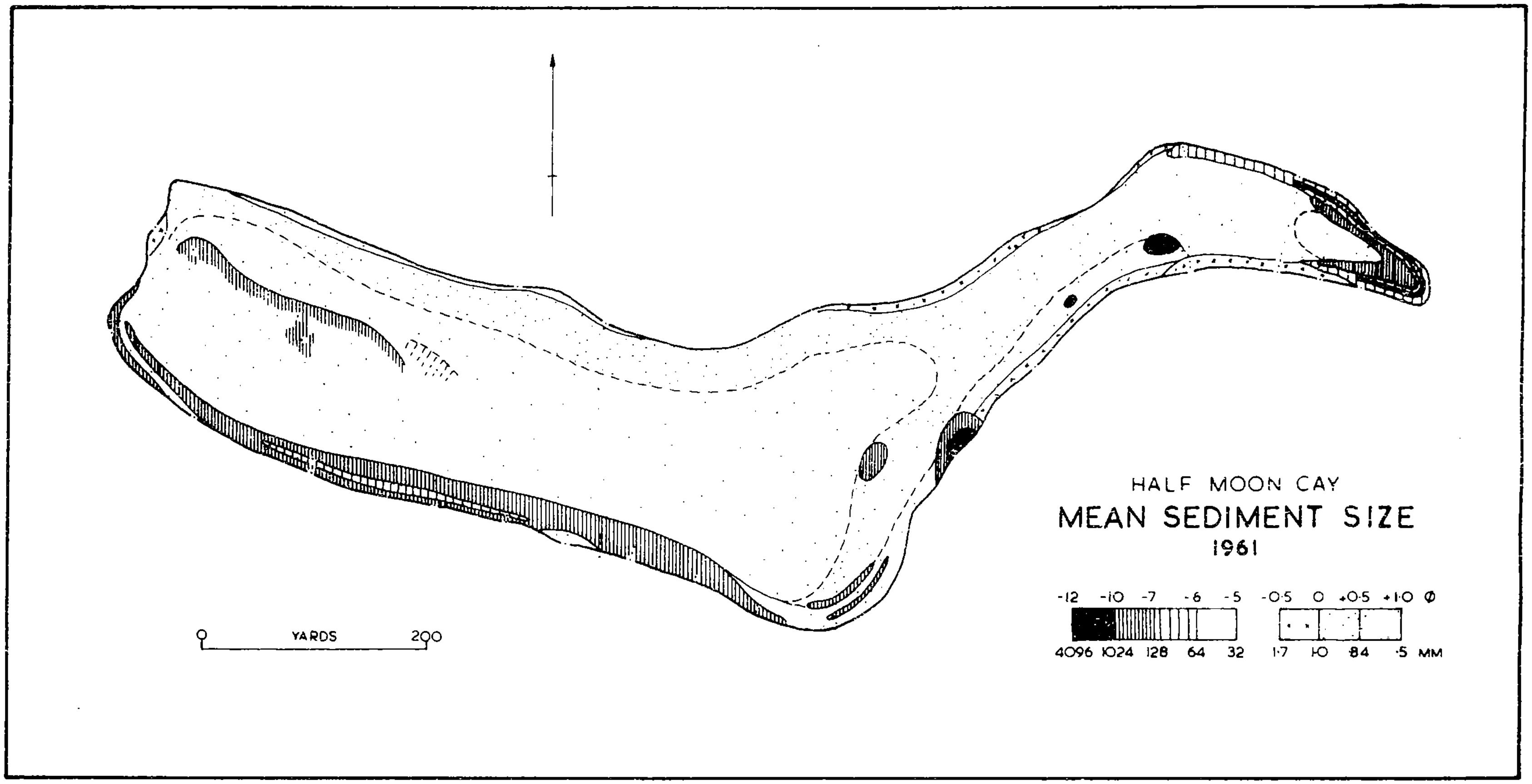
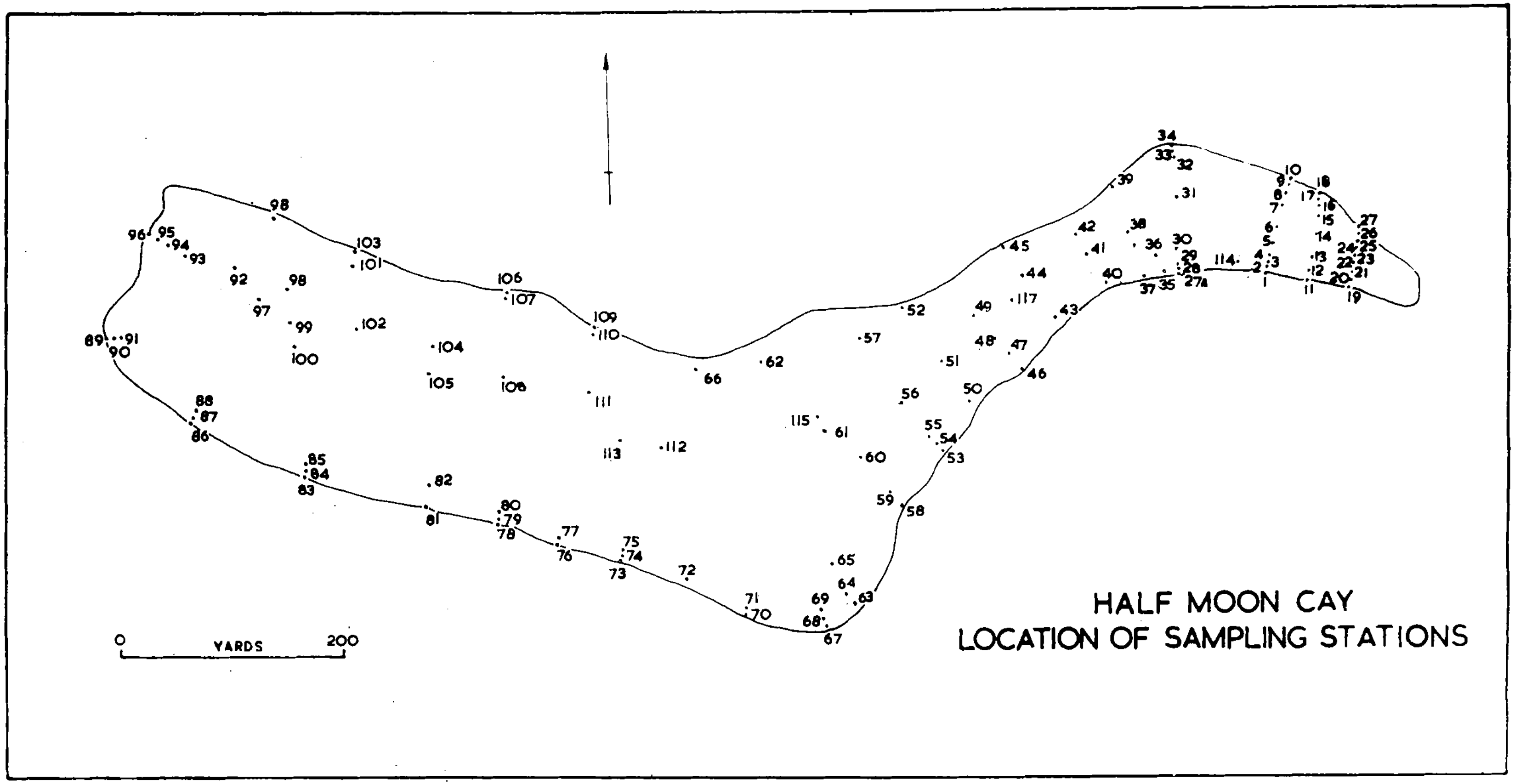

HALF MOON CAY
MEAN SEDIMENT SIZE
1961
-12 -10 -7 -6 -5
4096 1024 128 64 32
-0·5 0 +0·5 +1·0 Ø
1·7 1·0 ·84 ·5 MM
0 YARDS 200

Figure 12



HALF MOON CAY
LOCATION OF SAMPLING STATIONS

Figure 13

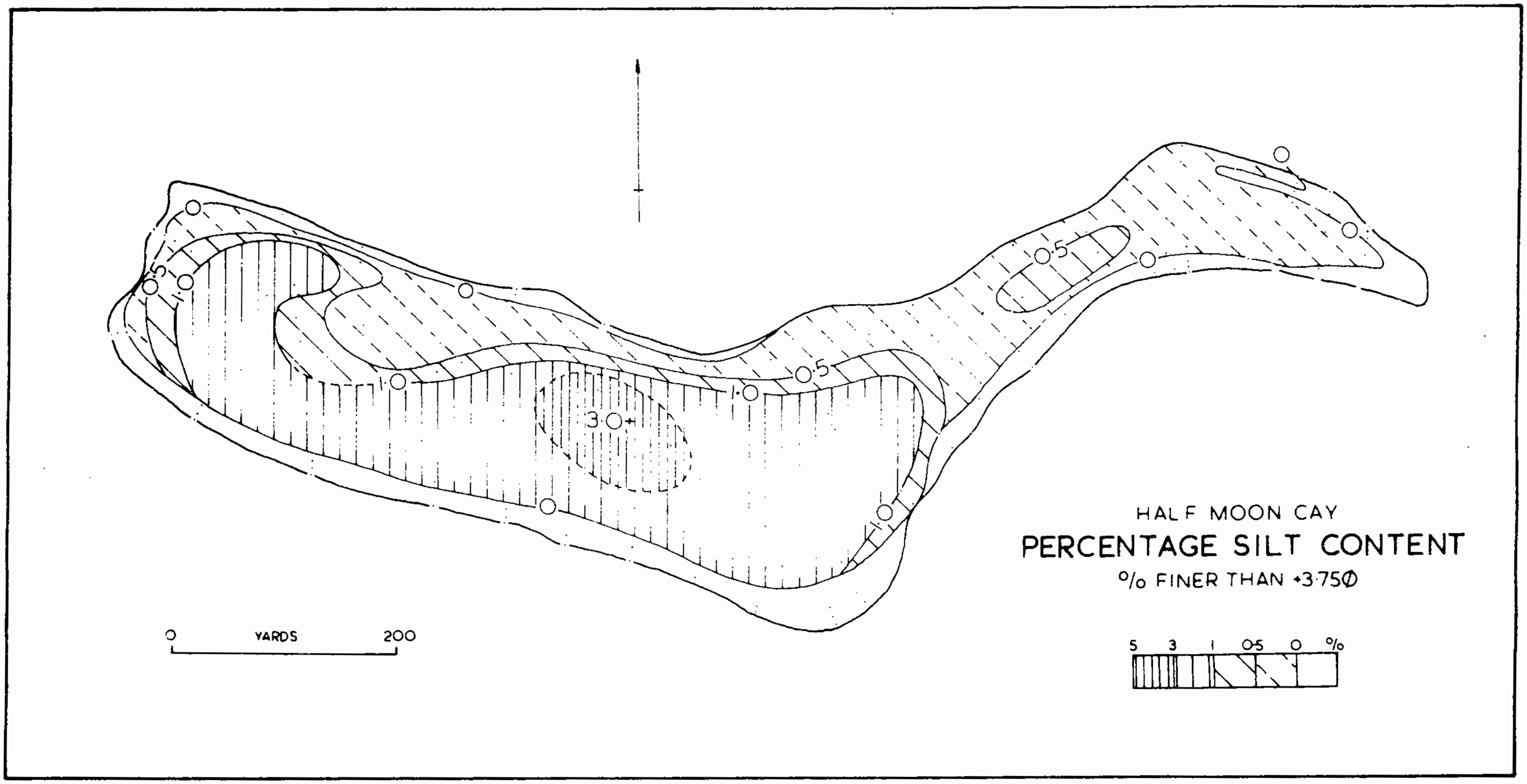

HALF MOON CAY
PERCENTAGE SILT CONTENT
% FINER THAN +3·75Ø
5
3
1
0·5
0
%
0
YARDS
200
·5
1·
3·0
1·0
0·5
0·5
1·0

Figure 14

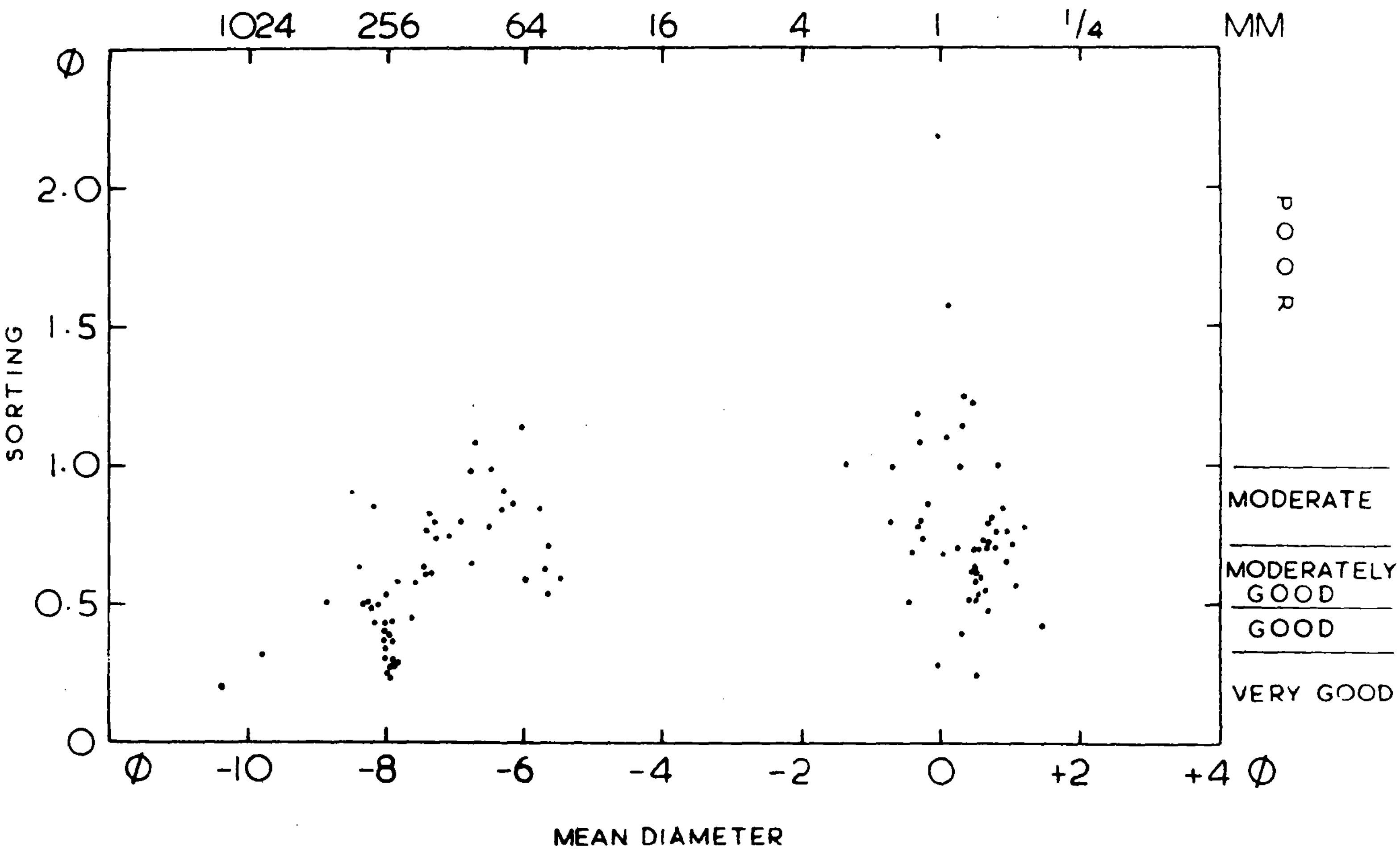


Figure 15. Mean size and sorting of Half Moon Cay sediments

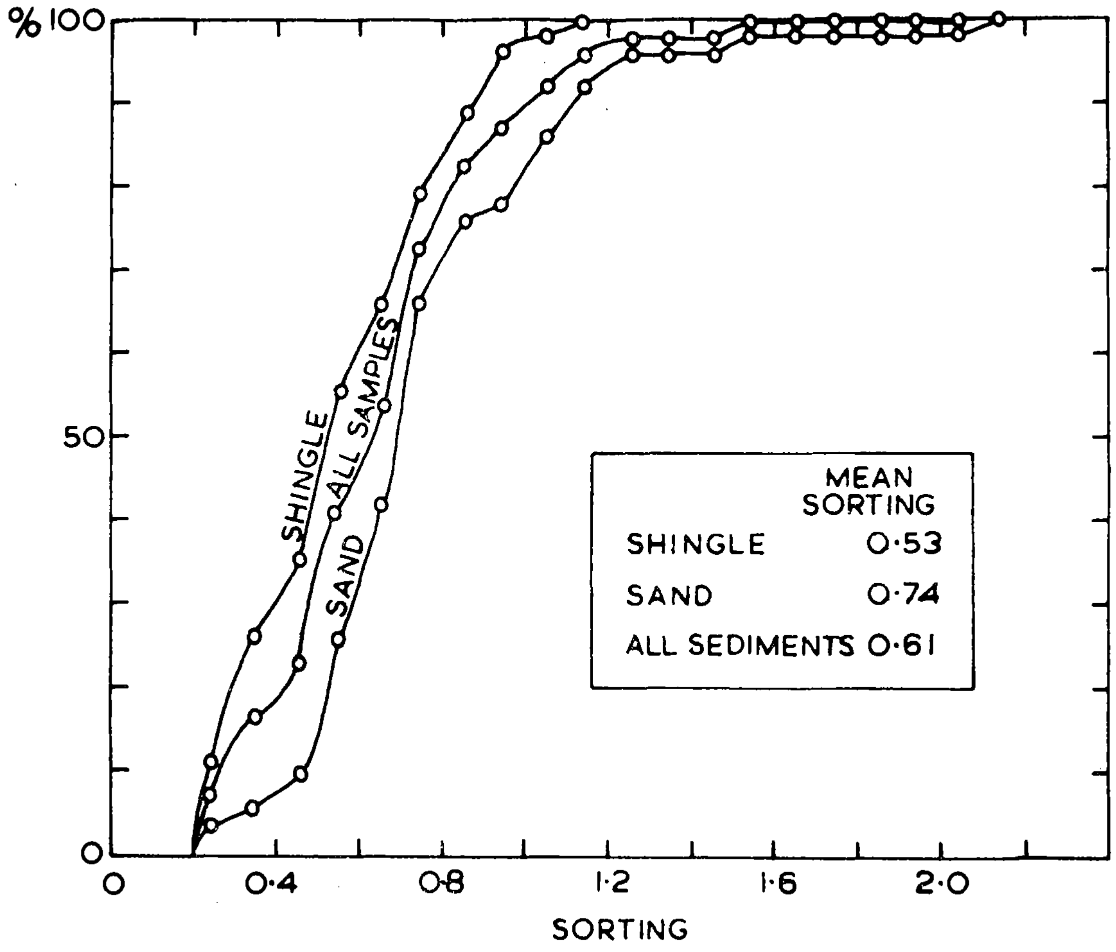


Figure 16. Frequency curves of sorting in sand and shingle sediments at Half Moon Cay