CARBONATE SAND CAYS OF ALACRAN REEF, YUCATAN, MEXICO: SEDIMENTS

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ABSTRACT

Carbonate beach sediments have sorting values averaging about .40φ, and subtidal sediments are poorly sorted with sorting values averaging 1.1φ. Halimeda dominates the coarser sands and coral becomes more abundant in finer sands. Roundness and polish are caused by abrasion, and are greatest where rate of supply is lowest and wave energy is highest.

INTRODUCTION

Alacran Reef lies about 70 miles north of the Yucatan Coast, and is the best-developed atoll of a series of carbonate highs rising from about 150 feet of water that line the edge of the Campeche Bank. Literature and general morphology are reviewed in Folk (1967) and will not be duplicated here. A very thorough work on the grain size and composition of submerged sediments of the reef, and a description of a core through it have been published by Bonet (1967); Bonet and Rzedowski (1962) discussed cay vegetation in detail. Hoskin (1968) investigated mineralogy of the muds, and Logan et al. (1968) described in detail the geology and evolution of the Yucatan platform.

Alacran Reef (Fig. 1) has a well-developed windward reef on the eastern side, and a central lagoon heavily choked with a maze of coral. All seven sand cays occur on the lee rim of the reef. Sediments of Isla Perez, the most complex cay, have been discussed by Folk and Robles (1964). This paper concerns grain size distribution, composition and roundness of the sediments of the other six cays.

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GRAIN SIZE DISTRIBUTION

Previous Work

There is a great deal of grain size data on Recent carbonate sediments; for examples, see Vaughan (1918), Bramlette (1926), Thorp (1936a, 1936b), Todd (1939), Stark and Dapples (1941), Emery, Tracey and Ladd (1954), Carroll (1957), McKee, Chronic and Leopold (1959), Maxwell, Day and Fleming (1961), Tracey, Abbott and Arnow (1961), Emery (1962), Maxwell, Jell and McKellar (1964), Fosberg and Carroll (1965), Guilcher (1965).

Unfortunately the great bulk of this data is presented in the form of histograms, based on 16 sieve intervals; often, no statistical parameters are computed--and if they are, the obsolete Trask measures of 1930 and 1932 (Median, S0) are generally used. These measures are inadequate, because they measure only the central 50% of the size distribution, whereas—if one wishes to discriminate between depositional environments—the most critical region is in the tails (Folk, 1966). Furthermore, in all geologic environments, both sorting and skewness values strongly depend on the mean grain size, and without scatter plots to show the interrelationship of the several size parameters, a great deal of potential interpretation is lost.

More embracive phi statistics and/or size parameter scatter plots have been used for carbonates by Folk (1962), Hoskin (1962, 1963, 1966), Folk, Hayes and Shoji (1962), Folk and Robles (1964), Stoddart (1964, 1966), Swinchatt (1965), and Bonet (1967). Because of the difference in manner of data analysis, only the grossest comparison may be made between these recent papers and the older histogram-oriented results.

It has been commonly noted that beach sediments are well sorted and that submerged sediments are not (Todd, 1939; Maxwell, Day and Fleming, 1961, Emery, 1962; Maxwell, Jell and McKellar, 1964) though there are some exceptions (Swinchatt, 1965). But inasmuch as sorting is a close function of average grain size, this postulate cannot be satisfactorily verified with size sorting plots which show that sediment of the same given mean size is really more poorly sorted underwater than on the beach (Folk, 1962; Folk and Robles, 1964; Stoddart, 1966). To be useful in paleogeographic studies of limestones a quantitative line should be established between the two environments on size sorting plots, and the amount of overlap assessed.

Considering the beach environment itself, it is important to examine the role of wave energy in mean size and sorting—e.g. how do size and sorting differ on protected versus exposed beaches. It is generally true that sand on leeward or lagoonal beaches is finer than that on exposed, windward beaches (Carroll, 1957; Folk, Hayes and Shoji, 1962; Folk and Robles, 1964; Fosberg and Carroll, 1965; Folk, 1967). However, in sediment of the same mean size there apparently is little difference in sorting between protective or exposed beaches (Folk, 1962,
Samples taken low on the beach are coarser than those high on the beach (Todd, 1939; Emery, 1962; Folk, 1967) and this is also true for terrigenous sands (Otvos, 1965).

One must also evaluate the strong control that type of organism and its breakage mechanism exerts on size/sorting plots (e.g. Folk and Robles, 1964; Stoddart, 1964; Fosberg and Carroll, 1965).

Because skewness varies from dominantly positive to dominantly negative as a function of mean grain size, blanket statements of skewness, divorced from an attendant grain size, are rather meaningless. However, most carbonate beaches do tend to be symmetrical to negatively skewed, i.e. they have a tail of coarser grains (Stark and Dapples, 1941; McKee, Chronic and Leopold, 1959; Folk, Hayes and Shoji, 1962; Folk and Robles, 1964; Fosberg and Carroll, 1965).

This degree of skewness is also generally true of terrigenous beach sands (e.g. Mason and Folk, 1958; Ellis, 1962; Friedman, 1961, 1965, 1967; Sevon, 1966; Tanner, 1966; Martins, 1967; and others). However, Todd (1939) found about equal numbers of (+) and (-) skewed sands in her study of carbonate beaches, as did Pilkey, Morton and Luternauer (1967).

The predominant negative skewness can be caused either by (1) winnowing of fines by wave action, in effect amputating the fine tail of a normal distribution; or (2) addition of a stray coarser mode, resulting from inclusion of large fragments which can roll easily on a smooth, firm sand beach.

ALACRAN RESULTS

Methods

Samples collected on the cays of Alacran were divided into three groups: beach surface samples, buried layers beneath the beach, and submerged samples. In the beach surface samples, the top layer of the beach was sampled, generally a one inch cube at the top of the sand, midway in the wave swash zone or foreshore. At each locality a trench was dug; if layers deeper in the trench appeared to be a different grain size or composition than the surface layer, they were also sampled and designated as "buried samples". Where differences did exist, the deeper layers were generally coarser grained than the surface sample. Again a one-inch cube of sand was taken, usually at a depth of between two to eight inches from the surface.

Submerged samples were taken by wading out from shore, and were all in three feet of water or less. Sampling here was necessarily cruder, and the surface material was scooped up in a small bottle from a spot one or two inches in diameter.
Samples were analyzed using screens spaced at 1/2φ intervals, following the method described in Folk and Robles (1964). Though sieve sizes are different from hydraulic sizes (see Maiklem, 1968, for an excellent discussion), sieve sizes best correspond with size measurements made microscopically on ancient calcarenites.

**Mean size and sorting**

Geologic meaning of the size parameters can best be visualized on the plot of size versus sorting. Grain size must be examined in two ways: (1) viewed as a whole, with samples from all six cays combined, and (2) viewed individually for each cay. Viewed in combination (Fig. 2) the beach surface samples range from fine calcarenite to fine calcirudite, or approximately 2.5φ to -1.0φ (.18 to 2.0 mm). This plot does not include the beach ridges of coral sticks. Sorting varies from very well sorted to moderately well sorted, two-thirds of the samples falling in the range of $\sigma_I = .30$ to .60φ. The average sorting value is about .40φ (well sorted). There is a weak association between mean grain size and sorting, such that the finest sands are best sorted (at a mean of 2.5φ, $\sigma_I = .25φ$), while sands of mean sizes 1.0φ and coarser have $\sigma_I$ of about .50φ. The attainment of best sorting at 2.5φ is also true of other carbonate beach sediments, of most terrigenous beach sands, and of many dune and river sediments. This is the size of sand most easily moved by both water and wind currents.

On this plot, submerged samples are clearly (possibly fortuitously well) segregated from the beach surface samples, by a $\sigma_I$ boundary of about 0.7φ; using this boundary, only 5% of the samples are misclassified. The submerged samples are medium to coarse calcarenite (0φ to 2φ). Sorting values are much poorer, two-thirds of the samples ranging in $\sigma_I$ from about .8 to 1.4φ (moderately to poorly sorted), and averaging 1.1φ. Submerged samples were taken from areas of bare sand, and also from areas that were vegetated with turtle grass; some of the turtle grass areas are finer (1.5-2φ) and show poorest sorting of all (because of a relatively high carbonate mud content) but other "grass" samples show size and sorting similar to the submerged bare sand areas. A roughly arcuate trend associates mean size with sorting for the bare sand samples. Bonet (1967) found $\sigma_I$ values of over 1.0φ for submerged samples; Stoddart (1966) in the Maldives also found a $\sigma_I$ of 1.0 best separated beach from submerged samples.

Buried beach samples overlap the beach-surface samples and submerged samples, with intermediate sorting values, $\sigma_I$ generally running between .40 and 1.0φ (well to moderately sorted). The reason for this overlap is that sediment on that beach surface becomes buried as the water level rises (i.e. at higher tides) and deposits a new layer of sediment on top. During this period, the older layers are of course submerged--thus take on the grain size character of submerged sediments--and are not subject to the winnowing and sorting action that takes place on the overlying "beach" surface.
In the initial analysis of the data the size parameters for each island were plotted using color coding. It became evident that East and West Desterrada, which are located at the north end of the reef, formed coincident trends on the size/sorting plot, and therefore could be treated together. Similarly, Pajaros and Chica, at the south end, were a homogeneous group and could be combined. Desertora, Desaparecida, and Perez (data from previous work) each possessed their peculiar trend.

With the exception of Desaparecida, each island or island-pair shows a similar arcuate inverted-V trend on the size-sorting diagram, with poorest sorting at some intermediate grain size; but when all islands are combined on one graph each trend is shifted right or left so that complete overlap occurs and they blend to produce an almost formless triangular blob. Thus the trends for the individual islands (Fig. 3) have been summarized in Fig. 3a, where the shifts in trends are evident. Moral: do not combine too much data when trying to evaluate relationships!

On these five islands as well as on Isla Perez, the cause of the arcuate trend appears to be mixing of two main constituents: relatively coarse flakes of Halimeda at \(-0.5\) to \(0.5\) (0.7-1.4 mm), and fine grit rich in coral at about \(1.5\) to \(2.5\) (.18-.35 mm). The trends are not as sharp on these islands as they were on Isla Perez, because wave abrasion has worn the particles more severely to produce a complete range of intermediate sizes. Abrasion masks the inherent breakage modes of these skeletal particles and thus blurs the size/sorting curve.

Isla Desaparecida data shows little or no systematic trend. As will be shown later, Desaparecida shows a great difference in composition from the other islands of Alacran atoll, inasmuch as it has very little coarse Halimeda, and all skeletal particles are very well rounded. Hence the very different size/sorting pattern, because particles no longer show the size modes that result from their inherent breakage mechanism.

**Skewness and kurtosis**

Considering all six cays except Perez, beach surface samples have skewness averaging \(-0.01\), with \(s = 0.18\) (Fig. 4). The central two-thirds of the skewness values actually range between \(-0.18\) and \(+0.14\). Curves classified as "near-symmetrical" form 49% of the samples, "positive-skewed" 22%, and "negative-skewed" 29%. Only 14% show strong skewness beyond \(+0.30\) or \(-0.50\). Thus beach surface samples hover close to normality, and in this respect are unlike terrigenous beaches which are usually negative-skewed.

Of the submerged and buried samples, mean skewness is \(-0.09\), with \(s = 0.29\). Two-thirds of the samples range between \(-0.38\) and \(+0.21\). "Near-symmetrical" curves form only 27%, "positive-skewed" 24% and "negative-skewed" 49% of the samples. Fully 39% of samples show extreme
skewness values beyond $\pm .30$. Thus submerged and buried samples are less normal, show a wider range of extreme skewnesses and are dominantly coarse-skewed (tail of coarse grains).

More instructive is a scatter plot of skewness as a function of mean size (Fig. 5). Here there is a quite strong association in a sinusoidal trend, similar to that shown by sands and gravels on Isla Perez (Folk and Robles, 1964). Essentially normal curves occur at positions of prominent modes in the sediment, e.g. about $M_z = + 0.4\phi$ (dominantly Halimeda flakes), and about $M_z = 2.1\phi$ (subequal coral grit and Halimeda). Starting with the coarse mode ($+ 0.4\phi$), samples become more positive skewed as the finer mode is added, until maximum positive skewness of about $+ .20$ is reached at a mean size of about $1.0\phi$; these samples consist of about $3/4$ coarse mode and $1/4$ fine mode. At about $1.3\phi$, where both modes are equal, the curves pass the $0.0$ skewness point; then as more fine mode is added to dominance, the curve becomes negative-skewed, reaching maximum negative skewness of about $- .30$ at a mean of $1.7\phi$ (one-quarter coarse mode and three-quarters fine mode). Although there is considerable scatter about this trend, given the mean size, one can predict skewness to within $\pm .20$ $Sk_I$ units of the theoretical value.

The skewness trend is only mildly shown by the beach surface samples, but is much more extreme in buried and submerged samples; both reach maxima and minima of skewness at the same mean size value, but the absolute values of skewness are more extreme in the submerged and buried samples.

Submerged and buried samples tend to be negatively skewed because all consist dominantly of rather fine beach sand, to which a few coarser fragments have been added, such as coral sticks, larger unbroken Halimeda flakes, etc.

Kurtosis in this suite of samples showed little of interest. For beach-surface samples, mean $K_G$ was $0.520$, and two-thirds of the values fell between $0.48$ and $0.57$; for buried and submerged samples, mean $K_G$ was $0.518$ and the two-thirds range was $0.46 - 0.57$. Plots of skewness vs. kurtosis revealed that most "very leptokurtic" values were from submerged samples and were also strongly skewed (either $+$ or $-$), but a plot of $M_z$ vs. $K_G$ showed only a buckshot scatter.

**Grain composition**

Sediments of Alacran Reef consist entirely of carbonates, and those of the cays apparently consist entirely of contemporary skeletal fragments—there is no reworked beachrock, oolite or carbonate aggregates. However, submerged sediments, deeper than 150'-200', contain small amounts of spar-cemented aggregates, probably broken from the cemented old carbonate mound underlying the reef (Hoskin, 1963, p. 53).
Gravels, found in quantity only on the exposed south coasts of Isla Perez and Pajaros, consist very largely of coral-sticks rubble, made up of finger-like joints of Acropora cervicornis, the staghorn coral. A few scattered blocks of more massive corals (Montastrea, Diploria, or Acropora palmata) litter the seaward side of Islas Perez and Pajaros. Relationships of the coral gravel have been described previously on Isla Perez (Folk and Robles, 1964) and also hold true for Pajaros.

Composition of the sands was determined by examining thin sections of samples representative of the complete grain size range on each island. In each thin section a count of 100 points was made; sample-to-sample variation warrants no further precision. Samples were also examined with binocular microscope for general appearance of the fragments. Point count data shows that beach sands of Alacran consist predominantly of two constituents. Porous white flakes of Halimeda, a calcareous green alga, dominate the coarser sands while coral grit is abundant in the finer sands. Only Isla Desaparecida departs from the following summary; it will be discussed later.

Results of this and other work show that the abundance of any given organic component in a sample (such as Halimeda or coral, for example) is not only a matter of ecology or productivity of the organism, it is also very strongly a function of grain size of the sediment. Beaches supplied with the same assemblage of organic materials will have very different compositions depending on whether they are fine sands or coarse sands. In particular, on Alacran, the relative proportion of Halimeda and coral is markedly influenced by grain size of the sediment.

Thus Halimeda forms approximately 80% of the sand with a grain size of -1φ (2 mm); about 65% of the 0φ (1 mm) sand; and about 45% of the sand between 1φ and 2.5φ (0.5 to 0.18 mm). By contrast, coral forms only 5% of the -1φ (2 mm) sands, 15% of the 0φ (1 mm) sand, and reaches 25% at 1φ (0/5 mm), and 45% at 2φ. These relations are shown in Fig. 6.

As an overall grand mean, Halimeda makes up 52% and coral 28% of the samples. Of the other constituents, mollusc fragments average almost 10% but drop off rapidly below 1.5% (.35 mm); coralline algae average about 5%; Peneroplid foraminifera about 3%; and all others 3%. The latter group includes a few small foraminifera, pink Homotrema rubra crusts, echinoid fragments, gorgonian spicules, pellets, and unknown skeletal debris. The close relationship of organic composition with grain size is shown in Fig. 7, a graph of the (Halimeda)/(Halimeda plus coral) ratio plotted against mean grain size of the sample. In general if the mean grain size is - 0.5φ (1.4 mm) the proportion is 9:1 Halimeda over coral. There is a linear decrease in this ratio with diminishing size, such that at 2φ (.25 mm) the ratio is 1:1.
Isla Desaparecida differs greatly from the other cays, which all fall along the same composition vs. size trend line. For a given grain size, Desaparecida is much higher in coral and lower in Halimeda, the H/H + C ratio ranging from 1:1 in the coarser sands to 1/4:1 in the finer ones.

An explanation for this difference may be that Desaparecida is a temporary islet, which is nonexistent much of the year, when it consists of a submerged bar shifting, current-swept sand. Thus there is nothing to provide protection for the contemporary growth of Halimeda plants, and indeed we have found no Halimeda tracts off the coast of this islet.

On all the islands, it is noticeable that the coarse Halimeda flakes tend to have their pores empty and look "fresh" while the finer Halimeda fragments generally have their pores filled by growth of a mass of needles. Presumably this difference means that the larger flakes have only recently been liberated by death of the plant, while the smaller flakes are much older fossils which have been worn down to relatively small size and thus have been internally cemented. Moreover, on Desaparecida even the few coarser Halimeda fragments have their pores largely filled, thus are probably derived from long-dead plants and not from contemporary ones.

A correlation matrix was calculated using the I.B.M. 1620 computer at Allegheny College. Analysis of the composition and mean grain size data quantitatively substantiated relationships suggested from the hand-drawn scatter plots. Omitting the samples from Isla Desaparecida (because of the totally different trend of Halimeda and coral vs. grain size), the expected relationships were verified (see correlation network diagram, Fig. 8). Samples of fine grain size are much higher in coral \((r = + .90)\) and lower in Halimeda \((r = -.73)\); consequently coral and Halimeda show a strong negative correlation \((r = -.72)\). Molluscs tend to be associated with the coarser sands \((r = -.51)\) and of course also avoid coral \((r = -.62)\); coralline algae are similar to mollusc fragments in occurrence. Other constituents either are present in such small amounts (average under 5%) or show such weak correlations that they are not worth placing in the diagram.

Abundance and Grain Size of Halimeda in Other Areas.

Halimeda is so abundant on Alacran reef, and its occurrence is so closely tied with grain size, that it is instructive to examine its occurrence in other modern carbonate areas to see if the same size relationships obtain.

In the Caribbean and the Gulf of Mexico carbonate areas, Halimeda is extremely abundant as reported by Steers (1940a, 1940b), and Steers, Chapman and Lofthouse (1940) in Jamaica; Van Overbeek and Crist (1947) stress its overall great abundance as a sediment constituent, with
particular examples from Puerto Rico; Thorp (1936a), Ginsburg (1956), and Swinchatt (1965) describe its occurrence in south Florida; Daetwyler and Kidwell (1959), Cuba; Purdy (1963a, 1963b) and many earlier workers report its abundance in the Bahamas; Hoskin (1962, 1963, 1966) and Folk and Robles (1964) show its abundance on Alacran and it is also common on protected areas in the vicinity of Isla Mujeres, Quintana Roo (Folk, Hayes and Shoji, 1962; Folk, 1967). Stoddart (1964) describes its occurrence on Half-Moon Cay, British Honduras.

In the Pacific area, Halimeda seems much less common as a beach sediment, although it is important in many lagoonal areas. It has been reported by many authors, two examples being David and Sweet (1904), Funafuti; and Emery, Tracey and Ladd (1954), Bikini. Hoskin (1963, p. 54) tabulates abundance in eleven reef areas, and found that Halimeda makes about 30-40% of submerged sediments. Hillis (1959) shows worldwide distribution maps of the various species.

We have shown that on Alacran, as a generalization, most Halimeda tends to be concentrated in the coarse sand to granule range, i.e. about 0.5 mm to 4 mm (1φ to 2φ) as measured by sieving. Data from other areas shows similar results. For example, inspection of Bramlette's (1926) data shows Halimeda most abundant in the -1 to +1φ range. McKee, Chronic and Leopold (1959) gave the average size as -1φ, and Emery (1962) had it most abundant in the coarsest sand. Folk and Robles (1964) showed that it dominated Isla Perez sediments between -1φ and +1φ, and Hoskin (1966) in Alacran lagoon pinnacle sediments found Halimeda to be about -1φ (2 mm). Stoddart (1964) in a detailed study found Halimeda had a mode about 0φ, and maximum -2φ. Folk and Robles examined the manner of breakdown, individual "leaves" or segments being -2 to -2φ, the average size of Halimeda after beach abrasion about 0φ, and the ultimate size on abrasion, 10φ (1 μ) dust or needles. Upchurch and McKenzie (1968 oral presentation) found in Bermuda that it generally broke to 0 to 1φ grains. In contrast, Maxwell, Jell and McKellar reported Australian Halimeda most common in the 1 to 2.5φ grade, making it about one-fourth the typical grain size of Halimeda reported from elsewhere. Fosberg and Carroll (1965) place it in the -2 to -3.5φ grade, much coarser than other workers.

**Roundness and Polish**

Estimating the amount of abrasion in carbonate environments is difficult. First, no good standard scale of roundness is available, like those established for quartz sand grains or pebbles, although Pilkey, Morton, and Luternauer (1967) set up a scale for abraded mollusc fragments, Fosberg and Carroll (1965) used a petrographic abrasion scale based on a particular spiny foraminifer, and Bathurst (1967) used a scale developed for use with terrigenous grains. Second, carbonate grains from various organisms have a tremendous range in fragility, shell architecture, etc., and break and abrade by grossly different mechanisms. Third, the original shape of many particles (e.g. foraminifera) is
already round, and one must try to separate true abrional rounding from inherent roundness. Fourth, the rate of supply (crop renewal rate) greatly differs from one organism to the next, and from one locality to the next, so there is a complex problem of roundness being affected both by varying rate of supply, and varying rate of abrasion. Fifth, fragments may be abraded by wave action, by wind abrasion during periods spent in dunes, and by activities of organisms that may either break their prey into angular pieces like crabs, or pass it through their gut, perhaps rounding them by solution or abrasion. Sixth, because most carbonate particles are so soft and round so rapidly, rapid local variations are to be expected between, for example, dune vs. beach vs. submerged carbonate sediments, or between windward and leeward sides of islands, or between freshly dead skeletons and those reworked by erosion of older sand banks on the cays, where grains had been abraded in previous cycle. Some of these factors have been discussed by Wentworth and Ladd (1931), Swinchatt (1965) and Moberley (1968).

Despite these difficulties, the writers have made an estimate of roundness of the carbonate grains. Roundness was estimated under a binocular microscope at magnifications of 9X to 45X. The only satisfactory way to do this is to allow direct sunlight to fall on the particles as they lie loosely scattered on a dull black background; in this way polish can be seen best. Samples were analyzed in random order to prevent operator bias.

The best indicator of abrasion is coral grit, because (1) it is usually distributed throughout all grain sizes, (2) it is found in most modern tropical carbonate sediments, not only in the Caribbean but almost everywhere else, (3) all fragments started out as sharply angular pieces broken from the larger masses (no problem of "original roundness"), (4) the "crop renewal rate" is fairly slow--not as rapid as Halimeda, (5) it is durable, not so fragile and apt to be rebroken after being rounded as does Halimeda, (6) it takes and holds a good polish, and (7) it forms equant particles that are grossly similar in shape to quartz particles. Therefore most of the following data on roundness is based on examination of coral grit.

Halimeda shows abrasion fairly well, but is very fragile unless the pores are filled with aragonite, and the rapid growth rate means that beaches are continually supplied with a flood of freshly broken material. It generally does not take a good polish because it is too soft and friable. Some attention can be paid to the broken but polished and edge-rounded pieces of mollusc shells. Peneroplid foraminifera also take good polish but are unsatisfactory for roundness estimations because of their disc-like original shape. The following table is a summary of the data, made by binocular evaluation of the bulk unsieved samples, not by counting individual grains.

E. Desterrada: Subangular to subround, uniform. Polish slight, most on E and N coast.
W. Desterrada: Subround to subangular, trifle more round on NW shore.
Polish slight to good, uniform geographically.

Desaparecida: Round to subround, uniform.
Polish uniformly good.

Desertora: Subround to subangular, trifle more round on E half.
Polish moderate.

Perez: Mostly angular, but subangular on N and E coasts.
Mostly dull, but polish moderate on NE coast.

Chica: Subangular, slightly more round on NE.
Polish slight.

Pajaros: Angular to subangular, most angular on Cuello de Coral, roundest midway on E coast and on N coast.
Mostly dull, but polish moderate midway down E coast.

From this table it is evident that in this area of relatively low wave energy and high organic productivity, there is considerable variation in roundness and polish from island to island and even from one part to another of the same island. Here on Alacran, polish and roundness definitely go hand-in-hand, and polish is undoubtedly the result of abrasion not chemical processes.

The variation in degree of abrasion can be explained as the result of the interplay of two main variables, (a) rate of supply and (b) wave energy. The main factor explaining gross roundness differences from one island to another is the rate of supply. Those islands close to living reefs and supplied, especially during storms, with large amounts of freshly-broken reef debris, contain the most angular sands (Fig. 9A), thus Perez and Pajaros have the dullest and most angular sand. Isla Desaparecida, on a broad sand flat with no flourishing coral reef or Halimeda flats nearby, and also on the part most to leeward of the entire Alacran atoll, has the best rounded and polished sand (Fig. 9B). The other islands are intermediate in reef proximity, and intermediate in roundness and polish. Locally on the islands, rate of supply also plays a role. This factor is markedly shown on Perez and Pajaros, which both have extensive ridges or pavements of broken coral-sticks (A. cervicornis) on their south, west and north sides, and both have mostly dull, angular sand where the coral sticks ridges are most abundant. On both islands, coral stick pavement is lacking on the east coast, and on both islands, greatest roundness is reached on the east coast, farthest away from the occurrence of coral-stick ridges or pavements. The coral-stick ridges are usually near living reefs, hence there is always an easily replenishable supply, and they continually break down to provide a new fresh source of angular coral grit.
A second factor is wave energy. In most of the islands, the best rounding and polish occurs on either east-facing or north-facing coasts. It is probably not a coincidence that the most frequent summer winds are from the east, and the strongest common winter winds are from the north. Doran (1955), Emery (1962), Folk, Hayes and Shoji (1962) and Fosberg and Carroll (1965) mention the general polish and roundness of carbonate sands on exposed beaches in other areas.

These relationships are presented in the idealized diagram, Fig. 10, where roundness is presented as a function of both wave energy and rate of supply, and various Mexican carbonate areas are placed on it. Pilkey and Luternauer show no relationship of roundness with wave energy in their area; I would assume it is because in their area, all wave energies fall within what I would call the "high" range (open Atlantic).

CONCLUSIONS

1. Beach surface samples are "well-sorted" ($\sigma_I = .40$) and submerged samples are poorly sorted ($\sigma_I = 1.1$); they are clearly differentiated on a size-sorting scatter diagram, by a boundary line of $\sigma_I = .70\phi$.

2. Individual islands have distinct inverse-V trends of sorting as a function of grain size. This is caused by the mixture of organisms and the varying amount of abrasion. The position of the inverse-V trend shifts from one island to another.

3. Skewness is a sinusoidal function of mean grain size. Beach sediments average nearly normal, while submerged samples are more non-normal with a dominance of negative skewness.

4. Over half of the beach sand is composed of Halimeda, and coral makes up more than one-fourth. Halimeda dominates the coarser sands, and coral is most abundant in fine sands, thus there exists a very strong correlation between grain size and composition of these sands. In many areas of the world, Halimeda tends to break to grains of about 1 mm modal diameter.

5. Roundness in carbonates is best estimated by studying only coral fragments. On Alacran, roundness and polish are both the results of abrasion, and are highest where the rate of supply is low and/or the wave action is greatest.

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Figures 1-10
Figure 1. Alacrán Reef, Yucatán. Arrows show wind direction, with length proportional to wind frequency and arrow thickness proportional to velocity. The windward side of the atoll is marked by a continuous massive coral reef (X pattern), and the lagoon is largely filled in with anastomosing coral ridges and patches. The six sand cays of this report all lie on the lee side of the atoll and are designated as follows: ED, WD, East and West Desterrada; Dp, Desaparecida; Ds, Desertora; Ch, Chica; and Pj, Pajaros. Sediments of Isla Perez were discussed earlier.
Figure 2. Scatterplot of Mean Size (M₂) vs Sorting (σ₁). Beach surface samples (solid circles), the field enclosed by a solid heavy line, almost all have sorting values better than 0.70φ and average .40φ. Submerged samples, enclosed by a heavy dashed line, almost all have sorting values worse than .70φ, averaging 1.10φ; those on grassy bottoms tend to be finer than those on bare, current-swept bottoms. Buried samples within the beach (open circles, all enclosed by a light dashed line) overlap the two fields.
Figure 3. Size vs sorting trends for four related island-groups, showing beach-surface samples (solid circles) and buried samples in the beach (open circles). Each island-group has its own size-sorting trend, but this trend differs in position from one island-group to another though maintaining a roughly similar arcuate form. The star provides a constant reference point for all graphs. Chica and Pajaros have the coarsest sediments (trend shifted to left) and Desertora has the finest sands.
Figure 3a. Trends of Fig. 3 combined in one graph to show the shifts; trend of Perez data (Pz) added. The minimum of best sorting at about 1.5-2.5φ represents material that is composed of about half Halimeda and half coral grit, and this is also the most mobile size for sand. The other minimum $\sigma_I$ value occurs at about -1φ to 0φ and represents modal concentrations of nearly pure Halimeda segments.
Figure 4. Frequency curve of skewness values for beach surface samples (heavy line), most of which are near-symmetrical; and submerged samples (dashed line), which are more negative-skewed.
Figure 5. Mean ($M_2$) vs Skewness ($Sk_1$). Beach surface samples show a sinusoidal trend, with most nearly symmetrical samples having mean sizes of about 2-2.5\(\phi\) and 0-0.5\(\phi\) (Stars). Submerged samples tend to be much more non-normal and are dominantly negatively-skewed. Legend as in Fig. 2.
Figure 6. Constituent composition, plotted as a function of the mean grain size of the total sample. For five of the islands (Solid circles), fine sands consist of subequal Halimeda and coral, while coarse sands are largely Halimeda. Samples from Isla Desaparecida (Dp) (Open circles) contain more coral and less Halimeda. Molluscs and coralline algae are minor constituents in all size grades.
Figure 7. The Halimeda (H) to Coral (C) ratio as a function of mean grain size of the sample. Halimeda predominance increases in coarser sizes. Samples from Isla Desaparecida (Dp) are abnormally low in Halimeda.
Figure 8. Correlation network diagram based on a matrix of r-values.

With the number of samples analyzed, r-values over $\pm .35$ are significant at the 5% level, and over $\pm .46$ at the 1% level. No weaker correlations are shown on this diagram. Positive correlations shown by cross-bars on the connecting lines. Strength of connecting lines indicates numerical value of $r$. Finer grained sands correlate very strongly with high coral percentage. The finer the sand, the less abundant are Halimeda, Molluscs, and Coralline algae, giving strong (-)r values.
Figure 9. Beach-surface grains of 0 to 0.5\(\phi\) diameter from Isla Pajaros (A) and Isla Desaparecida (B), showing high contrast in rounding, mainly a reflection of rates of supply; Pajaros is near an active reef site, while Desaparecida lies on a barren flat of shifting sand. Fragments are \textit{Halimeda} (chalky white) and coral (grayish).
Figure 10. Idealized diagram pointing out the relation between roundness and polish as the result of both rate of supply of organic debris, and wave height (approximate). All data from beach-surface samples.

"Al" represents the most of the cays on Alacrán Reef: East and West Desterrada, Chica, and Desertora, where variation in abrasion is mainly the result of wave energy, being greatest on the north and east coasts. "Dp", Desaparecida, has rounder grains because of a lesser rate of supply. Sands of Perez and Pajaros "Pz-Pj" are generally more angular because of the greater rate of supply (they are nearer the reef edge), but show wide variation from one coast to the other; in both, roundest grains are on the east coast ("e"), because of greatest wave energy combined with locally lower supply rate.

Alacrán data is compared with that from Isla del Carmen (Campeche) and Isla Mujeres (Quintana Roo). Mujeres lee beaches "MjL" are angular, windward beaches "MjW" are much more round, and the beaches of Isla Cancun "Cnc" have extremely well rounded and polished grains; in these areas, and in the Isla Mujeres region, both rate of supply and wave energy seem equally important in controlling roundness.