

BEACH FORESHORE SEDIMENTOLOGY AND MORPHOLOGY IN THE APOSTLE ISLANDS OF NORTHERN WISCONSIN¹

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ABSTRACT: Foreshore sediments and slopes of 39 beaches in the Apostle Islands of northern Wisconsin were found to be related to various measures of wave energy, wave steepness and offshore slope. Stepwise regression analysis was used to link the response variables with the process variables. Wave parameters were hindcast using the S-M-B wave hindcasting procedure and were also inferred from foreshore morphology.

Mean grain size of the foreshore sediments appears to be very marginally related to the process variables and is primarily a function of local source materials. Sorting of the sediments shows a strong positive relationship with the percentage of gravel in the sample and a weak positive relationship with angle of wave approach and wave height indicating that coarse sediment, poor sorting, strong longshore movement, and high energy are linked to some degree. Weakly negatively skewed sediments are associated with high energy and/or strong longshore movement which flatten and coarsen the foreshore, serving to weaken the winnowing effect of backwash and increasing the degree of trapping of fines, respectively. Low energy situations with a minimum of longshore drift operate to add finer material to the foreshore and thereby steepen it which facilitates the winnowing process, producing strongly negatively skewed sediments. More platykurtic grain-size distributions are associated with the relatively coarse-textured, less negatively skewed sediments comprising flatter foreshores while the more leptokurtic grain-size distributions typify the relatively fine-textured, more negatively skewed sediments characteristic of steeper foreshores.

Foreshore slopes are related to mean grain size, wave energy and wave steepness. Steep foreshore slopes are associated with fine-textured sediments, suggesting the effects of constructive wave activity. Foreshore slopes are also generally inversely related to both wave steepness and wave energy.

INTRODUCTION

This paper attempts to link in a causal fashion a number of beach foreshore parameters collected from 39 beaches in the Apostle Islands of Lake Superior in northern Wisconsin with selected coastal processes characterizing the individual beaches. The conceptual framework is of the process-response model type (Whitten, 1964; Krumbein, 1968). Process variables include hindcasted wave statistics, wave characteristics inferred from foreshore morphology, and offshore slope, while response variables include the four moments of the foreshore grain-size distribution and foreshore slope. A statistical procedure, stepwise regression, is used to link each response variable with the appropriate process variable(s). A model of foreshore sedimentology and morphology has been constructed on the basis of the analysis.

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DISCUSSION

Study Area

The Apostle Islands form the northernmost land area in the state of Wisconsin, extending the northeast trend of the Bayfield peninsula out into Lake Superior (Fig. 1). The islands were selected for study because within the group there is a wide variety of wave energy situations ranging from exposed, high energy locations on the lakeward periphery of the island group to sheltered, low energy locations on islands close to the mainland and/or in the lee of other islands. The foreshores of 39 individual Apostle Island beaches located in embayments and along the margins of cusped forelands, spits, and tombolos provided the response variables for the analysis.

Sediment sources for most Apostle Island beaches appear to be offshore sources and the products of shoreline erosion. Offshore sources probably provide much sediment, because sedi-

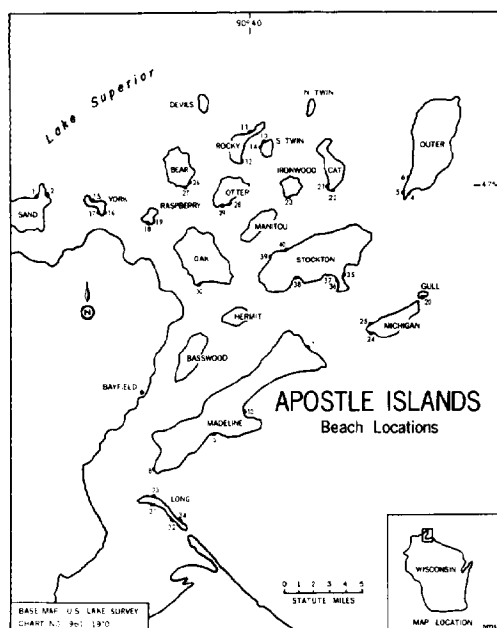


FIG. 1.—Location of study beaches in the Apostle Islands. Study beaches are numbered. Beach No. 3 (not labeled) on the east side of Sand Island was omitted from the study because of a large number of piers.

ment composing coastal landforms drowned by the post-Algoma rise in lake level (Martin, 1916; Hough, 1958) are subject to reworking. Inspection of beach gravels suggests that eroding glacial drift is important in providing beach sediment, because many, perhaps 50%, of the gravels are erratics. Materials derived from eroding dune-crested coastal depositional landforms are locally important as suggested by foreshore grain-size parameters which are more typical of dunes than foreshores, indicating a rather recent introduction of dune sands into the nearshore-beach environment. Foreshore grain-size parameters are also markedly different from grain-size parameters reported for the local sandstone bedrock by Hamblin (1961) and Hite (1968), suggesting the erosion of island bedrock supplies only minor amounts of sediment at best.

Sediment Sample Collection and Processing

Sediments were collected exclusively from the upper part of the foreshore of the 39 study beaches. Because distinct systematic variations in foreshore sediment have been recognized (Evans, 1939; Miller and Zeigler, 1958), it was

considered necessary to standardize the point of sampling within the foreshore. Standardization of sampling point locations permits valid comparisons between beaches (Bascom, 1951). A total of 140 sediment samples were collected in June, 1970 with the number of sampling sites per beach being proportional to beach length in a manner such that a sample was collected for at least every 300 m of beach length. After the general location of a given sampling site was determined, the precise section of upper foreshore to be sampled was determined in a random fashion. At each site, four closely spaced samples were obtained and then combined into a single composite sample as Krumbein (1934) suggests.

Sands and gravels were analyzed separately. The sand fractions were split into 15 to 20 g splits and then magnetic grains were removed with a hand magnet. The percentage of magnetic grains was expected to be high in view of the long history of iron mining in the region. It was feared that the presence of a large proportion of fine particles with high specific gravities would make process interpretations of grain-size distributions difficult. However, the mean weight percentage of magnetic sand grains for all samples was only 1.52% and the fears proved to be groundless. The sand splits were subsequently sieved through 7.5 cm diameter sieves in an Allen-Bradley Sonic Sifter with the sieves being spaced $\frac{1}{4}$ ϕ apart. The entire gravel fraction of the original samples was measured manually at $\frac{1}{4}$ ϕ intervals after strongly magnetic gravels were removed with a hand magnet. The average weight percentage of gravel (material coarser than 2 mm) for all samples was 9.2 %. The results of the sand and gravel analyses were then combined using the "splitting factor" method described by Folk (1968).

The method of moments was used to determine the several basic parameters of the grain-size distributions. The mean grain size, standard deviation, skewness, and kurtosis for all samples were calculated by computer using four computational formulae given in Griffiths (1967, p. 90). For all 140 samples, the average mean grain size is 0.64 mm, the mean phi standard deviation is 0.766, the mean phi skewness is -0.506, and the mean phi kurtosis is 4.843.

Wave Hindcasting Procedure

The S-M-B wave hindcasting system (U. S. Army Coastal Engineering Research Center, 1966, p. 19) was used to generate all of the

deepwater wave statistics which constitute some of the process variables in the present study. Wave characteristics for the individual beaches were estimated for three different time intervals: 1951–1960 period, representing average, long-term conditions; April to July, 1970, the ice-free period immediately preceding the initiation of field work; and the period of significant wave action occurring immediately prior to sampling. This approach seemed required because individual foreshore characteristics respond at greatly different rates to changes in process intensity.

The 1951–1960 wave data and the April–July, 1970² wave data were generated by using the S-M-B system. This hindcasting system employs a nomogram constructed on the basis of empirical considerations into which values for fetch, wind velocity and wind duration are read to determine the significant wave height and significant wave period for a given fetch/wind situation. In the case of the annual waves, the wind statistics used were 10 year averages for Beaufort force categories 3–6 inclusive recorded at Duluth, Minnesota, some 60 miles west of the Apostle Islands and fetch values were measured from hydrographic charts. Wind durations had not been compiled for these winds, making it necessary to consider duration as nonlimiting during the hindcasting procedure. Summer waves were hindcast in essentially the same fashion as the annual waves except that the wind data used came from uncompiled observations made at the Coast Guard station at Bayfield, Wisconsin (Fig. 1). In the case of the summer waves, the wind velocities of Beaufort force categories 3–8, inclusive, were used in the hindcasting procedure. Only winds having a frequency of at least one-half of one percent were included in the hindcasting procedures. Also, adjustments were made for weather station location, the length of the ice-free period, and variations in fetch width prior to hindcasting the two sets of waves (Engstrom, 1973).

The wave heights and wave lengths hindcast for the annual and summer wave situations were used to derive two fundamental wave properties that are of geomorphic and sedimentologic significance: wave steepness and an index of wave energy. Wave steepness is determined by dividing the wave height by the wave length. A measure of the ability of an event to perform geomorphic work on the land-

scape, following Wolman and Miller (1960), is approximated by the product of the frequency and the magnitude of that particular event. Wave energy is directly proportional to both wave length and the square of wave height. The product of the square of wave height and wave length, when multiplied by the percentage frequency of the wind generating that wave, yields a useful measure of geomorphic work (Engstrom, 1973). This calculation was made for each Beaufort force category for each azimuth of possible wave approach for a given beach, yielding a large number of "wave work" values. Theoretically, the waves associated with large wave work values should be the most significant, in a geomorphic and sedimentologic sense, of the various waves reaching the beach. Accordingly, wave events characterized by large wave work values were sorted out from wave events characterized by small wave work values and their characteristics (height, length, steepness, angle of approach, and wave work values) were used as the principal process variables in the statistical analysis.

Foreshore width and foreshore slope were introduced into the study as surrogates for process variables. These variables were introduced in an effort to estimate the wave steepness and energy of the "final" wave event which, prior to sampling, performed geomorphically significant work on the beaches. Estimation of wave characteristics in this fashion not only provides information on the last significant geomorphic event affecting the beach but also yields information on the character of the waves upon reaching the foreshore. Wave characteristics at the foreshore differ from their deepwater condition in a number of ways and the S-M-B technique generates only deepwater wave dimensions.

Foreshore slope, measured in the field with hand level and stadia rod, may be used as a rough measure of wave steepness once the effect of mean grain size on slope has been statistically controlled. One or all of the linkages between foreshore slope, mean grain size, and wave steepness have been examined in nature by Bascom (1951), King (1972), and Dolan (1966) and in the laboratory by Rector (1954). Of interest here is the basic principle that foreshore slopes steepen as wave steepness decreases and flatten as wave steepness increases, assuming a constant mean grain size. Similarly, foreshore width, measured normal to the land-water contact, may be used as a measure of wave energy after the effects of mean grain size on width have been removed.

² Hereafter the 1951–60 wave data will be referred to as *annual waves* and the April–July, 1970 wave data will be referred to as *summer waves*.

The greater energy of the larger waves enables their swash to extend farther up the beach as compared to the effects of smaller waves of lesser energy (King, 1972). Mean grain size should affect foreshore width in an inverse fashion as coarser particle sizes increase percolation and thereby reduce swash volume, producing a relatively narrow foreshore. Statistical control of the effect of mean grain size on slope and width may be accomplished by designating mean grain size as a base variable in the stepwise regression procedure. Variation in foreshore slope and width, unexplained by mean grain size, may then be assigned respectively to wave steepness and wave energy.

Delivery to the surf zone of offshore deep-water wave energy is dependent upon offshore slope. Steeper offshore slopes permit more wave energy to reach the surf zone and flatter offshore slopes tend to damp out waves by increased bottom friction, reducing the amount of energy reaching the shoreline. Price (1954), Tanner (1960), Gorsline (1966), and Beall (1968) in their work on Gulf of Mexico beaches have all recognized the influence of offshore slope on wave energy delivery to the shoreline. Offshore slope was determined by measuring the slope from the land-water contact to the 30 foot isobath as shown on 1:24,000 topographic maps.

Statistical Procedures

Analysis of the data involved a series of preliminary normality transformations when required and a subsequent series of stepwise regression models. It was necessary to compute averages and use summing procedures in addition to employing magnitude and frequency analysis in order to reduce initial matrices of process and response parameters into a more manageable number of variables prior to analysis. Mean grain size, sorting, skewness, kurtosis, foreshore width, and foreshore slope values that were employed in the analysis represent averages for each beach. Wave characteristics were either averaged or summed or left in their original form. The Kolmogorov-Smirnov test was then used to test for the normality of all variable distributions before the stepwise regression procedure was initiated.

Stepwise regression as used here refers to a selection procedure that attempts to find an "... optimal subset of independent variables by including them in and excluding them from the regression equation according to certain criteria" (University of Wisconsin Computing Center, 1969, p. 55). The criteria are the sig-

TABLE 1.—Stepwise regression models

Model name	Model description	Number of beaches in model
1. all beaches model	A model incorporating data from all the beaches sampled.	39
2. spit model	A model incorporating data only from beaches developed on the margins of spits, cusped forelands, and tombolos.	27
3. west-facing beaches model	A model incorporating data only from beaches with a western exposure.	17
4. bay-head beach model	A model incorporating data only from bay-head beaches.	12

TABLE 2.—Wave process variables appearing in final regression equations

Variable acronym	Variable description
1. ANNANGLE	The angle of deepwater wave approach of the most important work performing annual wave*.
2. ANNHTE	The height of the most important work performing annual wave.
3. ANNSB5	The average steepness of waves generated by Beaufort force 5 winds during the average annual ice-free period.
4. ANNSTP	The steepness of the most important work performing annual wave.
5. LOGSTOEN	The log of the sum of wave work values for all the summer waves reaching a beach.
6. LOGSUMWORK	The log of the wave work value associated with the most important work performing summer wave.
7. SUMANGLE	The angle of deepwater wave approach of the most important work performing summer wave.
8. SUMHITE	The height of the most important work performing summer wave.
9. SUMSTP	The steepness of the most important work performing summer wave.

* The phrase "most important work performing ... wave" refers to the particular wave event affecting a given beach during either the annual or summer period which has the largest wave work value for the period under consideration. (See "Wave Hindcasting Procedure" section.)

nificance levels of partial correlation coefficients which, in this instance, were set at 0.10 for both inclusion and exclusion from the regression equation.

In the subsequent sections each of the grain-size parameters, in addition to foreshore slope, will be discussed as to their relationship with the particular process variables identified as being statistically significant in any of the several stepwise regression models employed. Several stepwise regression models for each response variable were used because sample numbers of process variables and beach types show some variation (Table 1). The relative importance of the process variables in the final regression equation can be assessed by examining the magnitude of the partial correlation coefficients. Parentheses after the multiple and linear correlation coefficients or their explained variation equivalent will give the significance level. Process variables in the final regression equation will be identified and their partial correlation coefficients followed by the calculated significance level will appear in the following parentheses. Table 2 lists the acronyms for and provides a description of the various wave process variables appearing in the final regression equations.

Mean Grain Size

Spatial variations in the mean grain size of foreshore sediments of Apostle Island beaches are shown in Figure 2. Inspection of the contours in Figure 2 indicates little relation between mean grain size and wave energy levels or other wave characteristics, all of which tend to vary rather systematically within the island group. It was anticipated that mean grain size would be inversely related (coarser material being represented by small or negative phi values) to wave energy as a review of the literature suggests. King (1972, p. 302), speaking of beaches, writes: "It is generally true that the particle size is larger where the wave energy is greater. This relationship applies both in space and time." Bascom (1951), Giles and Pilkey (1965), Ingle (1966), Gorsline (1966), and Hodgson (1966) have also all noted that grain size increases as wave energy increases along a coastline.

Only a small proportion of the variation in mean grain size could be explained by any of the process variables. In the all beaches model, ANNANGLE could account for only 7% (0.096) of the variation in mean grain size while SUMANGLE was only slightly more successful in the spit model, accounting for

12% (0.07) of the variation in mean grain size. These angles of wave approach were measured by noting the angular departure between the azimuth of deepwater wave approach and the azimuth of beach orientation. The negative sign of the relationships between mean grain size and ANNANGLE and SUMANGLE indicates that grain size increases as the angle of wave approach departs to a greater degree from the azimuth of beach orientation. It would seem logical to conclude, on the basis of vectoral considerations, that the amount of wave energy imparted parallel to the shoreline generally increases as ANNANGLE and SUMANGLE increase. Increases in ANNANGLE and SUMANGLE should result in an increase in the rate of longshore drift, leaving only the coarser sediments on the foreshore.

One other process variable, SUMSTP, was able to explain 29% (0.07) of the variation in mean grain size in the bay-head beach model. The positive sign of this relationship indicates that as wave steepness increases there is a corresponding decrease in mean grain size. It appears that SUMSTP is acting as a surrogate for inner island low energy regimes, because steepness generally increases as energy decreases in the more sheltered parts of the island group. Moreover, inspection of the appropriate correlation matrix shows that mean grain size is negatively correlated with the height ($r = -0.41$), length ($r = -0.49$), and wave work ($r = -0.32$) associated with the most important work performing summer wave as was anticipated.

The difference-of-means test indicates that the 27 spit and cusped foreland beaches have an average mean grain size (0.82 mm) that is significantly coarser than the average mean grain size of the 12 bay-head beaches (0.51 mm). The difference is significant at the 0.05 level. The difference may be attributed to the sheltering that adjacent headlands provide bay-head beaches while spits and cusped forelands extend unprotected into the open lake and/or into inter-island channels.

The general inadequacy of the process variables to explain the variation in mean grain size must be attributed to marked differences in the grain-size distributions available to near-shore coastal processes. There must be available at each beach enough material in the various size categories for the variations in process to become manifest. As Sahu (1964) has noted, the mean size of sediments can be attributed either to the average kinetic energy (velocity) of the depositing agent or to the

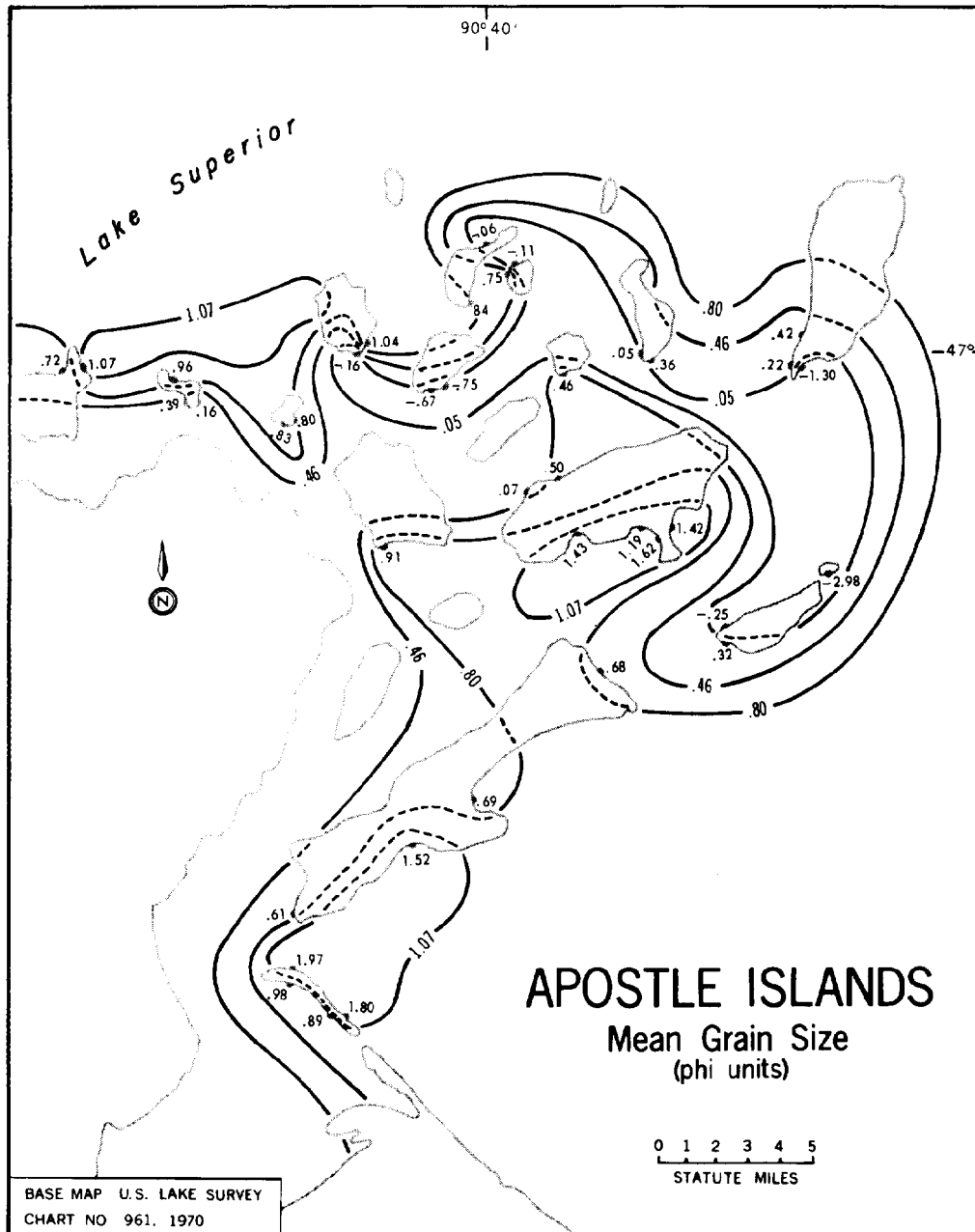


FIG. 2.—The distribution of foreshore sediment mean grain sizes. Values at beach locations represent means of all foreshore samples collected along that particular beach.

size distribution of the available materials. Shepard (1959) has concluded, except for local situations, that the relative coarseness of sand is not related to wave exposure but rather to

the type of source material present. Folk (1966) has also commented on the importance of source materials in controlling the statistics of grain-size distributions.

Some suggestions can now be made concerning the general configuration of the contours in Figure 2. The finest foreshore sediments are enclosed by the 0.48 mm (1.07 ϕ) contour and tend to be associated with bay-head beaches or beaches where dune materials have apparently been recently introduced into the nearshore zone. Evidence for the latter situation is supplied by the foredunes backing these beaches which often exhibit signs of truncation plus some individual grain-size distributions showing a positive skew which is usually considered indicative of dune sediments (Friedman, 1961). The coarsest foreshore sediments, enclosed by the 0.96 mm (0.05 ϕ) contour, tend to be associated with spit and cusped foreland beaches located in the interior of the island group.

Sorting

The degree of sorting of the foreshore sediments, as measured by the standard deviation of the grain-size distribution, has been mapped in Figure 3. Some correspondence in contour arrangement may be noted when Figures 2 and 3 are compared. More exposed, higher energy beaches were expected to be characterized by better sorting (lower standard deviation values) while poorer sorting (higher standard deviation values) was expected on less exposed, lower energy beaches. Analysis of Hawaiian littoral sand indicates that poor sorting was typical of bay-head beach sediments, while open coasts had better sorting (Moberly *et al.*, 1965). Similar sorting-energy relationships were also recognized in southwestern Ceylon by St. C. Swan (1967). Yet, all of the stepwise regression models show that no process variable contributed significantly to the explanation of sorting if the percent of gravel in the sample was also in the regression equation.

Only in situations where mean grain size was substituted for percent gravel in the regression equation could a few process variables emerge as making a significant contribution to explaining variations in sorting. In the bay-head beach model, 87% (0.0001) of the variation in sorting was accounted for by mean grain size (-0.917; 0.0001) and SUMANGLE (+0.768; 0.006). In the west-facing beaches model, 45% (0.02) of the variation was explained by mean grain size (-0.604; 0.01) and SUMHITE (+0.510; 0.04). Sorting becomes poorer as SUMANGLE and SUMHITE (the latter considered here as a measure of wave energy) increase. Increases in SUMHITE and SUM-

ANGLE should generally result in an increase in mean grain size. Mean grain size, or other measures of relative size such as percent gravel, have a strong influence on the sorting characteristics of a sedimentary deposit as will be indicated below.

A very strong positive relationship exists between the sorting of Apostle Island beach sediments and the percent gravel in the sediments. The log of percent gravel is capable of explaining 77% of the variation in sorting in the all beaches model. The negative mean grain size-sorting relationship and the positive percent gravel-sorting relationship which characterizes the foreshore sediment indicates that sorting becomes worse as mean grain size becomes coarser. Inman (1949) recognized that the Hjulström effect was capable of causing poorer sorting as median diameters increased from 0.18 mm (fine sand), the diameter of particles easiest to move. Coarse and fine sediments alike are put in motion as the threshold velocity increases above that required to move fine sand, producing a poorly sorted deposit. However, it appears that an upper size limit around 1 mm (Griffiths, 1951; Folk, 1968; and Sonu, 1972) exists for this sand size-sorting relationship. It is apparent from the statistical relationships described above and from the general range of observed mean grain sizes that Apostle Island foreshore sediments exhibit this well-documented sand size-sorting relationship.

Some suggestions can now be made concerning the relationship between sorting and the percent gravel in the foreshore sediments. It is possible that the larger gravel percentages reflect high swash-backwash velocities associated with higher waves as the SUMHITE-sorting relationship would suggest. These higher swash-backwash velocities did not exercise any degree of selection on available materials, resulting in poor sorting on deposition. Conversely, lower velocities, capable of moving only small percentages of gravel, were more restrictive in the selection of particle sizes moved, resulting in better sorting upon deposition. Gravels may also be introduced into the foreshore by ice push in the winter (Scott, 1927; Goldthwait, 1957) and/or by the exhumation during beach erosion of break-point step gravels previously buried during an episode of beach progradation. Once introduced into the foreshore, regardless of mechanism, the gravels encourage infiltration of fines and tend to constitute a persistent, often-inherited mode whose presence invariably leads to poorer sorting values for foreshore sediments.

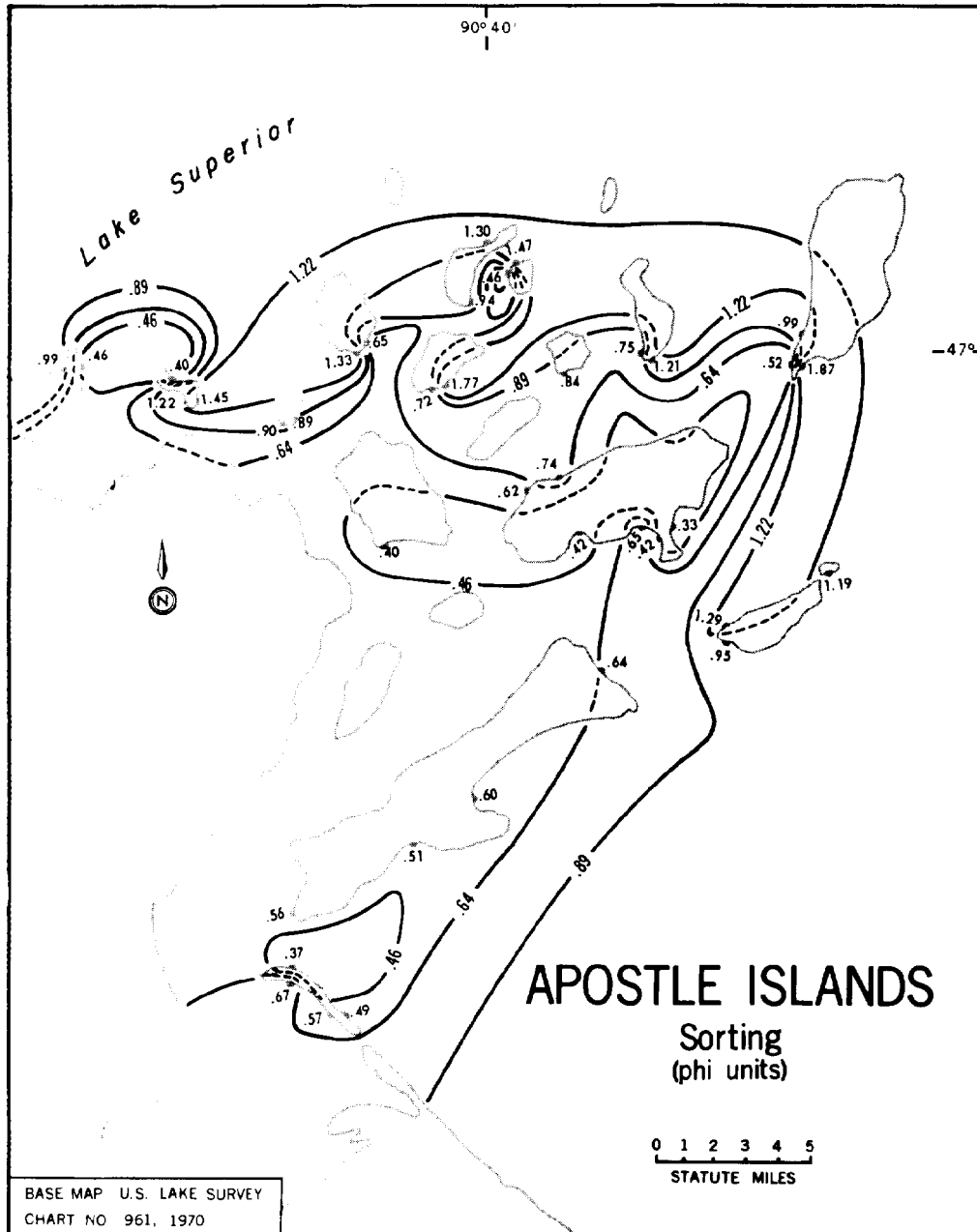


FIG. 3.—The distribution of foreshore sediment sorting (standard deviation) values. Values at beach locations represent means of all foreshore samples collected along that particular beach.

Skewness

Several process variables emerge as being statistically significant in explaining portions of the variation in the skewness of Apostle Island foreshore sediments. Figure 4 illus-

trates the distribution of average skewness values. Some 88% of the variation in the skewness of the bay-head beach sediments and 60% of the variation in the skewness of spit and cusped foreland beach sediments could be

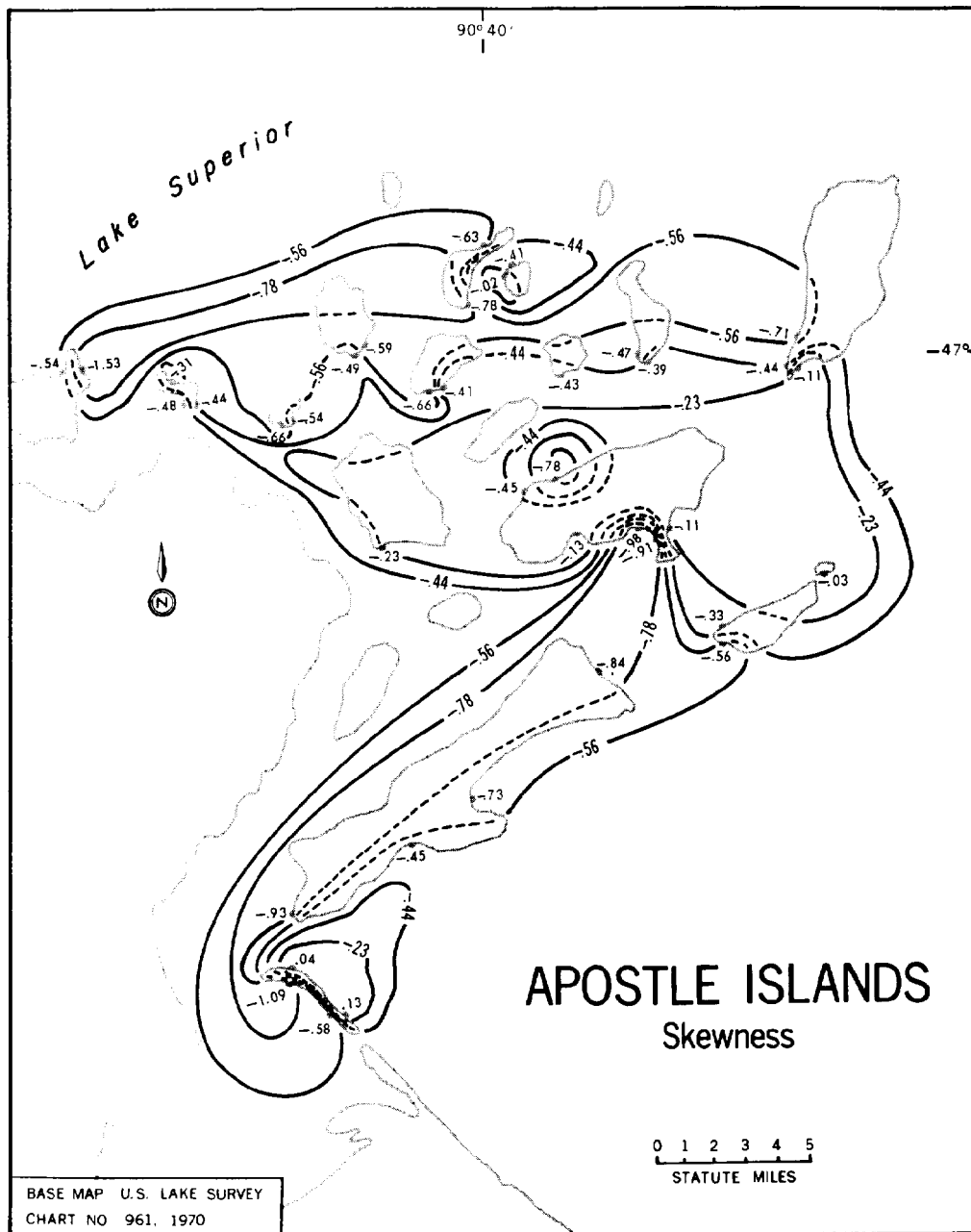


FIG. 4.—The distribution of foreshore sediment skewness values. Values at beach locations represent means of all foreshore samples collected along that particular beach.

attributed to a combination of 5 variables in the case of the bay-head beaches and to a combination of 3 variables in the case of the spit and cusped foreland beaches.

Most beach foreshores, with Apostle Island beaches providing no exception, display a negative skewness, indicating a grain-size distribution rendered asymmetrical by the presence of

a relatively large coarse tail of sediment. Selective removal of fines by backwash, truncating the fine end of the distribution without modification of the rest of the distribution, is generally considered the mechanism by which foreshore sediments become negatively skewed (Friedman, 1961; Martins, 1965; Sevon, 1966). Backwash that is weaker than the parent swash is necessary for winnowing to take place. Backwash velocities are reduced by a flat foreshore slope (Evans, 1939; Bagnold, 1940) and also by a loss of water through seepage into the foreshore sediments.

In the present study, 88% (0.01) of the variation in the skewness of bay-head beach sediments was accounted for by ANNANGLE (+0.921; 0.001), mean grain size (+0.909; 0.001), ANNSB5 (-0.903; 0.002), foreshore slope (-0.794; 0.02), and offshore slope (+0.670; 0.07). Some 60% (0.001) of the variation in skewness was explained by the combined effects of foreshore width (+0.677; 0.0002), ANNANGLE (+0.607; 0.001), and mean grain size (-0.341; 0.09) in the spit model.

The negative relationships between skewness and foreshore slope and between skewness and ANNSB5 will be considered first. The inverse skewness-ANNSB5 relationship indicates that increasing wave steepness is associated with more negatively skewed sediments. This relationship may be interpreted as suggesting that the destructive character of steep waves removes the finer end of the grain-size distribution, imparting a rather strong negative skewness to the foreshore sediments. However, this reasoning may be applied only to the early phases of steep wave attack because continued combing down of the foreshore flattens it, reducing the winnowing effect and producing less negatively skewed sediments as indicated by the inverse foreshore slope-skewness relationship. It follows that increasing foreshore slope steepness increases backwash velocity enough to remove much of the fine tail, producing strongly negatively skewed sediments.

Skewness is positively correlated with ANNANGLE, foreshore width, and offshore slope. It was suggested earlier that, as ANNANGLE increases, there is a corresponding increase in the rate of longshore drift and an increase in the coarseness of foreshore sediments. Similarly, increasing foreshore width and increasing offshore slope are expected to be associated with a coarsening of foreshore sediment because both variables imply increasing wave

energy. As the mean size of the sediments shifts toward the coarser particle sizes, a reduction of the coarse tail occurs because upper limits on the size of beach sediment exist. The result is a decrease in the magnitude of the negative skew. Also, a shift toward the coarse end of the distribution increases the opportunity for the infiltration of finer materials which can cancel out the effect of a coarse tail. Moreover, Friedman (1961) and Sonu (1968) have also both noted a tendency toward positive skewness in coarse-grained beach sediments compared to the typically more negatively skewed finer beach sediments.

The negative relationship between skewness and mean grain size in the spit model and the more pronounced mean negative skew of the bay-head beach sediments (-0.661) as compared to the coarser spit and cusped foreland beach sediments (-0.553) provides some confirmation of the above arguments. Not consistent with the arguments is the positive relationship between skewness and the mean grain size of bay-head beach sediments. Apparently the bay-head beach sediments, although strongly negatively skewed as a group, become less negatively skewed as mean grain size becomes finer, perhaps reflecting the addition of a mode to the fine end of the distribution.

Kurtosis

Stepwise regression analysis of the relationship between the kurtosis of the grain-size distribution and the process variables indicates that kurtosis is related to ANNANGLE, foreshore width, and foreshore slope. Kurtosis is also strongly related to the mean grain size, percent gravel, and skewness of the beach sediments. Average kurtosis values in the island group are depicted in Figure 5. In the spit model, 51% (0.0002) of the variation in kurtosis was accounted for by mean grain size (+0.757; 0.0001) and foreshore width (-0.607; 0.001). In the west-facing beaches model, 46% (0.01) of the variation in kurtosis was explained by mean grain size (+0.630; 0.009) and foreshore slope (+0.506; 0.05). ANNANGLE was the only significant process variable isolated by the all beaches and bay-head beach models accounting for 12% (0.03) and 28% (0.08) of the kurtosis variation, respectively. Correlation of the grain-size parameters of all 140 individual sediment samples indicates a relatively strong correlation ($r = -0.817$) between skewness and log kurtosis and a moderate degree of association ($r = -0.491$) between loglog percent gravel and log kurtosis.

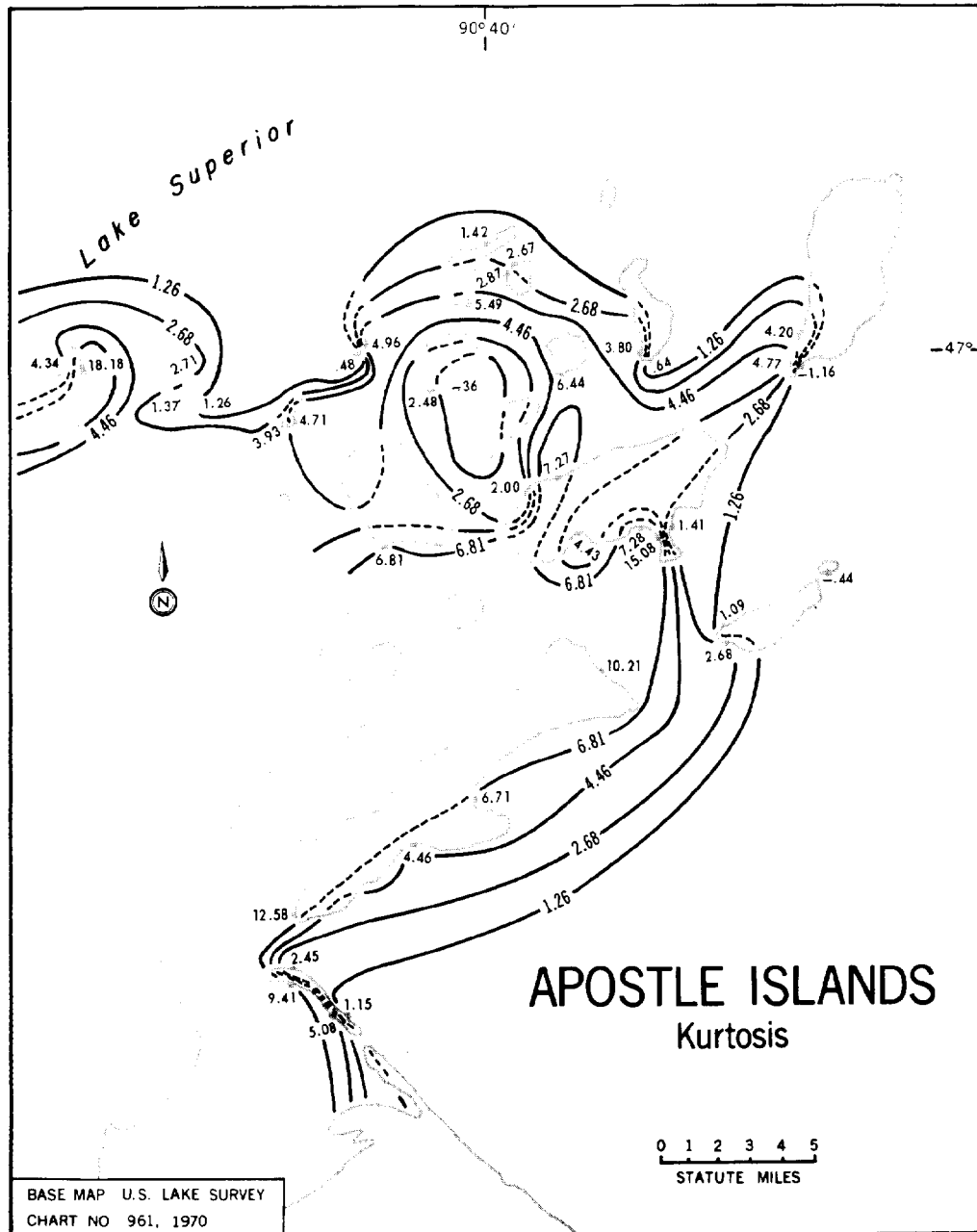


FIG. 5.—The distribution of foreshore sediment kurtosis values. Values at beach locations represent means of all foreshore samples collected along that particular beach.

Kurtosis, measuring the ratio of the sorting in the tails of the grain-size distribution to the sorting in the central portion, is perhaps the least understood of the four moments of the

grain-size distribution. Discrimination among sedimentary environments on the basis of kurtosis has not generally proved profitable (Mason and Folk, 1958; Shepard and Young,

1961; Friedman, 1961; Sevon, 1966). Koldijk (1968), however, reports that more exposed beaches are more leptokurtic (better sorting in the central part of the distribution than in the tails) than are sheltered beaches. The general inability of kurtosis to discriminate between environments may result from the fact that kurtosis is over-sensitive to random fluctuations (Baker, 1968).

Most appropriate to the kurtosis characteristics of Apostle Island foreshore sediments are the observations of Folk and Ward (1957) on the relations between grain-size parameters and gravel and sand modes in a bimodal river bar in Texas. Apostle Island foreshore sediments contain, on the average, 9.2% gravel. Folk and Ward report that additions of small amounts of gravel (3 to 10%) to the larger sand mode produces a strongly leptokurtic distribution and, as gravel constitutes larger and larger percentages of the sediment, kurtosis is reduced in absolute value, the distribution becoming more platykurtic. The positive mean grain size-kurtosis relationship and the negative loglog percent gravel-log kurtosis relationship indicates that the same relationship exists in the foreshore sediments under discussion.

These size-kurtosis relationships may be linked, in part, to changes in the size and sorting of the gravel fraction or mode of a sample compared to the size and sorting of the central sand fraction or mode of the same sample. The reduction in kurtosis with coarser mean grain sizes means that the gravel percentage in the sample is increasing and the coarse tail is getting larger. Sorting in the coarse tail would seem likely to improve as it increased in size and came to constitute a more pronounced mode. Such a sorting trend in the gravel mode would be accompanied by a decline in the kurtosis value assuming either no change or poorer sorting in the central part of the distribution. Poorer sorting in the central part of the distribution might even be anticipated during an increase in the gravel percentage as the central sand mode has now been reduced in relative size. Conversely, small percentages of gravel tend toward poor sorting in the coarse tail because of the very small number of gravel-sized particles involved. The much larger central sand mode tends toward better sorting and the result is higher values of kurtosis in samples with a low percentage of gravel. Finally, knowledge of the character of the fine end of the distribution would aid in further interpretation of these size-kurtosis relationships.

The strong negative skewness-kurtosis rela-

tionship is consistent with the observation of Folk and Ward (1957) that sands with 7 to 20% gravel are highly leptokurtic and negatively skewed. Negative skewness indicates that the finer mode is more abundant than the coarser mode. Smaller modes tend toward poorer sorting but larger modes toward better sorting, as suggested in the preceding paragraph, producing leptokurtosis in the grain-size distributions of Apostle Islands beach sediment.

The relationship between the process variables and kurtosis may be most conveniently interpreted in terms of the influence the process variables exert on the mean grain size of foreshore sediments. ANNANGLE and foreshore width are both negatively associated with kurtosis. Increases in both variables, as argued previously, are believed to be associated with increasing coarseness of the foreshore sediments and a reduction in kurtosis with coarser mean grain size has been demonstrated above. Foreshore slope, a variable acting as a surrogate for the steepness of the final wave event, is positively associated with kurtosis. Steep foreshore slopes appear to be the product of flat waves of low steepness that build up the foreshore by moving material onshore. The material most likely moved onshore is fine sand. The net result, in terms of kurtosis, of adding material to the fine mode until it constitutes the central portion of the grain-size distribution, is to increase the value of kurtosis. The grain-size distribution of sediment on a steeply sloping foreshore should be characterized by a small, poorly sorted coarse tail and a larger, well sorted central sand mode and a fine tail that is truncated because of the more effective backwash generated by the steep foreshore gradient.

Foreshore Slope

Foreshore slope, in addition to serving as an indicator of final wave steepness, was also treated as a dependent morphologic response variable in each of the several stepwise regression models. The distribution of average foreshore slope values, illustrated in Figure 6, is rather complex, suggesting that a number of independent variables are responsible for the character of the distribution. Over 40% of the variation in foreshore slope could be accounted for in four of the models. In the spit model, a combination of foreshore width (-0.882; 0.00001), offshore slope (-0.779; 0.00001), LOGSTOEN (+0.697; 0.0003), LOGSUMWORK (-0.664; 0.0008), ANNHTE (+0.471;

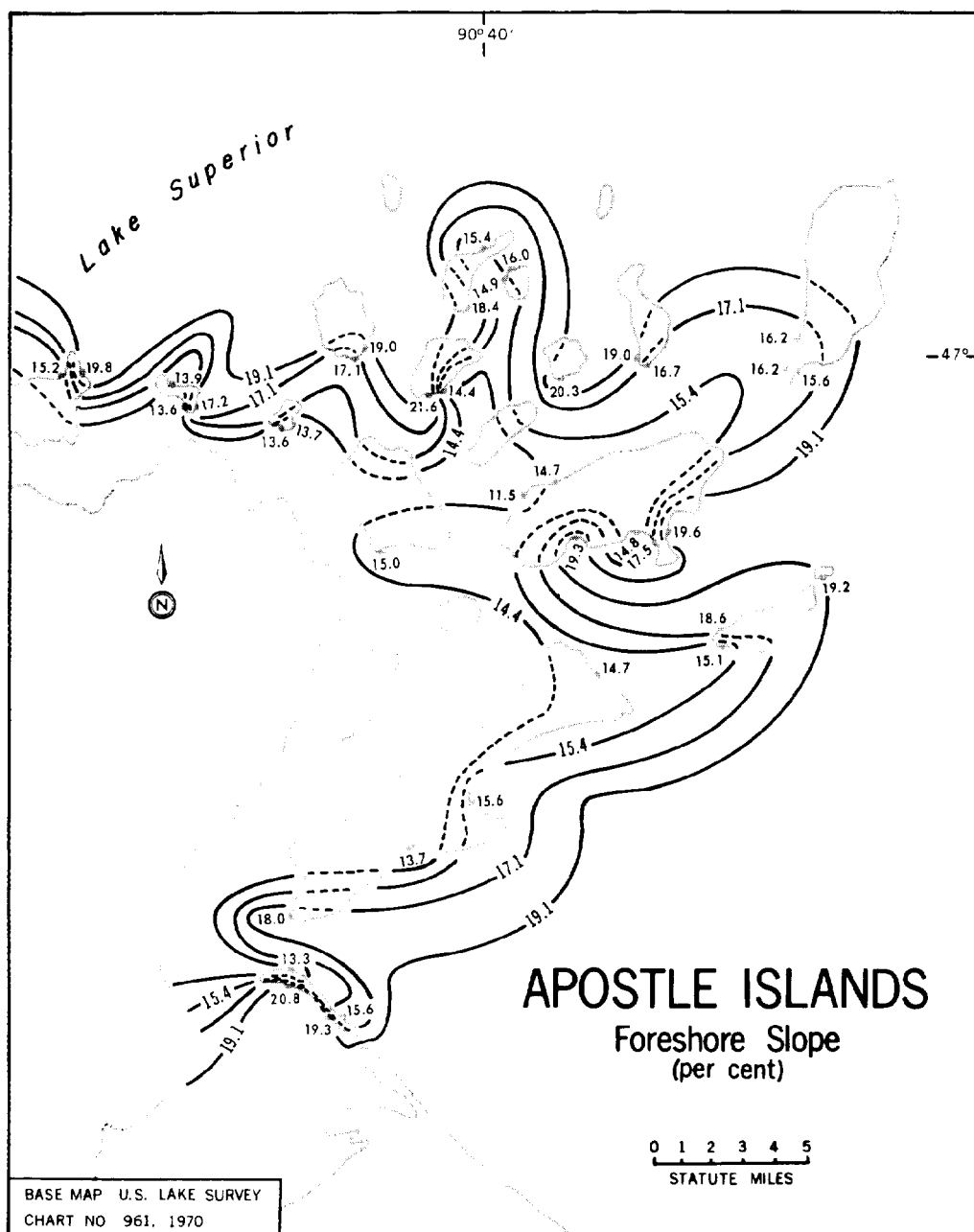


FIG. 6.—The distribution of foreshore slope values. Values at beach locations represent means of all foreshore slopes measured along that particular beach.

0.03), and mean grain size (N.S.)³ explained

³ The base variable mean grain size is in the equation but does not make a significant contribution (N.S.) toward explaining variation.

84% (0.00005) of the variation in foreshore slope. Some 69% (0.02) of the variation in foreshore slope was accounted for by mean grain size (+0.772; 0.009), ANNSTP (−0.705;

0.02), and foreshore width (-0.617 ; 0.06) in the bay-head beach model. In the west-facing beaches model, 68% (0.0003) of the variation in foreshore slope was attributed to foreshore width (-0.820 ; 0.0001) and mean grain size (N. S.). The all beaches model indicated that foreshore width (-0.534 ; 0.0008), ANNSB5 (-0.304 ; 0.07), offshore slope (-0.301 ; 0.07), and mean grain size (N. S.) could explain 44% (0.005) of the variation in foreshore slope.

A review of the literature indicates that foreshore slope is related to the mean particle size of the foreshore, wave steepness, wave energy, and wave length. The relations among mean particle size, wave steepness, and foreshore slope are perhaps the best understood. In an earlier section it was indicated that, holding particle size constant, an inverse relationship exists between foreshore slope and wave steepness. Bagnold (1940), Bascom (1951), and Ingle (1966) have all noted that foreshore slopes steepen as mean grain size increases. The relationship between energy and foreshore slope is inverse, according to Bascom (1951), as more protected beaches are steeper for any given sand size than are exposed beaches. This relationship suggests that the stronger backwash associated with high energy waves of any steepness is able to move most available particles into the surf zone and flatten the foreshore. The flattening effect of a large volume of backwash has been observed by King (1972) to account for the association between flatter foreshores and longer waves. King's observation, according to Norrman (1964), probably accounts for the fact that marine beaches typically display flatter gradients than lake beaches. Apostle Island foreshore slopes are no exception, averaging $9^{\circ}20'$.

Beach foreshore slopes in the Apostle Islands become steeper as mean grain size decreases, as is indicated by the positive relationship between the two variables in the bay-head beach model. This relationship suggests that steep foreshore slopes tend to be the product of constructive waves moving fine material onshore. ANNSTP and ANNSB5 both show negative relationships with foreshore slope as both laboratory and field evidence indicate. Foreshore width, LOGSUMWORK, and offshore slope are also inversely related to foreshore slope, indicating that increasing energy produces flatter foreshores such as Bascom's (1951) and King's (1972) works would suggest.

The relationship between both LOGSTOEN and ANNHTE and foreshore slope is positive and is therefore inconsistent with the relation-

ship of the other energy variables to foreshore slope. The sign of the relationship indicates that foreshore slopes steepen as energy increases, for LOGSTOEN and ANNHTE are alike measures of wave energy. This relationship may be interpreted as reflecting the coarse particle size-steep foreshore slope association mentioned earlier, because increasing energy usually results in the coarsening of foreshore sediments as the finer materials are moved offshore. These wave energy-foreshore slope steepness relations described here and in the preceding paragraph make it clear that variation in foreshore slope unaccounted for by mean grain size cannot be assigned primarily to variation in wave steepness as suggested in an earlier section but rather to both wave steepness and wave energy.

CONCLUSIONS

Based on the statistical analyses just described, it is possible to make some concluding remarks about the relationship between several Apostle Island foreshore sedimentologic and morphologic response variables and certain sets of process variables. However, concluding remarks advanced here need to be subjected to repeated testing as the statistical analyses are not wholly satisfactory for several reasons. In some instances, the magnitude of the coefficient of determination for a given stepwise regression model is inversely proportional to sample size. In the models with few observations, the number of process variables approaches the number of observations, so that the likelihood of a high, but artificial, correlation is increased. Harrison and Krumbein (1964) in their coastal study attempted to keep the number of observations at least 3 times as high as the number of process variables in order to avoid artificially high correlation coefficients. In most instances in the present study, the number of observations was at least 3 times the number of the process variables introduced into the regression equation. Other reasons for the analyses not being wholly satisfactory include the presence of unexplained variation in the response variables and variables not consistent in sign with other similar variables in the same regression equations. Also, some process variables require, in retrospect, some refinement in measurement. Clearly, further inquiry is necessary but, nevertheless, the analyses have permitted some conclusions to be drawn.

In a coastal study of a large area, mean grain size of foreshore sediments, although

partially influenced by wave parameters, is primarily a function of local source materials. Mean grain size is perhaps treated most realistically as an independent variable. Increasing angle of deepwater wave approach produces coarse foreshore material, presumably by removing fines as longshore processes intensify. Fine sediments are associated with the low energy regime of inner island beaches. Neither of the wave characteristic-mean grain size relationships are very strong; presumably often being masked by variations in source material. The contrast between the coarse sediments of spit and cusped foreland beaches and the fine sediments of bay-head beaches may reflect the greater protection provided bay-head beaches by neighboring headlands.

Sorting of foreshore sediments in the study area is primarily a positive function of the percent of gravel in the sample. Percent gravel is proportional to mean grain size; consequently, since source materials exert a strong influence on mean grain size, they similarly exert a strong influence on sorting. Two process variables, angle of summer wave approach and height of summer waves, assume limited importance only when mean grain size and not percent gravel is in the regression equation. Both variables are positively correlated with sorting, indicating that coarse sediment, high energy, strong longshore movement, and poor sorting are linked to some degree. The relationship between percent gravel and sorting may be a consequence of non-selective high swash-backwash velocities and/or infiltration into persistent gravel modes on the foreshore.

The skewness of foreshore sediments is related to wave steepness, foreshore slope and width, the angle of wave approach, offshore slope, and mean grain size. The postulated causal linkages among these variables can be briefly summarized as follows: (1) High energy and/or strong longshore movement erode and flatten the foreshore slope, leaving only the coarser particles behind. (2) The winnowing effect of backwash is reduced by the flat slopes, and fines are not removed but trapped among the coarse materials, producing weakly negatively skewed foreshore sediments. (3) Coarse mean grain sizes also reduce the possible size of the coarse tail, lessening the magnitude of the negative skew. (4) Conversely, low energy situations with a minimum of erosive longshore drift add relatively fine material to the beach and steepen the foreshore. The steep foreshore facilitates winnowing, so that a more negative skew is imparted to the

sediments. (5) Attack on any foreshore by steep waves probably initially accelerates the winnowing process, but continued combing-down of the foreshore eventually produces a flatter foreshore with a coarser, more positively skewed distribution of sediment than existed prior to the attack by steep waves.

Variations in kurtosis are most conveniently discussed by extending the arguments applied to skewness. Significant variables in the regression equations for kurtosis include mean grain size, foreshore width, foreshore slope, and angle of wave approach. Relatively coarse, less negatively skewed sediments on flat foreshores are also the more platykurtic. More platykurtic distributions show a tendency toward improving sorting in the tails relative to the sorting in the central part of the distribution, presumably indicating a rather large, fairly well sorted coarse mode and a larger and fairly well sorted finer mode. Steep foreshores composed of strongly negatively skewed sediments with a relatively fine mean grain size are also more leptokurtic than sediment on flat foreshores. More leptokurtic foreshore sediments on Apostle Island beaches presumably involve a very small, poorly sorted coarse mode, a large, well sorted, fine-grained central mode and a truncated fine tail.

The foreshore slopes of Apostle Island beaches are strongly dependent upon mean grain size, wave energy parameters, and wave steepness. Fine mean grain sizes are associated with steep slopes, indicating that these slopes are the product of constructive wave activity, whereas flat slopes result from destructive waves. Wave steepness is inversely related to foreshore slope, as many observations in nature and in laboratory studies have demonstrated. An increase in an energy parameter (foreshore width, offshore slope, etc.) is also associated with a decrease in foreshore slope steepness.

A composite model of beach foreshore sedimentology and morphology in the Apostle Islands can be constructed from the conclusions stated in the preceding paragraphs. Flat foreshores composed of sediments that are coarse, poorly sorted, weakly negatively skewed, and platykurtic in their grain-size distributions are the end products of steep waves of high energy that approach over steep offshore slopes at large angles from the azimuth of beach orientation. Steep foreshores composed of sediments that are fine, well sorted, strongly negatively skewed, and leptokurtic in their grain-size distributions are the end products of flat waves of low energy that approach over flat offshore

slopes at small angles from the azimuth of beach orientation. The mean size of available materials at a beach site, however, has a marked influence on foreshore morphology and sedimentology and can often obscure the model described above.

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