

GRAIN SIZE IN LAMINAE OF BEACH SAND^{1,2}

K. O. EMERY

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

ABSTRACT: Use of a small corer having a piston controlled by a screw-in drive shaft permits the collection of a series of thin (1.67 mm) slices of sand deposits. Several slices are required to penetrate a single coarse- or fine-grained lamina on foreshores of beaches. Grain-size analysis of the sand in each slice by settling tube was followed by computation of statistical parameters. The results show that the slices have a much broader range of median diameter, are better sorted, and are more positively skewed than are those for a composite core of the same sands. This means that investigations of beach-sand sources and of hydraulic conditions of erosion and deposition based upon sand texture may be better served by analysis of laminae than of total sample.

INTRODUCTION

Beach sands have long been known to contain many laminae (Thompson, 1937) that differ in grain size and mineral content. General observations and laboratory analyses (Sanders, 1965; Clifton, 1969) show that the fine-grained laminae contain most of the dark heavy minerals (magnetite, ilmenite, garnet, etc), and the coarse-grained laminae contain most of the light minerals (quartz, feldspar, and calcite). The differences in mineral composition and grain size appear to be due to differences in competence of the fast landward rush of wave swash followed by the slower oceanward return of the water (Emery and Gale, 1951; Clifton, 1969; Waddell, 1973, 1976). An additional important control of erosion-deposition (and thus of laminae) is the position where the water table intersects the beach surface (Emery and Foster, 1948; Grant, 1948; Duncan, 1964; Pollack and Hummon, 1971). Landward of the watertable outcrop the backwash is lessened by the amount of water that escapes into the sand, whereas oceanward of it the backwash is augmented by escaped groundwater. In effect, this means that erosion by swash is concentrated seaward of the water table at the time of the swash, and deposition is concentrated landward of it. Laminae are to be expected

only above the water table on the foreshore.

Simple hand lens or binocular observations of grain size are sufficient to describe vertical grading and general structure of laminae (Reineck, 1974), but collection of individual thin laminae for precise laboratory analysis is difficult. First attempts at precise sampling were made by Emery and Stevenson (1950), who made vertical thick sections (400-500 microns thick) of beach sands that had been cemented naturally into beachrock or were cemented artificially by clear plastic. The grains encountered during each of 15 to 25 microscope traverses across the thick-sections were measured, converted to volume, and corrected for small grains obscured behind larger ones. The major technical problem was that too few grains were encountered on each microscope traverse to satisfactorily define the size-frequency curve for that traverse; moreover, the method was far too time consuming to be used for routine studies of beach sands. A better method developed by Clifton (1969) consists of planing the beach at a slight angle across the bedding to exaggerate details of bedding. Samples were obtained by pressing a glass plate coated with Canada balsam against the bevelled sand surface, and then incremental layers within laminae were scraped off with a razor blade for grain-size and mineral analysis. Again, the number of grains for each sub-sample was small.

The difficulty in measuring the grain-size distribution in beach-sand laminae both during field and laboratory phases has caused most sedimentologists to ignore the problem

¹ Manuscript received 19 Dec. 1977; revised 21 March 1978

² Contribution No. 4069 of the Woods Hole Oceanographic Institution

of depositional factors. Usual procedure is merely to collect a handful (literally) of sand from each of a series of specified points along or across beaches, bag each sample, and return them to the laboratory for grain-size analysis. Not much better is collection of the top 1 or 2 cm or collection above major discontinuities, but these methods serve as useful compromises between the ideal and the easiest methods. Best has been sampling of sands deposited under observed conditions above sand surfaces marked by dye or by careful measurement against calibrated pins (Clifton, 1969; Sonu, 1972, for example). Grain-size analysis may be by sieving (basically measuring the two smaller diameters of grains) or by settling tube (basically measuring the two larger diameters). Many articles have been published on the comparability of grain-size analyses by sieving and settling, but the author considers the settling methods more valid because the sediment-water relationships by settling are more nearly the same as those for erosion, transportation, and deposition in nature.

Once the grain-size distribution has been measured, the data often are treated by sophisticated statistical methods usually requiring a computer. The simple fact is that if the original sample of beach sand is poor, no amount of statistical treatment can satisfactorily measure what was not sampled. To illustrate, size distribution frequency curves of the fine-grained and coarse-grained laminae would be expected to have log-normal Gaussian shapes with peaks at different grain diameters. For composite samples these curves should be broader with peaks at intermediate positions and shapes that are distorted according to the total volumes and grain-size distributions of fine and coarse laminae in the sample of beach sand that was collected. The literature of beach sands is replete with illustrations of bimodal and skewed grain sizes in samples (*e.g.*, Tanner, 1958; Friedman, 1967; Sonu, 1972; Chakrabarti, 1977). Explanations have centered around different sources of the grains and changes in eroding, transporting, and depositing processes, but another cause of bimodal and strongly skewed sands may be the sampling of various ratios of contrasting coarse- and fine-grained laminae.

Need for a simple fast method to obtain

thin layers of beach laminae led to renewed effort during July and August of 1977. Most of the methodology was developed on beaches of Cape Cod that are widest and sandiest at this time. A speaking tour during late August provided an opportunity to sample some beaches of California and Hawaii, increasing the variety of beach environments for the study.

METHODS

Grain-size measurements by weight or volume require several grams of sediment, so if the samples are to represent a thin depth range they must be from a large area. Experimentation resulted in development and use of a short corer, 4.7 cm in diameter and containing a freely moving teflon piston whose position along the core barrel could be controlled precisely by turning a piston rod screw-threaded through a hole at the closed end of the core barrel (Fig. 1). In operation, the open end of the corer with the piston retracted about 5 cm was pushed into the sand, dug out, and inverted. Successive slices 1.67 mm thick (about 4.5 gm) were ejected, each by one full turn of the piston

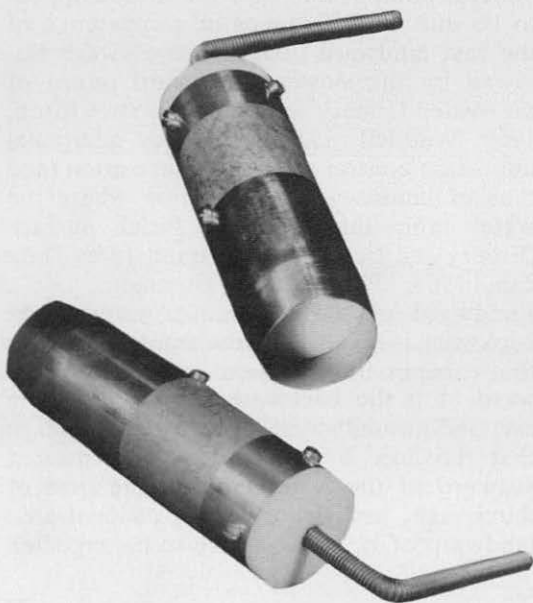


FIG. 1.—Two views of small core sampler for collecting thin (1.67 mm) layers of sand for analyses of beach laminae. Inside diameter is 4.7 cm and length of steel barrel 15.0 cm.

rod judged by a mark on the core barrel. The individual slices were scraped into plastic bags and returned to the laboratory for analysis.

Grain-size analysis was made with the settling tube developed by Zeigler *et al.*, (1960) and modified by Schlee (1966). This method can handle small samples, and the weight of sand deposited from the water column is automatically recorded on strip paper from which weight percentages of grains at any desired time (size) intervals can later be measured. The high degree of sorting of the sands required measurements at $\frac{1}{4}$ ϕ intervals in order to define the shapes of the cumulative curves.

Statistical measures of median diameter, sorting, skewness, and kurtosis may be computed in several ways: the simple quartiles used by Trask (1932, p. 70-76) or the complex computer-determined moments of Schlee and Webster (1967) at the extremes,

or by approximations from a few points of cumulative curves (Inman, 1952; Folk and Ward, 1957). Comparisons of the various statistical methods (Folk, 1966; Jones, 1970) reveal no overwhelming superiority of moment measures over graphical ones based upon enough percentiles to outline the grain-size frequency distributions. The simple method of Inman was chosen, based upon the 5, 16, 50, 84, and 95 weight percentiles of the cumulative curves.

Altogether, 28 cores were collected from beach foreshores, nearly all of which consisted of laminated sand. Seven cores were from beneath the surface water—below low tide level, and none of these were laminated, although a few contained coarse layers perhaps left from previous storms. One other core was of sand homogenized or well stirred *in situ* for estimation of the errors in measurement of statistical parameters in naturally deposited sands. These 36 cores provided

TABLE 1.—Position of cores from beaches

Core No.	General Locality	Elev. re Low Tide cm	No. Slices	Relative Positions
1	Saconnet Hills, W. Falmouth, MA.	-25	15	North end of beach
2	Saconnet Hills, W. Falmouth, MA.	-25	18	South part of beach
3	Saconnet Hills, W. Falmouth, MA.	+5	20	15 m from 2
4	Saconnet Hills, W. Falmouth, MA.	+13	20	1 m from 3
5	Saconnet Hills, W. Falmouth, MA.	+21	20	1 m from 4
6	Sippiwisset Highlands, W. Falmouth, MA.	-25	17	South part of beach
7	Sippiwisset Highlands, W. Falmouth, MA.	0	25	9 m from 6
8	Sippiwisset Highlands, W. Falmouth, MA.	0	26	15 m from 7
9	Sippiwisset Highlands, W. Falmouth, MA.	+90	21	15 m from 8
10	Sippiwisset Highlands, W. Falmouth, MA.	+170	27	12 m from 9
11	Sippiwisset Highlands, W. Falmouth, MA.	-+100	24	Homogenized
12	Gansett, Woods Hole, MA.	+15	21	East part of beach
13	Gansett, Woods Hole, MA.	+35	25	2 m from 12
14	Gansett, Woods Hole, MA.	+55	20	2 m from 13
15	Gansett, Woods Hole, MA.	+75	20	2 m from 14
16	Fay Beach, Woods Hole, MA.	+20	10	Middle of beach
17	Surf Drive, Falmouth, MA.	+10	20	East end of beach-groin
18	Surf Drive, Falmouth, MA.	+25	14	2 m from 17
19	Surf Drive, Falmouth, MA.	+40	14	2 m from 18
20	Surf Drive, Falmouth, MA.	+55	13	2 m from 19
21	Dowse Beach, Osterville, MA.	-25	11	Middle of beach
22	Dowse Beach, Osterville, MA.	+20	24	8 m from 21
23	Dowse Beach, Osterville, MA.	+40	24	2½ m from 22
24	Dowse Beach, Osterville, MA.	+60	23	2 m from 23
25	Dowse Beach, Osterville, MA.	+80	26	2 m from 24
26	Point Gammon, W. Yarmouth, MA.	+30	24	Middle of beach
27	Coast Guard Beach, Eastham, MA.	-25	23	Middle of beach
28	Coast Guard Beach, Eastham, MA.	+10	23	6 m from 27
29	Coast Guard Beach, Eastham, MA.	+50	25	6 m from 28
30	Coast Guard Beach, Eastham, MA.	+80	22	9 m from 29
31	Coronado Hotel, San Diego, CA.	+20	23	North end of beach-breakwater
32	Santa Monica, CA.	+30	27	2 km north of breakwater
33	Sunset Beach, Monterey, CA.	+20	27	Middle of beach
34	Lanakai, Oahu, HI.	+25	27	Middle of beach
35	Kahala Hotel, Oahu, HI.	+10	27	East end of beach—imported fill
36	Keauhou Bay, Hawaii, HI.	+40	27	North end of beach—rocky

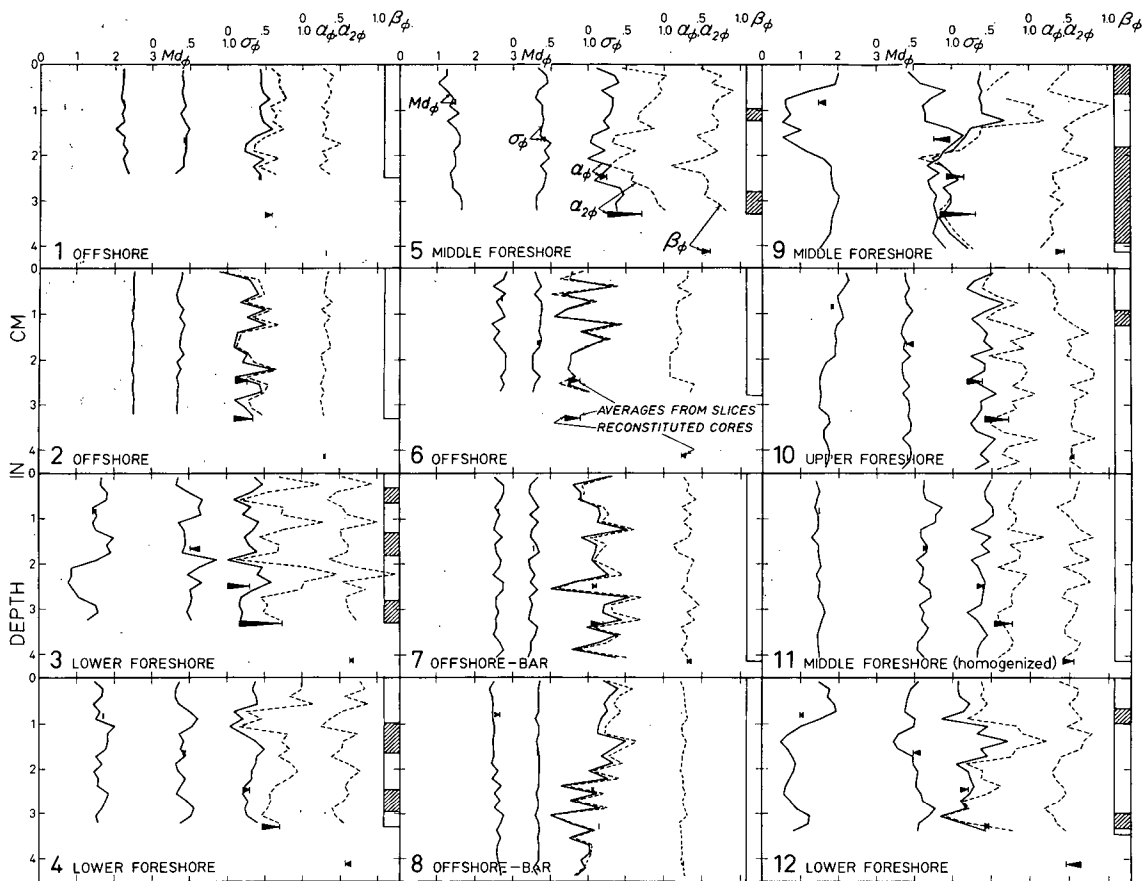


FIG. 2.—Plots with depth below sand surface of phi median diameters, deviation measures, first phi skewness measures, second phi skewness measures, and phi kurtosis measures for slices from cores 1 to 12, whose locations are given in Table 1. Dashed lines denote the second phi skewness measure and the phi kurtosis measure, both of which are based upon commonly imprecise 5% and 95% phi percentiles. Parameters computed by hand or with a small electronic calculator. Diagonal hatching on core logs to right of plots indicate visible fine-grained (usually dark) laminae. Arrow-like symbols denote average parameters for all slices (vertical line at point of arrow) and parameters for reconstituted cores (butt of arrow).

773 slices for measurement and computation. In addition, the sand from all slices of a given core were collected from the bottom of the settling tube, combined, dried, and several aliquot parts were analyzed for comparison with the data from the separate slices. Possible losses during collection of the 86 aliquots caused some undesirable error, so instead the original cores were "reconstituted" by averaging the percentages for $\frac{1}{4}\phi$ intervals in every slice in each core, drawing a new cumulative curve, and determining new statistical parameters for the core. The median diameters of reconstituted cores proved to average 0.08 phi unit finer than those of the aliquots, a satisfyingly small difference.

Specific localities for the 36 cores listed in Table 1 shows that many of them are from profiles intended to reveal changes in sand texture across the beaches and at various elevations above low tide.

RESULTS

Phi median diameters, phi deviation measures, first phi skewness measures, second phi skewness measures, and phi kurtosis measures for all slices of each core are presented as vertical logs for easy comparison (Figs. 2, 3, 4). Arrangement of the panels also permits comparisons of results for successive cores within a series across the beach at several localities. In addition, horizontal

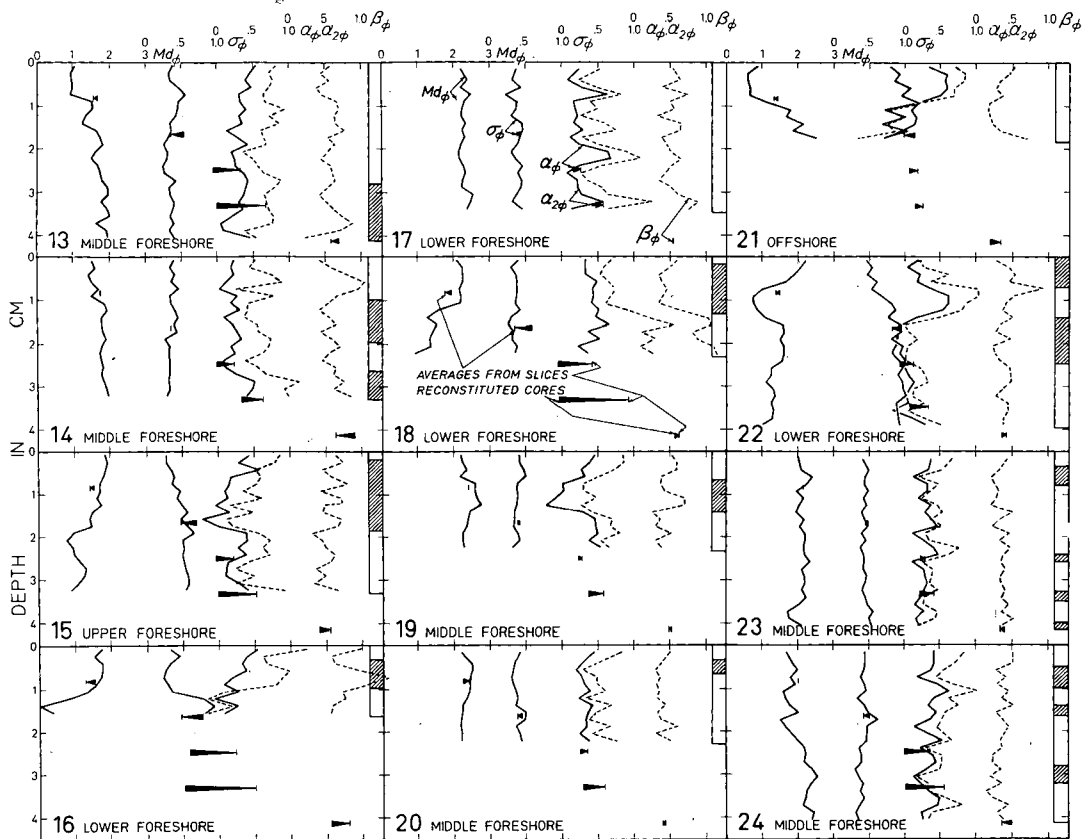


FIG. 3.—Same as Figure 2, but for cores 13 to 24.

arrow-like symbols denote the difference between parameters averaged for all slices in a core and parameters for the same composite reconstituted core (Fig. 2, core 6; Fig. 3, core 18).

Most fine-grained (usually dark) laminae observed at the coring sites correspond well with the finer median diameters of slices within the laminae and usually with other parameters as well. The second phi skewness measures and the phi kurtosis measures (shown by dashed lines) are more erratic than the phi median diameters, phi deviation measures, and first phi skewness measures, because they are based partly upon the 5 and 95 weight percentiles. These percentiles are particularly subject to error in analysis because their small weights represent only the tails of the main grain-size distributions.

Notably, the largest variations in all parameters occur along the lengths of most cores from the foreshore, and they corre-

spond with the light and dark laminae that were observed. Least variations are in the cores from offshore (under water at low tide) and in the homogenized core (Fig. 2, core 11). The original texture at the site of core 11 must have been about the same as at the nearby core 9 (Fig. 2). Thus the variations along the lengths of core 9 (and probably those along the lengths of most offshore cores) are more measures of error in collection, analysis, and computation than measures of actual textural variations in the sand.

Parameters from the averaged slices and the reconstituted cores (arrow-like symbols of Figs. 2, 3, 4) were further compared in X-Y plots of Figure 5. Clearly, the phi median diameters of all slices and of total (reconstituted) cores are nearly identical. The phi deviation measures of most averaged slices are smaller than those of corresponding reconstituted cores, with most points lower and right of the line of perfect correspondence.

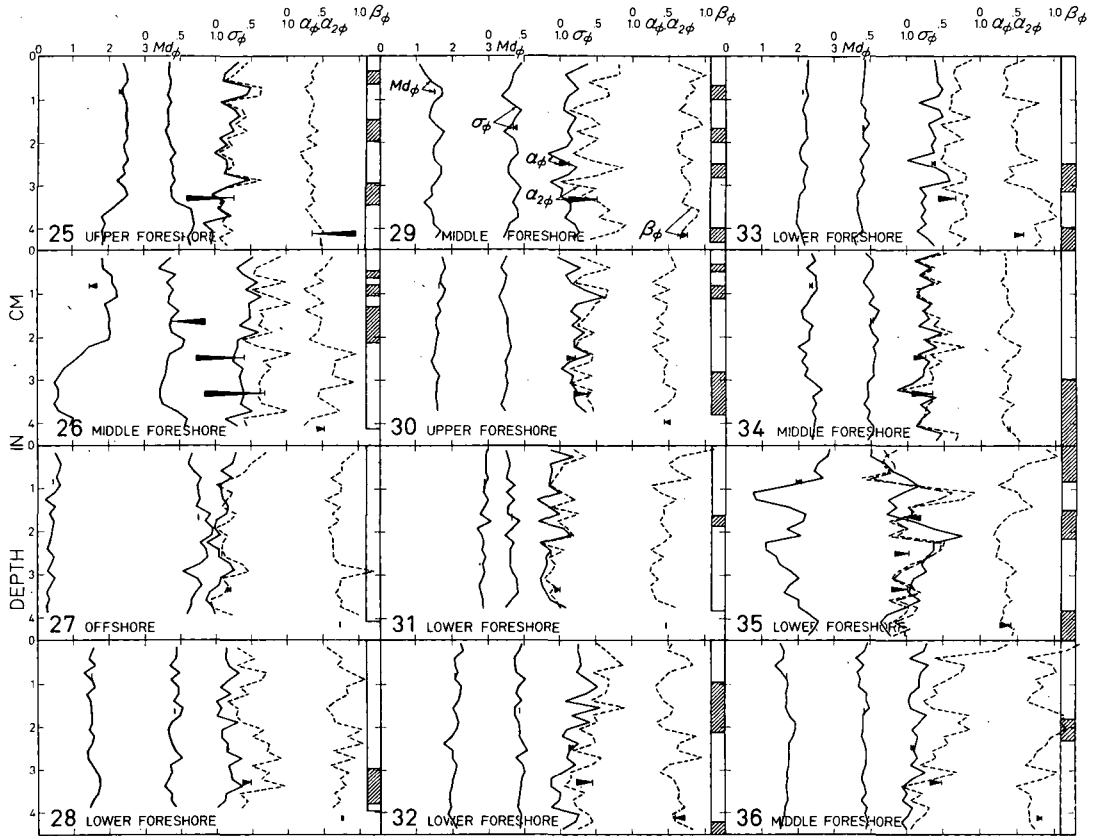


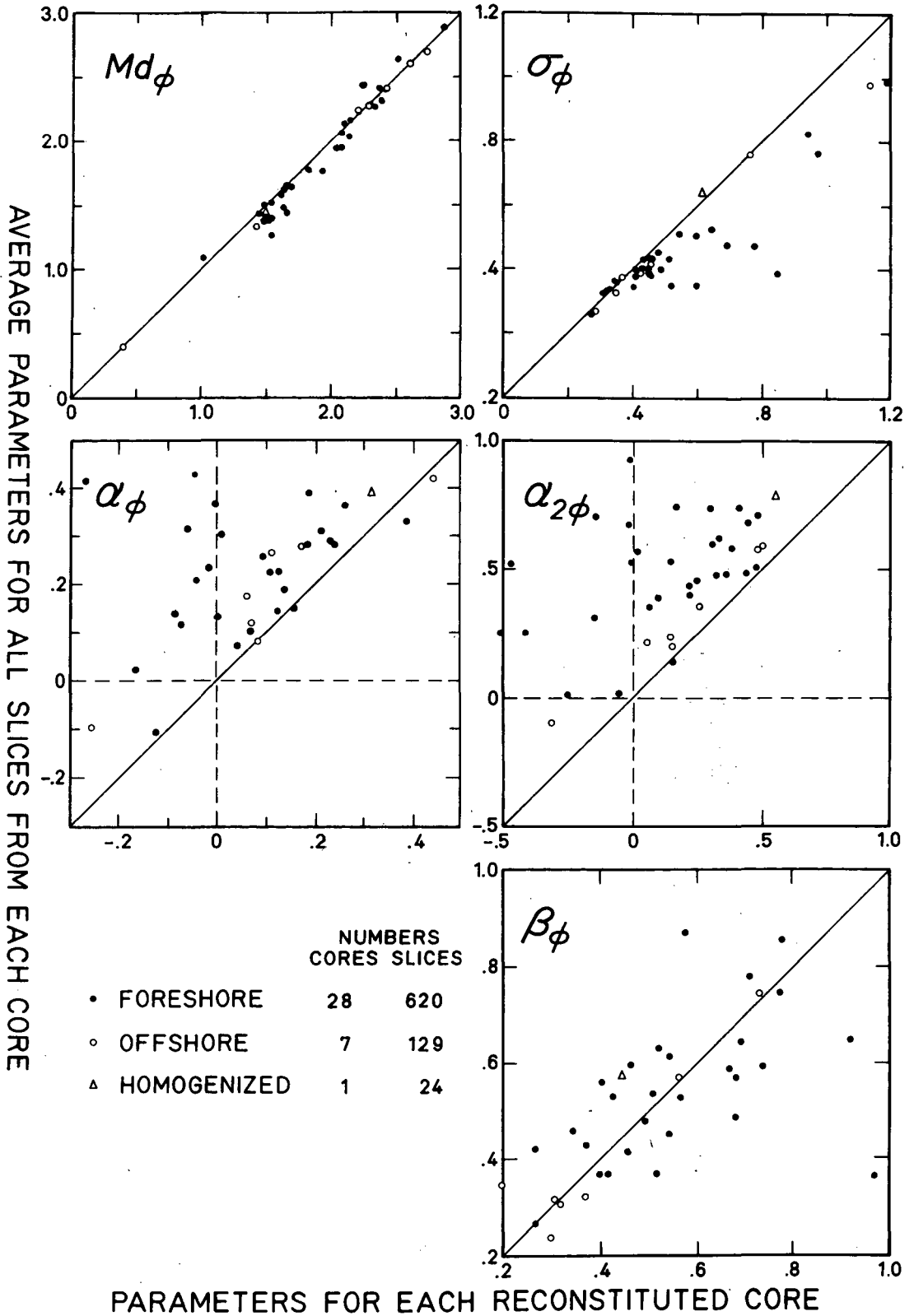
FIG. 4.—Same as Figure 2, but for cores 25 to 36.

The differences are much greater for the foreshore cores than for offshore cores and the homogenized core. Similarly, the two measures of phi skewness are more positive for averaged slices than for reconstituted cores. Note also that both measures of phi skewness are dominantly positive (especially the set for averaged slices). These measurements contrast with those made by many other workers, who found dominant negative skewness for beach sands (Friedman, 1961), or more negative skewness for beach than dune sands (Mason and Folk, 1958). Analyses of a few beach sands from Cape Cod by sieving showed negative skewness whereas analyses by settling provided positive skewness values, according to Schlee, Uchupi, and Trumbull (1964). Phi kurtosis measures in Figure 5 are best described as

randomly symmetrical—probably typical anyway for that parameter.

The panels of Figure 5 omitted the observed variations of the parameters for each slice in the interest of simplicity. However, the ranges for phi deviation measures and first phi skewness measures are shown in Figure 6. The large ranges support the logs of Figures 2, 3, 4 in showing that beach sands are much more variable than would be inferred from analyses of single composite sand samples. The same sort of information about variability of beach sands is illustrated by a comparison of phi deviation measures versus phi median diameters (Fig. 7). The impression of wide scatter of data is reduced when one considers that the plot represents only a small part of the total expectable ranges for most kinds of sediment (insert

FIG. 5.—X-Y plots of parameters derived from averages for slices versus parameters for reconstituted cores. Each point represents a single core.



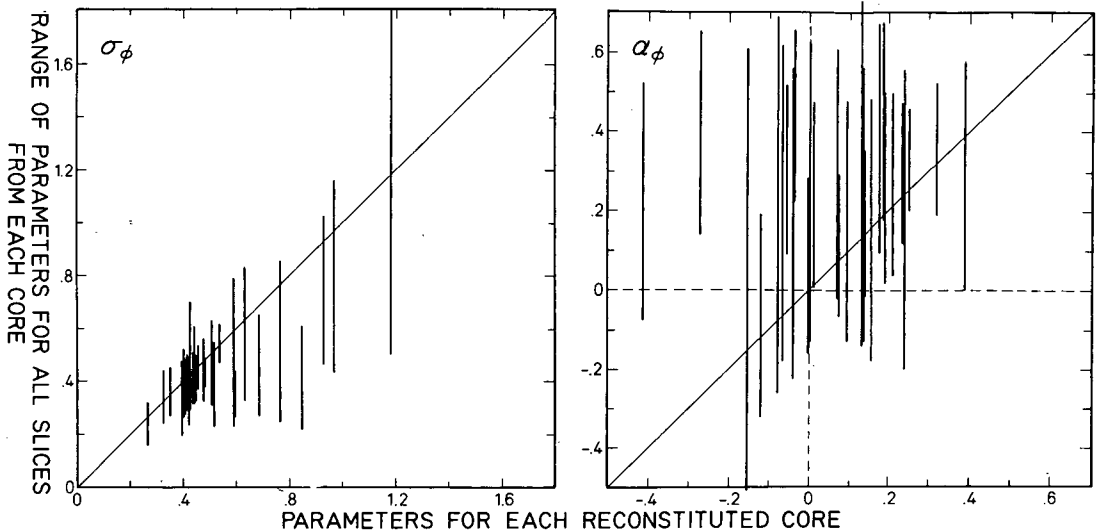


FIG. 6.—Same plot for phi deviation measures and first phi skewness measures as in Figure 5, except that bars show measured ranges of parameters for all slices in each of the foreshore cores only (same relative scales as in Fig. 5).

in upper right corner). A mean curve of phi deviation measure against phi median diameter would rise upward and outward from the small lined square in the insert. Much of the variation of points within the body of Figure 7 comes from individual cores of the 36-core set, as though due to special conditions such as derivation from artificial fill

of sand (core 35), protection from large waves (core 31), nearby cliffs of glacial till (core 16), etc. As others (Nordstrom, 1977, for example) have found, the statistical parameters of beach sands are controlled by more than just degree of exposure to waves. The concentration of points in the lower right part of Figure 7 reflects previous observations that the best sorted sands are those having median diameters between 2 and 3 phi units (Hjulström, 1939; Inman, 1949). Note that the circles (representing reconstituted cores) denote poorer sorting for the reconstituted cores than for the individual slices.

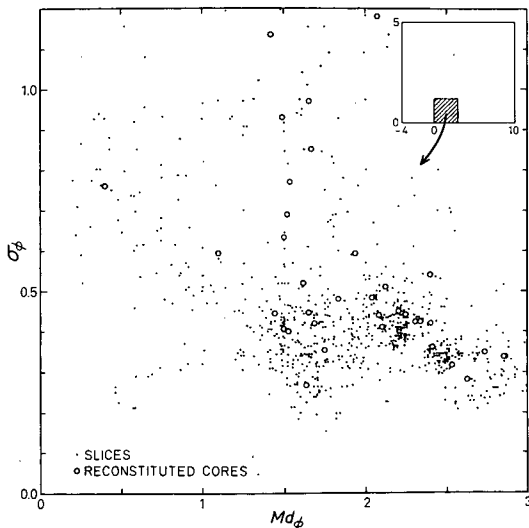


FIG. 7.—Scatter plot of phi deviation measures versus phi median diameters for all slices and all reconstituted cores.

CONCLUSIONS

The results of this study, as expressed in the illustrations and verified by field observations, permits several conclusions regarding laminated beach sands:

1. Lamination due to swash appears to be restricted to the foreshores, absent in the offshore, and generally absent on berms.

2. Differences in textural parameters between coarse laminae and fine laminae are great enough to (a) require better sampling of foreshores than is permitted by previous methods, particularly when the intent is to investigate sources of the sands or hydraulic

conditions of deposition, (b) influence patterns of textural parameters in grids or along lines of beach sand samples, (c) cause anisotropy in permeability of the sand, and (d) permit depth variation of total heavy minerals (and microfossils) and the ratios between minerals or microfossils of different specific gravity or shape.

3. Phi skewness measures for most laminae are positive, and for composite foreshore samples slightly less positive. Earlier findings of typical negative skewness for beach sands may have been based upon samples from beaches containing dominantly fine-grained laminae as well as upon analysis by sieving.

Sedimentologists who may believe that the above results are different from those obtainable by sieving or by other statistical treatments are encouraged to test their preferred methods on new samples. In the process they will broaden and extend geographically the inquiry into laminae within beaches and other sedimentary deposits.

ACKNOWLEDGMENTS

This study was made possible by a grant from National Oceanic and Atmospheric Administration (NOAA) Office of Sea Grant (grant no. 04-6-158-44106), which provided salary support for Cynthia Wigley. Her careful collection of cores from Cape Cod beaches and settling-tube analyses of all samples is the basis for this study. Support for the author is from the Henry Bryant Bigelow Chair in Oceanography. Appreciation is due M. C. Miller, D. A. Ross, and John Schlee for criticisms of the manuscript.

REFERENCES

- CHAKRABARTI, A., 1977, Polymodal composition of beach sands from the east coast of India: *Jour. Sed. Petrology*, v. 47, p. 634-641.
- CLIFTON, H. E., 1969, Beach lamination: Nature and origin: *Mar. Geol.*, v. 7, p. 553-559.
- DUNCAN, J. R., JR., 1964, The effects of water table and tide cycle on swash-backwash sediment distribution and beach profile development: *Mar. Geol.*, v. 2, p. 186-197.
- EMERY, K. O., AND J. F. FOSTER, 1948, Water tables in marine beaches: *Jour. Mar. Res.*, v. 7, p. 644-654.
- EMERY, K. O., AND J. F. GALE, 1951, Swash and swash mark: *Trans. Am. Geophys. Union*, v. 32, p. 31-36.
- EMERY, K. O., AND R. E. STEVENSON, 1950, Laminated beach sand: *Jour. Sed. Petrology*, v. 20, p. 220-223.
- FOLK, R. L., 1966, A review of grain-size parameters: *Sedimentology*, v. 6, p. 73-93.
- FOLK, R. L., AND W. C. WARD, 1957, Brazos bar: A study in the significance of grain-size parameters: *Jour. Sed. Petrology*, v. 27, p. 3-26.
- FRIEDMAN, G. M., 1961, Distinction between dune, beach, and river sands from their textural characteristics: *Jour. Sed. Petrology*, v. 31, p. 514-529.
- FRIEDMAN, G. M., 1967, Dynamic processes and statistical parameters compared for the size-frequency distributions of beach and river sands: *Jour. Sed. Petrology*, v. 37, p. 327-354.
- GRANT, U. S., 1948, Influence of the water table on beach aggradation and degradation: *Jour. Mar. Res.*, v. 7, p. 655-660.
- HJULSTRÖM, F., 1939, Transportation of detritus by moving water: *In* Trask, P. D. (ed.), *Recent Marine Sediments*, London, Thomas Murby & Co., p. 5-31.
- INMAN, D. L., 1949, Sorting of sediments in the light of fluid mechanics: *Jour. Sed. Petrology*, v. 19, p. 51-70.
- INMAN, D. L., 1952, Measures for describing the size distribution of sediments: *Jour. Sed. Petrology*, v. 22, p. 125-145.
- JONES, T. A., 1970, Comparison of the descriptions of sediment grain-size distributions: *Jour. Sed. Petrology*, v. 40, p. 1204-1215.
- MASON, C. C., AND R. L. FOLK, 1958, Differentiation of beach, dune, and aeolian flat environments by size analysis, Mustang Island, Texas: *Jour. Sed. Petrology*, v. 28, p. 211-226.
- NORDSTROM, K. F., 1977, The use of grain-size statistics to distinguish between high- and moderate-energy beach environments: *Jour. Sed. Petrology*, v. 47, p. 1287-1294.
- POLLACK, L. W., AND W. D. HUMMON, 1971, Cyclic changes in interstitial water content, atmospheric exposure, and temperature in a marine beach: *Limnology and Oceanography*, v. 16, p. 522-535.
- REINECK, H.-E., 1974, Vergleich dünner Sandlagen verschiedener Ablagerungsberichte: *Geol. Rundschau*, v. 63, p. 1087-1101.
- SANDERS, J. E., 1965, Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms: *In* G. V. Middleton (ed.), *Primary Sedimentary Structures and their Hydrodynamic Interpretation*: *Soc. Econ. Paleontologists Mineralogists, Spec. Publ. 12*, p. 192-219.
- SCHLEE, J., 1966, A modified Woods Hole rapid sediment analyzer: *Jour. Sed. Petrology*, 36, p. 403-413.
- SCHLEE, J., E. UCHUPI, AND J. V. A. TRUMBULL, 1964, Statistical parameters of Cape Cod beach and eolian sands: *U.S. Geol. Survey Prof. Paper 501-D*, p. D118-D122.
- SCHLEE, J., AND J. WEBSTER, 1967, A computer program for grain-size data: *Sedimentology*, v. 8, p. 45-53.
- SONU, C. J., 1972, Bimodal composition and cyclic characteristics of beach sediments in continuously changing profiles: *Jour. Sed. Petrology*, v. 42, p. 852-857.
- TANNER, W. F., 1958, The zig-zag nature of type I and type IV curves: *Jour. Sed. Petrology*, v. 28, p. 372-375.
- THOMPSON, W. O., 1937, Original structures of beaches, bars, and dunes: *Bull. Geol. Soc. Am.*, v. 48, p. 723-751.
- TRASK, P. D., 1932, *Origin and Environment of Source Sediments of Petroleum*: Houston, Gulf. Publ. Co., 323 p.

- WADDELL, E., 1973, Dynamics of swash and its implications to beach response: Louisiana State Univ., Coastal Studies Inst. Tech. Rept. 139, 49 p.
- WADDELL, E., 1976, Swash—groundwater—beach profile interactions: *In* Davis, R. A. and R. L. Ettington, (eds.), Beach and Nearshore Sedimentation: Soc. Econ. Paleontologists and Mineralogists, Spec. Publ. 24, p. 115-125.
- ZEIGLER, J. M., G. G. WHITNEY, JR., AND C. R. HAYES, 1960, Woods Hole rapid sediment analyzer: *Jour. Sed. Petrology*, v. 30, p. 490-495.