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TRACING SEDIMENT MASSES BY GRAIN SIZE MODES*

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ABSTRACT

The thesis is presented that many sediments are mixtures of two or more simple sedimentary components, each with particle size distributions approaching statistical normality. The multiple-component mixtures are non-normal and are frequently polymodal. By study and dissection of size frequency curves into the distributions of the individual components, we can trace the geographic distribution of the components in the mixed sediments. Individual components tend to retain their own characteristics (mean or mode, standard deviation, etc.) except when systematically modified by the processes causing transportation and mixing.

This system of analysis has been applied to a study of the surface sediments of the continental shelf of the northwest Gulf of Mexico. The sediment distribution is complex because of the multiplicity of sources, the transgression of the sea across the shelf following the Wisconsin glaciation, and the periodic variations in wind and current systems during this transgression. Rate of deposition is low on much of the shelf today and thin layers of surface sediment are being reworked with the underlying sediments by currents and burrowing organisms. The result is that more than half of these sediments are multiple-component. A natural grouping of the components by modal size delineates the distributions of the sediment masses even when they are mixed.

INTRODUCTION

For many years geologists and sedimentologists have used sedimentary particle size distributions to attempt to solve geological problems. Some of these attempts have been successful, but many have not. It is apparent that some of these problems are not amenable to solution by considering grain size distributions, while others could have been solved by other techniques of expression of the distributional characteristics. A system of analysis is presented in this paper which sacrifices some of the rigor and quantitative objectivity of many of the commonly used systems, but which offers some hope of leading to an understanding of complex sediments rather than mere description. Although this system is neither new nor original, it has been largely neglected in the past.

The nature of sedimentary particle size distributions requires expression in terms of shape description of some graphic representation of the distribution, or in terms of descriptive statistics assuming a distribution function. The use of descriptive statistics, such as median or mean, standard deviation, skewness, and kurtosis, is based on the assumption that the grain size distributions approach statistical normality, usually either arithmetic normal or log normal. Deviations from normality are then evaluated. These deviations are usually quite significant except in the case of well sorted sands. In many cases these deviations probably arise because the sed-

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iments are mixtures of two or more components. Each of the components may in itself be a normally distributed sediment, but the mixture is non-normal. If the secondary, tertiary, and other components are present in large enough proportions and are sufficiently separated from each other, the composite distribution is polymodal. The system of analysis proposed in this paper is the study of frequency curves of the distributions to identify the modes representing these components of multiple-component sediments. The geographic distributions of the individual components or sediment masses can then be traced, even when mixed.

Methods

Most of the grain size distributions utilized in this study of the continental shelf of the northwest Gulf of Mexico were made by standard laboratory techniques in the sedimentology laboratory of the Scripps Institution of Oceanography. The results of hydrometer analysis of the silts and clays (Day, 1950) were combined with settling tube analyses (Emery, 1938, Poole, et al., 1951) of the material coarser than 62 microns. Sodium Hexametaphosphate was used as a dispersing agent. Cumulative curves were plotted generally on logarithmic-probability (phi-probability) scale. Some of the analyses of nearshore sediments from off the central Texas coast were prepared by Inman and Chamberlain (1955), who recognized their bimodal character. In addition to the analyses made in the laboratories of the Scripps Institution, the raw data for Stetson's (1953) size analyses have been used, and J. D. Frautschy of the Scripps Institution supplied size distributions of a large number of closely spaced samples from off southwestern Louisiana collected for the U.S. Geological Survey. Inasmuch as size analyses made in different laboratories are not entirely comparable, it has been necessary to interpret these results rather conservatively to avoid introducing bias.

After the cumulative distribution has been plotted (Figure 1 A), the frequency curve is derived from it. The frequency curve is defined as the first derivative of the cumulative curve. This can be obtained by a graphical method (Krumbein, 1934) or by a mathematical method of differentiation (Brotherhood and Griffiths, 1947). This latter method consists of taking the successive first, second, and third differences for obtaining an approximate derivative. This produces precision in the results unwarranted by the data available in this study and is too time-consuming for study of a large number of samples (750 in the present study). A graphical method was likewise found unsatisfactory because the analyses prepared by other workers were plotted on different types and scales of graph paper.

A less precise mathematical method was adopted (Figure 1 A, 1 B) which consists of taking only first differences corresponding to uniform one quarter phi unit in tervals on the abscissa grain size scale. The $\Delta\%$ (change in cumulative percent) corresponding to each $\Delta Ø = \frac{1}{4}$ (quarter phi interval in grain size where $Ø = -\log_2$ of the diameter in mm.) is then plotted as the ordinate of the first derivative frequency curve (Figure 1B) and the smooth curve is drawn by eye. In extremely peaked distributions, additional intermediate points are also obtained.

From the frequency curve thus produced, the positions of the modes were determined to the nearest $^1/_{10}$ phi unit. No modes were considered significant on the basis of single points, and care was taken to avoid producing modes from unrealistic-

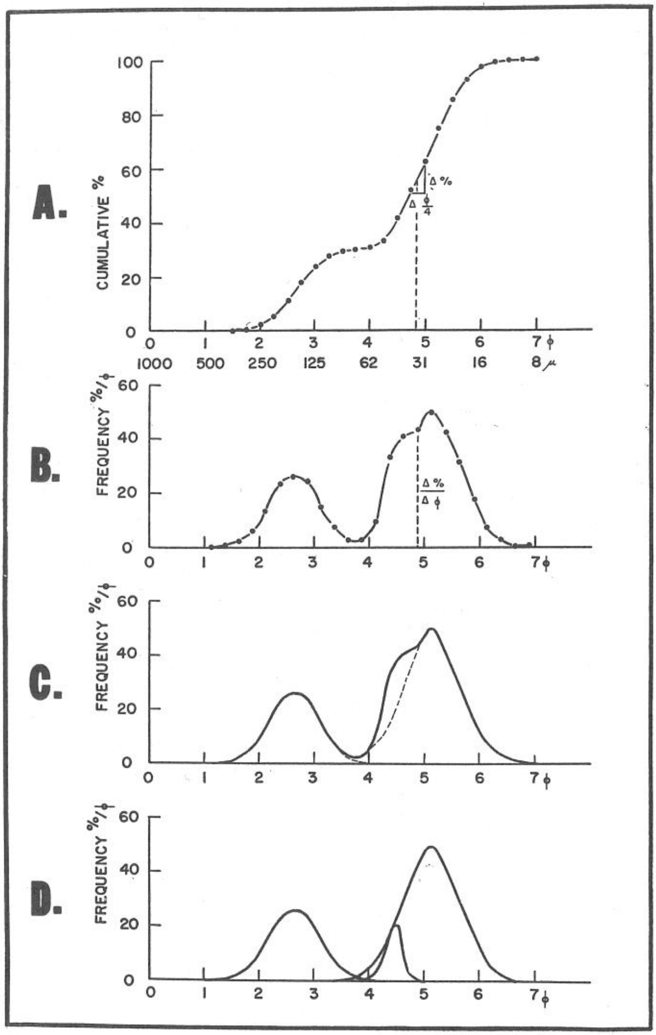

FIG. 1.—*The method of approximate differentiation of the cumulative size distribution used to obtain the frequency curve. The ratio of* $\frac{\Delta \%}{\Delta \phi}$ *over each interval of the cumulative curve (fig. 1A) is plotted as the ordinate of the frequency curve at the midpoint of the interval (fig. 1B). The first step in the dissection of the polymodal frequency curve into its component distributions, assuming each to be approximately log normal, takes place in 1C. The resulting component distributions are replotted in 1D, and adjusted to be symmetrical and approximately normal.*

appearing bends in the cumulative curves. This latter precaution is particularly necessary in the region of the distribution curve where results of different techniques of measurement are adjusted together, for example, at 62 microns (4 phi) where settling tube or sieving measurements are fitted to the pipette or hydrometer results (Inman, 1953, Figure 9). A bad fit can produce a spurious mode in the frequency curve.

Ideally a polymodal or multiple-component frequency curve should be dissected into the component gaussian normal distributions. An electronic computer program would be necessary to do this practically. Lacking such a program, it is possible to estimate this by eye as shown in Figure 1 C, 1 D. The sum of the component distributions equals the total composite distribution. The relative abundances of each component are proportional to the areas under the individual frequency curves. Each frequency curve can furthermore be described by standard statistics, such as mean and standard deviation, the mean being the same as the mode if it is indeed normally distributed.

The distribution demonstrated in Figure 1 was synthesized by addition of the three components shown in Figure 1 D. Whereas it is only bimodal, it consists of three components representing 30%, 8%, and 62% of the total mixed sediment respect ively. This composite curve shows a strong resemblance to many of the distributions from the continental shelf of the northwest Gulf of Mexico. It is suggested that closer scrutiny of frequency curves of many modern and ancient sediments from other parts of the world will show that they too are multiple-component. Many, but certainly not all, of the deviations from normality may be due to mixing of sediments.

When sediments are mixed, each component will tend to retain its own characteristics, i.e., its mean, standard deviation, etc. will remain the same unless modified by the transporting process. If we can recognize the characteristics of the components present in sufficiently large proportions, then we should be able to trace each sediment mass by detecting its presence in the mixed sediments. The mean or mode and standard deviation should remain approximately uniform or else show a systematic variation: the relative proportion of the component will, however, vary from sample to sample.

Bimodal distributions can be produced from a single sediment mass under some conditions of transport and sorting, but these possibilities are not considered very probable in the present study. Ripple formation can result in different modes on the crests and in the troughs (Inman, 1957, Figure 18), but this difference is generally not pronounced in the range of sand sizes considered here. Secondary modes could also conceivably be present due to a very abundant proportion of mineral species with different density, such as heavy minerals, if the analytical technique does not approximate the sorting mechanism of the transportational process. This possibility is also neglected in the present study.

Application

This study of grain size mode distributions was first attempted as a part of the study of the sediments of the continental shelf of the northwest Gulf of Mexico (Curray, 1960). Examination of cumulative curves of about 750 grain size distributions suggested that a large number of them are polymodal and multiple-component.

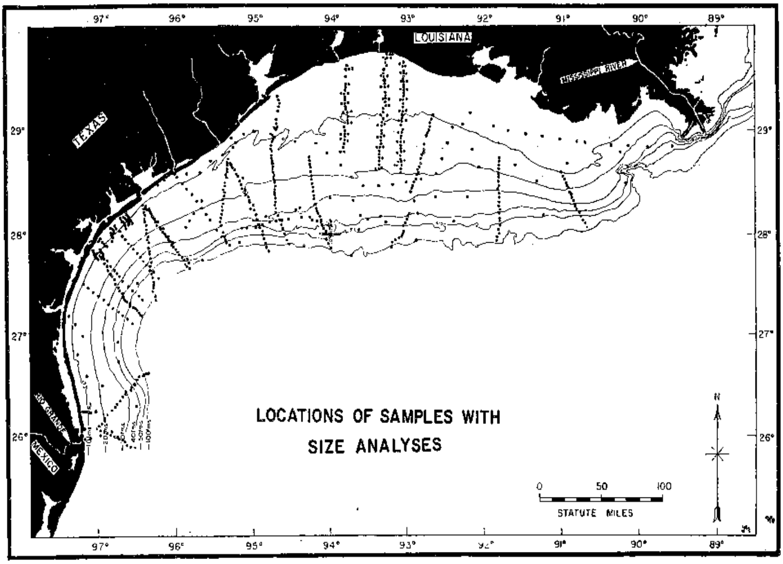

FIG. 2.—*Location chart of the* 750 *samples on the continental shelf or the northwest Gulf of Mexico with size analyses. Modified from Curray* (1960).

Description by standard parameters is of little value for doing more than identifying the gross characteristics of the texture. Grouping and plotting of the modal sizes, however, shows patterns of distribution which agree well with the conclusions of other phases of the study.

The sediments of the Gulf of Mexico are introduced into the basin by rivers. Sands from the river loads are deposited near the mouths of the rivers for redistribution by waves and longshore transport. The muds or fine sediments, on the other hand, are deposited as blankets of sediment farther from shore quite independently of the sands. The result is a linear sand body near the shore and a blanket of shelf mud at a distance and direction from the source depending upon the distributing currents.

There are many sources of sediment in the Gulf (Figure 2), principally the Mississippi River, the rivers along the western Louisiana and eastern Texas coast, and the Rio Grande along the United States-Mexico boundary. Each of these river sources independently contributes a linear sand body and a thin blanket of shelf mud in equilibrium with the present wind and current systems and the present position of sea level. During the recent past, however, the sea has transgressed the continental shelf due to the melting of the Wisconsin glaciers (Curray, 1960).

Evidence from the study of radiocarbon dates of relict shallow water and shoreline shells in the Gulf and study of the morphology of drowned barrier spits shows that sea level stood at -48 fathoms approximately 17,000 years B.P. (Before Present). Extrapolation suggests that the shore was at the edge of the shelf (-65 fathoms) perhaps 18,000 to 20,000 years B.P. The transgression across the shelf was not smooth and continuous, but was instead interrupted by several periods of reversal and regression during readvances of the continental glaciers. During these brief

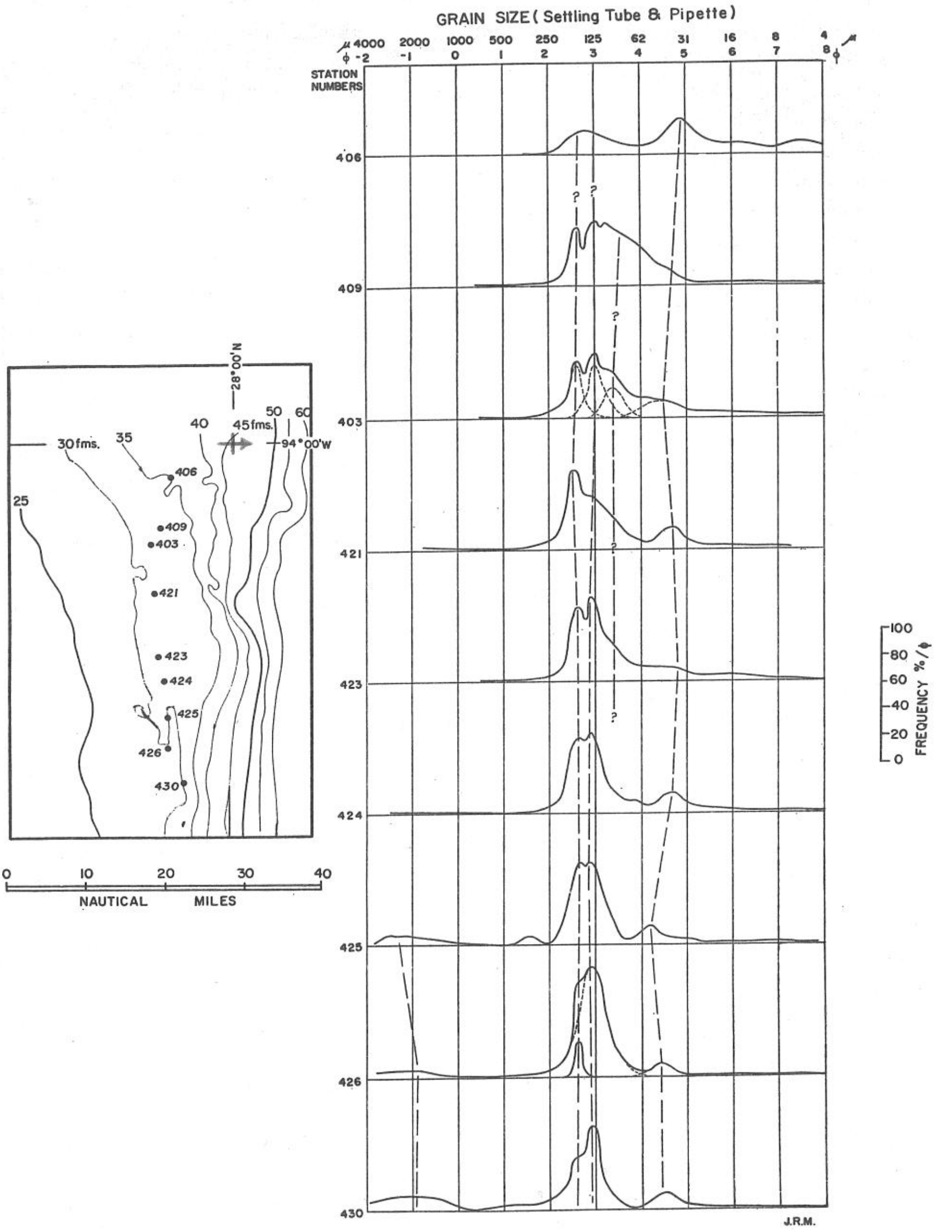

FIG. – *Location chart and frequency curves of a series of nine samples from the continental shelf of the northwest Gulf of Mexico to demonstrate the correlation between components* ***of*** *polymodal mixed sediments. The components vary from sample to sample mainly in relative abundances.*

periods of regression, the wind system was different, and the directions of the longshore and semi-permanent currents were changed accordingly. Changes and local reversals of the current direction resulted in changes of the loci of deposition of the linear sand bodies and the blankets of shelf muds coming from each river source.

The result of the many variations in the environmental conditions during this period of transition from a glacial to an interglacial epoch has been the compounding and mixing of overlapping sediment bodies. Present deposition is very slow or negligible on much of this shelf, and there has been time for reworking and mixing by burrowing organisms and by hurricane wave surges, especially when superimposed on tidal currents and semi-permanent currents. Wherever the rate of deposition is slow with respect to the rate of reworking, primary structures such as bedding have been destroyed, and the shelf muds have been reworked and mixed with the underlying basal sands of the transgression, Some of the mixed sediments are irregularly interbedded and mottled, but others are mixed to homogeneity.

Locations of the 750 samples with size analyses used in this study are shown in Figure 2. The edge of the continental shelf lies at about 65 fathoms in most of the area. The areas of the shelf covered with shelf facies muds are those north of about 27° N., and west of about 96° W., and the area between about 93° W. and the Mississippi delta. Most of the remainder of the shelf is covered primarily with the basal shoreline and nearshore sands of the transgression following the Wisconsin glaciation. More than half of the samples analyzed are polymodal, and considerably more than that are probably multiple-component.

The size frequency curves of a series of nine samples from near the 30 fathom depth between 94° and 95°W. are shown in Figure 3. This part of the shelf is covered with relict shoreline and nearshore sands, slightly reworked and mixed with minor amounts of silt from other sources and other periods of deposition during the transgression. All of the distributions contain several distinct components, some of which can be traced through all of the 50 mile series of samples. Some of these components are shown as distinct modes, whereas the less abundant ones are shown as terraces or shoulders on the sides of other modes. Possible dissections into the component distributions are shown for two of the curves, stations 403 and 426.

Some coarse modes have been identified as shell fragments and Foraminifera by binocular microscope examination. The proportions of these constituents are relatively minor, however, in the modes considered here finer than about ½ mm. Applicability of this technique has been suggested for tracing the distributions of clastic carbonate species in a more richly carbonate environment for all of the sand size range (C. C. Daetwyler, personal communication).

In studying the distributions of all of the samples on the continental shelf in this area, it was necessary to group the modes into classes. Many different groupings are possible, but because of the extreme complexity of the sediments, the size of the area, and the sparcity of the sample coverage relative to this complexity, it was not possible to correlate the fine details of the distributions as has been done in Figure 3. Instead, large groups were considered in an attempt to illustrate the gross features of the distributions of the major sediment masses. The distributions of four groups are illustrated in Figures 4, 5, 6, and 7. The arrows shown are the probable general direction of transport during the various periods of deposition of the sediment masses as deduced from other considerations of the study (Curray, 1960). Each of

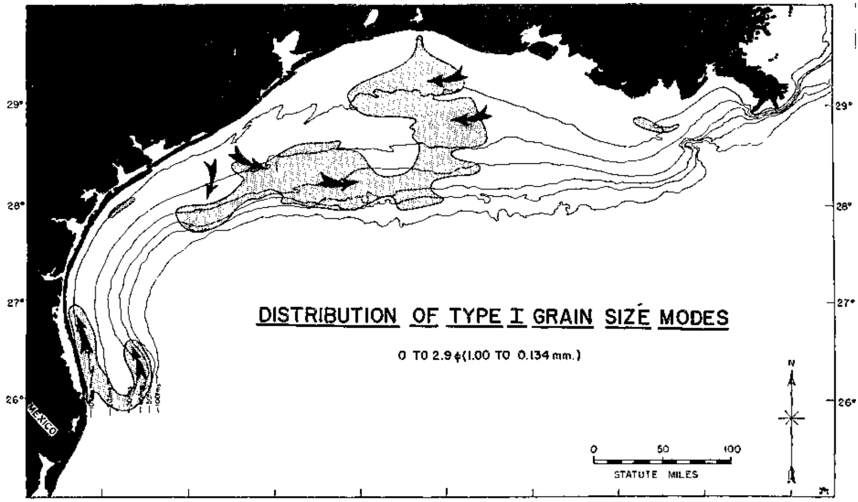

FIG. 4.–*Distribution of grain size modes of 0 to* 2.9 Ø (1.00 *to* 0.134 *mm) surface sediments. Most of these mode are between* 2.0 *and* 2.9 Ø (0.250 *and* 0.134 mm). *From Curray* (1960).

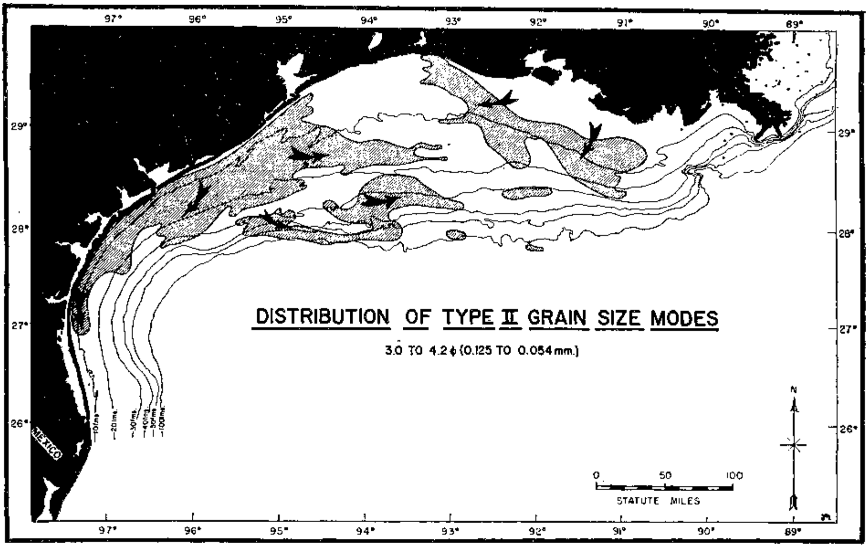

FIG. 5.—*Distribution of grain size modes of* 3.0 *to* 4.2 ø (0.125 *to* 0.054 *mm.*) *of surface sediments. From Curray* (1960).

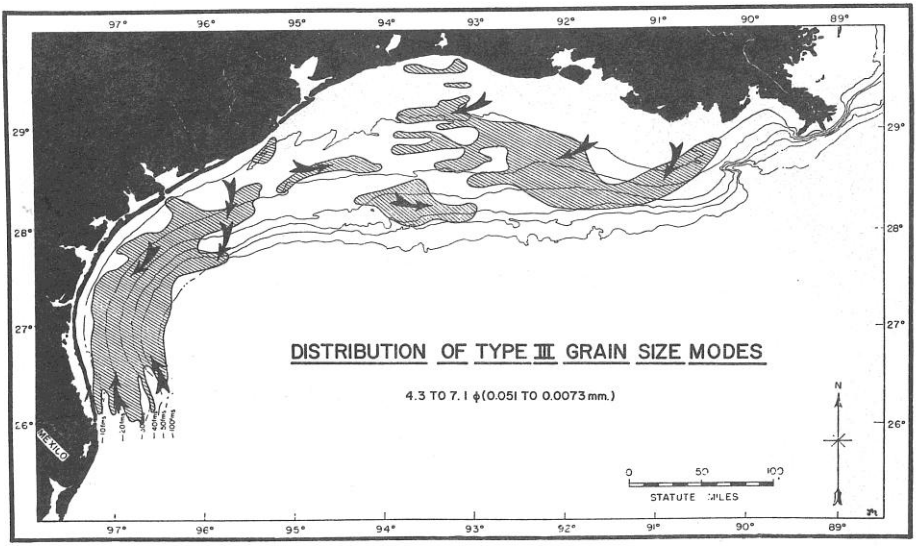

FIG. 6 – *Distribution of grain size modes of* 4.3 *to* 7.1 Ø (0.051 *to* 0.0073 *mm.) of surface sediments. From Curray* (1960).

these types is In Itself composed of a complex of smaller sediment masses of varying ages and sources, which group together Into the size ranges indicated.

Types I (predominantly fine sand) and II (approximately very fine sand) (Figures 4 and 5), the two principal sand size types, are widely but independently distributed on the shelf. The illustrations indicate the presence only of these modal sizes and do not necessarily imply that these sediments are predominately sandy. These two types were apparently derived either from different sources or during different periods of time. Type I was the predominant sand type during parts of the transgression, whereas type II was the predominant sand type during other parts of the transgression. The modern beaches and many of the present nearshore deposits are type II sand. Some overlap occurs between these two types, suggesting independent emplacement and postdepositional mixing.

Type III mode (Figure 6, approximately the silt range) appears to be a dominant part of the shelf facies muds brought to the shelf during a major part of the Holocene transgression and post-transgressional time. Type IV modes (Figure 7, approx imately clay size) are the finest differentiates of the shelf facies muds, and are present mainly at the distal ends of the postulated routes of transport of the suspended muds during and after the transgression.

It is particularly significant in these four group patterns that geographic overlap occurs between all of the types. This overlap can be observed by comparison of the separate patterns or by the composite pattern of Figure 8. Approximately one third of the shelf shows overlapping of the modal size groups. Examination of the finer details of the distributions, as in Figure 3, shows even more overlapping than this. This overlapping demonstrates that sediment masses were distributed independently and have subsequently been mixed. As examples, note the overlap zones between

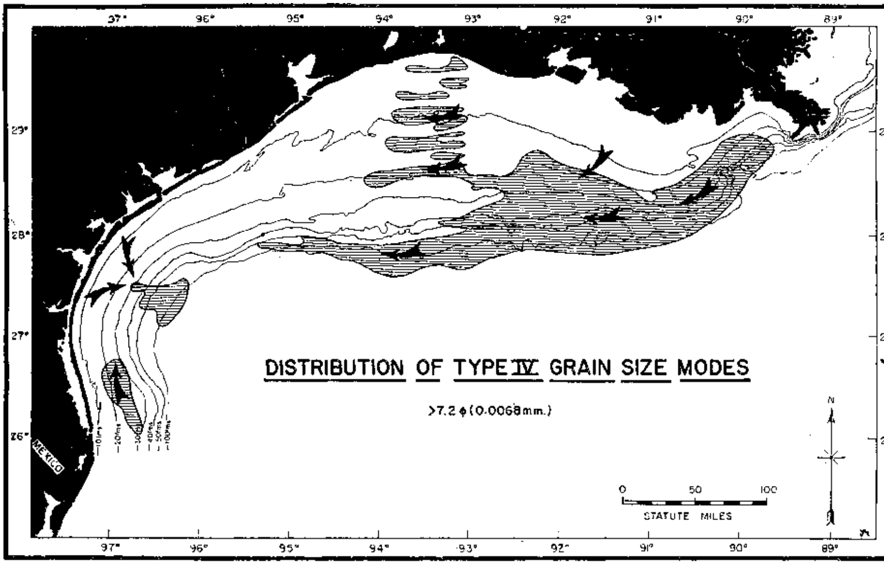

FIG. 7.—*Distribution of grain size modes of finer than* 7.2 ø (0.0068 *mm.*) *of surface sediments. From Curray* (1960).

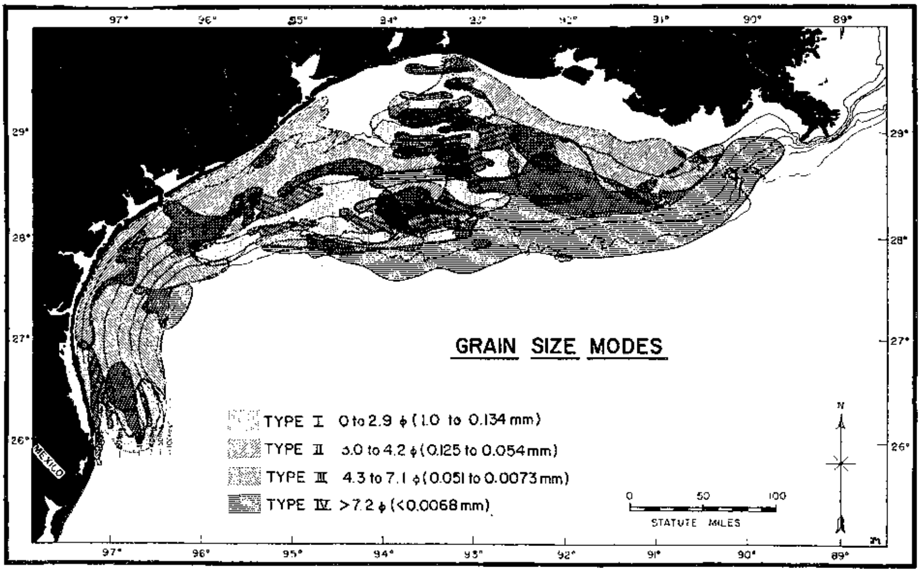

FIG. 8.—*Composite diagram of the four groups of grain size modes to demonstrate the overlapping between the group and the frequency of polymodal, multiple-component, mixed sediments.*

types III and IV at 27° 20° N. in the western part of the area and from 91° to 93°W. in the middle of the shelf of the eastern part of the area. This shows that the change to finer sediment farther from shore in these areas is not a continuous gradation, but is instead an overlapping and mixing between two blanket deposits of shelf facies muds.

CONCLUSIONS AND SUGGESTIONS

1. Some simple sedimentary particle size distributions tend to approach statistical normality, but many natural sediments are non-normal because they consist of several of these simple components mixed in varying proportions. The individual components tend to retain their characteristics (mean and mode, standard deviation, etc.) even when mixed, unless they are systematically modified by the transportational processes.
2. More than half of the surface sediments of the continental shelf of the northwest Gulf of Mexico are multiple-component. It is suggested that closer scrutiny of many other modern and ancient sediments will show that they are not the simple, single component distributions previously believed.
3. If we are to study sedimentary particle size distributions in this manner, we should prepare our analyses carefully: we should use close-spaced observations in settling tube, hydrometer, and pipette analyses, and close sieve intervals, and we should guard against spurious modes in the frequency curves produced by poor fits between results of different analytical techniques, such as the sand-silt boundary, or by oversized holes in sieves.
4. We need an electronic computer system for performing the more complex operations on the data. A computer program is now in operation at the Scripps Institution for reducing raw size data to the cumulative and frequency curves, but no program has yet been published for mathematical dissection of compound curves into the component parts.
5. This technique is certainly no panacea for all problems involving considerations of particle size distributions. Many problems cannot be solved or clarified any more by this system than by other systems, but it is suggested that solutions to some problems should be attempted in this way. While this method in its present form is less rigorously quantitative than the use of descriptive statistics, it does force us to look at the distributions and attempt to understand them rather than simply describing them.

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