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Many sediments, including the fine-grained pelagic deposits, possess polymodal grain size distributions. Resolution of individual modes show them to be related either to compositional fractions or to depositional processes or both, and sometimes permits the tracing of dispersal patterns. The Cahn sedimentation balance provides a means of obtaining continuous cumulative size distribution curves of fine-grained sediments. The resultant cumulative curve is processed by computer to yield a size frequency curve which is often found to be polymodal. This frequency curve is resolved into its individual components by means of an analog computer. The method is discussed in detail and illustrated by means of a test study of pelagic sediments from the Northwest Pacific. Samples collected nearest land have the most components and the best sorted components. Fifteen modes were decanted from five samples and X-rayed. Similar components from different samples were found to have similar

compositions when plotted on a feldspar-kaolinite-mica ternary diagram. Based on like composition and nearly identical mean size values, it is possible to trace the sedimentary components from sample to sample.

Textural Analysis of Fine-Grained Sediments: Pelagic Sediments of the Northwest Pacific

by

Robert Keith Oser

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Professor of Oceanography
In Charge of Major

Redacted for Privacy

Chairman of Department of Oceanography

Redacted for Privacy

Dean of Graduate School

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Typed by Marcia Griffin for Robert Keith Oser

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SIZE ANALYSIS OF FINE-GRAINED SEDIMENTS

Introduction

The study of sediments is based on the description of the properties of their constituent particles. One of the most widely used of these properties - because it is conveniently measurable - is the particle size distribution of the sediment. This information sometimes allows inferences regarding the environment and mode of deposition of the sediment.

Numerous methods have been developed to determine the particle size distribution of a sediment. The most direct method, although time consuming and tedious, is the counting and grouping according to size of a finite number of particles using a microscope.

Most other methods of size analyses of the fine fraction of sediments (<62 microns) involve procedures in which the particle size is determined by its settling rate through a fluid medium. The mathematical relationship between size and settling velocity was developed by Stokes (1851). According to Stokes' Law, the velocity of a spherical particle settling in a fluid medium is:

$$V = \frac{2}{9} g \frac{(d_1 - d_2)}{\eta} r^2$$

where V = velocity of particle (cm/sec)

g = gravitational acceleration (980 cm/sec^2)

d_1 = density of settling particle (g/cm^3)

d_2 = density of fluid medium (g/cm^3)

η = viscosity of fluid medium in poises

r = radius of spherical particle (cm).

Sediment particles, however, differ in several ways from the ideal conditions assumed by Stokes' Law. The particles rarely all have the same density and few are true spheres. For practical reasons, however, a constant density and particle sphericity are usually assumed. Thus the results of particle size analyses by sedimentation techniques are based on hydraulic values rather than on actual dimensions and have a comparative rather than an absolute value.

A number of methods exist for determining the particle size distribution of the fine fraction of a sediment. However, each of the methods suffers from limitations which introduce ambiguity into the data. Some methods have an optimum size range, several necessitate the unavoidable introduction of turbulence into a steady settling state, and others require a large amount of sediment. But perhaps the greatest shortcoming of size analyses procedures in general is that the resulting size frequency curves are usually constructed from relatively few observational data points. This situation, when it exists, is mainly a consequence of the man-hours required to do a more thorough analysis and a sensitivity of the method insufficient to detect small changes in the particle size distribution.

It is often assumed that the distribution of particles in a sediment that is fully adjusted to its environment approaches log normality (Rogers, 1959; Spencer, 1963; Tanner, 1964) or arithmetic normality (Doeglas, 1946; van Andel and Postma, 1954). Only in such a case is a limited number of data points not a serious disadvantage; since a symmetrical distribution requires relatively few data points to fit the curve. If, however, the sediment accumulation results from the mixing of two or more normal distributions, the resulting composite distribution will depart from statistical normality - and be polymodal - a condition that may be common (Curray, 1960; Tanner, 1964; van Andel, 1964). With a large sampling interval naturally occurring modes and the sedimentary components they represent may be overlooked entirely. In a study of the areal distribution of various individual sedimentary components within a basin, a method to determine the particle size distribution with sufficient sensitivity to detect the presence of all the naturally occuring modes within the sample is of great use. It would also be useful to accurately resolve the polymodal frequency distribution into its individual sedimentary components such that the mean and standard deviation of each could be determined. These parameters can be used to trace separate sedimentary components within the basin (Curray, 1960).

This paper describes an electronic sedimentation balance for obtaining a continuous particle size distribution of the less than 62 micron fraction of a sediment, a computer program for processing the raw sedimentation data into cumulative and size frequency curves, and a method for resolving the polymodal size frequency curve into its normal components. The use of this method of analysis is demonstrated in a study of a suite of surface samples from the Northwest Pacific Ocean.

Review of Particle Size Methodology

The historical development of methods of size analyses reflects the diverse techniques various investigators have used in an attempt to obtain precise quantitative expressions of the particle size frequency distribution. With the exception of actually counting and grouping different size particles using a microscope and of dry sieve techniques, most of the methods of particle size analyses deal with material settling from a suspension. For fine sediments, these methods use Stokes' Law to determine the rate at which different size particles settle in a fluid and from this information subsequently obtain the particle size frequency distribution of the sample.

There are two types of particle size determinations which utilize Stokes' Law: those in which the material is physically separated into size fractions, the proportions of which are subsequently determined, and those in which the size fractions are computed from analytical data without actual separation. The first group includes elutriation and decantation. Separation of particles into size classes with the elutriation method involves settling of a sediment suspension in a rising fluid current of constant velocity; particles with settling velocities less than the current velocity will be carried away. This method is most suitable for fine sands and coarse silts but requires great quantities of fluid to achieve the complete separation of various size classes (Gripenberg, 1939).

Decantation involves allowing an originally homogenous suspension to settle for periods of sufficient duration for particles greater than a certain diameter to settle to the bottom. The supernatant liquid is then removed and the procedure repeated until the decanted fluid is clear. This method is effective for the coarse silt fractions but is quite time consuming for smaller grain sizes.

In 1915, Odén (cited in Krumbein and Pettijohn, 1938, p. 157) developed an automatic balance which measured the amount of sediment accumulating with time at a certain depth in a settling column and showed how the cumulative curve could be calculated from the sedimentation curve. Odén's theory of sedimenting systems formed the basis for future indirect methods of size analyses.

A manometric sedimentation apparatus was developed by

Wiegner (1918: cited in Gripenberg, 1939, p. 551). It is based on the determination of the decrease in hydrostatic pressure of a sedimenting suspension with time. The precision of this method is usually low because changes in the level of the manometer fluid are small and can be influenced by variations in air pressure. There also exists the possibility that the manometer fluid and suspension may mix, thus interfering with sedimentation.

The pipette method was developed independently by Robinson (1922) and Jennings, Thomas, and Gardner (1922). In this method the decreasing concentration with time of a suspension is determined by withdrawing a sample at a predetermined depth, drying it and weighing the residue to determine the proportion of particles in the desired size intervals. This method was perfected and thoroughly tested by Hooghoudt (1945: cited in van Andel and Postma, 1954). By virtue of the simple instrumentation required, the mathematical soundness of its theory, and its potentially high reproducibility, the pipette method is widely used. However, the introduction of turbulence during sampling disrupts the steady settling state (Sullivan and Jacobsen, 1958) and the samples are fairly large so that frequent sampling at closely spaced intervals disrupts the settling column. Thus pipette analysis is limited to a small number of measurements spaced about 1 ϕ apart.[1]

Moum (1965) described a falling-drop apparatus for the fine-grained size analysis of up to 20 samples per day. A drop is taken out of a sedimenting system and injected into a column of an organic liquid of slightly lower density. The time required for the drop to fall a certain distance is a measure of its density and hence particle concentration. The small size of the subsamples and the rapidity of sampling introduce minimal disturbance and fairly close-spaced observations can be obtained (up to 0.2 ϕ).

Instead of taking a sample and weighing it, Bouyoucos (1927) used a hydrometer to determine the density of a sedimenting suspension. The rapidity and simplicity of the procedure are reasons for its popularity. The method was perfected by Day (1955) who solved the problem of determining the exact depth at which the density is determined. However, creation of turbulence during insertion results in a relatively large error. Sternberg and Creager (1961) compared the relative efficiencies of the pipette and hydrometer methods and showed that the accuracy of the hydrometer increases with increasing concentration and that within the 6-24 g/l range the pipette method has better reproducibility.

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[1] 1 ϕ = $\log_2$ (diameter is mm); Krumbein (1936).

The photometric method depends on the absorption of light by particles in suspension (Simmons, 1959); the rate of change of absorption is proportional to the settling rate of the particles. This method has the advantage that only a small (0.25 g) sample is required. It is reliable, provided that the relation between the extinction coefficient and the concentration is known for the entire particle range and that the particles are opaque (Sullivan and Jacobsen, 1958).

A more recent method of particle size analysis is the Coulter Counter (Sheldon and Parsons, 1967). It operates on the principle that if an electric field is maintained in an electrolyte, a particle passing into this field will cause a change in electrical properties provided the resistivity of particles and electrolyte differs. The particle will displace its own volume of electrolyte and the recorded change will be proportional to particle volume. Size analyses by this technique cannot be compared to those determined by sedimentation because the Coulter Counter measures particle volume rather than settling rate. It works best in applications where the size variation is small because with a large aperture it is difficult for the instrument to resolve small and large pulses in close succession.

There are numerous variants of these methods. Complete reviews of the theories, variations, and refinements of these methods are presented by Krumbein and Pettijohn (1938, p. 91-181), Gripenberg (1939), Twenhofel and Tyler (1941, p. 46-66) and Sullivan and Jacobsen (1958).

Instrumentation

The instrumentation used in this study to determine the particle size distribution of a sample consists of a Cahn Particle Sedimentation System, a Lauda K-2/RD Constant Temperature Bath and Circulator, and a Leeds and Northrup Speedomax Type W Strip Chart Recorder (Plate 1).

The Cahn Particle Sedimentation System includes a #2800 Particle Sedimentation Accessory and a #200 Model R. G. Electrobalance. The Particle Sedimentation Accessory includes glassware, stirrup assembly, balance pan, and balance stand. The glassware consists of three concentric glass cylinders - an outer thermal bath container, a middle cylinder containing the sedimentation fluid, and an inner tube, 50 mm in diameter and open at both ends, in which particle sedimentation takes place. The stirrup assembly consists of two nylon cords which hang between the inner and middle cylinders and couple the balance pan to the weighing mechanism of the electrobalance. The balance stand serves as a windshield and as a base for the weighing mechanism. An adjustable locating bar on the stand helps to align the cylinders, balance pan, and weighing mechanism. The electrobalance, accurate to $\pm 0.01\%$ of true sample weight, is based on the null-balance principle. As the weight on the settling pan

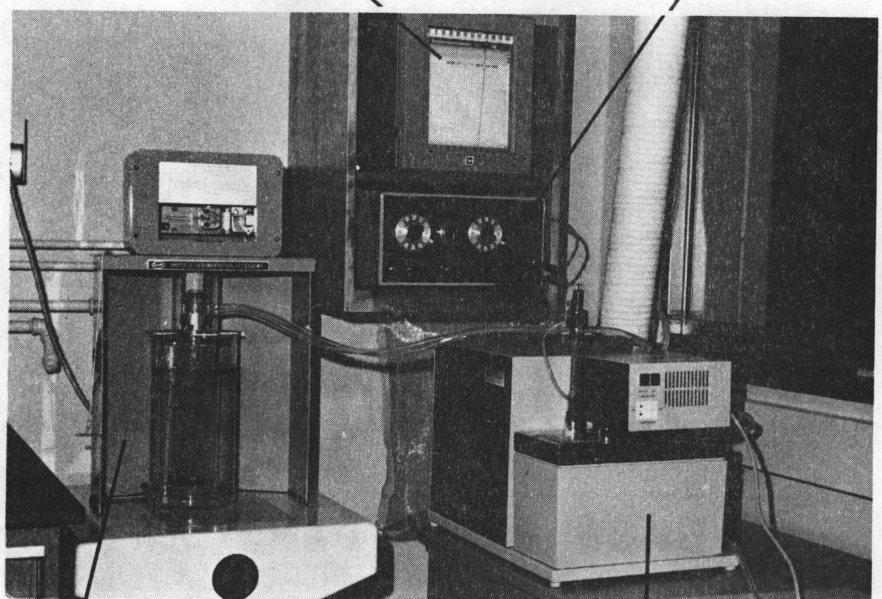

Plate 1. Cahn Particle Sedimentation System.

increases due to sedimenting particles, the beam has a tendency to deflect. This causes a proportional change in light to a phototube and a corresponding change of the phototube current which is amplified,, filtered, and recorded on a strip-chart as a continuous sedimentation curve. As the beam tends to deflect, moreover, the change in the phototube current is applied to a coil attached to the balance beam, which is in a magnetic field. The current in the coil exerts an electromagnetic force on the beam equal to the change in sample weight to restore it to its original position. Thus the beam is always in dynamic equilibrium and appears to be locked in place (Cahn Instrument Co. Electrobalance Manual n. d.). The result of this self-balancing action is that the pan remains stationary and the settling suspension is not disturbed at any time during the analysis. Although a Cahn #1389 External Filter was used to reduce noise, the system is very sensitive to building vibrations. The computer program, however, also filters noise from the data.

A Lauda K-2/RD Constant Temperature Bath and Circulator (Plate 1) accurate to $\pm 0.02^{\circ}C$ was used to maintain a constant temperature within the sedimentation fluid. This control is essential as changes in temperature during an analysis cause changes in viscosity and produces convection currents which affect sedimenting particles (Krumbein and Pettijohn, 1938, p. 102).

Particle Size Analysis Procedure

Samples to be analyzed were treated with buffered (pH 7) 10 percent hydrogen peroxide to disperse the sediment and to remove organic matter, disaggregated with an ultrasonic generator, sieved wet on a 0.062 mm sieve, and washed with filtered distilled water. A 0.1 to 1.0 gram split, diluted to 50 ml in a test tube, is brought to 20.0°C in the water bath. After the balance is calibrated with a 250 mm distilled water sedimentation column, 50 ml of the water is removed with a pipette. The test tube containing the sample is agitated until the sediment is dispersed and the slurry is poured into the top of the settling tube. The suspension is stirred until mixed while the balance pan is held against the bottom of the settling tube. After the suspension is mixed, the stirrup assembly is connected to the weighing mechanism and the recorder actuated. The turbulence created by stirring ceases in a few seconds. The accumulating sediment weight is then recorded as a function of time. The sedimentation data is recorded continuously, automatically, unattended, and without disturbances to the settling suspension. The settling time required to determine the size distribution of the 4 to 9 ϕ fraction of a sample is 20 hours and 20 minutes although the time can be reduced if a shorter column is used; however, this reduces the resolution at the coarse end of the size range.

Computer Analysis

As sedimentation proceeds, all particles of a given sedimentation radius[2] settle at the same rate. At any given time, the amount of sediment which has settled onto the balance pan consists of those fractions which have had time to settle out completely and portions of those fractions which have not completely settled out due to their smaller size, and hence slower settling time.

Odén (1915) has shown that the sum of the partially sedimented fractions at any point on the sedimentation curve is equal to the first derivative of the total amount (P) which has settled onto the balance pan ($\frac{dp}{dt}$) multiplied by the settling time (t). If this differentiation is carried out at a series of settling time intervals, a cumulative curve can be constructed. A computer program for the Control Data Corporation 3300 Computer and written by Dr. G. Ross Heath, Department of Oceanography, Oregon State University, performs this operation and differentiates the cumulative curve to obtain the size frequency curve and computes the moment, Inman (1952) and Folk and Ward (1957) statistics for each sample.

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[2] Sedimentation radius is the radius of a sphere of the same specific gravity and of the same terminal uniform settling velocity as a given particle in the same sedimentation fluid (Wadell, 1934).

It is desirable to use a small class interval of the particle size distribution in order to achieve maximum resolution of the particle size distribution. The sediment weights, therefore, were obtained from the sedimentation curve at 1/10 ϕ intervals from 4.0 to 9.0 ϕ for a total of 51 data points for each sample. The times (t) in minutes at which the readings were obtained were calculated from an expression of Stokes' Law:

$$D = \left(\frac{K}{t}\right)^{1/2}$$

where D is the diameter in microns and K is a system constant which need only be determined once for each set of instrument conditions (Ventron Instrument Company Bulletin 122 A). Here

$$K = \frac{0.3\ h\ \eta\ 10^8}{(d_p - d_l)g}$$

where,

h = column height in cm (25.0)

η = viscosity of the sedimentation fluid in poises at 20^oC (0.01005 for distilled water)

d_p = assumed density of particle in g/cm^3 (2.65)

d_l = density of sedimentation fluid in g/cm^3 at 20.0^oC (0.99823 for distilled water)

g = acceleration due to gravity in cm/sec^2 (980)

substituting,

$$K = \frac{(0.3)\ (25.0)\ (0.01005)\ 10^8}{(2.65 - 0.99823)\ 980} = 4656.415 \text{ minutes x microns}^2$$

for this system. From 9.0 to 16.0 ϕ, the curve is an extrapolation of the trend indicated by the last three data points (i. e., 8. 8, 8. 9, and 9. 0 ϕ) and is not representative of the true distribution. Consequently, the subsequent discussion is limited to the 4. 0 to 9. 0 ϕ range of actual data.

The raw data are reduced to cumulative and frequency distributions (Figure 1) by numerical differentiation of a cubic spline fit curve. Basically, the spline fit curve is constructed by fitting cubic curves to successive triplets of data points (yielding 49 cubic equations for the 51 data points between 4 and 9 ϕ), then joining the curves so that the entire spline curve is differentiable twice, and its curvature is minimized. This operation, performed on a CDC 3300 computer, eliminates the graphical procedures previously used to extract frequency distributions.

In practice, noise in the raw data is magnified by differentiation, and it was found necessary to require that the slope of the cumulative curve be non-negative (i. e. $C_n \geq C_{n-1}$) and to smooth the cumulative distribution by use of a five point moving average. After differentiation of the smoothed cumulative curve, the frequency curve is also smoothed with a five point moving average, to reduce spikiness and eliminate negative frequency values.

If any of the modes on the size frequency curve are sharply pointed, additional smoothing can be performed at the discretion of the investigator by the computer by specifying an arbitrary

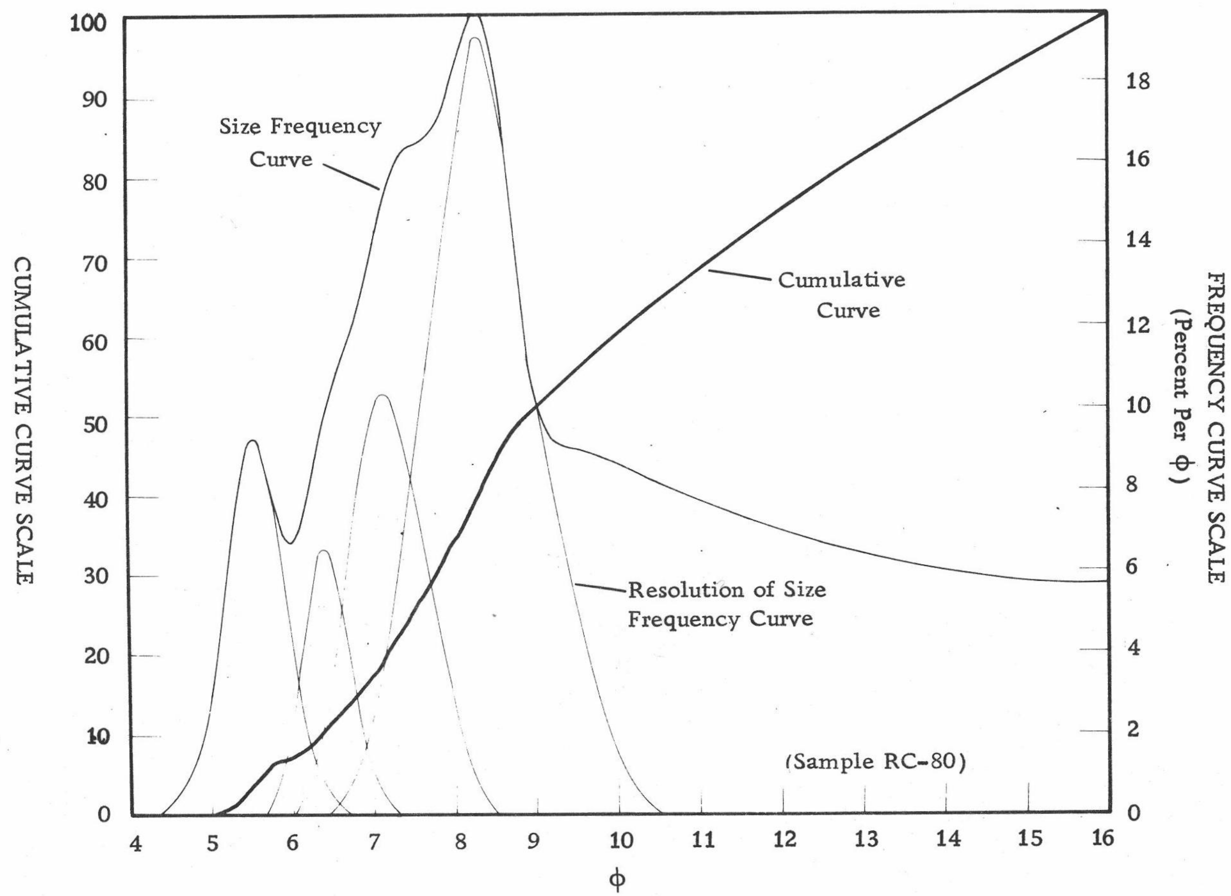


Figure 1. Computer generated cumulative curve and resolved frequency curve.

"smoothing factor" which reduces the overall curvature of the spline fit curve (Figure 2). The additional smoothing, however, will not only reduce peakedness but can also remove small shoulders in the frequency curve. It is essential, therefore, that the same smoothing factor be used for all samples from any one study so that the final size frequency curves reflect uniform processing procedures and permit comparison of the modal characteristics from sample to sample. A smoothing factor of 1.5 was used on the curves presented in this paper.

Reproducibility

Inman (1952) showed that, statistically, the median diameter of a sediment distribution is more reproducible than smaller or larger ϕ diameters, and Royse (1970) has suggested that the median diameter may therefore be taken as an index of the maximum reproducibility of the size analysis method. Careful pipette analysis, has a reproducibility of the median diameter of ± 0.2 ϕ units.

To test the reproducibility of the method described here, two splits of sample 1013-B and a rerun of split #1 were analyzed with the Cahn System (Figure 3, Table I). The Inman median values for different splits of the same sample are within 0.02 ϕ units, and the particle size distributions are quite similar. The slight shift of modes may reflect the precision of the system or the physical effect

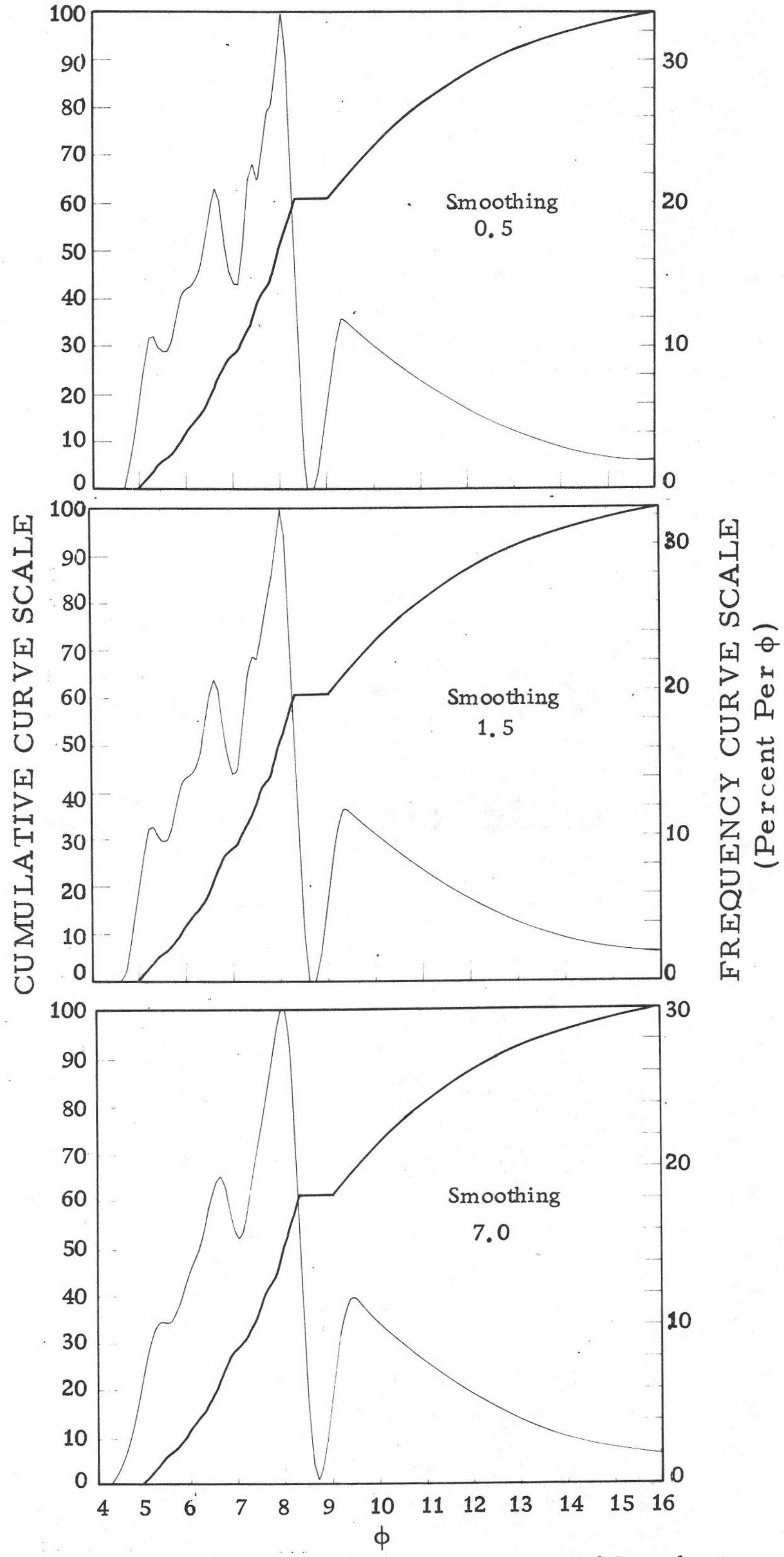


Figure 2. Effect of various smoothing factors on same sample.

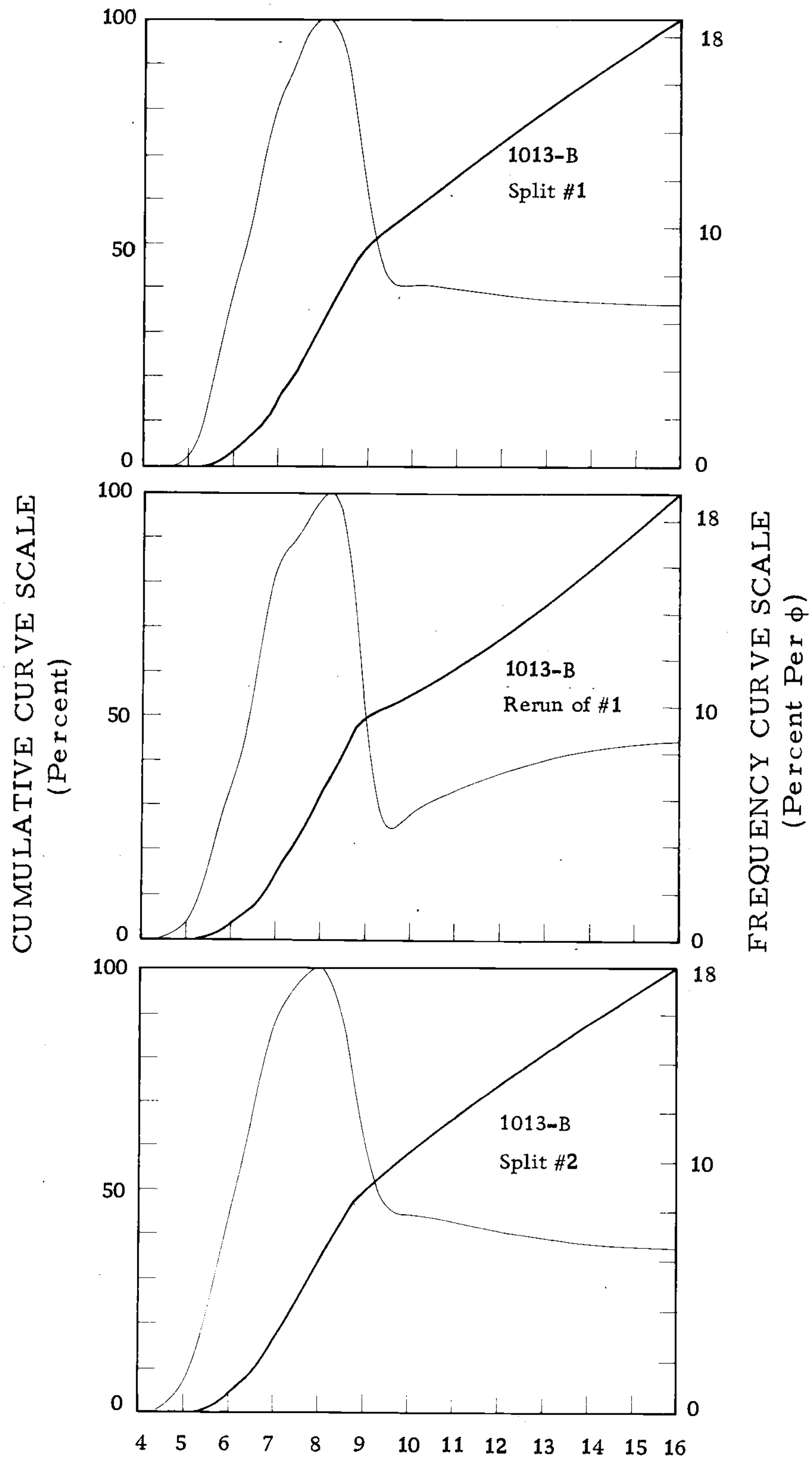


Figure 3. Cumulative and size frequency curve of three runs of same sample.

of repeated candle-filtering and washing.

Table I. Reproducibility of mean size.

Sample	Inman Median Value (ϕ)
1013-B (1)	9.14
Re-run (1)	9.16
(2)	9.14

Resolution of Size Frequency Curves

If a particle size distribution approximates a Gaussian distribution, statistical moment measures or their graphical approximations can be used to describe deviations of the curve from normality (Inman, 1952; Folk and Ward, 1957). If, however, the sediment results from the mixing of two or more normally distributed sedimentary components, the composite curve is no longer Gaussian but rather represents the sum of two or more normal distribution functions with various means, dispersions, heights, and areas. Depending on the mean position and relative sizes of each component, the composite may be markedly polymodal. The use of moment measures or their graphical approximations to describe such a composite distribution is not a statistically valid technique (McCammon, 1962; Sharp and Fan, 1963; van Andel, 1964; Tanner, 1964). Instead sediment is best described by resolving the composite distribution into its several normal components and determining the statistical parameters of each component (Curray, 1960; Folk and Ward, 1957; Harris, 1958). Generally, graphic methods (Harding, 1949; Cassie, 1954) on probability paper have been used to resolve polymodal frequency curves into their normal components. This is acceptable if the modes are distinct but loses precision in direct proportion to the amount of overlap between component distributions. In this study, an analog computer capable of generating composite curves from individual predetermined distributions is used.

The Du Pont 310 Curve Resolver is an analog computer specially designed to resolve overlapping peaks in experimental curves (Müller, 1966). The system utilizes a series of up to ten function generator channels which can be programmed with Gaussian, Lorentzian, Poisson, or other symmetrical distribution functions. For the purpose of this study, the channels were programmed with Gaussian distributions because individual sedimentary components have normal distributions Curray (1960). Each of the ten channels has a control module for the individual adjustment of the height, width, baseline position, and skewness of its curve.

Resolution of a polymodal curve into its components by this method is an operationally straightforward procedure. The image of the curve to be resolved is projected by mirrors on an oscilloscope screen. The operator estimates how many components exist in the composite curve and activates a like number of function-generator channels. The computer electronically sums the generated peaks and displays them on the screen. The operating controls for each channel are used to adjust the baseline position, height, and width of each component distribution independently. This procedure is continued, and channels added or deleted, until the synthetically generated curve is exactly superimposed on the projected data curve. After the curve is fitted, each component curve can be presented separately for analysis and an integrator simultaneously indicates what percentage of the total area of the composite curve is contributed by each component. A resolution of a size frequency curve is shown in Figure 1.

Some of the polymodal size frequency curves were resolved at several different times to determine the repeatability of the technique in the absence of operator bias. Although it was possible, in some cases, to change the widths and heights of the component curves slightly, the number of modes and their means remained fixed. It may be noted, however, that by this approach no absolute proof exists that a unique solution was obtained. Because of the additivity effect of the different shaped overlapping curves, the apexes of the resolved curves do not always lie exactly beneath the modes of the frequency curve. This casts doubt on the validity of the usual procedure of determining the positions of individual modes by visual inspection (for example, Curray, 1960).

SEDIMENTARY COMPONENTS OF NORTHWEST PACIFIC PELAGIC SEDIMENTS

Mineralogy of Northwest Pacific Sediments

The deposition of sediments in the northwest Pacific is influenced by volcanic activity along the western and northern margins, the presence of marginal trenches preventing passage of coarse terrigenous material to the central region, and by the relatively small size of direct influx of river water into the Pacific Basin. The large rivers, rather than emptying directly into the Pacific, discharge into contiguous but separate settling basins. The sediments, thus protected from turbidite and hemipelagic deposition, are derived from fine particles which settled out or were precipitated from the overlying water column and are true pelagic deposits. In these deposits, the relative amounts of clay minerals are related to the sources and transport paths of solid phases from the continents and to the injection of volcanic materials (Griffin et al., 1968).

The sediments of the northwest Pacific represent material derived from a number of different source areas and are introduced by a variety of processes. The evidence that one of these processes is wind transport is extensive (Rex and Goldberg, 1958; Hurley et al., 1959, and Rex et al., 1969). Volcanic ejecta of the circum-Pacific volcanic belt constitute an important part of the wind transported material. Horn et al. (1969) found distinct ash layers in cores obtained 800 miles seaward of the volcanic island arcs and continents. The percentage contribution of volcanic ash to the sediment, however, is difficult to establish due to its susceptibility to alteration.

Griffin and Goldberg (1963) show that, while illite is ubiquitous in the north Pacific, the amount of montmorillonite, chlorite, and kaolinite is a function of location - the montmorillonite being most abundant near Asia, chlorite increasing in abundance with latitude, and kaolinite being confined to near-shore environments. Oinuma and Kobayashi (1966) confirm this and show that illite increases westward as a result of its introduction into the East China Sea by the Yellow and Yangtze Rivers of northeast China. The quartz content of pelagic sediments is in large part of eolian origin, especially in coarser size fractions, but much of the finer-grained quartz together with suspended clay minerals may be transported via sea water from the continents to pelagic areas of deposition (Arrhenius, 1963). This is confirmed by the occurrence of quartz and feldspar, together with other minerals, suspended in seawater near Japan and in the East China Sea (Ishii and Ishikawa, 1964). Finally, the pelagic sediments contain biogenous components which are coarsest along the Equator and in shallow areas (Arrhenius, 1963).

Thus the sediment at a given location may consist of a number of independent sedimentary components representing different source areas and modes of transportation. Even when subsequently mixed, individual components tend to retain their original size distribution characteristics (mean, standard deviation, etc.) which can be used to identify and trace the sediment (Curray, 1960).

Particle Size Distributions of Northwest Pacific Sediments

The methods previously described were used to study twelve surface sediment samples collected between Hawaii and Japan (Figure 4). Samples prefixed by "J" were collected on the Japanyon Expedition (Scripps Institution of Oceanography, 1961) and the RC-80, 1013-B, 1019-9, and 1019-10 samples on U. S. Naval Oceanographic Office surveys of 1968 and 1969.

The geographic position and water depth of samples are listed in Appendix I, cumulative curves, particle size frequency curves, and resolutions of the polymodal distributions are presented in Appendix II. Limbs of several of the resolutions are outside the coarse flank of the size frequency curve. This situation exists because the computer program was written to process raw data of both coarse and fine-grained size analysis and then to subsequently smooth the join. Because the study was restricted to the fraction 2-62 microns, the coarse flank of the size frequency curve is slightly over-smoothed.

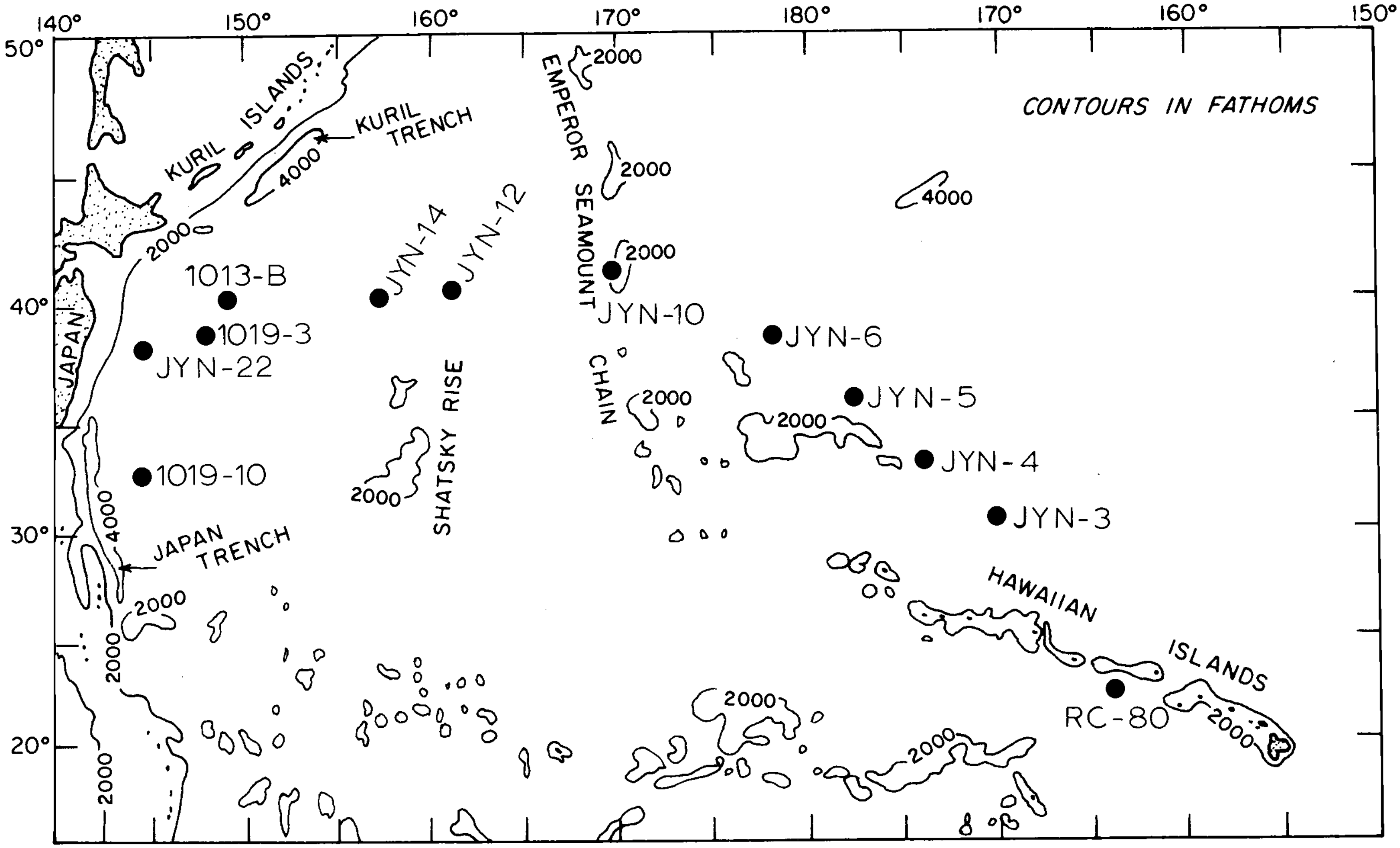


Figure 4. Sample locations.

Statistics of Sedimentary Components

If a particle size frequency curve approaches a Gaussian distribution, moment measures, or their graphical approximations, can be used to describe deviations from normality. The mean, standard deviation, skewness, and kurtosis of a distribution are used as measures of the average grain size, particle size dispersion, asymmetry, and peakedness, respectively, of the frequency curve. If, however, the distribution departs significantly from a normal curve, these mathematical parameters are no longer relevant. In such a situation, it may be informative to examine the separate sedimentary components of the sample rather than the sum of the components.

In Folk and Ward's (1957) terminology, most of the samples of this study are very poorly sorted (Appendix III). On the other hand, the individual component distributions of these composite curves are moderately to well sorted, using the distance from the mean of each distribution to the inflection points on the limbs as a standard. The estimated standard deviations of the component distributions is smallest for samples collected near Japan and generally increase eastward. The smallest value found is 0.3 for five of the components in sample Jyn-22 while the components comprising samples Jyn-4 and Jyn-5 have the largest standard deviation with a value of 0.87 (ranges 0.8-1.0 and 0.8-0.9, respectively). The components of the sample collected nearest to Hawaii, RC-80, have an average standard deviation value of 0.45 (range 0.3-0.6).

Three to five sedimentary components are found in the 4 to 9 ϕ size interval of each sample. The number of components within a sample is generally highest off Japan, decreases eastward, and then increases again toward the Hawaiian Platform (Figure 5). A slight negative linear correlation, significant at the 5% level, exists between the number of components and distance from land (r^2 = 16%; number of samples, 27).

The mean of each component is influenced by the size range of the source material and efficiency of the transporting medium. Samples Jyn-6, 5, 4, and 3 have no component with a mean diameter coarser than 6 ϕ (Figure 6), RC-80 collected near the Hawaiian Islands, has one component with a mean coarser than 6 ϕ, and 1019-10, 1019-3, 1013-B, Jyn-22, Jyn-14, Jyn-12, and Jyn-10, which are closest to Japan, have either one or two components with a mean coarser than 6 ϕ.

Although exceptions exist, the components with the coarsest mean constitute the smallest percentage of the 4 to 9 ϕ fraction of the sample. Conversely the component with the finest mean usually constitutes the largest percentage. However, the analysis was only carried out between 4 and 9 ϕ and the percentage contribution of the finest component (8 to 9 ϕ) would be reduced if the next finer (i.e.,

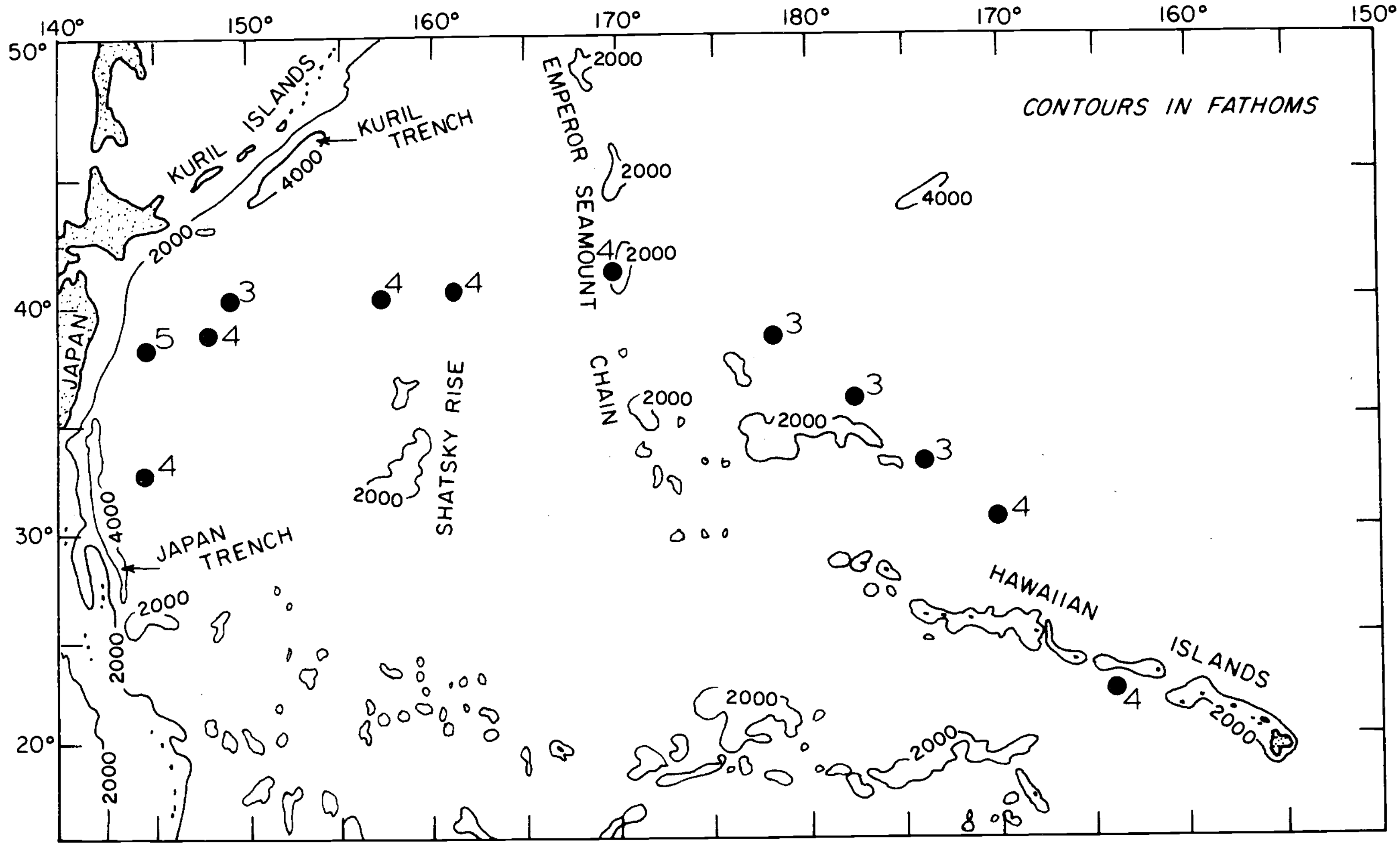


Figure 5. Number of sedimentary components within the samples.

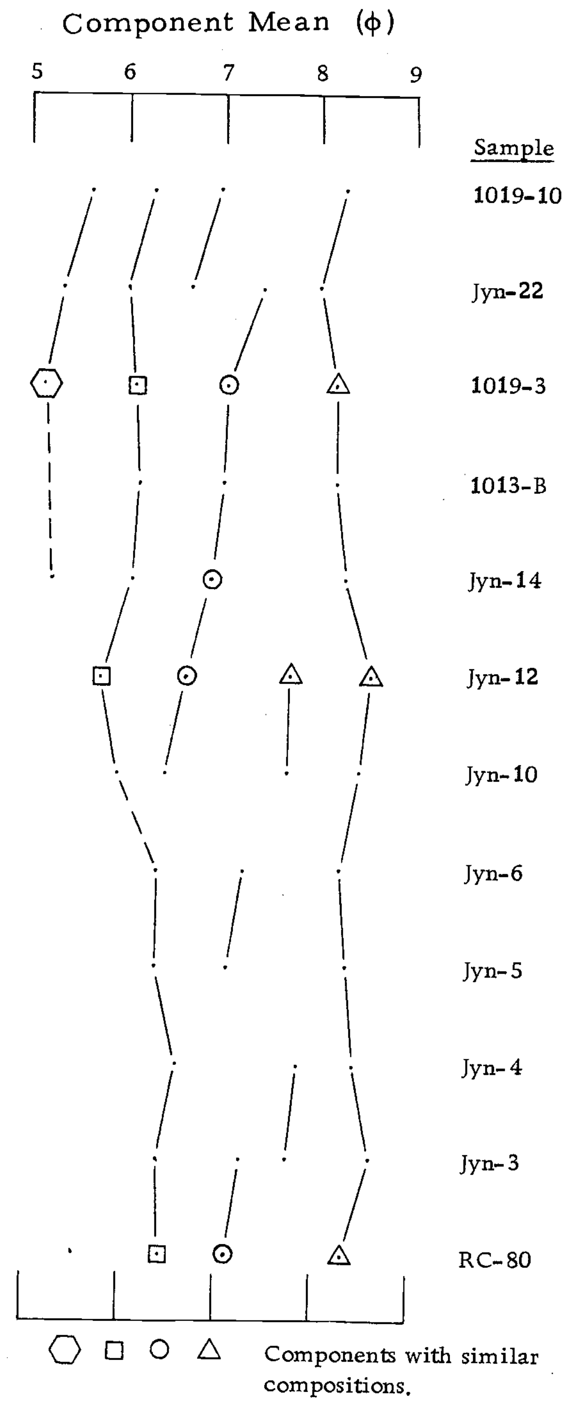


Figure 6. Distribution of sedimentary components between Hawaii and Japan.

mean $\gg 9\ \phi$) component were taken into account.

Mineralogy of Individual Modes

If the components of a samples' particle size frequency curve represent distinct and separate sedimentary contributions to the sediment, then the mineralogy of a component may be expected to be distinct from other components of the same sample. Most of the components overlap to such a degree that it is impossible to sample them in a reasonably pure state. Several samples, however, had modes which are relatively free from overlap. In these samples a size interval corresponding to each of these components was isolated by decantation and used to determine its composition (Table II). The interval was chosen to include the mean of the component and to minimize overlap. Each size limit was decanted five times until the supernatant water was clear, when separation was assumed to be reasonably complete.

Microscope slides were made of all the decanted intervals, and the crystalline material in each mode was identified using X-ray diffraction techniques (Rex, 1969). The coarse material decanted from component #1 of samples 1019-3, Jyn-12, and RC-80 was ground for two hours under water in a Fisher grinder. Sediment from the other modes was used without further preparation. The decanted sediment was dried, mounted on planchets, and X-rayed with copper K-alpha

Table II. Decanted interval of components.

Sample	Mode No.	Mean Size of Component ϕ	Interval Decanted (ϕ)
1019-3	1	5.25	4.3 - 5.6
	2	6.10	5.6 - 6.6
	3	7.10	6.6 - 7.5
	4	8.19	8.0 - 8.5
Jyn-14	3	6.90	6.8 - 7.3
Jyn-12	1	5.75	5.0 - 6.0
	2	6.66	6.4 - 6.9
	3	7.73	7.6 - 7.9
	4	8.55	8.4 - 8.7
Jyn-5	2	7.10	6.9 - 7.5
	3	8.37	8.3 - 8.8
RC-80	1	5.52	5.0 - 5.8
	2	6.42	6.0 - 6.7
	3	7.14	6.9 - 7.3
	4	8.34	8.3 - 8.7

radiation.

The method used to identify the minerals present and to determine their relative abundances is that described by Rex (1969). The minerals identified in each of the intervals and their relative percentages are listed in Table III.

Several facts are readily apparent from Table III. Calcite appears only in components 2 and 3 of Jyn-5. Microscopic analysis of mode 2 of Jyn-5 revealed that it consists almost entirely of one species of coccolith, <u>Coccolithus</u> <u>pelagicus</u> (Plate 2). Mode 3 of Jyn-5 also has coccoliths present, but in a much lesser amount. This is probably due to overlap with mode 2 or possibly to the fact that the size distribution of the coccoliths may be skewed towards the fines due to the presence of immature plates or fragmentation and dissolution of mature plates.

Also evident from Table III is that the percentage of quartz varies little within the components sampled with the exception of low values in Jyn-5 and in the first two modes of RC-80 which was obtained near Hawaii and is rich in feldspar.

The values of feldspar, kaolinite and mica show significant variations from mode to mode and also from sample to sample. When the relative percentages of these three minerals are plotted on a ternary diagram, several distinct groupings occur (Figure 7). This fact together with the observation that the mean size values of

Table III. Mineralogy of isolated modes.

Sample	Mode No.	Quartz	Feldspar	Kaolinite	Mica	Chlorite	Calcite
1019-3	1	49	41	5	5		
	2	47	33	8	8	4	
	3	51	23	11	11	4	
	4	50	16	17	12	5	
Jyn-14	3	52	23	11	10	4	
Jyn-12	1	58	28	7	7		
	2	47	21	12	15	5	
	3	52	20	17	11		
	4	51	19	21	9		
Jyn-5	2	17	5	7	5		66
	3	26	6	13	9		46
RC-80	1	20	80				
	2	36	46	9	9		
	3	44	28	15	13		
	4	52	15	13	13	7	

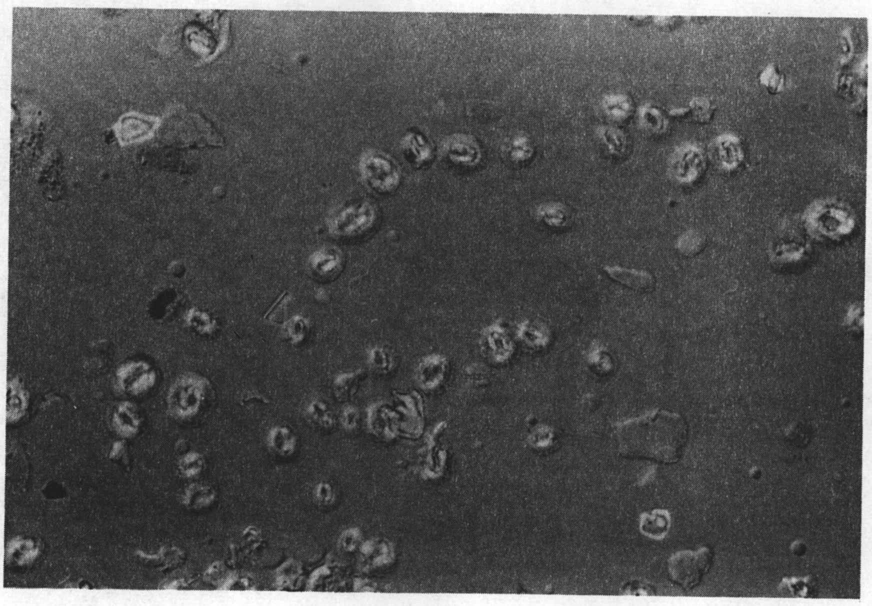
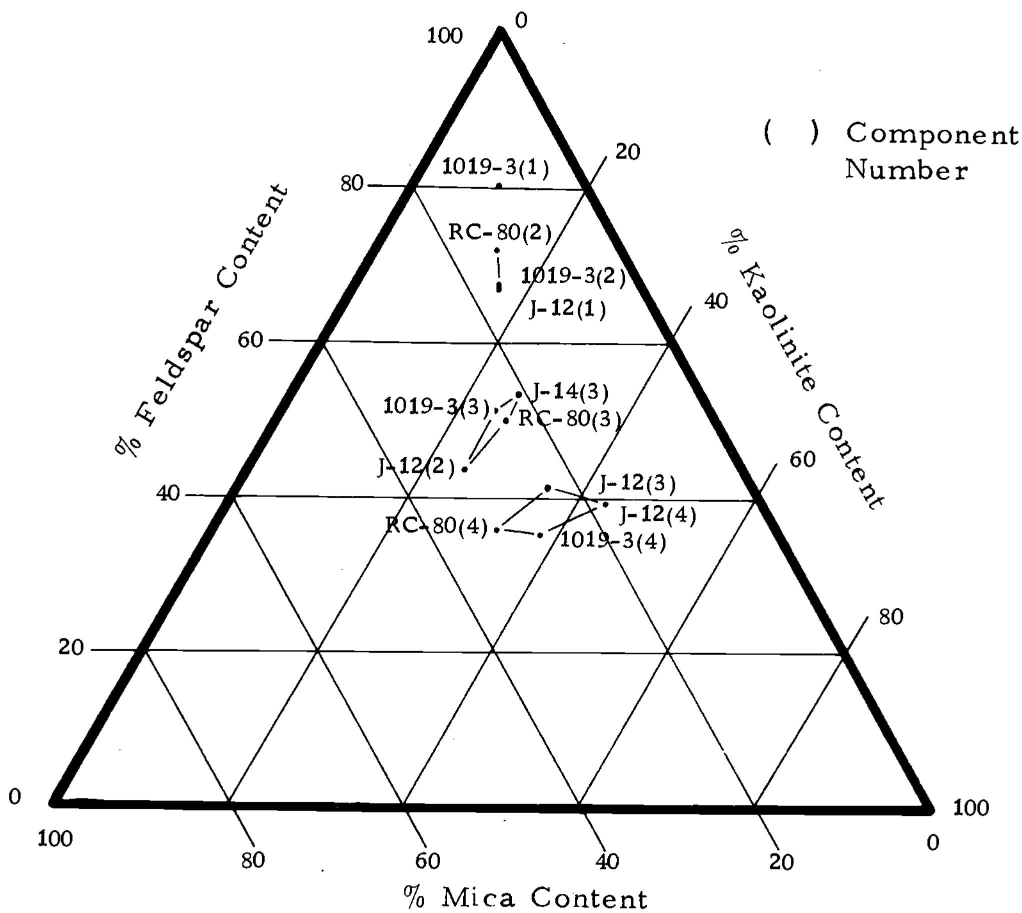


Plate 2. Photo-micrograph of sedimentary component 2, sample Jyn-5. Component consists predominantly of <u>Coccolithus</u> <u>pelagicus</u>.



Compositional groupings:

1. RC-80(2)	2. Jyn-14(3)	3. Jyn-12(3)
1019-3(2)	1019-3(3)	Jyn-12(4)
Jyn-12(1)	RC-80(3)	RC-80(4)
	Jyn-12(2)	1019-3(4)

Figure 7. Groupings of sedimentary components based on similar composition.

all the components in any one group are nearly identical indicates that the same sedimentary component can be identified and traced from sample to sample.

Although the relative abundances of certain minerals can be used to categorize the components, amorphous phases constitute a large proportion of the particles within the components. A random count of 100 particles from modes one and two of samples 1019-3, Jyn-12, and RC-80 showed that between 42 and 58% of the grains are volcanic glass.

Discussion

If the sedimentary components within a sample were free from overlap of adjoining components, it would be possible to sample them, determine their composition, and subsequently map the areal distribution of each. Unfortunately most of the components overlap. Although it is impossible with the available data to describe definitively the distribution of the components, the similarity and the mean sizes of the components allow some inferences regarding their distribution between Japan and Hawaii.

The fact that a slight, yet statistically significant, negative linear correlation exists between the number of components within a sample and distance from land, and that components with the coarsest means are confined to areas near land suggests that these components represent local eolian or river input. Component 1 of RC-80 consists mostly of volcanic glass and feldspar and probably represents a local volcanic contribution to the sediment.

Component 1 of 1019-3 consists of volcanic glass, quartz, feldspar, kaolinite, and mica. The mean of this component is quite similar to that of mode 1 of Jyn-22, 1019-10, and Jyn-14; these modes probably all represent the same sedimentary component (Figure 6).

Components 2 of 1019-3 and RC-80 and component 1 of Jyn-12 have similar mineralogy and mean size; possibly, this component can be traced in all samples (Figure 6).

Modes 3 of RC-80, 1019-3, and Jyn-14 and mode 2 of Jyn-12 likewise have a similar composition (Figure 7). The means of mode 4 of Jyn-22, modes 3 of 1019-3, 1013-B, and Jyn 14, and mode 2 of Jyn-12 and Jyn-10 show a systematic change and probably represent the same sedimentary component. The mean size of this component is coarsest near the crest of the Emperor Seamounts and becomes progressively finer toward Asia. It appears doubtful that the component can be traced to mode 3 of RC-80 near Hawaii.

Mode 2 of Jyn-5 consists almost wholly of coccoliths and undoubtedly represents a biogenous contribution to the sediment which can be traced to Jyn-6.

The composition of modes 4 of 1019-3, Jyn-12, and RC-80 are all similar in composition (Figure 7). The mean value for the finest mode of all the samples varies from 8.0 to 8.6 ϕ (Figure 6). This median value corresponds quite closely to the global eolian component of Windom (1969). It is interesting to note that although the mean value varies somewhat, the variation is gradual from sample to sample.

The remaining modes were not sampled and can only be traced short distances on the basis of the similarity of their means. They may represent local volcanic activity, biogenous contribution, or possibly a reworking of other components present in the sediment.

Conclusion

A method of size analysis of the fine fraction of deep-sea sediments and an example of the use of the procedure to define and trace sedimentary components within a depositional basin have been described. Instrumentation of sufficient sensitivity to detect small changes in the size distribution, and the use of closely-spaced observations in the analysis to eliminate the possibility of missing sedimentary components are important elements of this procedure.

The computer-generated size frequency curves of northwest Pacific particle size distributions are polymodal. A specially designed analog computer was used to resolve the polymodal frequency curve into its normally distributed components. Some of the components for which overlap is minimal were decanted and their composition determined. Several groups of components with a similar composition were found. One component was found to consist almost entirely of one species of coccoliths.

Components of similar composition which have nearly identical or systematically varying mean size values can be identified in different samples. The components within a sample may represent widely different origins and distributing agents. The use of the procedures described in this paper enables the sedimentologist to identify, examine, and trace the separate components of pelagic sediments.

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APPENDICES

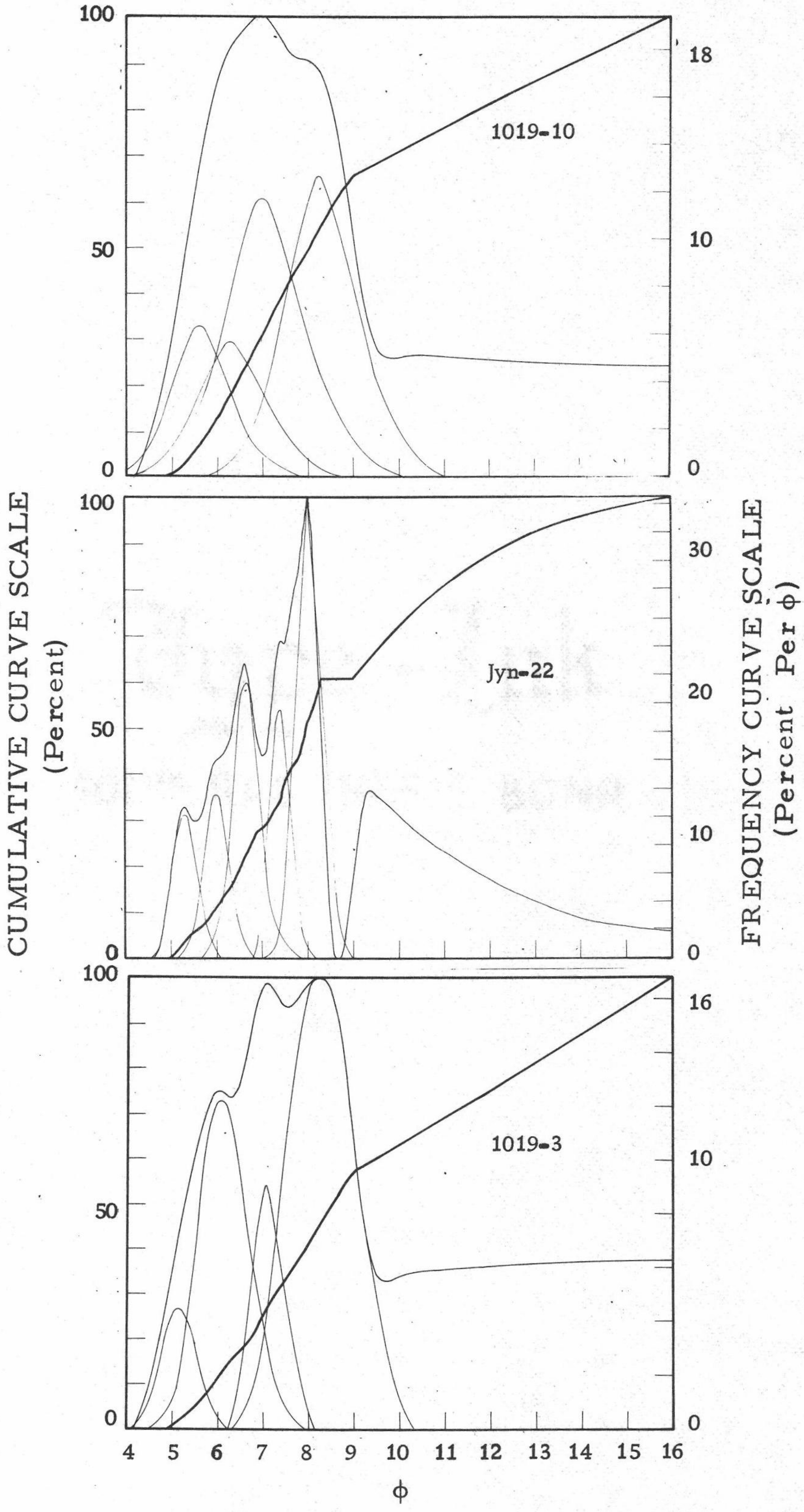
APPENDIX I

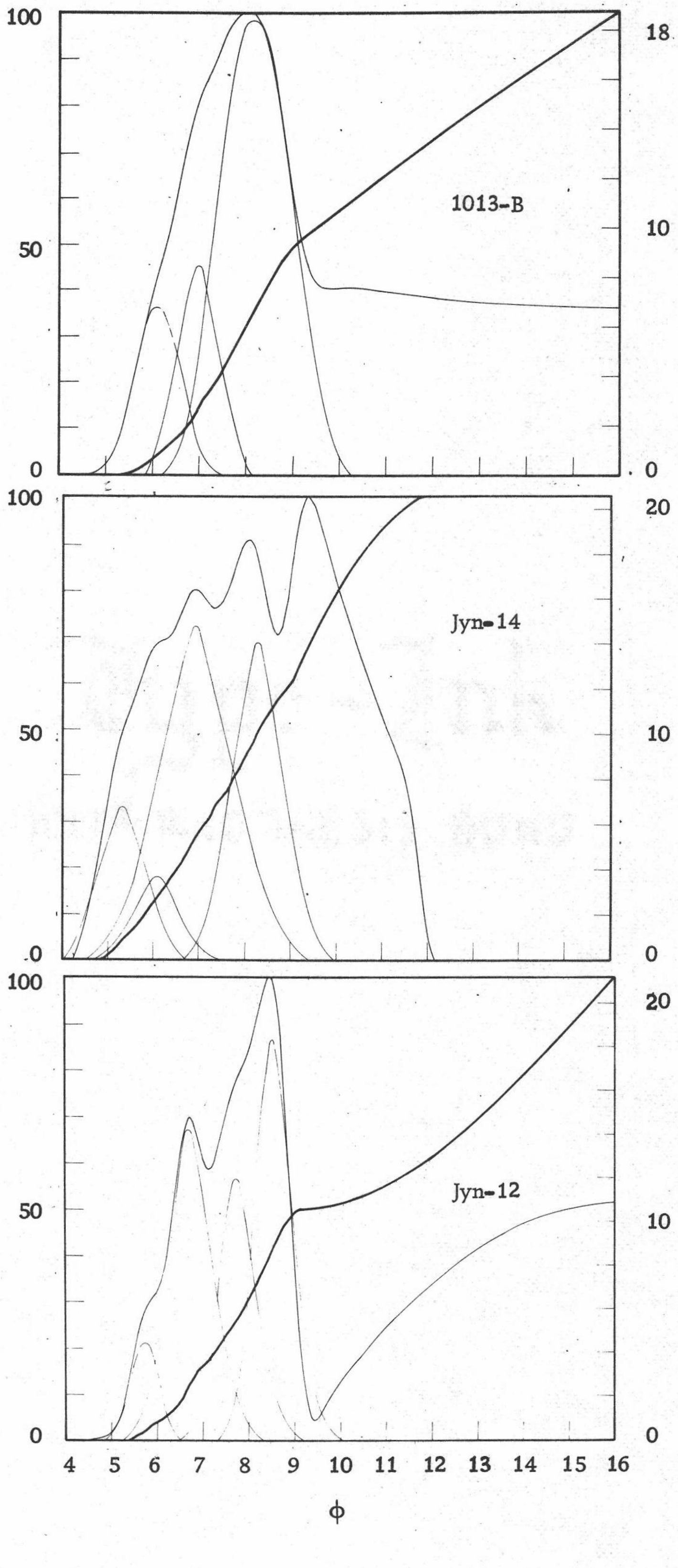
Sample Locations

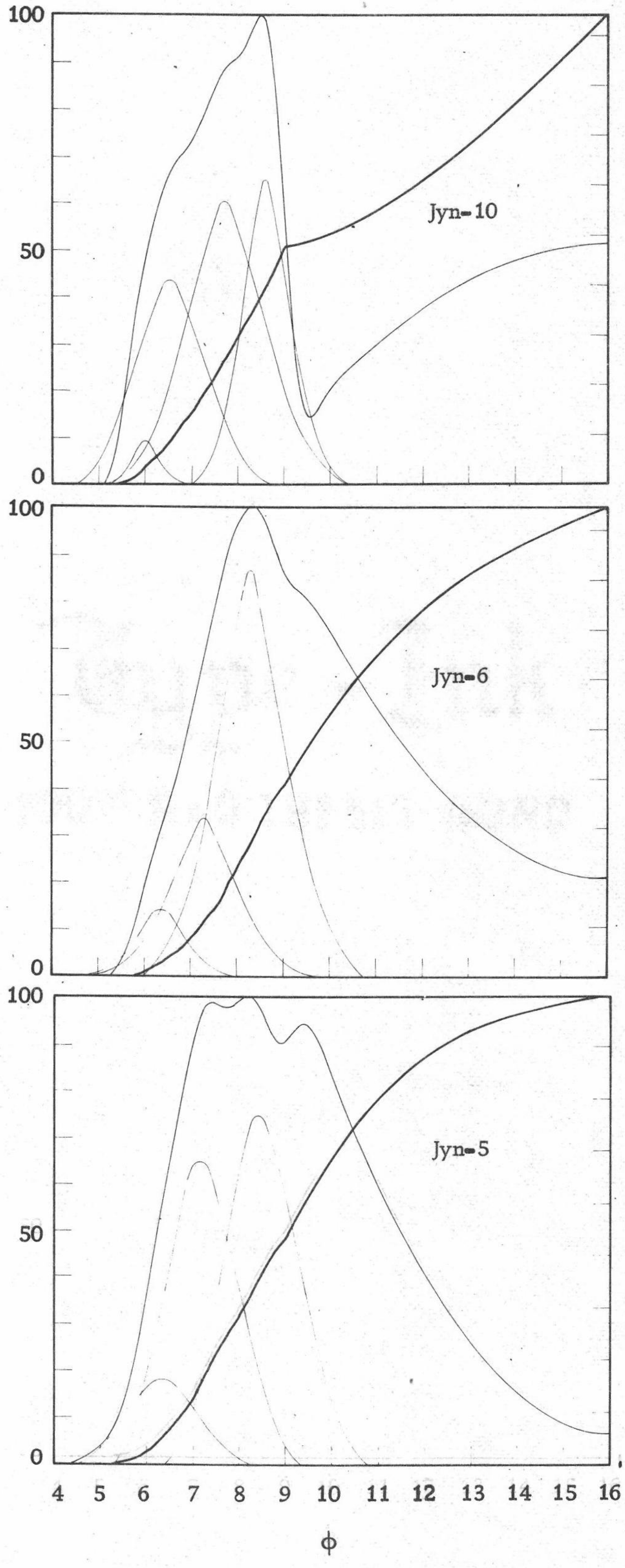
Sample	Latitude	Longitude	Water Depth (meters)
1019-10	32°14'N	144°31'E	5780
JYN-22	37°21'N	144°30'E	5650
1019-3	38°00.5'N	147°46'E	6172
1013-B	39°21.5'N	148°59'E	5596
JYN-14	39°19'N	156°57'E	5635
JYN-12	39°47'N	160°53'E	5510
JYN-10	40°30'N	169°48'E	5550
JYN-6	37°56'N	178°10'E	5250
JYN-5	35°25'N	177°43'W	4320
JYN-4	33°04'N	174°15'W	5530
JYN-3	30°19'N	170°21'W	5490
RC-80	22°10.5'N	163°50'W	4720

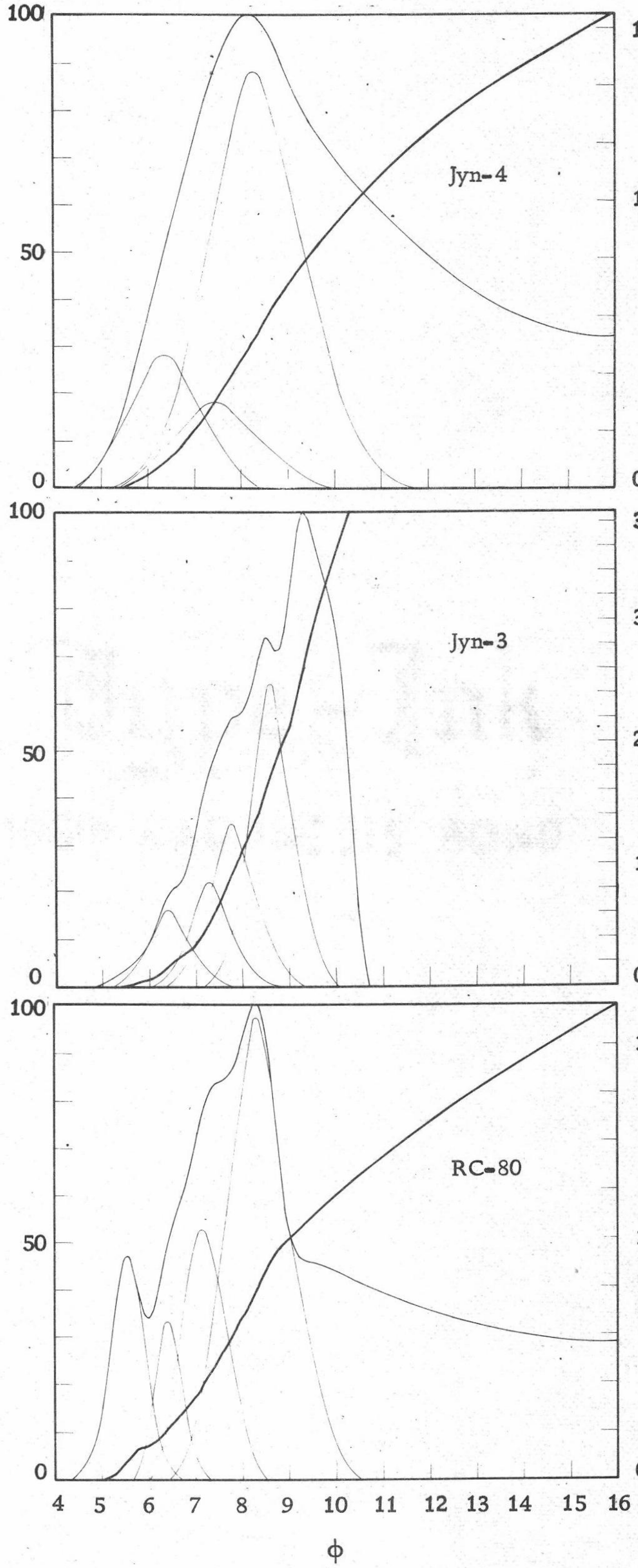
APPENDIX II

Cumulative and frequency curves of the particle size distributions. Normal resolutions of the size frequency curves.


CUMULATIVE CURVE SCALE
(Percent)
FREQUENCY CURVE SCALE
(Percent Per ϕ)
1019-10
Jyn-22
1019-3
100
50
0
18
10
30
20
16
4
5
6
7
8
9
10
11
12
13
14
15
16
ϕ


100
50
0
18
10
0
1013-B
100
50
0
20
10
0
Jyn-14
100
50
0
20
10
0
Jyn-12
4 5 6 7 8 9 10 11 12 13 14 15 16
φ


100
50
0
18
10
0
Jyn-10
100
50
0
18
10
0
Jyn-6
100
50
0
16
10
0
Jyn-5
4 5 6 7 8 9 10 11 12 13 14 15 16
φ


100
50
0
16
10
0
Jyn-4
100
50
0
38
30
20
10
0
Jyn-3
100
50
0
18
10
0
RC-80
4 5 6 7 8 9 10 11 12 13 14 15 16
ϕ

APPENDIX III

Sample Statistics

Sample	Folk and Ward Sorting	Mode No.	Mean ϕ	Estimated Standard Deviation	Relative Percentage of Mode
1019-10	3.07	1	5.60	.7	14.5
		2	6.25	.7	15.0
		3	6.96	.7	36.5
		4	8.25	.8	34.0
JYN-22	2.57	1	5.31	.3	10.5
		2	5.98	.3	12.5
		3	6.65	.3	24.5
		4	7.40	.3	16.5
		5	8.00	.3	36.0
1019-3	3.28	1	5.15	.4	5.0
		2	6.10	.5	29.5
		3	7.06	.4	14.0
		4	8.20	.8	51.5
1013-B	3.06	1	6.10	.5	14.0
		2	7.00	.5	17.0
		3	8.18	.9	69.0
JYN-14	1.89	1	5.22	.5	14.0
		2	6.06	.5	8.0
		3	6.90	.7	48.0
		4	8.27	.5	30.0
JYN-12	3.33	1	5.75	.3	6.0
		2	6.66	.4	34.0
		3	7.73	.4	24.0
		4	8.55	.4	36.0
JYN-10	3.27	1	5.91	.3	2.5
		2	6.41	.9	27.5
		3	7.68	.9	42.0
		4	8.46	.6	28.0
JYN-6	2.53	1	6.34	.6	8.0
		2	7.26	.7	27.0
		3	8.25	.8	67.0
JYN-5	2.23	1	6.33	.9	12.0
		2	7.10	.8	41.0
		3	8.37	.9	47.0

Sample	Folk and Ward Sorting	Mode No.	Mean ϕ	Estimated Standard Deviation	Relative Percentage of Mode
JYN-4	2.82	1	6.36	.8	17.0
		2	7.44	.8	13.0
		3	8.28	1.0	70.0
JYN-3	1.14	1	6.40	.5	11.0
		2	7.27	.5	15.0
		3	7.75	.5	27.5
		4	8.62	.5	46.5
RC-80	3.07	1	5.52	.4	15.0
		2	6.42	.3	8.5
		3	7.14	.5	21.5
		4	8.34	.6	55.0