DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

# A review and comparison of the hydrophotometer and pipette methods in the analysis of fine-grained sediment

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Open-File Report 87-514

August 1987



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## ABSTRACT

Fifty-nine detailed hydrophotometer analyses and twelve pipette analyses were performed on the same sediment in an effort to assess the precision, reproducibility and comparability of these two fine-grained size analysis techniques. The data demonstrate differences in mean diameter, standard deviation (sorting), precision and reproducibility, and typically, the hydrophotometer shows a sediment that is coarser by an average of 0.8 phi units over the same sediment analyzed by pipette. Sediment analyzed with the hydrophotometer is enriched in silt and depleted in clay relative to the same sediment analyzed by pipette, while the pipette shows a wider range of particle sizes and fewer modes than does the hydrophotometer.

A comparison reveals that in this study, the pipette is more consistent and has better precision for mean diameter, standard deviation, and weight percent determinations for each size interval studied. The deficiencies in the pipette method include a longer and more tedious analysis, and it is more susceptible to operator error and changes in laboratory conditions over the time of an analysis. Deficiencies in the hydrophotometer method include poorer precision and an inability to assess material in size intervals below $2\mu$ .

Based on this study the hydrophotometer is best for assessing trends (finning or coarsening) in the size distribution of the sediment, especially when the analysis must be performed rapidly, and the sediment is silt rich (> 80%) and poor in the clay-size component (< $2\mu$). The pipette method is best suited for samples rich in clay-size material where analysis time is not a problem, and a more precise determination of the actual percent clay and size distribution is desired.

# INTRODUCTION

A variety of electronic and manual methods have been devised and employed in the analysis of fine-grained sediment. Since 1922 with the development of the pipette method by Jennings, Thomas and Gardner (1922) and its refining by Krumbein (1932) for application to detrital sediment, fine-grained size analysis has evolved from a manual/mechanical mode to an electronic mode. Electronic instrumentation includes; the hydrophotometer, that employs photo-extinction principles described by Rose (1954), Simmons (1959) and McKenzie (1963), and Jordan and others (1971); the Malvern laser sizer that determines particle size from the angular distribution of forward scattered light (McCave and others 1986); the Coulter and Elzone particle counters that determine particle volume from electronic resistivity (Sheldon and Parsons, 1967; Swift and others, 1972; McCave and Jarvis, 1973; Stein, 1985); and the Sedigraph that employs x-ray attenuation principles (Kunst, 1973; Vitturi, and Rabitti, 1980; and Stein, 1985).

Since the early 1980's it has become evident that the variety of size-analysis techniques available are not similarly standardized, give different results for similar samples (Singer 1986), and have varying degrees of accuracy and precision. Consequently, to attain a better understanding of the hydrophotometer used in our laboratory, specifically its precision, accuracy and comparability to pipette, we performed multiple analyses of the same sediment with both the hydrophotometer and pipette.

The U.S.G.S. Marine Sediment Lab participated in a similar study with Rice University (Singer 1986). In all, twenty laboratories participated in the Rice University study, that was an effort to assess the standardization of a variety instruments used in textural analyses of fine-grained sediment, by using both sorted and unsorted silt and clay samples. Singer attempted to assess not only different instruments, but also different laboratories employing the same instruments and methods (Singer 1986). Her study evaluated a settling tube, Coulter Counter, hydrophotometer, Sedigraph, pipette and two laser particle sizers. The U.S.G.S. Marine Sediment Laboratory provided one of two sets of hydrophotometer data used in the study. The results of the comparison revealed some interesting problems in generating and interpreting the data from the variety of methods available for fine-grained size analysis. Singer

(1986) showed that the Coulter Counter, Malvern Laser Sizer, Sedigraph, and hydrophotometer results from sorted silt samples were in general agreement. Contrasting, data generated from the analyses of unsorted silt and clay demonstrated minimal agreement (Singer 1986). Singer also found that in all analyses, the results of pipetting showed the most variability, and the results from the Spectrex Laser Particle Counter were not comparable with the other instruments in this study. Major discrepancies in results were found to exist in the size distribution of samples containing clay-size particles and the detail with which each instrument analyses the clay fraction. Singer (1986) found that the instruments fall into two broad categories. The laser based sizers and Coulter Counter do not detect particles below a minimum size, whereas the hydrophotometer, pipette, and Sedigraph are total sedimentation methods reporting percentage finer than the lowest analysis point (Singer 1986). The Sedigraph resolves particle size down to 0.24μ (12ϕ) while the hydrophotometer and pipette method report clay as a single weight percent (Singer 1986). These differences affect the statical calculations and interpretations derived from the resulting statistics. Singer also found that the statistics can be misleading especially when the sediments contain a significant clay fraction, and that mean phi values may be off as much as 2 phi units if the unresolved components are factored into the calculations.

The study described in this report was performed to assess the reproducibility and precision of the hydrophotometer used by Marine Geology through triplicate analyses of two of the six samples analyzed in the Singer report (samples 3 and 4; Singer 1986), duplicate analyses of marine sediment from the shelf adjacent to the Russian River of northern California, and multiple analyses (59) of marine sediment from Shelikof Strait, Alaska. Finally, the major focus of this study is to compare the pipette method that is based on Stokes' Law of settling to the automated hydrophotometer that is based on photo-extinction principles as related to Stokes' law. This is accomplished through multiple analyses of the same marine sediment with both the hydrophotometer and pipette. This study improves on the Singer study in that it focuses with more detail on the hydrophotometers' reproducibility, only two techniques are compared rather than the variety of techniques assessed by Singer, and finally, all analyses were performed in the same laboratory allowing for better control during the study.

## PRINCIPLES OF OPERATION

### Hydrophotometer

The hydrophotometer is a linear photometric device that is based on the photo-extinction theory (Rose 1954). The theory, principles and early instrumentation were first introduced by Wagner (1933) for use in measuring silt-sized cement particles. The photo-extinction theory and instrumentation were subsequently examined both theoretically and experimentally, and improved by Rose (1954), Simmons (1959), and McKenzie (1963), culminating with the development of the first marketable hydrophotometer for geological lab use by Jordan and others (1971).

The basic working theory of the hydrophotometer is the relation of the change in the percent transmission of light that is passed through a sediment suspension to differential particle settling as determined by Stokes' law (Jordan and others 1971). Rose (1954) shows that the photo-extinction principle depends on the amount of light absorption that occurs by the particles in suspension. The hydrophotometer takes light transmission readings at times that correspond to specific sizes derived from Stokes' law. As settling proceeds the sediment suspension clarifies and percent transmission increases. Thus, the hydrophotometer measures the rate and amount of change of light absorption in a sediment suspension and that is related by Stokes' law to particle settling diameter (Simmons 1959).

Stokes' law is described by the equation:

$$v = \gamma(\Delta P)d \div 18\eta$$

where $v$ = velocity; $\gamma$ = gravitational acceleration; $\Delta P$ = the difference between the specific gravity of the particles and the fluid medium, $d$ = particle diameter and $\eta$ = the viscosity of the medium. Stokes' law is not applicable to all particles settling in a fluid, and strictly it is only valid under the following conditions.

1. The motion of the particle in the fluid is streamline.
2. The fluid extends for an infinite distance around the particle.
3. The fluid must be of infinite extent in relation to the particles.
4. Particles must have reached terminal velocity.
5. Particles must be rigid, smooth, and spherical.

6. No slippage or shear must take place between the particle and the fluid.
7. The particles must be greater than 0.5μ and smaller than 50μ.

Two obvious deviations that geological particles present to the above assumptions are their non-spherical and non-smooth nature. A third deviation is that the size-range over which Stokes' law is valid, is somewhat different than the size range of the particles that comprise certain sediment. Theoretical and experimental studies by Arnold (1911) and Krumbein and Pettijohn (1938) have shown that although in theory Stokes' law is only valid following the above assumptions, it is also valid in the range of silt- and clay-sized particles in laboratory situations.

Both Rose (1954) and Simmons (1959) show how light transmission values can be converted to weight percents by using an extension of the Beer-Lambert law. Letting $I$ be the intensity of the incident light and $I_O$ the intensity of the transmitted light, then the relation between $I$ and $I_O$ is given by the equation:

$$\ln\frac{I}{I_O}=kCl\sum_{d=0}^{D}K_x N d_x^2$$

where $k$ is the ratio of the projected area of a particle to its diameter; $C$ is suspension concentration; $l$ is the length of the light path through the suspension; $N$ is the number of particles of size $d_x$ ; and $K_x$ (the extinction coefficient) is the ratio of the apparent projected area of a particle of diameter $d_x$ to the true projected of a particle of diameter $d_x$ (Rose 1954, Simmons 1959, and Jordan and others 1971). For any laboratory situation k, C, and l are constant, and the value for $K_x$ may be taken from a curve provided by Rose (1954).

Having values for $I_O$ at times t1, t2,...tn as calculated by Stokes' law, Rose (1954) and Simmons (1959) show that a plot of $\ln\frac{I}{I_O}$ vs $d_x$ defines a curve the area of which is proportional to the total weight of the sample. When material in the size range $d_1$ to $d_2$ is considered Rose shows that:

$$\ln\frac{I}{I_{O_1}}-\ln\frac{I}{I_{O_2}}=kCl\sum_{d=0}^{D}K_x N d_x^2$$

The area below the curve delineated by the points $\ln\frac{I}{I_{O_1}}$ and $\ln\frac{I}{I_{O_2}}$ is proportional to the weight of the

material in a particular size range. In converting light transmission to weight percent the photo-extinction theory assumes that:

1. The particles are opaque and there is no reflection between the particles and the walls of the vessel.

2. The factor $K_x$ includes all deviations in light obscuring power of a particle from that given by the usual laws of geometrical optics.

3. Particle concentration is such that no two particles fall on the same line parallel to the light beam.

By applying normal laws of optics Rose (1954) was able to show that particles behave similar to a lens and the assumptions are satisfactorily fulfilled in the size range from 2 to 60μ. The requirements for opacity, reflection, and particle concentration are met when there is a sufficient difference between the refractive index of the particles and the fluid medium (as exists between water and sedimentary particles), the photo-cell is suitably positioned and restricted to limit the angle of light reception thereby eliminating the reception of scattered light (Simmons 1959), and particle concentration does not exceed 1% by volume. The assumption for the extinction coefficient, $K_x$, is fulfilled by the curve supplied by Rose (1954) that gives values of $K_x$ for particles from 0 to 80μ. Rose also provides a method of applying a correction for the extinction coefficient, which for some particle sizes is appreciable (Simmons 1959). Both Rose (1954) and Simmons (1959) state that the photo-extinction theory breaks down for flaky transparent material below the 2μ (9ϕ) size because a flat slab cannot deviate a light beam.

Pipette

The pipette method is probably the oldest and most widely employed method of fine-grained size analysis. The pipette method is based on Stokes' law, and it is a sedimentation technique that determines sedimentation diameter that is a function of particle size, shape and density. Unlike hydrophotometric techniques that are based on photo-extinction principles as they relate to Stokes' law, the pipette method involves the withdrawal of sediment samples at precalculated times and depths as determined by Stokes' law. In a pipette analysis the first sample is taken at such time and depth that it represents the total amount of silt and clay. At the time of sampling no particular size fraction has completely settled past the sampling point. Subsequent withdrawals are taken such that a particular size

fraction has settled past the sampling point. All material remaining in suspension and subsampled is thus finer than that which has settled past the sampling point. Obvious disadvantages of this method include a longer and more tedious analysis, a higher chance for operator error and sample disturbance during subsampling, and a potential for changes in laboratory conditions over the period of the analysis.

One procedure of size analysis makes it an artificial measurement of the natural size-distribution of the sediment. In nature, particles of silt- and clay-size material combine to form flocs and aggregates that settle out of the water column. The procedures used in preparing sediment for grain size analysis destroys the bonds that form the flocs and aggregates, thereby disaggregating the sediment. Thus, grain size analysis measures the size-distribution of the disaggregated particles and not the flocs and aggregates that actually comprise the sediment. This method of preparation is performed to standardize the technique so that each individual investigator and laboratory measures the same thing, thus making the results and textural parameters more comparable from laboratory to laboratory. The problem here is that although most investigators measure the size distribution of disaggregated sediment, they may not measure it in the same way (i.e. pipetting vs hydrophotometer), thereby making results difficult to compare.

## METHODS

To assess the precision of the hydrophotometer, two samples, previously used in an intercalibration experiment conducted by Rice University (Singer 1986) were selected. The two samples, #3 and #4, are silts that were prepared by Singer for interlab comparison by decantation. The absolute size ranges are not known, but the composition and approximate size range is. Sample #3 is a quartz-silt having an approximate size range of 37-18μ (4.75-5.75ϕ), and sample #4 is a glacial silt having an approximate size range of 37-25μ (4.75-5.25ϕ). Both samples were analyzed 3 times with a hydrophotometer. A second test of reproducibility of the hydrophotometer was performed by duplicate size analyses of the silt-clay fraction of 10 samples of marine sediment from the shelf adjacent to the Russian River, California.

The sample used to assess precision and comparability between the hydrophotometer and the pipette methods is the silt-clay fraction of a marine sandy mud (26% sand, 42% silt and 31% clay) collected in Shelikof Strait, Alaska. The sample was mixed to insure homogenization and 18 subsamples weighing between 5 and 10 g were taken for analysis; 6 were dedicated for hydrophotometer analysis and 12 for pipette analysis.

Techniques used to determine the size distribution of the samples are slightly modified from methods described in Folk (1968) and Carver (1971). Samples were first treated with hydrogen peroxide to oxidize organic carbon and disperse the sediment. Following oxidation, excess peroxide was removed by heating samples to a gentle boil. Solubles were removed by two successive washings under centrifugation with distilled water.

Gravel (> 2mm), sand (2mm-63μ), and silt and clay (< 63μ) were segregated and removed from the Russian River samples by wet-sieving. Segregation differed slightly for the Shelikof Strait sediment in that the sand and coarse-silt fraction (2mm-38μ) was sieved off leaving a silt-clay fraction of material < 38μ for size analysis. The silt-clay fraction for each sample was collected in a 1000 ml graduated cylinder in preparation for either hydrophotometric techniques described by Jordan and others (1971) and Torresan (1984), or pipette analysis as described by Carver (1971).

There is one source of error introduced into the size analysis. Wet-sieving segregates sediment into the respective size fractions based on their least cross-sectional area while sedimentation analysis that is based on Stokes' law, determines the sedimentation diameter based on settling velocity. The use of sieving to segregate samples introduces size dependent constraints into the sedimentation analysis at the 63μ sand-silt cutoff. Thus, material that physically falls through the sieve as silt-size material, may have a density such that it settles and behaves like sand. The converse is also true, material categorized as sand based on sieving may actually settle as silt owing to particle size, shape and density.

Following the transfer of the combined silt-clay fraction to one of 18 graduated cylinders, each sample was treated with 5-10 ml of a 0.1% sodium hexametaphosphate solution to prevent flocculation (Carver 1971). Each cylinder was then filled to 1000 ml with distilled water. To insure complete homogeneity, the fluid-sediment column was agitated with a stirring rod for two minutes.

Following agitation of each of the six graduated cylinders dedicated for the hydrophotometer, 10 representative aliquots were withdrawn with a pipette and analyzed yielding a total of 60 analyses (only 59 analyses were completed owing to one flawed data set). The remaining cylinders were used to perform a total of 12 pipette analyses. Both techniques were performed at at 1/2 phi intervals from 63-2μ (4-9ϕ). The unresolved component finer than 2μ (9ϕ) was summed as percent finer than 2μ. For the hydrophotometer analysis, a small aliquot (1-5 ml) was withdrawn and placed into a special cell. Each cell was then filled to a precise 8 cm fall distance. Sample density was adjusted by the addition of either sample or distilled water so that the initial light transmission values ranged between 15 and 45%. The hydrophotometer employed was a Cimax TSS model 800S. This particular model is an automated version of that described by Jordan and others (1971), in that a microprocessor controls agitation, data collection and calculation of phi interval weight percent for 10 samples simultaneously. Sample agitation is performed by rocking the sample rack back and forth (from a vertical to a horizontal position and back) 6 times.

The raw data for all analyses was processed with the U.S.G.S. Marine Geology computerized sediment size-analysis program (SEDSIZE), that calculates and plots the descriptive statistical parameters used to characterize the grain-size distribution. All grain-size statistics are given in both mm and phi units, and all statistics discussed are moment measures. Much of the data were also processed using the statistical routines available on Minitab, a general purpose data analysis system available on the U.S.G.S Marine Geology computer system.

## RESULTS AND DISCUSSION

### Hydrophotometer Precision Tests

Two samples (#3 and #4) used in an earlier study (Singer 1986) were analyzed 3 times each with the hydrophotometer for this study. The results are presented in figures 1 and 2, and appendix 1.

It is evident from figure 1 that sample 3 has similar frequency curves and values for mean phi and standard deviation. The frequency curves for the three analyses of sample 3 overlap, and the three mean phi and standard deviation values are within 0.3 phi and 0.09 phi units of each other respectively (fig.1). The three values for mean phi are within 3.5% of the average mean phi (4.90ϕ), and the three values for standard deviation are within 11% of the average standard deviation (.4798), attesting to the good precision of the hydrophotometer in this phi range using this standard (fig. 1). The greatest disparity in the results occurs in the ability of the hydrophotometer to reproduce specific size interval weight percents (appendix 1).

Like sample 3 the three analyses of sample 4 are also similar (fig. 2). The frequency curves overlap, and the values for mean phi and standard deviation are within 0.2 and 0.22 phi units of each other respectively (fig. 2). The three values for mean phi are within 2.6% of the average mean phi (4.81), and likewise the three values for standard deviation are within 3.1% of the average standard deviation (.4030) reflecting the high degree of precision for this set of data. Similar to sample 3 the greatest difference occurs in the hydrophotometers' ability to duplicate the values for weight percent for each size interval analyzed. This problem will be discussed later upon examining the reproducibility of data from size interval to size interval using marine sediment rather than artificially sorted sediment. Summarizing, it appears that the hydrophotometer performs well with artificially sorted standards, although the data for sample 4 show a higher degree of precision than do the data for the analysis of sample 3.

A second test of precision was performed by duplicate analyses of marine sediment from the shelf adjacent to the Russian River of northern California. Raw data, grain-size statistics and histograms of the size distribution are presented in figure 3, table 1 and appendix 2. The textural parameters

generally agree and in fact, some are exact duplicates (table 1). The mean phi values are within 0.3 phi units of each other for the duplicate analyses (table 1), and within 3.0% of the average mean phi for each set of duplicate analyses. Evident from the frequency curves the size distributions also agree as they have similar shapes and modes (fig. 3 and table 1). The data appear to show a favorable comparison between the duplicate analyses, especially in samples with a high percentage of silt over clay.

## Comparison of the Hydrophotometer and Pipette Methods

Results of this study show that there are notable differences between the hydrophotometer and pipette methods used in fine-grained size analysis. The results are summarized in tables 2-4 and were distilled from the data in appendices 3 and 4.

Once 10 samples have been placed into the hydrophotometer minimum analysis time for a 4 cm fall distance and the same sample interval employed in this study is 3 hours and 20 minutes. An equivalent pipette analysis requires a minimum of about 9 hours. Unlike the pipette the hydrophotometer does not disturb the settling process during sampling, thereby reducing potential operator error. Once a hydrophotometer analysis is initiated all sampling and data tabulation is automated. In contrast, pipetting requires that the operator withdraw specific sample volumes at predetermined times and depths. The samples must then be dried and weighed before the data can be tabulated, thereby introducing a variety of potential errors including the disruption of settling, improperly placed and timed sample withdrawals and weighing errors. Thus, with respect to analysis time and ease of operation, the hydrophotometer is significantly faster, easier to use and has a lower potential for operator error over the pipette method. This agrees with the findings of Rose (1954), Simmons (1959) and Jordan and others (1971).

The range in weight percent values (max% - min%) for each 1/2 phi sample interval is larger and more variable for the hydrophotometer than it is for the pipette (figs. 4 and 5; tables 2 and 3). The values determined by the hydrophotometer for weight percent in each sample interval ranged from 7% to over 16% within any one sample interval (fig. 4 and table 2). Contrasting, the range in the same values for the pipette analysis is smaller and less variable than the corresponding hydrophotometer data

(fig. 5 and table 3). Pipette values have a minimum range of 1.7% and a maximum range of 8.2% for any one sample interval, showing that a higher degree of precision is attained with the pipette. This observation is corroborated by the standard deviation values for mean weight percent presented in tables 2 and 3. These data show that the standard deviation of the mean weight percent in each 1/2 phi sample interval ranges from a low of 1.37% to a high of 4.86% for the hydrophotometer (table 2), whereas pipette values range from a low of 0.48% to a high of 2.06% (table 3), implying better precision for the pipette analysis.

Figure 6 is a plot of the average mean diameter (average mean phi) vs the minimum and maximum mean diameter (mean phi) values for each individual set of ten hydrophotometer analyses (524A-524F), for all 59 hydrophotometer analyses, and for the pipette data. Figure 6 shows that the hydrophotometer analyses have a larger range of mean phi values than does the corresponding pipette data. Again, the data show that the pipette method results in a higher degree of precision. Likewise, comparing standard deviation values for the average mean phi (table 2 and 3) it is evident that the hydrophotometer value is three times larger than the corresponding pipette value (0.25$\phi$ vs 0.06$\phi$), verifying its lower precision.

Similar observations are made when comparing the cumulative curves derived from the two techniques (fig. 7). The six representative pipette curves exhibit a much narrower range of dispersion than the corresponding hydrophotometer curves, confirming the better precision of the pipette method in this study. These results are in direct contrast with similar studies performed by Jordan and others (1971) and Singer (1986), that show a higher precision was attained with the hydrophotometer.

Perhaps the higher degree of variability shown by the hydrophotometer in this study reflects the way light transmission values are converted to sedimentation diameters by application of photo-extinction principles described by Rose (1954) and Simmons (1959). Rose shows that the precision and validity of the photo-extinction principles decay below 2$\mu$ (9$\phi$) owing to the nature and shape of clay-size particles and the way they deviate and transmit light. Possibly, the amount of clay present in the sample affects the precision with which the hydrophotometer performs. Rose (1954) and Simmons (1959) both believe that the hydrophotometer is best applied to silt-size particles between 63 and 2$\mu$.

Another major difference observed in this study is a disparity in the percent silt and clay calculated by each technique for the same sediment (tables 2-4). Similarly, the values calculated for average mean phi, standard deviation, skewness and kurtosis reflect this difference: that is for the same sediment, the hydrophotometer consistently determines a larger value for percent silt, a smaller value for percent clay, portraying a slightly coarser and better sorted sediment than does the pipette (table 4). This observation is in general agreement with data presented by Simmons (1959) and Singer (1986). For this study the hydrophotometer determines that clay averages 14.63% of the sediment whereas the pipette averages 37.90% (table 4). The disparity in percent silt and clay determined by each technique is also evident in the average moment measures (table 4). The average mean phi for the hydrophotometer is 7.69 phi with a standard deviation of 1.90 phi (table 4). Notably disparate are the pipette data that average 8.48 and 2.55 for mean phi and standard deviation respectively (table 4). Simply, the pipette data averages 0.8 phi finer than the same sediment analyzed with the hydrophotometer, and the larger average mean phi and standard deviation values reflects the apparently higher amount of clay present as determined by the pipette method.

Average skewness and kurtosis values also mirror the disparity in percent silt and clay calculated by each method (table 4). Skewness and kurtosis values for the hydrophotometer show the size-distribution to be apparently coarser and more peaked than the pipette data. The coarser skew and more peaked nature of of the hydrophotometer data implies a silt-rich and clay-poor sediment relative to the pipette data. Conversely, the relatively higher clay content of the pipetted sediment is expressed by lower skewness and kurtosis values, reflecting a broader, more finely-skewed range of particle sizes relative to the hydrophotometer data. Similarly, the representative cumulative frequency plots and histograms of the particle size-distributions show the pipetted sediment to have a broader and finer range of particle sizes than the same sediment analyzed with the hydrophotometer (figs. 7 and 8).

Representative histograms of the pipette analyses are bell-shaped, and have an even distribution of material between 31 and 2μ (5 and 9ϕ) when compared to the hydrophotometer histograms (fig. 8). Also evident is the polymodal nature of the hydrophotometer histograms when compared to the pipette data. Not only are the hydrophotometer histograms enriched in silt and depleted in clay relative to the pipette samples, but individual modes are more numerous and more distinct than those derived by

pipette analysis.

Typically, histograms representing the hydrophotometer data all start with an initial mode of 3 to 5 percent of the population in the 63 to 44 μ (4 to 4.5ϕ) range. This drops off to near zero between 31 and 15.6μ (5 and 6ϕ). The drop is followed by a strong jump to between 15 and 20 percent in the 20.8 to 10.4μ (5.5 to 6.5ϕ) size-range as evident in figure 8. Analogous results were observed in the hydrophotometer analysis of samples 5 and 6 in the study by Singer (1986). Contrasting, the pipette histograms display a stepped and progressive increase of material from 63 to 20.8μ (4 to 5.5 and 6.5ϕ) where the primary mode appears. Similar observations are made when comparing the cumulative frequency curves derived from the two techniques (fig. 7).

Summarizing, the data shows the pipette to portray a finer and more poorly sorted sediment than the same sediment analyzed with the hydrophotometer. Pipette data in this study is less variable and more reproducible attesting to better precision. This contrasts with data presented by Simmons (1959), Jordan and others (1971) and Singer (1986) who show that pipette data of similar sediment is less consistent, more erratic, more variable, and less reproducible than corresponding hydrophotometer data. With respect to the interlaboratory study conducted by Singer (1986), operator technique and laboratory conditions can strongly influence the results. Since the pipette method relies more on laboratory conditions and operator technique, it is not unexpected that there is more variability in the results of her interlaboratory study than this intralaboratory study.

## CONCLUSIONS

Based on a review of literature, an intercalibration study by Singer (1986) and the results of this study, certain observations and conclusions are evident.

1. Rose (1954) shows that the photo-extinction method upon which the hydrophotometer is based apparently decays below 2μ (9ϕ). Rose (1954) and Simmons (1959) therefore believe that the photo-extinction method is best suited for the analysis of silt-size particles between 63 and 2μ.

2. The hydrophotometer is faster and easier to use than the pipette.

3. Pipetting is more tedious, slower and more susceptible to operator error and laboratory conditions.

4. The hydrophotometer consistently calculates a coarser mean diameter (by 0.8ϕ) and portrays a sediment that appears enriched in silt and depleted in clay relative to the same sediment analyzed with the pipette.

5. The hydrophotometer has a lower precision for mean diameter and weight percent values than does the pipette.

6. Individual modes are more numerous and more distinct in the hydrophotometer histograms relative to pipette histograms of the same sediment, showing that the hydrophotometer characterizes a sediment that is apparently coarser and more polymodal in nature that the corresponding pipette data.

7. Based on the lower precision and apparent polymodal nature of the hydrophotometer data in this study, inferences made on population modes would appear to be more tenuous for the hydrophotometer data than carefully collected pipette data.

8. Comparing the studies by Simmons (1959), Jordan and others (1971), Singer (1986) and this

study, it is apparent that interlab comparison of the hydrophotometer are more consistent and reproducible than interlab pipette analysis. However, intralab or intraoperator hydrophotometer and pipette analysis can show the opposite results- higher precision is realized with one operator comparing different methods. Thus, comparing the inter- and intra- lab/operator results is tedious.

9. More detailed testing employing both standards and natural sediment, combined with a detailed statistical analysis is required to obtain a better understanding of the differences and strengths and weaknesses of both techniques. Testing will help assess the effects of natural sample variability, and systematic instrument and operator error.

## IMPLICATIONS AND RECOMMENDATIONS

Based on the results of this and other studies, it is evident that the use of either the hydrophotometer or pipette methods for fine-grained size analysis should be dictated by several situations. First, the hydrophotometer should be used when comparing data from other studies that also employed the hydrophotometer. Because the hydrophotometer employs photo-extinction principles as they relate to Stokes' law, the hydrophotometer determines lower values for percent clay than the pipette method, thereby making comparisons between methods unfavorable. As a result of this disparity in percent clay the hydrophotometer may deliver an artificial size distribution because it may not include a substantial proportion of the material finer than 2 μ in its size-distribution curve. As demonstrated here and in a study by Singer (1986), the hydrophotometer generally does not compare favorably to pipette analyses, especially when the sediment analyzed has a considerable component of material finer than 2μ. Therefore, the hydrophotometer should be used when comparing to other size data generated with a hydrophotometer.

If speed in analysis and general sedimentary trends are required (i.e. coarsening or finning across a study area or down core) then the hydrophotometer may fulfill your requirements. Since this study and Singers' study show that the hydrophotometer compares best with other hydrophotometer data and that precision apparently decreases with increasing clay content, it is suggested that the hydrophotometer be used for silt-rich samples containing < 20% clay. Rose (1954) and Simmons (1959) also state that the hydrophotometer is best suited for the size-analysis of silt particles between 60 and 2μ in size.

Contrasting, should time requirements not constrain the study; should the size analysis require determinations of size-distribution information below 2μ; should comparisons be made to size-distribution data determined via pipette analyses; and should the samples to be investigated have substantial quantities of material finer than 2μ, the pipette or other methods (i.e. Coulter Counter) is suggested as the size-analysis technique.

ACKNOWLEDGEMENTS

I would like to thank Peter Barnes and Shawn Dadisman for their critical reviews and helpful discussions of the manuscript. I would also like to thank Grace Fong for providing the hydrophotometer analyses of the Russian River sediment, and Phyllis Swenson who did the drafting.

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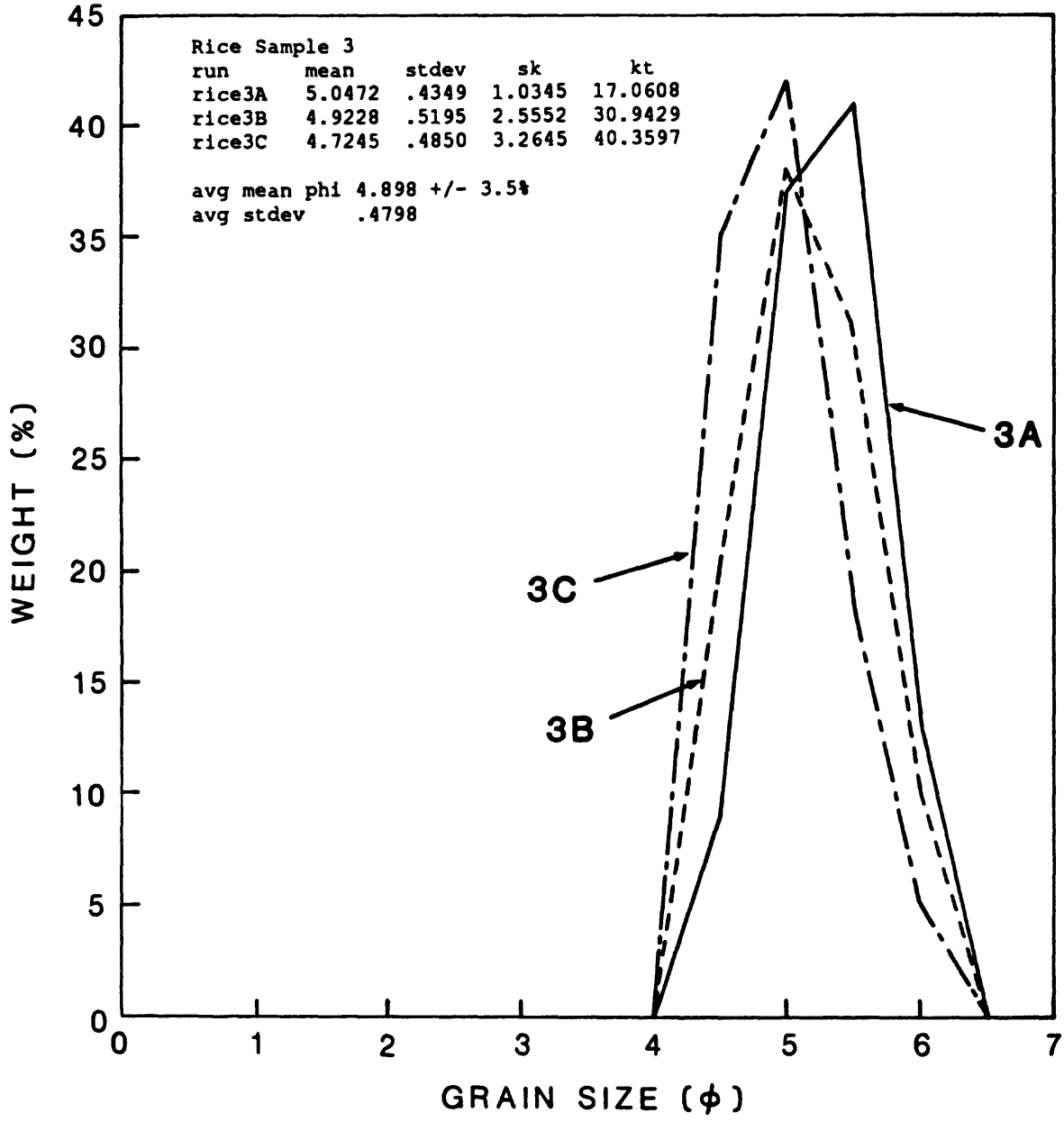


FIGURE 1. Frequency curves and histograms showing 3 replicate runs of sample 3, a quartz-silt with an approximate size range of 37-18μ (4.75-5.75ϕ) . Also included are the mean ϕ, standard deviation (stdev), skewness (sk) kurtosis (kt), the average mean, % error for the average mean, and average standard deviation.

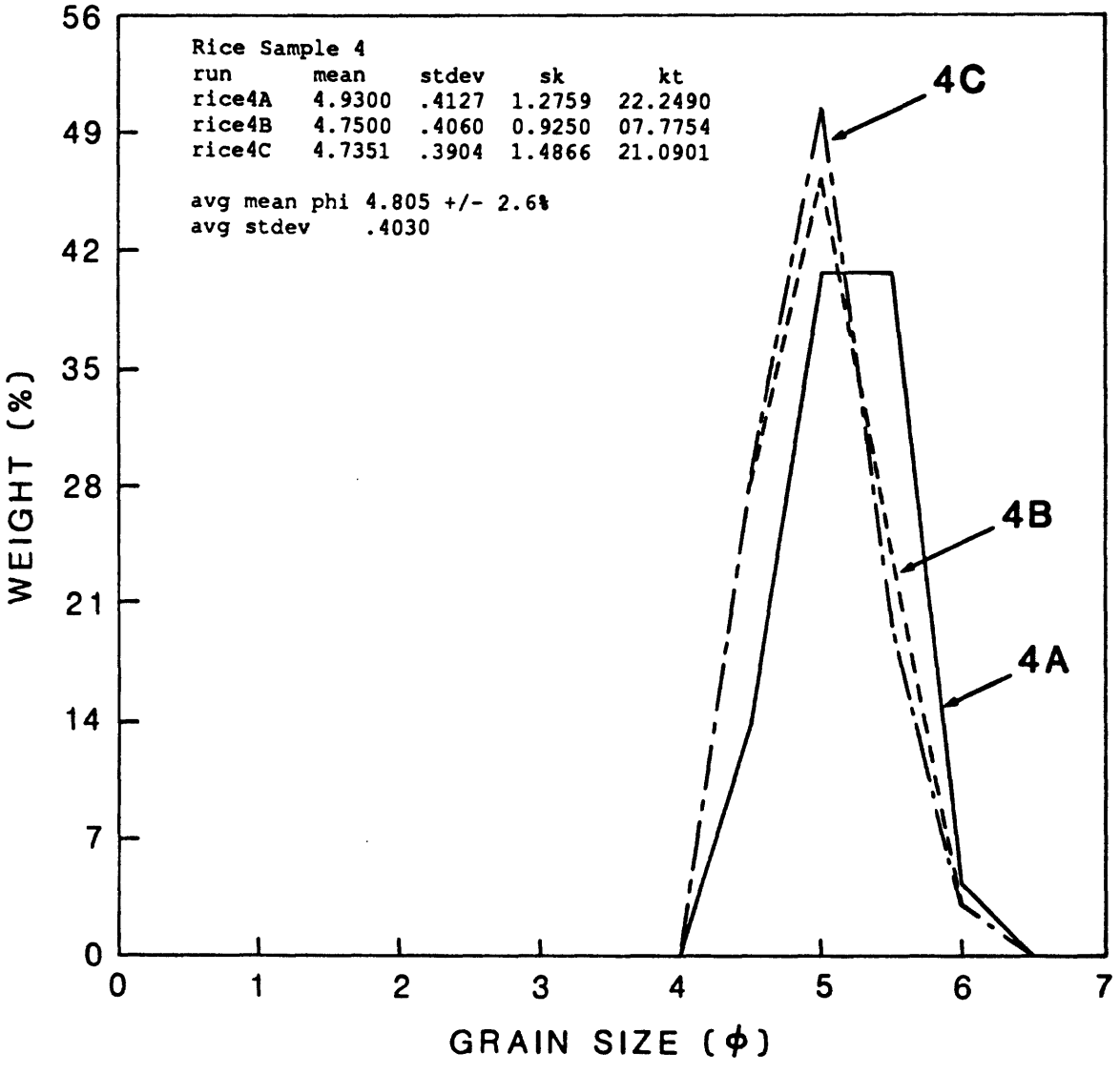


FIGURE 2. Frequency curves and histograms showing 3 replicate runs of sample 4, a glacial-silt with an approximate size range of 37-25μ (4.75-5.25ϕ). Also included are the mean ϕ, standard deviation (stdev), skewness (sk), kurtosis (kt), the average mean, percent error for the average mean, and the average standard deviation.

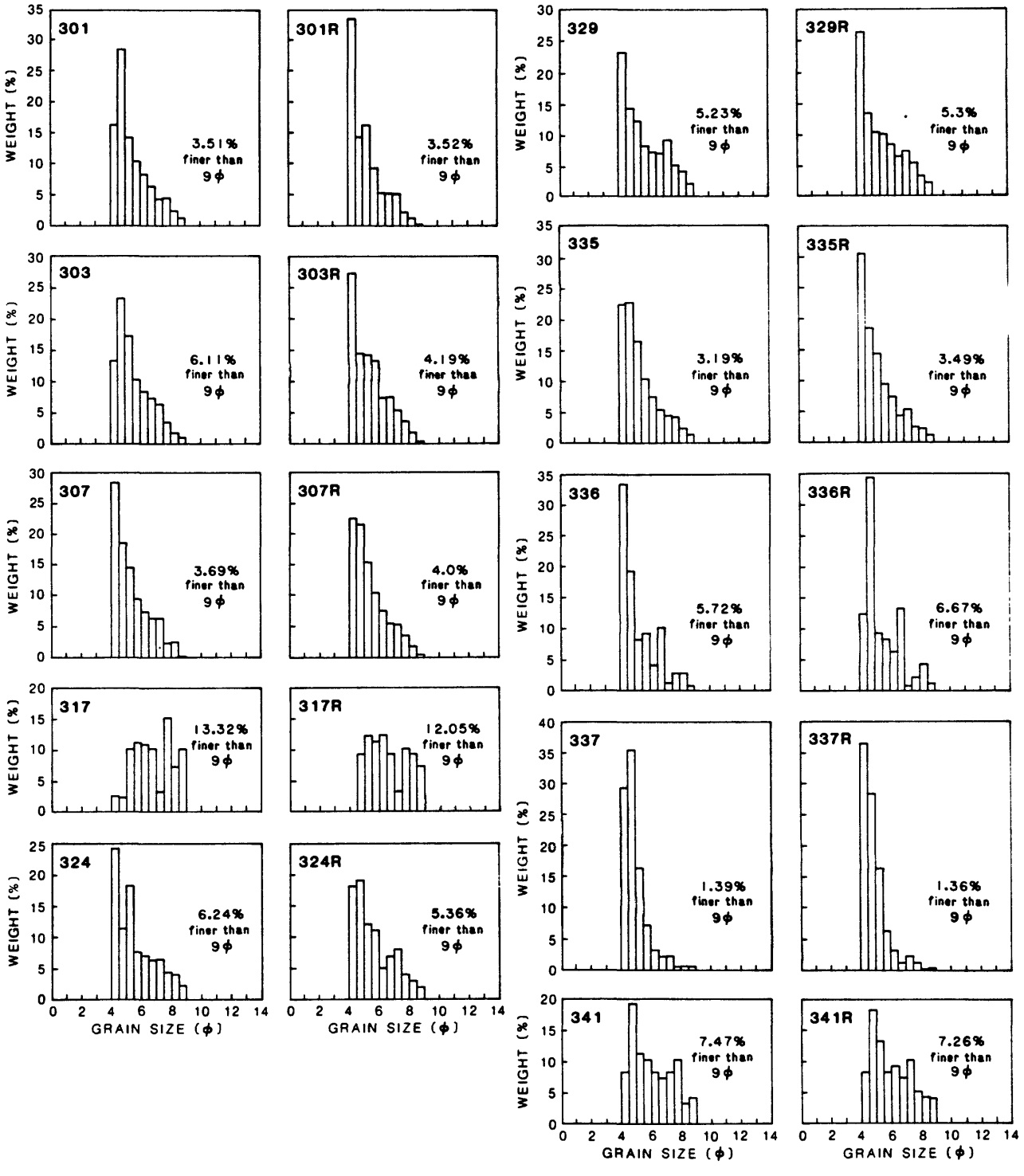


FIGURE 3. Histograms generated from duplicate analyses of the silt-clay fraction of 10 marine sediment samples from the continental shelf adjacent to the Russian River, northern California.

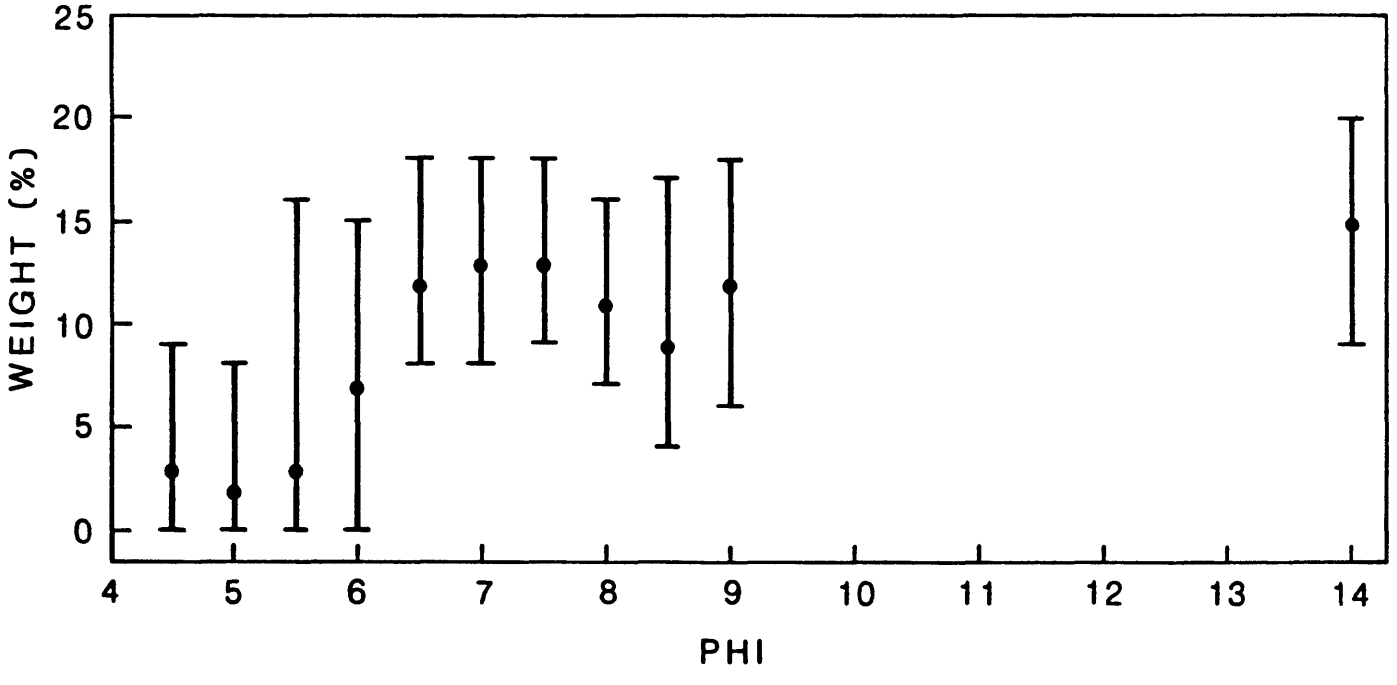


FIGURE 4. Plot of mean weight percent vs the minimum and maximum weight percent values for each phi interval analyzed with the hydrophotometer.

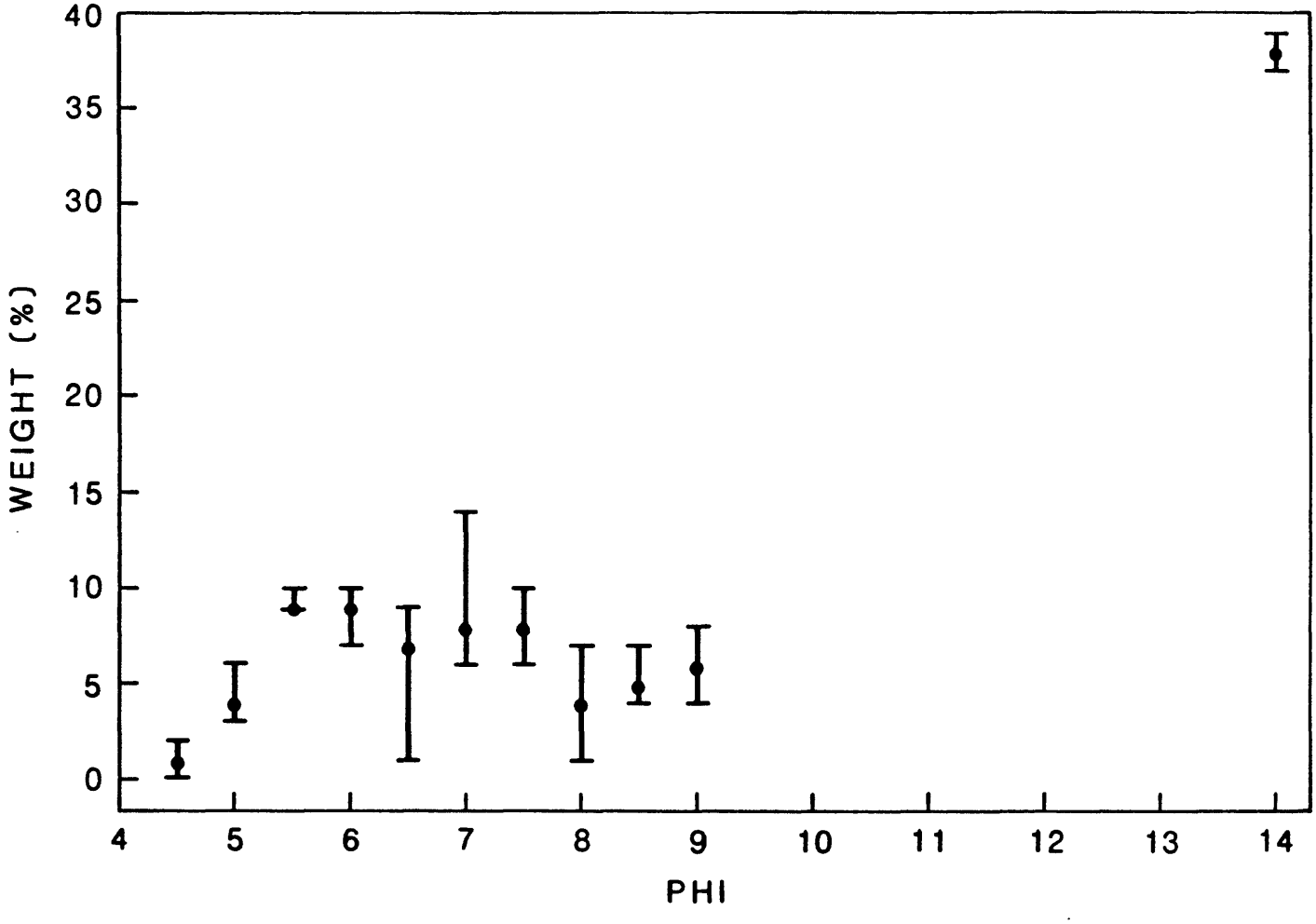


FIGURE 5. Plot of mean weight percent vs the minimum and maximum weight percent values for each phi interval analyzed with the pipette.

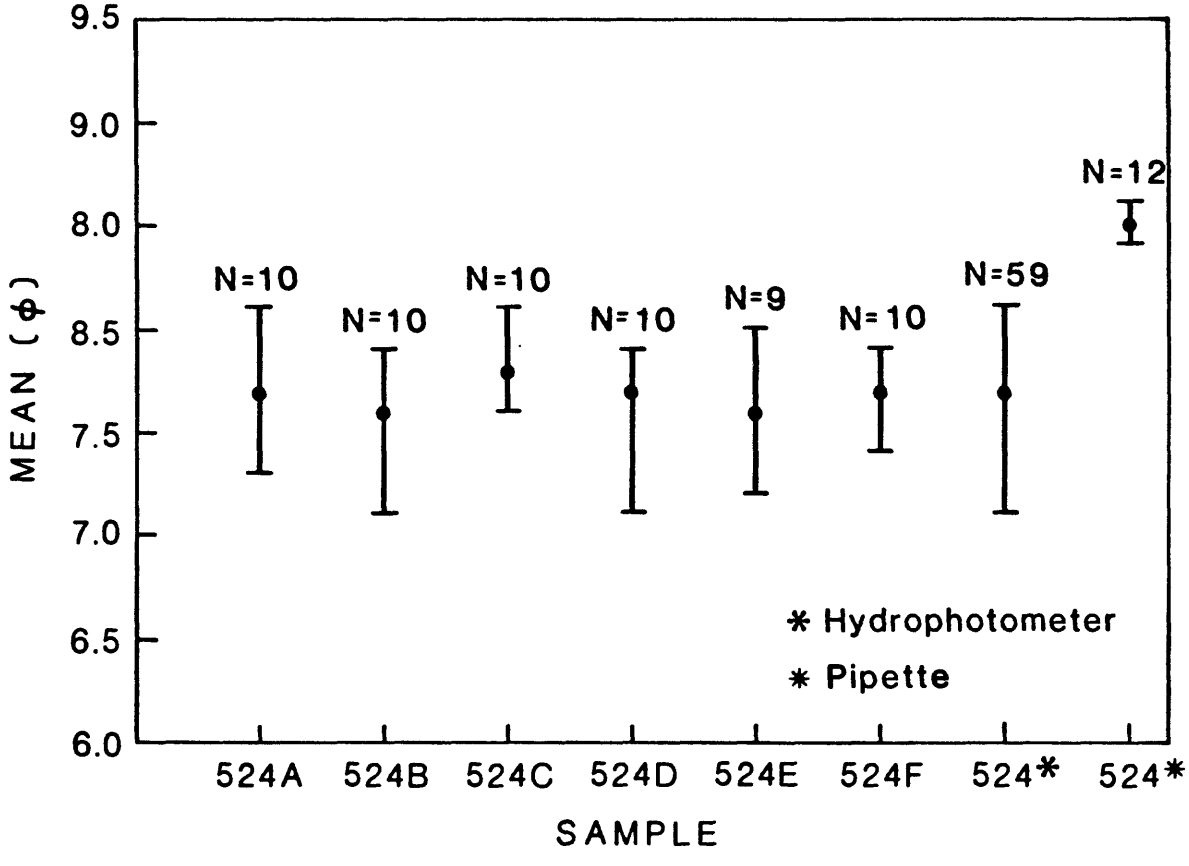


FIGURE 6. Mean phi vs sample group plots for each set of hydrophotometer data (524A-524F), all 59 hydrophotometer analyses and the 12 pipette analyses. Error bars show minimum and maximum phi in each sample group analyzed.

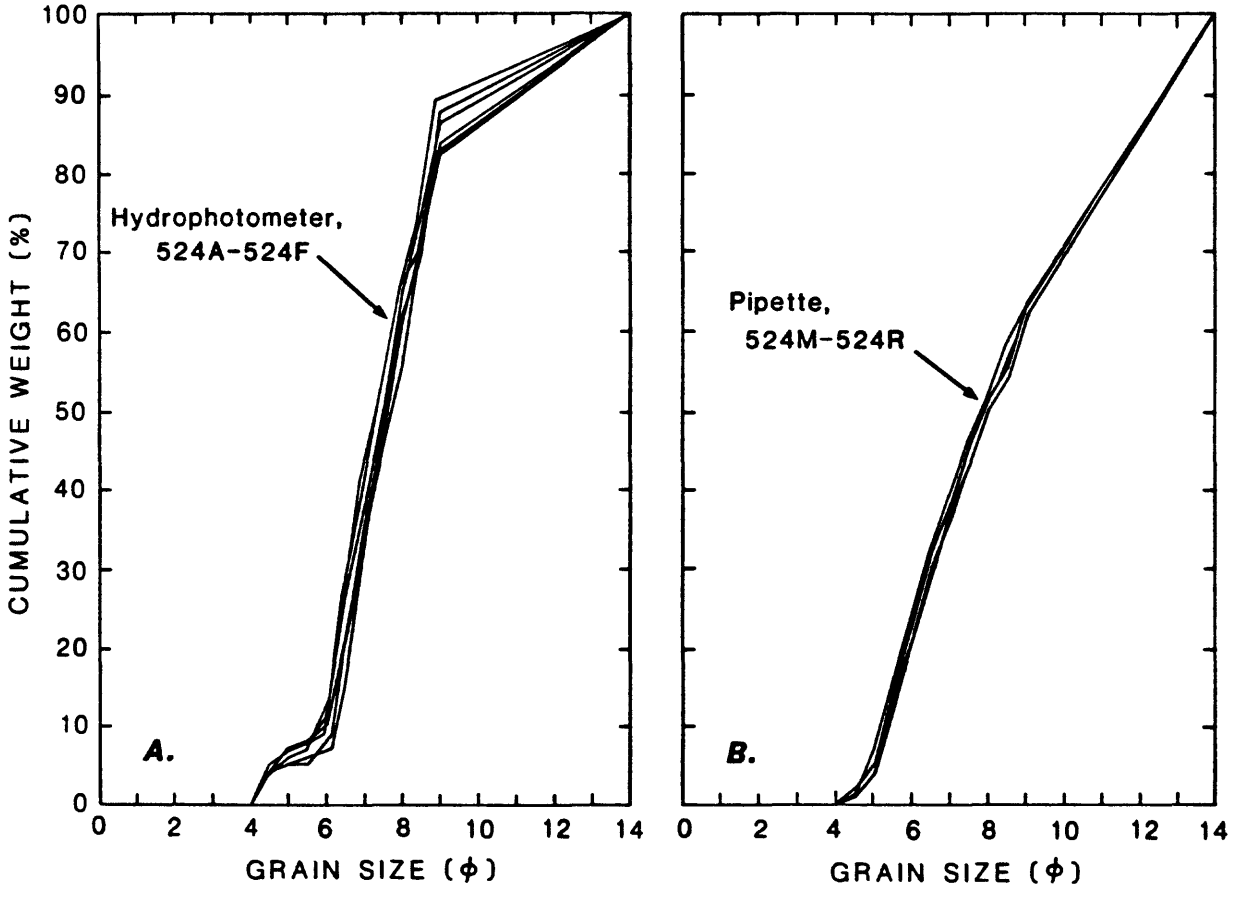


FIGURE 7. Representative cumulative frequency curves for 6 hydrophotometer and 6 pipette analyses of the same sediment. Note the smoother nature, better overlap and less dispersion of the pipette curves, and higher component of silt in the hydrophotometer curves.

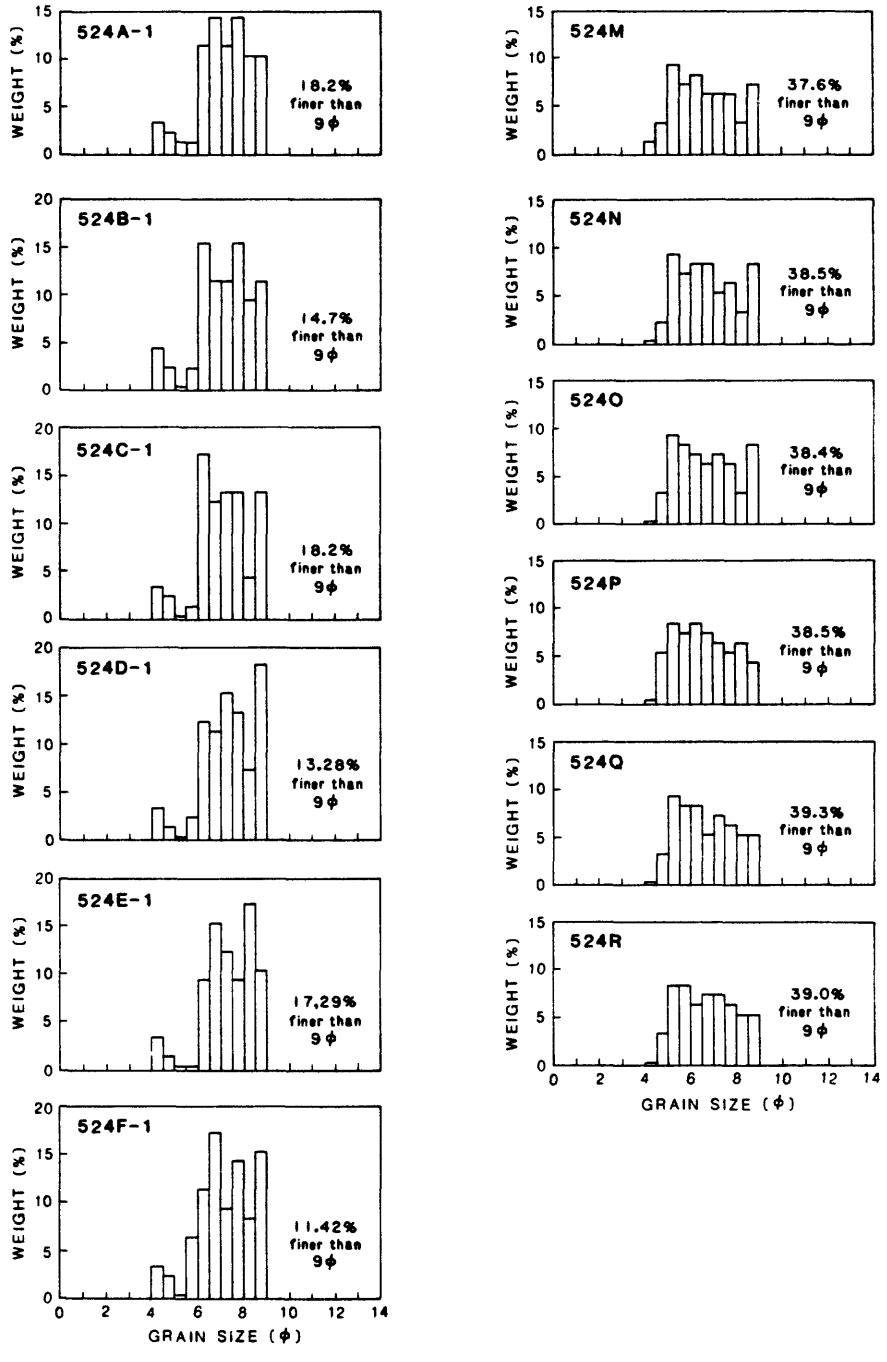


FIGURE 8. Representative histograms for 6 hydrophotometer analyses and 6 pipette analyses of the same sediment. Note that the pipette histograms appear more bell-shaped and are depleted in silt relative to the hydrophotometer histograms. Also evident is the small mode that decreases from 4 to 5.5ϕ in the hydrophotometer data, whereas the pipette data increases from 4 to 5.5ϕ.

## TABLE CAPTIONS

TABLE 1: Percent silt, percent clay and the moment measures of the size distribution for the duplicate analyses of the Russian River sediment.

TABLE 2: Summary statistics for the 59 hydrophotometer analyses presented in appendix 3. Data includes the number of analyses, the mean, median, standard deviation, and minimum and maximum values for the weight percent of material in each phi interval analyzed.

TABLE 3: Summary statistics for the 12 pipette analyses presented in appendix 2. The data includes the number of analyses, the mean median, standard deviation (stdev), and minimum and maximum values

TABLE 4: Average values for percent silt, percent clay and the average moment measures of the size distribution for the hydrophotometer and pipette analyses presented in tables 2 and 3.

TABLE 1. Hydrophotometer derived grain-size parameters.

| SAMPLE | %Silt | %Clay (<2u) | Mean Phi | SD | Sk | Kt |
|---|---|---|---|---|---|---|
| 301 | 96.49 | 3.51 | 5.69 | 1.57 | 1.94 | 7.30 |
| 301r | 96.48 | 3.52 | 5.50 | 1.58 | 2.07 | 7.97 |
| 303 | 93.89 | 6.11 | 5.95 | 1.78 | 1.82 | 6.14 |
| 303r | 95.81 | 4.19 | 5.68 | 1.64 | 1.90 | 7.12 |
| 307 | 96.31 | 3.69 | 5.56 | 1.59 | 1.99 | 7.58 |
| 307r | 96.00 | 4.00 | 5.66 | 1.61 | 1.99 | 7.46 |
| 317 | 86.68 | 13.32 | 7.43 | 1.99 | 0.77 | 2.85 |
| 317r | 87.95 | 12.05 | 7.17 | 2.01 | 0.91 | 3.02 |
| 324 | 93.76 | 6.24 | 6.00 | 1.90 | 1.48 | 4.82 |
| 324r | 96.64 | 5.36 | 6.01 | 1.81 | 1.48 | 5.02 |
| 329 | 94.77 | 5.23 | 6.02 | 1.84 | 1.36 | 4.67 |
| 329r | 94.70 | 5.30 | 5.96 | 1.83 | 1.43 | 4.91 |
| 335 | 96.51 | 3.49 | 5.64 | 1.58 | 1.95 | 7.29 |
| 335r | 96.81 | 3.19 | 5.54 | 1.58 | 1.93 | 7.26 |
| 336 | 94.28 | 5.72 | 5.64 | 1.83 | 1.89 | 6.32 |
| 336r | 93.33 | 6.67 | 5.95 | 1.86 | 1.74 | 5.60 |
| 337 | 98.61 | 1.39 | 5.09 | 1.14 | 3.12 | 15.81 |
| 337r | 98.64 | 1.36 | 5.05 | 1.16 | 3.04 | 15.21 |
| 341 | 92.53 | 7.47 | 6.46 | 1.91 | 1.20 | 4.04 |
| 341r | 92.74 | 7.26 | 6.45 | 1.90 | 1.21 | 4.05 |

TABLE 2. Summary statistics for 59 hydrophotometer analyses.

| Phi | mm | N | MEAN% | STDEV | MIN | MAX | RANGE |
|---|---|---|---|---|---|---|---|
| 4.5 | 0.044 | 59 | 3.202 | 1.373 | 0.31 | 8.52 | 8.21 |
| 5.0 | 0.031 | 59 | 2.058 | 1.054 | 0.45 | 7.58 | 7.13 |
| 5.5 | 0.022 | 59 | 3.217 | 4.189 | 0.22 | 16.35 | 16.13 |
| 6.0 | 0.016 | 59 | 6.704 | 4.857 | 0.27 | 15.19 | 14.92 |
| 6.5 | 0.011 | 59 | 12.489 | 2.219 | 8.07 | 17.80 | 9.73 |
| 7.0 | 0.008 | 59 | 12.882 | 2.284 | 8.17 | 17.95 | 9.78 |
| 7.5 | 0.006 | 59 | 13.403 | 2.526 | 8.72 | 18.44 | 9.72 |
| 8.0 | 0.004 | 59 | 10.892 | 2.287 | 6.81 | 16.44 | 9.63 |
| 8.5 | 0.003 | 59 | 8.906 | 2.078 | 4.01 | 17.24 | 13.23 |
| 9.0 | 0.002 | 59 | 11.618 | 3.062 | 5.73 | 18.37 | 12.64 |
| 14.0 | 0.0001 | 59 | 14.629 | 2.640 | 8.66 | 19.92 | 11.26 |
| AVERAGE STATISTICS | | | | | | | |
| Mean Phi | | 59 | 7.6875 | 0.2486 | 7.070 | 8.10 | 1.03 |
| SD | | 59 | 1.9010 | 0.0824 | 1.730 | 2.08 | 0.35 |
| Sk | | 59 | 0.7292 | 0.1075 | 0.550 | 0.95 | 0.40 |
| Kt | | 59 | 2.9886 | 0.2302 | 2.470 | 3.41 | 0.94 |

TABLE 3. Summary statistics for 12 pipette analyses.

| Phi | mm | N | MEAN% | STDEV | MIN | MAX | RANGE |
|---|---|---|---|---|---|---|---|
| 4.5 | 0.044 | 12 | 0.764 | 0.492 | 0.00 | 1.73 | 1.73 |
| 5.0 | 0.031 | 12 | 3.848 | 0.828 | 2.98 | 5.93 | 2.95 |
| 5.5 | 0.022 | 12 | 9.411 | 0.481 | 8.57 | 10.16 | 1.59 |
| 6.0 | 0.016 | 12 | 8.632 | 0.698 | 7.47 | 9.66 | 2.19 |
| 6.5 | 0.011 | 12 | 7.390 | 2.059 | 1.25 | 8.98 | 7.73 |
| 7.0 | 0.008 | 12 | 7.787 | 2.047 | 5.64 | 13.87 | 8.23 |
| 7.5 | 0.006 | 12 | 8.200 | 1.608 | 5.62 | 9.98 | 4.36 |
| 8.0 | 0.004 | 12 | 4.468 | 2.049 | 1.46 | 6.90 | 5.44 |
| 8.5 | 0.003 | 12 | 5.288 | 1.144 | 3.54 | 6.88 | 3.34 |
| 9.0 | 0.002 | 12 | 6.313 | 1.248 | 4.17 | 8.27 | 4.10 |
| 14.0 | 0.0001 | 12 | 37.896 | 0.877 | 36.61 | 39.27 | 2.66 |
| AVERAGE STATISTICS | | | | | | | |
| mean phi | | 12 | 8.4825 | 0.0637 | 8.40 | 8.57 | 0.17 |
| SD | | 12 | 2.5500 | 0.0256 | 2.51 | 2.59 | 0.08 |
| Sk | | 12 | 0.0917 | 0.0310 | 0.05 | 0.13 | 0.08 |
| Kt | | 12 | 1.3975 | 0.0160 | 1.37 | 1.43 | 0.06 |

Table 4. Average grain-size parameters.

| | avg %silt | avg %clay | avg mean phi | avg SD | avg Sk | avg Kt |
|---|---|---|---|---|---|---|
| Hydrophotometer | 85.37 | 14.63 | 7.69 | 1.90 | 0.73 | 2.99 |
| Pipette | 62.10 | 37.90 | 8.48 | 2.55 | 0.09 | 1.40 |

# APPENDICES

APPENDIX 1: Hydrophotometer weight percent data for the triplicate analyses of samples 3 and 4, used to generate the plots shown in figures 1 and 2.

APPENDIX 2: Weight percent data, moment measures, modal analysis and frequency and cumulative frequency plots for the duplicate analyses of the Russian River shelf sediment.

APPENDIX 3: Data generated from the 59 hydrophotometer analyses. Data is presented as weight percent of material for each 1/2 phi size-interval analyzed from 4 to 9$\phi$ . The column labelled 14 represents the percentage of material (clay) as a single weight percent finer than the lowest analysis point of 9.0 phi. Also included are the mean phi, sorting as standard deviation (stdev), skewness (sk) and kurtosis (kt) for each of the 59 analyses.

APPENDIX 4: Data generated from the 12 pipette analyses. Data is presented as weight percent of material for each 1/2 phi interval analyzed from 4 to 9 phi. The column labelled 14 represents the percentage of material (clay) as a single weight percent finer than the lowest analyses point of 9.0 phi. Also included are the mean phi, sorting as standard deviation (stdev), skewness (sk) and kurtosis (kt) for each analysis.

Appendix 1. Particle size distribution.

| phi | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 14.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | 0.044 | 0.031 | 0.022 | 0.016 | 0.011 | 0.008 | 0.006 | 0.004 | 0.003 | 0.002 | 0.0001 |
| SAMPLE | WEIGHT PERCENT | | | | | | | | | | |
| 3A | 8.92 | 36.75 | 41.17 | 12.69 | 0.39 | 0.02 | 0.02 | 0.01 | 0.00 | 0.00 | 0.03 |
| 3B | 20.12 | 38.05 | 31.20 | 10.02 | 0.31 | 0.04 | 0.07 | 0.05 | 0.03 | 0.00 | 0.11 |
| 3C | 34.93 | 42.08 | 17.85 | 4.66 | 0.22 | 0.14 | 0.02 | 0.00 | 0.00 | 0.00 | 0.10 |
| 4A | 14.30 | 40.81 | 40.25 | 4.36 | 0.15 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 | 0.03 |
| 4B | 27.50 | 46.78 | 23.26 | 2.26 | 0.03 | 0.04 | 0.05 | 0.03 | 0.02 | 0.03 | 0.00 |
| 4C | 27.56 | 50.57 | 19.55 | 2.23 | 0.00 | 0.04 | 0.03 | 0.00 | 0.00 | 0.00 | 0.02 |

## Appendix 2. Particle size distribution.

| phi | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 14.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | 0.044 | 0.031 | 0.022 | 0.016 | 0.011 | 0.008 | 0.006 | 0.004 | 0.003 | 0.002 | 0.0001 |
| SAMPLE | WEIGHT PERCENT | | | | | | | | | | |
| 301 | 16.46 | 28.65 | 14.51 | 10.26 | 8.13 | 6.29 | 4.29 | 4.45 | 2.40 | 1.05 | 3.51 |
| 301r | 33.47 | 14.91 | 16.57 | 9.60 | 5.79 | 5.64 | 5.59 | 2.92 | 1.81 | 0.18 | 3.52 |
| 303 | 13.14 | 23.11 | 17.87 | 10.65 | 8.72 | 7.32 | 6.30 | 3.66 | 1.97 | 1.15 | 6.11 |
| 303r | 27.63 | 14.47 | 14.38 | 13.48 | 7.13 | 7.64 | 5.01 | 3.82 | 1.97 | 0.28 | 4.19 |
| 307 | 28.87 | 18.09 | 14.99 | 9.55 | 7.41 | 6.26 | 6.22 | 2.19 | 2.68 | 0.05 | 3.69 |
| 307r | 22.52 | 21.93 | 15.76 | 10.91 | 7.99 | 5.48 | 5.16 | 3.60 | 2.00 | 0.65 | 4.00 |
| 317 | 2.77 | 2.03 | 10.79 | 11.82 | 11.53 | 10.82 | 3.51 | 15.12 | 7.49 | 10.80 | 13.32 |
| 317r | 0.84 | 9.75 | 12.17 | 11.37 | 12.67 | 9.88 | 3.42 | 10.62 | 9.72 | 7.51 | 12.05 |
| 324 | 24.61 | 11.77 | 18.11 | 7.97 | 7.09 | 6.15 | 6.79 | 4.77 | 4.15 | 2.35 | 6.24 |
| 324r | 18.87 | 19.32 | 12.39 | 11.75 | 5.68 | 7.18 | 8.25 | 4.88 | 3.99 | 2.33 | 5.36 |
| 329 | 23.32 | 14.98 | 12.33 | 8.45 | 7.35 | 7.18 | 9.16 | 5.02 | 4.28 | 2.70 | 5.23 |
| 329r | 26.12 | 13.43 | 10.90 | 10.40 | 8.46 | 6.50 | 7.16 | 5.89 | 3.76 | 2.08 | 5.30 |
| 335 | 22.20 | 22.92 | 16.26 | 10.41 | 7.07 | 5.84 | 4.20 | 4.03 | 2.42 | 1.16 | 3.49 |
| 335r | 30.76 | 18.48 | 14.03 | 9.41 | 7.03 | 4.92 | 5.47 | 2.80 | 2.25 | 1.46 | 3.19 |
| 336 | 33.49 | 19.64 | 8.85 | 9.05 | 4.36 | 10.92 | 1.40 | 2.93 | 2.96 | 0.68 | 5.72 |
| 336r | 12.03 | 34.00 | 9.15 | 8.54 | 6.86 | 13.36 | 0.90 | 2.77 | 4.68 | 1.04 | 6.67 |
| 337 | 29.11 | 35.26 | 16.66 | 7.08 | 3.51 | 2.48 | 2.22 | 0.74 | 0.82 | 0.73 | 1.39 |
| 337r | 36.56 | 28.63 | 16.20 | 6.50 | 3.94 | 1.99 | 2.11 | 1.57 | 0.48 | 0.66 | 1.36 |
| 341 | 8.55 | 19.57 | 11.66 | 10.10 | 8.63 | 8.00 | 8.42 | 10.31 | 3.24 | 4.05 | 7.47 |
| 341r | 8.50 | 18.14 | 13.96 | 8.58 | 9.96 | 7.77 | 10.38 | 5.88 | 4.76 | 4.81 | 7.26 |

## Appendix 3. Particle size distribution.

| phi | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 14.0 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | 0.044 | 0.031 | 0.022 | 0.016 | 0.011 | 0.008 | 0.006 | 0.004 | 0.003 | 0.002 | 0.0001 | | | | |
| SAMPLE | WEIGHT PERCENT | | | | | | | | | | | MOMENT MEASURES | | | |
| | | | | | | | | | | | | mean | stdev | sk | kt |
| 524a-1 | 3.75 | 2.32 | 1.70 | 1.25 | 11.13 | 14.55 | 11.82 | 14.14 | 10.29 | 10.85 | 18.20 | 7.95 | 1.98 | 0.55 | 2.68 |
| 524a-2 | 5.04 | 0.91 | 3.79 | 10.49 | 14.93 | 11.60 | 11.28 | 10.80 | 8.64 | 8.11 | 14.41 | 7.51 | 1.98 | 0.78 | 2.97 |
| 524a-3 | 2.02 | 2.41 | 0.73 | 0.40 | 11.94 | 15.93 | 18.29 | 10.59 | 7.59 | 10.88 | 19.22 | 8.02 | 1.94 | 0.68 | 2.64 |
| 524a-4 | 2.01 | 2.94 | 0.81 | 9.99 | 11.87 | 11.55 | 18.44 | 8.32 | 7.82 | 11.60 | 14.65 | 7.69 | 1.89 | 0.79 | 2.99 |
| 524a-5 | 3.98 | 1.71 | 6.26 | 12.34 | 11.64 | 11.89 | 11.45 | 10.37 | 9.29 | 7.17 | 13.90 | 7.44 | 1.97 | 0.83 | 3.01 |
| 524a-6 | 5.01 | 1.68 | 4.15 | 11.46 | 13.20 | 11.59 | 11.15 | 11.47 | 7.23 | 9.39 | 13.67 | 7.46 | 1.97 | 0.78 | 3.00 |
| 524a-7 | 2.07 | 2.07 | 0.42 | 0.65 | 8.54 | 17.55 | 15.60 | 14.66 | 8.31 | 10.21 | 19.92 | 8.10 | 1.92 | 0.65 | 2.62 |
| 524a-8 | 3.75 | 2.53 | 9.63 | 11.21 | 13.97 | 10.50 | 11.72 | 8.65 | 5.62 | 9.53 | 12.89 | 7.31 | 1.98 | 0.88 | 3.07 |
| 524a-9 | 1.62 | 1.88 | 1.37 | 1.37 | 17.80 | 13.20 | 12.79 | 12.92 | 10.33 | 8.06 | 18.66 | 7.94 | 1.94 | 0.75 | 2.66 |
| 524a-10 | 0.31 | 1.55 | 7.05 | 15.19 | 12.56 | 11.48 | 11.95 | 7.84 | 7.55 | 11.24 | 13.28 | 7.50 | 1.89 | 0.95 | 3.04 |
| 524b-1 | 4.34 | 2.18 | 0.95 | 2.82 | 15.23 | 11.85 | 11.93 | 15.21 | 9.18 | 11.61 | 14.70 | 7.76 | 1.90 | 0.63 | 3.02 |
| 524b-2 | 2.88 | 3.04 | 1.59 | 0.96 | 10.56 | 15.49 | 10.73 | 13.54 | 11.32 | 14.98 | 14.91 | 7.90 | 1.85 | 0.56 | 2.99 |
| 524b-3 | 2.86 | 2.58 | 0.51 | 1.79 | 14.57 | 13.85 | 14.54 | 11.03 | 10.70 | 11.98 | 15.59 | 7.85 | 1.88 | 0.68 | 2.96 |
| 524b-4 | 1.49 | 0.85 | 5.52 | 13.42 | 12.13 | 12.58 | 11.54 | 8.27 | 10.52 | 11.79 | 11.89 | 7.52 | 1.82 | 0.89 | 3.21 |
| 524b-5 | 2.77 | 1.73 | 0.47 | 4.43 | 15.52 | 12.99 | 13.98 | 10.02 | 12.10 | 11.53 | 14.46 | 7.79 | 1.84 | 0.74 | 3.07 |
| 524b-6 | 2.87 | 1.38 | 0.54 | 1.32 | 13.03 | 13.70 | 15.12 | 12.57 | 12.84 | 11.75 | 14.88 | 7.90 | 1.80 | 0.70 | 3.15 |
| 524b-7 | 3.28 | 2.05 | 7.25 | 12.82 | 11.86 | 10.83 | 9.58 | 8.49 | 9.90 | 11.97 | 11.97 | 7.42 | 1.92 | 0.78 | 3.03 |
| 524b-8 | 6.76 | 1.55 | 16.35 | 10.30 | 9.85 | 9.83 | 9.74 | 6.81 | 8.13 | 9.48 | 11.20 | 7.11 | 2.01 | 0.84 | 3.06 |
| 524b-9 | 3.65 | 1.21 | 6.00 | 13.48 | 10.74 | 12.41 | 12.20 | 10.17 | 8.04 | 7.67 | 14.43 | 7.48 | 1.98 | 0.84 | 2.97 |
| 524b-10 | 3.27 | 2.27 | 1.31 | 4.47 | 15.89 | 11.50 | 16.92 | 8.80 | 10.61 | 9.57 | 15.39 | 7.73 | 1.91 | 0.73 | 2.96 |
| 524c-1 | 3.51 | 2.58 | 0.94 | 1.02 | 17.19 | 12.07 | 13.81 | 13.55 | 4.01 | 13.12 | 18.20 | 7.89 | 2.00 | 0.61 | 2.63 |
| 524c-2 | 1.04 | 2.29 | 3.09 | 10.77 | 14.21 | 12.44 | 11.50 | 11.50 | 7.62 | 9.33 | 16.21 | 7.70 | 1.95 | 0.84 | 2.78 |
| 524c-3 | 2.92 | 2.04 | 2.45 | 8.35 | 13.80 | 12.92 | 14.70 | 8.36 | 6.24 | 10.86 | 17.36 | 7.74 | 2.02 | 0.72 | 2.65 |
| 524c-4 | 3.10 | 1.02 | 0.88 | 9.32 | 14.86 | 10.83 | 17.68 | 8.02 | 8.30 | 9.03 | 16.96 | 7.75 | 1.97 | 0.77 | 2.77 |
| 524c-5 | 3.17 | 1.45 | 1.61 | 0.66 | 9.80 | 14.32 | 17.83 | 10.52 | 9.47 | 11.52 | 19.65 | 8.06 | 1.96 | 0.57 | 2.60 |
| 524c-6 | 1.13 | 3.29 | 1.28 | 5.24 | 14.15 | 12.73 | 16.55 | 9.95 | 8.14 | 10.06 | 17.48 | 7.85 | 1.94 | 0.76 | 2.71 |
| 524c-7 | 4.64 | 2.26 | 0.41 | 5.07 | 15.21 | 11.72 | 13.13 | 9.59 | 8.57 | 9.96 | 19.44 | 7.87 | 2.08 | 0.57 | 2.47 |
| 524c-8 | 2.85 | 0.47 | 0.77 | 12.81 | 13.19 | 10.44 | 14.76 | 9.33 | 7.66 | 9.27 | 18.45 | 7.81 | 2.02 | 0.73 | 2.56 |
| 524c-9 | 3.31 | 2.63 | 3.24 | 8.85 | 14.84 | 10.89 | 15.52 | 9.01 | 6.87 | 8.15 | 16.69 | 7.63 | 2.03 | 0.77 | 2.75 |
| 524c-10 | 1.90 | 2.20 | 1.43 | 0.58 | 14.74 | 16.34 | 14.39 | 8.66 | 7.88 | 13.10 | 18.78 | 7.99 | 1.95 | 0.67 | 2.58 |
| 524d-1 | 3.04 | 1.35 | 0.28 | 2.66 | 12.33 | 11.91 | 15.69 | 13.63 | 7.77 | 18.06 | 13.28 | 7.88 | 1.76 | 0.64 | 3.25 |
| 524d-2 | 4.44 | 3.29 | 0.53 | 6.47 | 12.88 | 10.32 | 13.35 | 12.56 | 8.38 | 15.97 | 11.81 | 7.63 | 1.84 | 0.58 | 3.16 |
| 524d-3 | 2.76 | 2.21 | 0.62 | 4.78 | 13.79 | 11.42 | 16.52 | 12.48 | 6.65 | 17.50 | 11.28 | 7.70 | 1.73 | 0.71 | 3.41 |
| 524d-4 | 2.43 | 1.15 | 2.29 | 8.45 | 13.21 | 10.67 | 13.10 | 14.21 | 7.10 | 16.49 | 10.90 | 7.64 | 1.74 | 0.75 | 3.37 |
| 524d-5 | 5.02 | 7.58 | 12.97 | 6.70 | 9.94 | 8.17 | 12.32 | 9.81 | 6.23 | 12.60 | 8.66 | 7.08 | 1.90 | 0.74 | 3.16 |
| 524d-6 | 3.55 | 1.16 | 1.42 | 0.72 | 8.07 | 15.07 | 17.33 | 12.47 | 9.08 | 18.37 | 12.76 | 7.89 | 1.74 | 0.59 | 3.40 |
| 524d-7 | 2.93 | 0.97 | 0.83 | 3.81 | 10.64 | 11.82 | 17.23 | 13.16 | 7.92 | 17.03 | 13.66 | 7.88 | 1.77 | 0.66 | 3.21 |
| 524d-8 | 8.52 | 2.63 | 13.74 | 9.49 | 8.67 | 8.19 | 10.66 | 9.90 | 6.03 | 13.21 | 8.96 | 7.07 | 1.94 | 0.71 | 3.20 |
| 524d-9 | 4.36 | 1.53 | 0.70 | 0.27 | 11.45 | 12.05 | 15.51 | 16.44 | 7.67 | 15.81 | 14.21 | 7.89 | 1.82 | 0.56 | 3.20 |
| 524d-10 | 2.93 | 2.50 | 1.10 | 0.35 | 10.38 | 12.47 | 14.30 | 15.43 | 9.46 | 16.96 | 14.12 | 7.93 | 1.79 | 0.56 | 3.18 |
| 524e-1 | 3.55 | 1.10 | 0.95 | 0.61 | 9.75 | 15.96 | 12.98 | 9.69 | 17.24 | 10.87 | 17.29 | 8.03 | 1.88 | 0.56 | 2.87 |
| 524e-2 | 3.20 | 1.80 | 1.14 | 11.85 | 10.48 | 12.51 | 13.96 | 8.42 | 12.55 | 9.59 | 14.50 | 7.67 | 1.91 | 0.74 | 2.96 |
| 524e-3 | 2.41 | 2.44 | 0.89 | 2.07 | 11.02 | 15.17 | 17.94 | 11.18 | 11.90 | 9.00 | 15.98 | 7.87 | 1.86 | 0.74 | 3.03 |
| 524e-4 | 1.92 | 1.92 | 0.39 | 4.20 | 8.99 | 17.95 | 13.60 | 12.56 | 12.30 | 9.87 | 16.30 | 7.92 | 1.85 | 0.75 | 2.96 |
| 524e-5 | 4.83 | 3.14 | 1.14 | 8.40 | 13.25 | 13.19 | 10.71 | 11.96 | 9.59 | 9.49 | 14.30 | 7.59 | 1.96 | 0.69 | 2.95 |
| 524e-6 | 1.67 | 0.45 | 2.05 | 10.46 | 14.65 | 13.97 | 12.28 | 8.64 | 10.89 | 8.88 | 16.06 | 7.74 | 1.91 | 0.86 | 2.85 |
| 524e-7 | 3.13 | 4.48 | 11.13 | 14.87 | 9.98 | 9.16 | 11.87 | 6.95 | 9.75 | 5.73 | 12.95 | 7.22 | 2.01 | 0.93 | 3.08 |
| 524e-8 | 2.29 | 1.05 | 11.47 | 9.90 | 12.86 | 11.85 | 9.75 | 11.16 | 9.04 | 6.89 | 13.74 | 7.42 | 1.96 | 0.89 | 3.04 |
| 524e-9 | 2.47 | 0.82 | 15.39 | 12.43 | 11.47 | 10.31 | 8.72 | 8.66 | 9.79 | 8.11 | 11.83 | 7.26 | 1.94 | 0.93 | 3.16 |
| 524f-1 | 3.51 | 2.20 | 0.43 | 6.09 | 11.16 | 17.07 | 9.76 | 14.37 | 8.29 | 15.70 | 11.42 | 7.67 | 1.77 | 0.68 | 3.36 |
| 524f-2 | 1.50 | 1.87 | 10.24 | 14.36 | 10.80 | 12.11 | 10.65 | 8.55 | 7.42 | 10.42 | 12.08 | 7.36 | 1.90 | 0.93 | 3.16 |
| 524f-3 | 3.61 | 1.84 | 1.12 | 6.64 | 12.60 | 17.21 | 10.25 | 12.06 | 9.23 | 11.78 | 13.66 | 7.67 | 1.87 | 0.74 | 3.12 |
| 524f-4 | 4.06 | 2.43 | 0.82 | 0.88 | 12.75 | 14.27 | 14.47 | 12.70 | 9.96 | 14.27 | 13.39 | 7.79 | 1.82 | 0.61 | 3.22 |
| 524f-5 | 3.92 | 1.27 | 1.44 | 14.11 | 9.74 | 16.36 | 10.61 | 9.41 | 8.80 | 11.69 | 12.65 | 7.53 | 1.88 | 0.79 | 3.15 |
| 524f-6 | 3.98 | 2.02 | 0.98 | 11.21 | 10.62 | 13.91 | 12.94 | 11.80 | 7.98 | 12.64 | 11.92 | 7.55 | 1.84 | 0.75 | 3.26 |
| 524f-7 | 2.71 | 2.29 | 1.58 | 12.12 | 12.34 | 13.61 | 11.04 | 9.07 | 8.81 | 13.60 | 12.83 | 7.59 | 1.87 | 0.77 | 3.06 |
| 524f-8 | 4.46 | 1.86 | 0.75 | 0.66 | 15.43 | 13.30 | 14.75 | 9.41 | 8.70 | 14.85 | 15.83 | 7.85 | 1.92 | 0.58 | 2.87 |
| 524f-9 | 3.37 | 2.33 | 0.22 | 5.97 | 14.52 | 13.42 | 14.47 | 11.63 | 8.65 | 9.55 | 15.87 | 7.74 | 1.93 | 0.73 | 2.91 |
| 524f-10 | 1.04 | 2.70 | 0.70 | 2.16 | 14.11 | 17.05 | 13.35 | 11.16 | 7.49 | 16.79 | 13.45 | 7.83 | 1.76 | 0.81 | 3.18 |

## Appendix 4. Particle size distribution.

| phi | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 14.0 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | 0.044 | 0.031 | 0.022 | 0.016 | 0.011 | 0.008 | 0.006 | 0.004 | 0.003 | 0.002 | 0.0001 | | | | |
| SAMPLE | WEIGHT PERCENT | | | | | | | | | | | MOMENT MEASURES | | | |
| | | | | | | | | | | | | mean | stdev | sk | kt |
| 524g | 1.73 | 3.32 | 9.53 | 9.53 | 7.94 | 6.93 | 9.96 | 2.02 | 5.49 | 5.34 | 38.20 | 8.44 | 2.59 | 0.10 | 1.38 |
| 524h | 0.16 | 3.90 | 8.88 | 9.66 | 1.25 | 13.87 | 9.98 | 3.90 | 4.36 | 6.23 | 37.81 | 8.51 | 2.51 | 0.11 | 1.40 |
| 524i | 0.77 | 3.69 | 9.99 | 9.38 | 6.61 | 8.15 | 8.76 | 3.07 | 6.76 | 5.84 | 36.98 | 8.43 | 2.55 | 0.12 | 1.41 |
| 524j | 0.83 | 4.80 | 9.49 | 8.97 | 8.03 | 7.51 | 9.91 | 1.46 | 5.74 | 6.05 | 37.20 | 8.40 | 2.58 | 0.13 | 1.39 |
| 524k | 1.13 | 3.25 | 10.16 | 8.61 | 8.89 | 6.63 | 9.46 | 2.68 | 5.36 | 7.06 | 36.78 | 8.42 | 2.55 | 0.13 | 1.41 |
| 524l | 1.18 | 4.14 | 9.34 | 8.51 | 7.33 | 7.69 | 9.82 | 2.60 | 6.39 | 6.39 | 36.61 | 8.41 | 2.55 | 0.12 | 1.43 |
| 524m | 1.03 | 3.30 | 9.91 | 7.84 | 8.98 | 6.92 | 6.71 | 6.09 | 3.92 | 7.74 | 37.55 | 8.48 | 2.55 | 0.09 | 1.41 |
| 524n | 0.53 | 2.98 | 9.53 | 7.47 | 8.40 | 8.00 | 5.62 | 6.88 | 3.84 | 8.27 | 38.48 | 8.57 | 2.52 | 0.05 | 1.40 |
| 524o | 0.19 | 3.85 | 9.55 | 8.25 | 7.94 | 6.64 | 7.13 | 6.51 | 3.54 | 8.00 | 38.39 | 8.54 | 2.53 | 0.06 | 1.39 |
| 524p | 0.73 | 5.93 | 8.57 | 7.83 | 8.05 | 7.54 | 6.44 | 5.34 | 6.88 | 4.17 | 38.50 | 8.47 | 2.59 | 0.08 | 1.39 |
| 524q | 0.00 | 3.87 | 9.00 | 8.75 | 8.33 | 5.64 | 7.40 | 6.90 | 5.30 | 5.55 | 39.27 | 8.57 | 2.54 | 0.05 | 1.37 |
| 524r | 0.89 | 3.14 | 8.98 | 8.78 | 6.93 | 7.93 | 7.21 | 6.16 | 5.88 | 5.12 | 38.98 | 8.55 | 2.54 | 0.06 | 1.39 |