AN ABSTRACT OF THE THESIS OF

JOSEPH PAUL DAUPHIN for the MASTER OF SCIENCE
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Title: SIZE DISTRIBUTION OF CHEMICALLY EXTRACTED QUARTZ USED TO CHARACTERIZE FINE-GRAINED SEDIMENTS

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Abstract approved: G. Ross Heath

Quartz is an ubiquitous component of marine sediments. Textural characteristics of this component reflect the dynamics of its transport and at the same time are indicative of its source.

Quartz may be extracted from marine sediments by means of a sodium pyrosulfate fusion and hydrofluosilicic acid dissolution without significantly modifying its size distribution. The size distribution of the chemically purified quartz is determined by means of a Cahn sedimentation balance which provides a continuous analog record. These records are digitized and computer processed to obtain size frequency distributions that subsequently are resolved for their modal components by means of an analog computer.

Three rather different sets of samples were studied to evaluate the application of this methodology to questions of the origin and dispersion of quartz in deep-sea sediments. Textural analysis of

chemically purified quartz reveals the following general features:

1. All the samples are polymodal in the 2 to 64 micron size range.

2. The modal character of quartz in river sediment persists in the marine environment and can serve as a provenance indicator.

3. Dispersal processes that act on a fine-grained sediment may change the relative proportions of the constituent quartz modes, but do not significantly alter the position of these modes. The way in which the relative proportion of the assorted modes vary within a depositional area may serve as a tool for mapping energy fields at the sea floor.

Size Distribution of Chemically Extracted Quartz Used to Characterize Fine-grained Sediments

by

Joseph Paul Dauphin

A THESIS

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Assistant Professor of Oceanography
in charge of major

Redacted for Privacy

Chairman of Department of Oceanography

Redacted for Privacy

Dean of Graduate School

Date thesis is presented March 2, 1972

Typed by Marjorie Hay for Joseph Paul Dauphin

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I also wish to thank Dr. T. C. Moore of the Department of Oceanography, Oregon State University for his helpful suggestions and also for serving as a member of my committee. Gratitude is also extended to Dr. A. R. Niem of the Department of Geology, Oregon State University, for serving as my minor advisor.

I wish to express sincere thanks to Dr. Tj. van Andel of the Department of Oceanography, Oregon State University, for his confidence and encouragement especially in the early stages of my career at Oregon State University.

Particular thanks are due to Dr. G. R. Heath, my major advisor, for giving me the opportunity to do this research and for his support and continued encouragement.

Discussions with Dr. T. C. Moore, Dr. J. Dymond, Mr. J. B. Phipps and Mr. R. K. Oser have greatly helped in the evaluation of the results from this study. This does not imply, however, that they necessarily agree with the conclusions presented here.

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SIZE DISTRIBUTION OF CHEMICALLY EXTRACTED QUARTZ USED TO CHARACTERIZE FINE-GRAINED SEDIMENTS

INTRODUCTION

Quartz in deep-sea sediments is essentially totally derived from continental sources (Rex, 1958) or from reworking of shelf and slope deposits. Authigenic and submarine volcanic sources are negligible; oceanically derived quartz has only been recognized on the crest of the East Pacific Rise (Peterson and Goldberg, 1962), and on Henderson Seamount (J. Dymond, personal communication, 1971). Quartz is ubiquitous in sediments primarily because of its relative mineralogical longevity. It is chemically stable in most environments and is highly resistent to mechanical destruction. Therefore, quartz found in deep-sea sediments should tend to preserve characteristics which reflect the dynamics of its transport and at the same time are indicative of its source. Such characteristics could be applied to the study of deep-sea sedimentary processes.

This study evaluates: 1) the effect of a chemical extraction technique on the original size distribution of sedimentary quartz; 2) the purity of the separated quartz; and 3) the potential value of the size frequency distributions of the chemically extracted quartz in characterizing fine-grained sediments.

METHODOLOGY AND INSTRUMENTATION

Figure 1 is a flow diagram which outlines in a general fashion the steps of the procedure developed and described in this study. The chemical extraction of quartz from fine-grained sediments basically involves a sodium pyrosulfate fusion (technique modified after Jackson, 1956) and post-fusion dissolution with hydrofluosilicic acid (technique modified after Syers _et al._, 1968).

Pyrosulfate Fusion

On heating, sodium pyrosulfate ($Na_2S_2O_7$) breaks down as follows:

$$Na_2S_2O_7 \longrightarrow Na_2SO_7 + SO_3$$

The SO_3 in the above reaction is a strong dehydroxylating agent and combines with structural water from silicates to form H_2SO_4. The fusion is carried out in silica crucibles which contain 200 mg. of sediment and 15 grams of $Na_2S_2O_7$. Normally, the first stage of pyrosulfate fusion is quite violent and requires careful attention and controlled heating with a meker burner. After the initial stage, the fusion proceeds in a less violent manner, so that the crucible can be strongly heated to complete the reaction. If the fusion vessels containing the sediment - $Na_2S_2O_7$ mixture are pre-heated to approximately 450° for 12 hours prior to fusion, the initial violent reaction

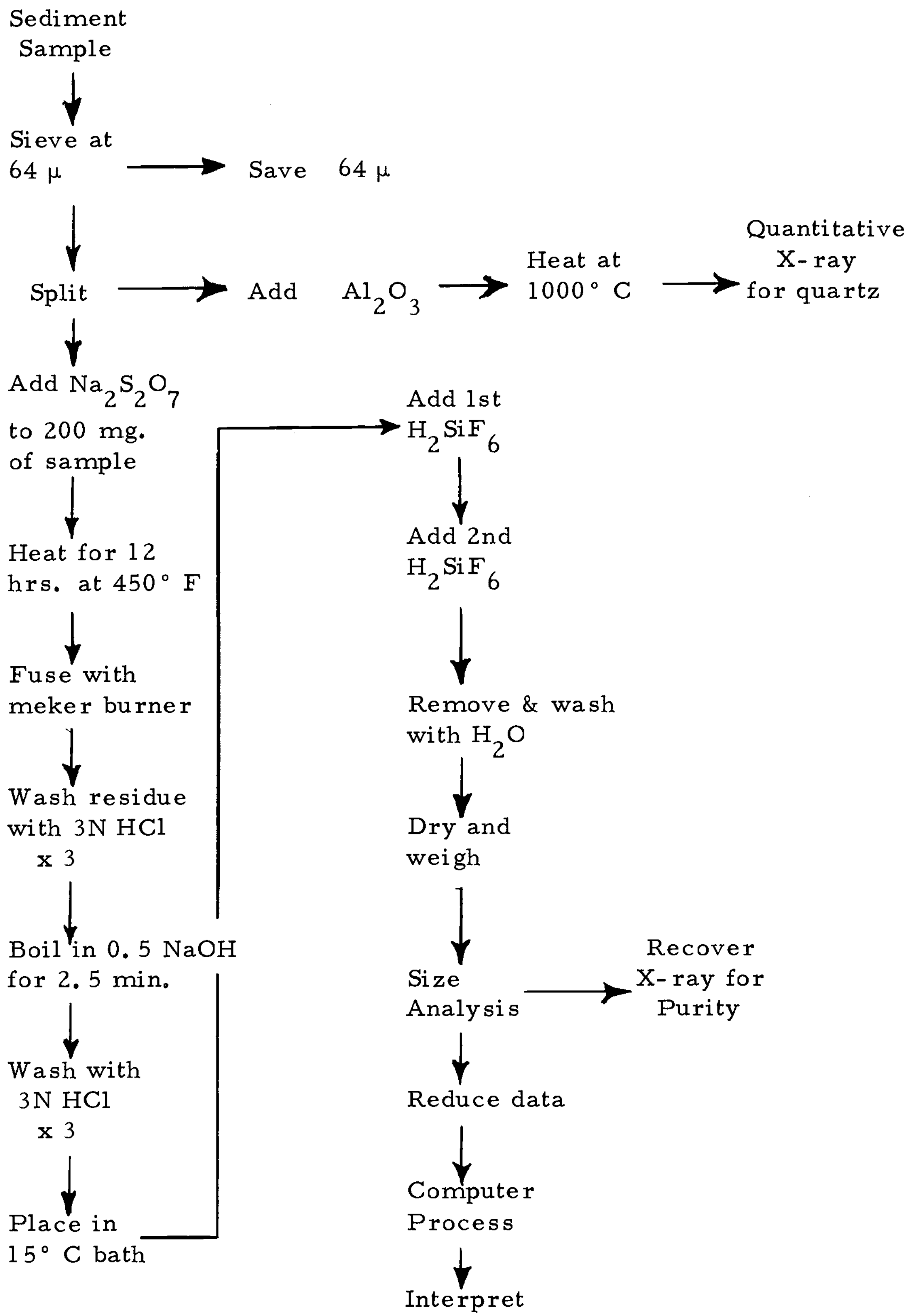

Figure 1. Flow diagram outlining the steps of the procedure.

is avoided. In the standardized procedure used in this study, the crucibles were pre-heated as above, then heated over meker burners for exactly 30 minutes.

One of the principle effects of the fusion step is the degradation of phyllosilicates by removal of hydroxyl units from their octahedral layers. This is followed by the stripping of octahedrally coordinated cations from these phyllosilicates by washing the fused residue with 3N HCl. Acid washing is repeated at least three times.

The remaining degraded silicate network is readily dissolved in hot 0.5 N NaOH. The acid-washed fusion residue is boiled for 2.5 minutes in the 0.5 N NaOH and then immersed in a bath of ice water to prevent the base from attacking quartz grains.

Minerals which resist dissolution by this process include zircon, topaz, tourmaline and feldspars high in sodium or potassium. Talc, pyrophyllite and tremolite partially resist dissolution (Jackson, 1956), and according to Syers _et al._ (1968), amphiboles and cristobalite are also resistant.

Hydrofluosilicic Acid Dissolution

Hydrofluosilicic acid (H_2SiF_6) attacks minerals which have aluminum in tetrahedral sites according to the reaction:

$$Al^{3} + 6F^{-} \longrightarrow Al\,F_6^{-3}$$

Pyrophyllite and talc have no aluminum in tetrahedral coordination, therefore, they are resistant to the H_2SiF_6 dissolution. Cristobalite also survives this treatment.

Hydrofluosilicic acid dissolution is carried out in 50 ml. polyethylene centrifuge tubes which are kept at 15° C ± 0.01° C in a Lauda K-2/R®[1] circulating constant temperature water bath for six days. Five milliliters of H_2SiF_6 were initially added to the residues from the fusion-dissolution technique described above. After a period of three days, another 5 ml. of H_2SiF_6 was added. On the sixth day, the residue is thoroughly washed with distilled water.

Because H_2SiF_6 tends to breakdown to free hydrofluoric acid, which attacks quartz and could seriously modify original grain size distributions, the dissolution step is the most critical phase of the treatment. The H_2SiF_6 is kept in a refrigerator and tumbled slowly and continuously in contact with quartz until it is to be used. This eliminates the accumulation of hydrofluoric acid before the treatment begins. In addition, the use of a low temperature bath allows for optimum dissolution while minimizing the breakdown of H_2SiF_6.

<u>Effect of Chemical Extraction on Quartz</u>

Jackson (1965) showed that pyrosulfate fusion did not affect

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[1] Brinkmann Instruments, Inc., Cantiague Road, Westbury, New Jersey 11590

quartz. His studies showed, however, that the NaOH treatment did attack quartz grains, the effect being most pronounced for small particles. For the three size fractions 20 to 50 microns, 5 to 20 microns and 2 to 5 microns, Jackson recovered 99.4 percent, 99.1 percent and 98.2 percent of the quartz. For the purposes of this study, such losses are negligible.

As mentioned earlier, however, the H_2SiF_6 dissolution technique is more likely to alter the size of the quartz particles. In order to evaluate the overall effect of the chemical treatment on the size distribution of quartz, samples of various sized particles, obtained by settling ground quartz according to Stoke's Law, were processed through the extraction procedures. The ground quartz was boiled in 2N NaOH to remove disordered surface layers prior to size fractionation. The mean phi[1] size of each fraction before and after the extraction procedure are plotted in Figure 2. For this study, the minor changes in size of the quartz particles produced by the extraction process can be ignored. Further evaluation of this effect and calculations of actual dissolution rates might be warranted for detailed studies of subtle variations in size characteristics of quartz in sediments.

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[1] phi = $-\log_2$ (diameter in mm). Because particle size distributions approach log normality (Krumbein, 1938) the use of phi, rather than linear units, (such as microns) facilitates interpretation of the data. Phi scales are logarithmic representations of size.

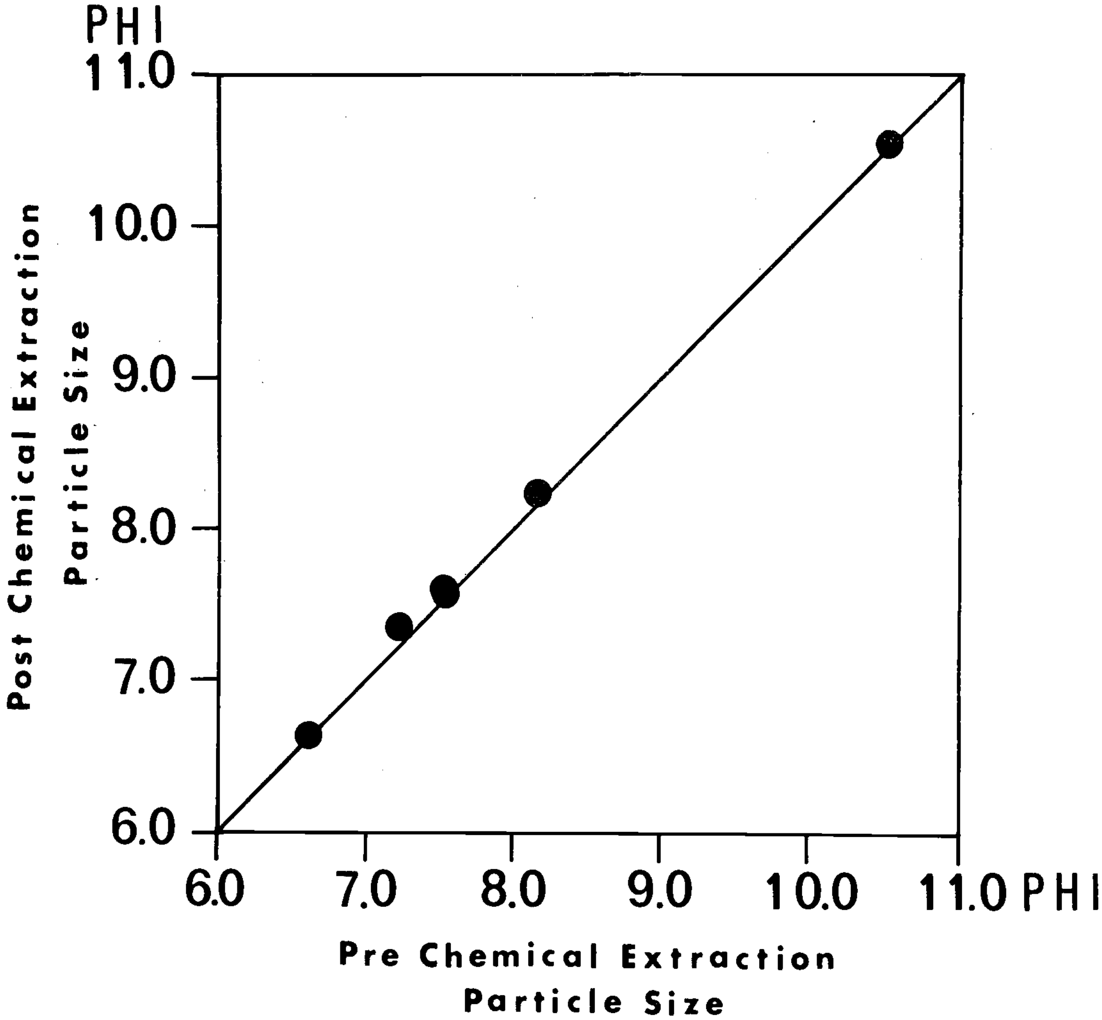

Figure 2. Plot showing quartz grain size before and after chemical extraction.

Effectiveness of the Chemical Extraction

In a later section, "Application of Methodology," sediment samples chosen to evaluate the quartz separates are described in some detail. For illustrative purposes, however, X-ray diffractograms of the post-extraction residues of several of these samples are shown in Figure 3. The diffractograms of Figure 3 are representative of the entire suite of samples examined in this study and show the range of purity of quartz obtained by the chemical extraction procedure. The diffractogram labeled Copper River, 1333, is of the least pure quartz residue. It contains a small amount of cristobalite, traces of talc, and a few small peaks of unidentified material which survived the extraction procedure.

The lack of contaminants evident in the diffractograms of Figure 3 and the minimal effect of the treatment on the size of quartz grains establishes conclusively that the chemical extraction procedure is an effective method of isolating quartz for textural analysis from fine-grained sediments.

Textural Analysis

A Cahn®[1] Particle Sedimentation system consisting of a #2800

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[1] Cahn Instruments, Division of Ventron, 7500 Jefferson Street, Paramount, California 90723

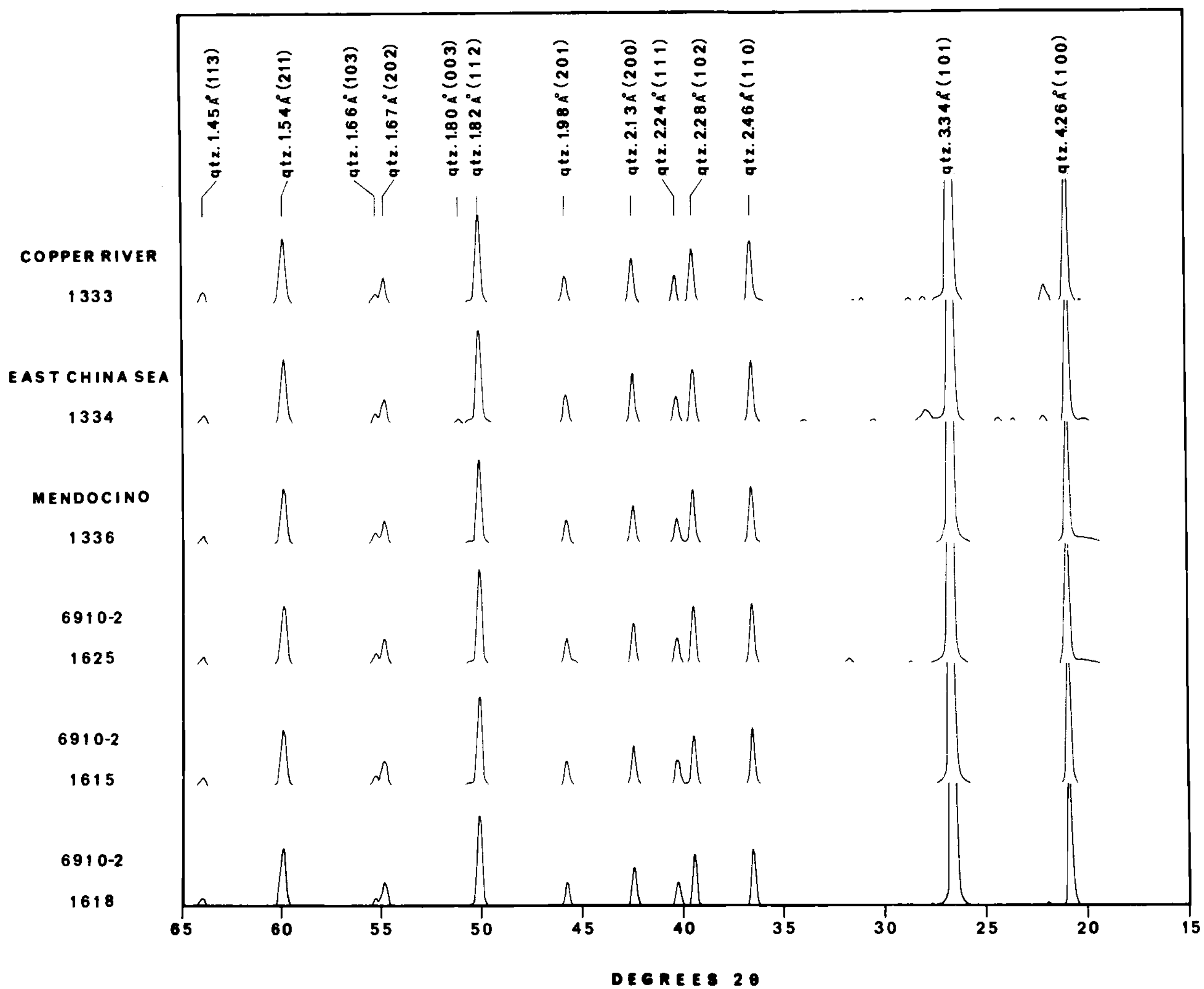

Figure 3. Representative X-ray diffractograms of post-extraction residues.

Particle Sedimentation Accessory and a #200 Model R. G. Electrobalance were used to determine the particle size distributions of the quartz residues. A Lauda® [1] K-2/RD circulating constant temperature bath was used to maintain the precise temperature control required by the system, and a Leeds and Northrup® [2] Speedomax Type W strip chart recorder was used to record a continuous analog trace of the electrobalance readings (Plate 1). This system continuously records the weight of sediment settling from an originally homogenous suspension to the bottom of a 25 cm column (Figure 4). The precision of the system can be evaluated by comparing the median diameters of splits of a single sample [Inman (1952) has shown statistically that the median diameter is the most reproducible characteristic of a particle size distribution]. Oser (1971) demonstrated that the continuous sedimentation technique used in this study has a reproducibility of 0.02 phi units. For comparison, careful pipette analysis has a reproducibility of the median diameter of 0.2 phi.

The analog data are digitized from 4.0 to 9.0 phi at 0.1 phi intervals corresponding to settling times calculated from Stoke's Law as follows:

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[1] Brinkmann Instruments, Inc., Cantiague Road, Westbury, New Jersey 11590

[2] Leeds and Northrup Company, 4901 Stenton Avenue, Philadelphia, Pennsylvania 19144

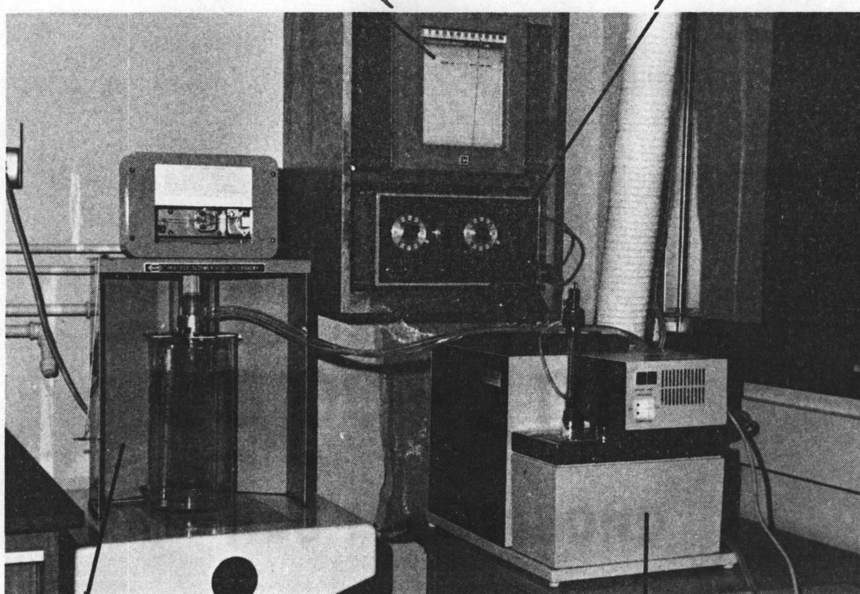

Plate 1. Cahn Particle Sedimentation System.

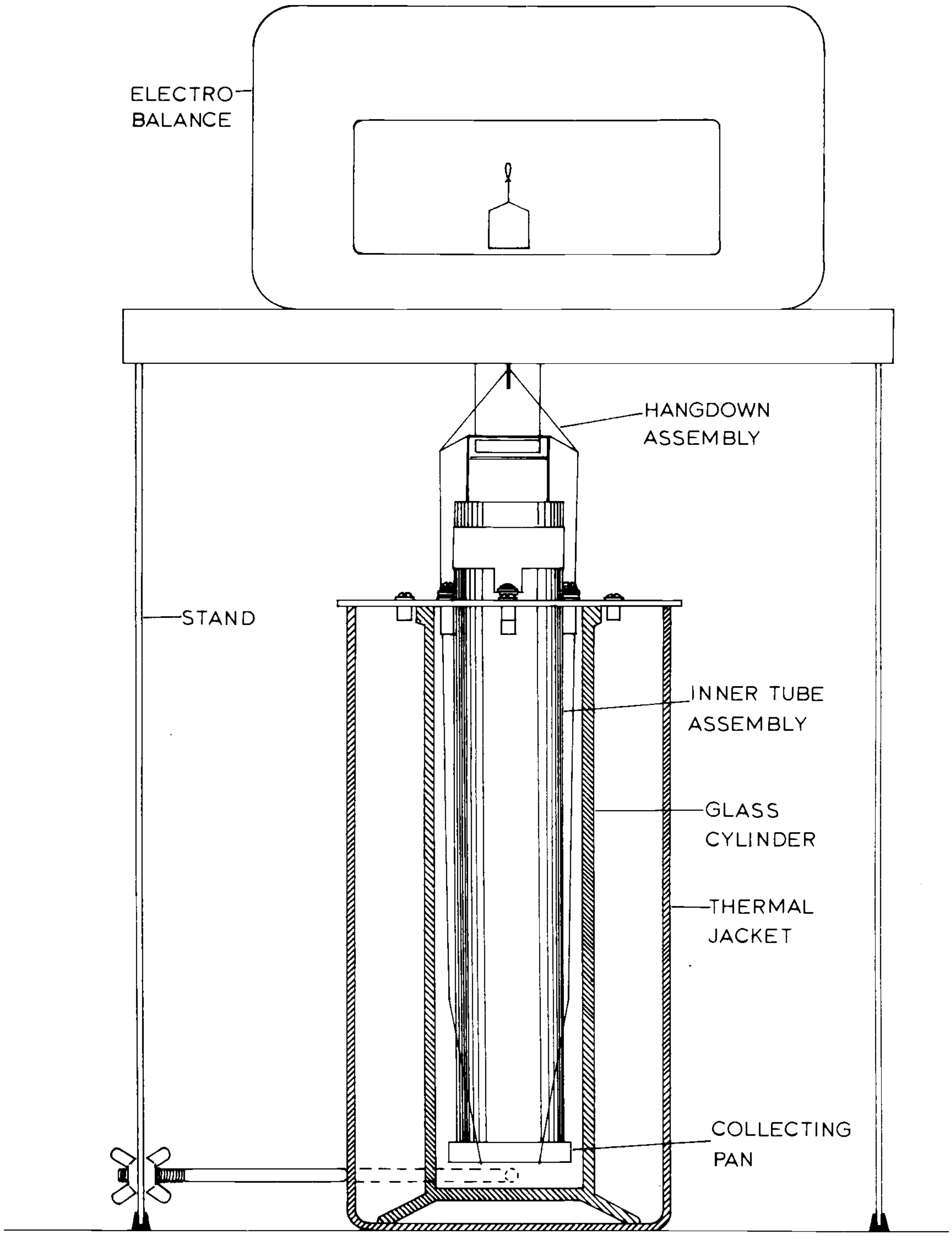

Figure 4. Schematic of cylinder assembly for sedimentation apparatus.

$$t = \frac{K}{D^2}$$

where D is the diameter of the particle and K is a systems constant:

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

where h = column height in centimeters

η = viscosity of the sedimentation fluid in poises

d_p = assumed density of particles in g/cm^3

d_f = density of sedimentation fluid g/cm^3

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

A single numerical differentiation of a cubic spline curve fitted to the raw data allows calculation of the cumulative particle size distribution (Oden, 1915), while a second differentiation leads to the frequency distribution. A computer program written by Dr. G. Ross Heath for the Control Data Corporation 3300 computer performs the appropriate numerical differentiations after initial digitization and keypunching of the data. The output of the program is in the form of plots of cumulative and frequency distribution of the particle size (Figure 5) as well as moment statistics and the graphic parameters of Inman (1952) and Folk and Ward (1957) as shown in Appendix II.

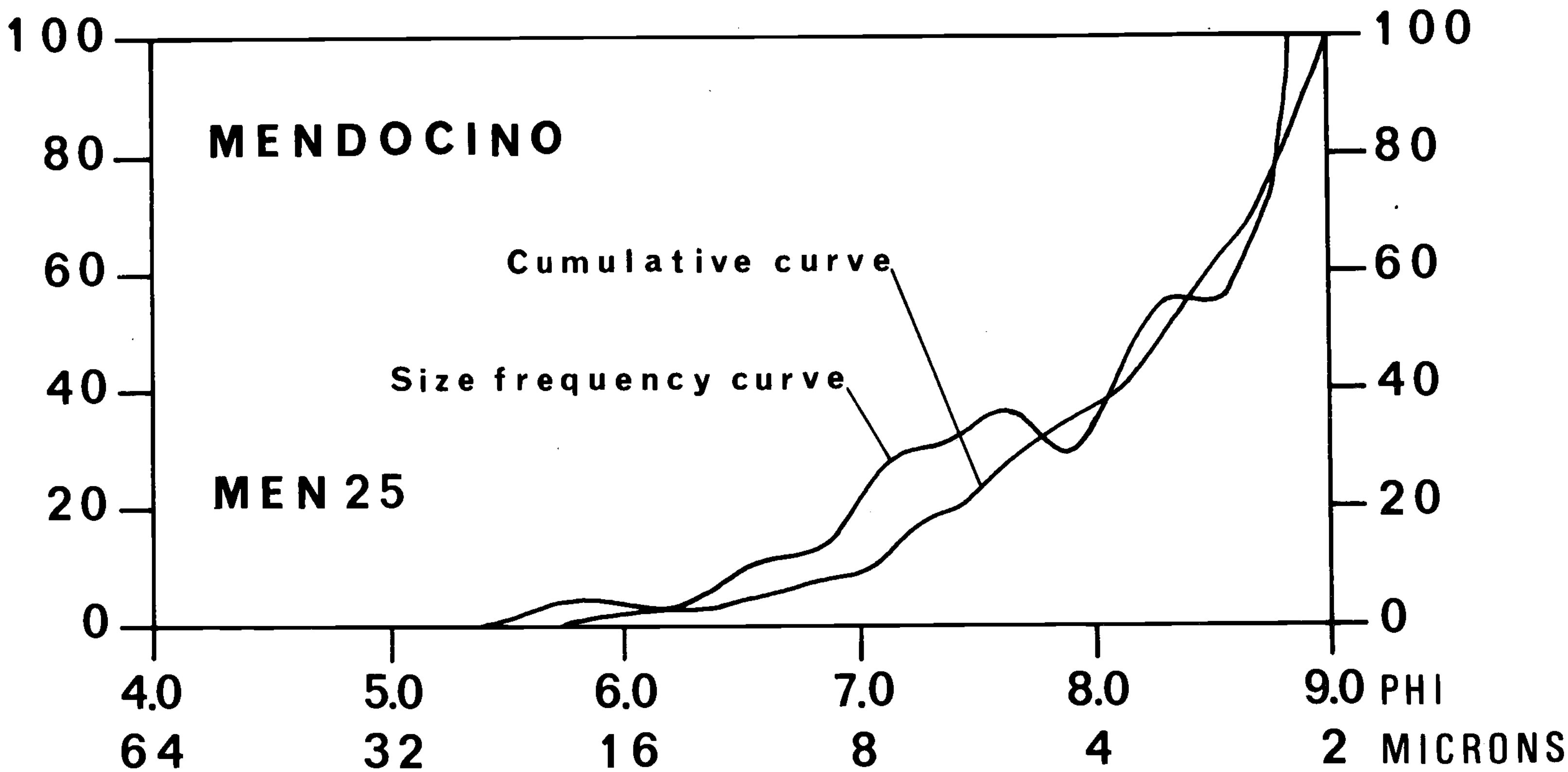

Figure 5. Sketch of computer plot of cumulative and size frequency distribution curves.

Resolution of Size Frequency Curves

A du Pont 310 Curve Resolver®[1] which is an analog computer capable of resolving the components of a polymodal distribution (Muller, 1966) was used to analyze the quartz size frequency distribution curves.

The curve resolver has up to ten channels which generate programmable distribution functions. In this study, the channels were programmed to generate Gaussian functions. The frequency curve to be resolved is placed on the curve resolver and is projected onto an oscilloscope by means of mirrors (Figure 6). The operator then matches the curve by varying the width, height and position (but not shape) of a minimum number of pure functions generated by the resolver. Figure 7 shows the frequency curve of Figure 5 with the modes resolved by the 310.

APPLICATION OF METHODOLOGY

In this section, the methodology already described is applied to three rather different sets of samples, to evaluate its application to questions of the origin and dispersion of quartz in deep-sea sediments.

The method was first applied to determine the textural

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[1] E. I. du Pont de Nemours and Co. (Inc.), Instrument Products Division, Wilmington, Delaware 19898

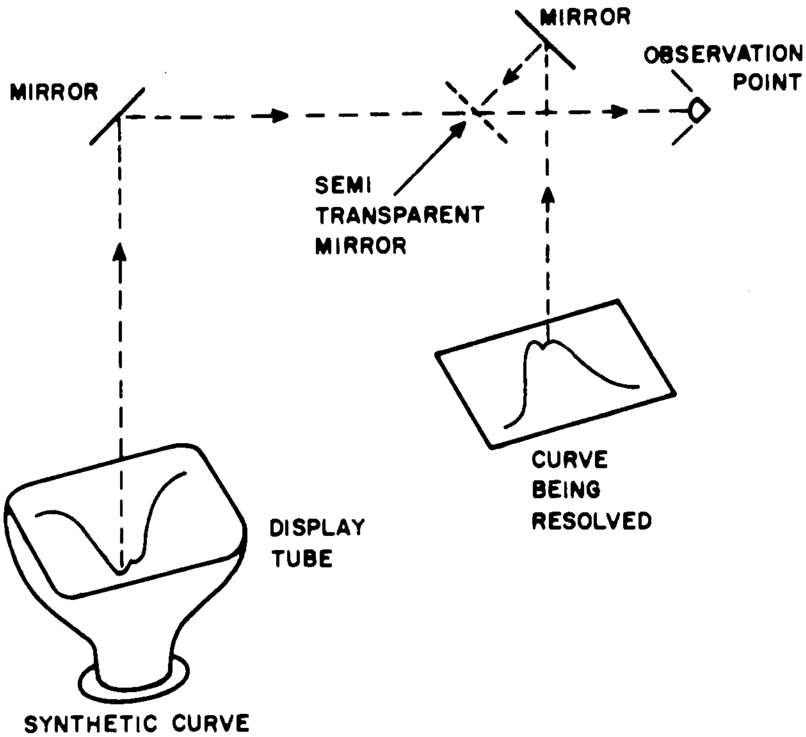


Figure 6. Sketch of the optical system for the du Pont 310 curve resolver.

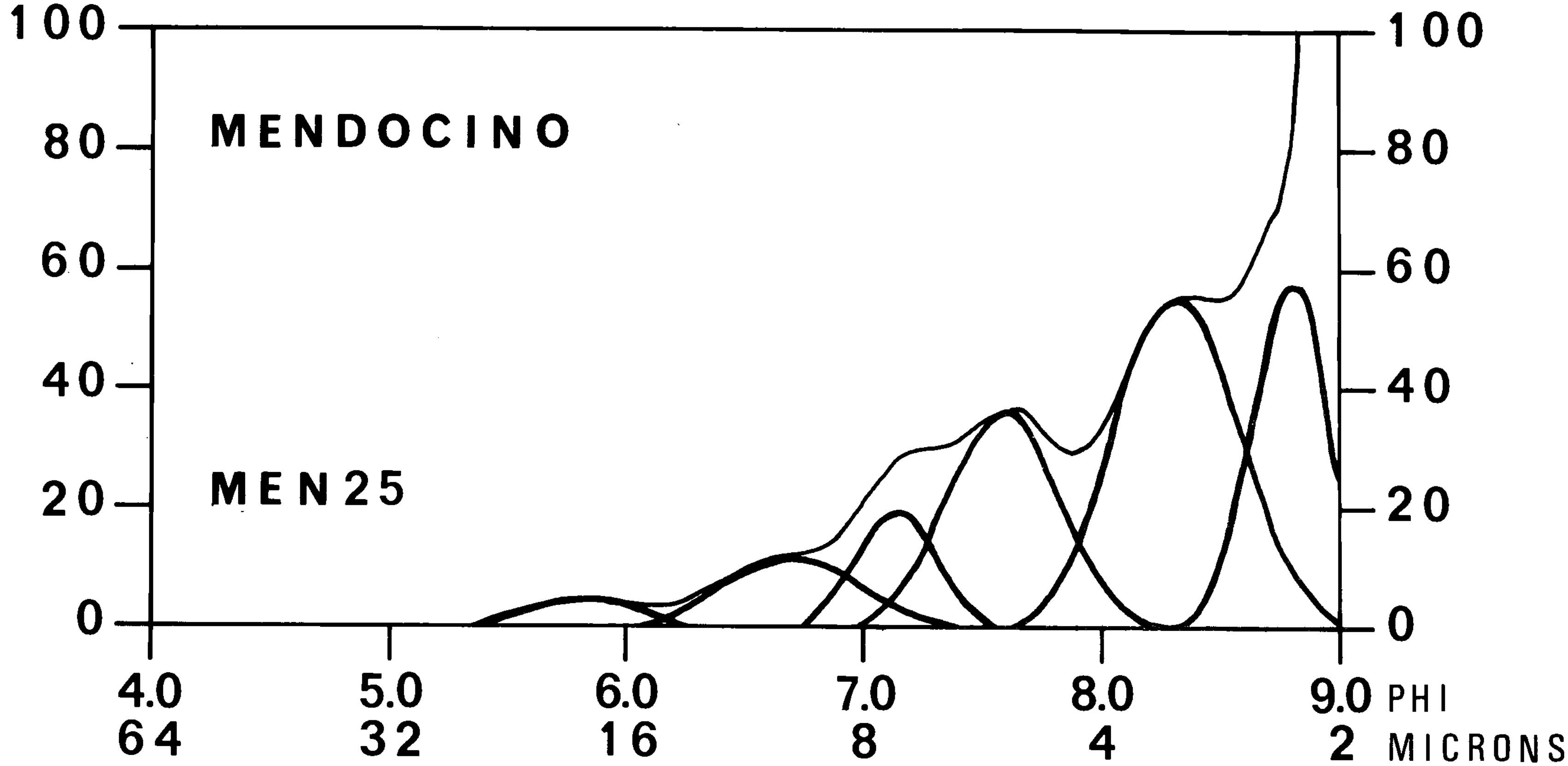


Figure 7. Normal resolution of a size frequency curve.

character of fine-grained quartz entering the ocean from the four major continental drainage systems supplying suspended sediment to the North Pacific Basin. These are the Columbia and Copper Rivers of the North American continent and the Yellow (Huang Ho) and the Yangtze (Ch'ang Chiang) Rivers of Asia. Figure 8 shows the mean annual discharge of sediment in millions of tons per year by these rivers, as well as the location of all samples used in this study.

The second application involved the study of two pairs of samples straddling the Mendocino Excarpment, to see whether a major deep-sea topographic barrier influences the textural character of fine-grained detrital quartz.

The third application was concerned with temporal variations of the size distribution of quartz in a northeast Pacific core spanning the last 30,000 years, that is, from the last glacial period to the present.

All samples are plotted on Figure 8 and exact locations together with water depths, and all other pertinent information for identification of the samples are given in Appendix I.

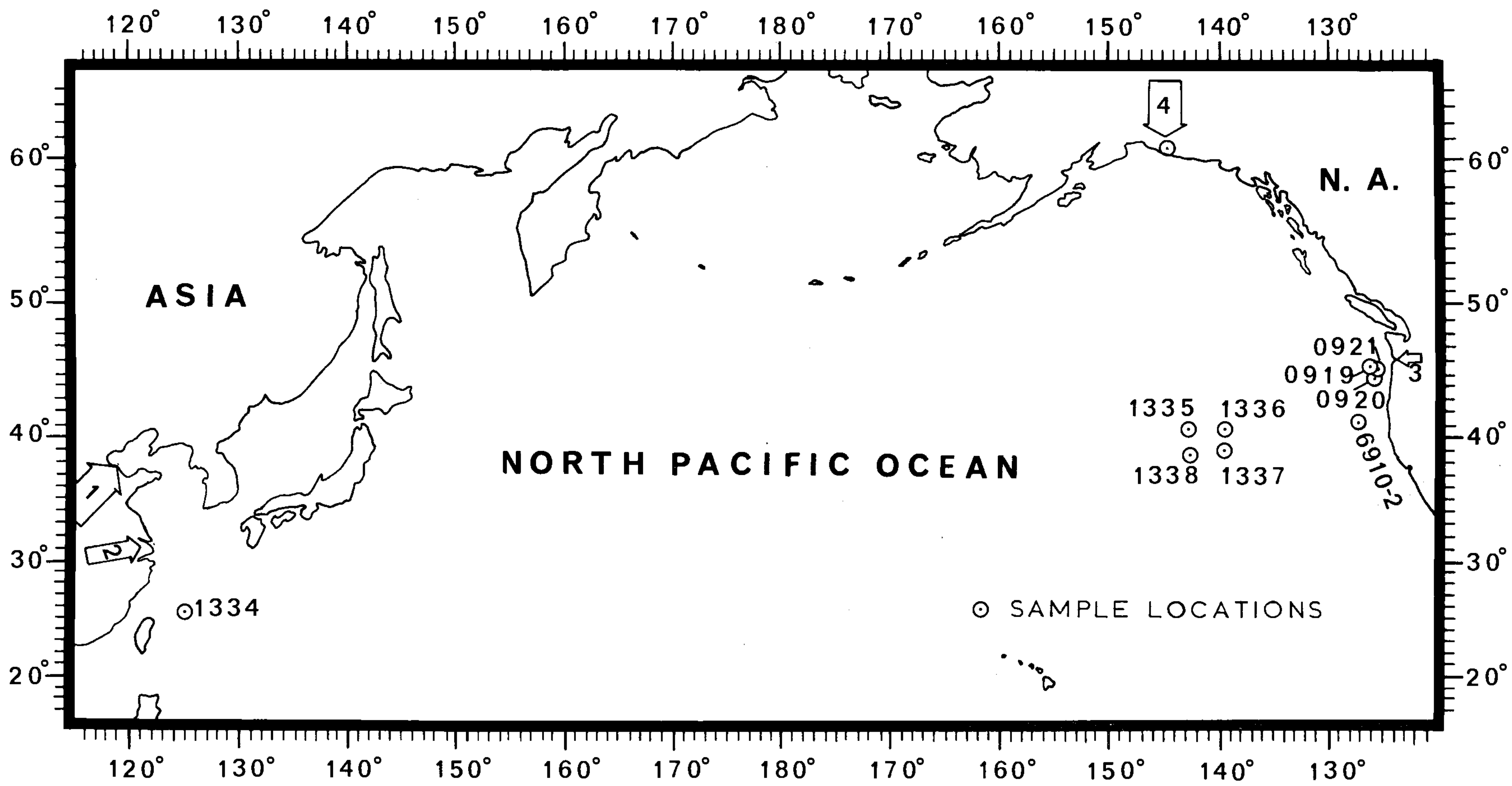
Major Drainage Systems of the North Pacific

Kuenen (1965) states that "rivers are by far the most important suppliers of sedimentary matter to the oceans." For deep-sea regions, this is certainly true where turbidity currents are relatively common events. However, since the last glacial period, the role of

Figure 8. Sketch map illustrating major North Pacific drainage discharges and sample locations. Arrows indicate positions of major drainages emptying directly into the North Pacific Basin. Areas of arrows are a function of the rates of solid discharge for the rivers based on figures given by Strakhov (1967) and Anon. (1960).

1. Yellow (Huang Ho), 630×10^6 tons/year;
2. Yangtze (Ch'ang Chiang), 275×10^6 tons/year;
3. Columbia, 36×10^6 tons/year;
4. Copper, 270×10^6 tons/year.

(modified after Horn _et al._, 1969)


120° 130° 140° 150° 160° 170° 180° 170° 160° 150° 140° 130°
60° 50° 40° 30° 20°
ASIA
N. A.
NORTH PACIFIC OCEAN
1
2
3
4
1334
1335
1336
1338
1337
0921
0919
0920
6910-2
SAMPLE LOCATIONS

turbidity currents as a major transport mechanism of sediment to the North Pacific has greatly diminished, due to drowning of river mouths and isolation of submarine canyon heads from their sources. Whether or not sediments brought to the North Pacific by rivers form an important fraction of the detrital phase found in deep-sea sediments far from land is a debatable question. Arrhenius (1963) suggests that the quartz, ranging in size from about 3 microns to less than 1 micron, found in pelagic sediments is probably the result of suspenoid transport from continents. In the region of 10° N in the equatorial Atlantic, Goldberg and Griffin (1964) postulate that the pelagic quartz is the result of transport from rivers draining adjacent continents. The most popular alternative to river input - eolian transport - has received support from the works of Rex (1958), Rex and Goldberg (1958), Heath (1968), Windom (1968), Bonatti and Arrhenius (1965). This mechanism is considered later in this paper.

East China Sea

The only sample available to characterize the major Chinese rivers (1334) was collected from the Okinawa Trough adjacent to the broad shelf of the East China Sea. As will become apparent, the degree to which this sample in fact typifies the Yellow and Yangtze Rivers is questionable.

The Yellow River (Huang Ho) taps a 486, 486 square mile sector across North China, between the Yinshan and Tsinling Shan. It drains the Loess Highlands region of China which is easily eroded and provides great quantities of sediment, especially during flood season. The Yangtze (Ch'ang Chiang) River system drains a 756,498 square mile zone across central China, between the Tsinling and Nan Ling Mountain systems. It has several large tributaries within China proper. Although these rivers carry huge loads of fine-grained loess, much of the shelf beneath the East China Sea is covered by relict Pleistocene sands (Niino and Emery, 1961). Thus, there is doubt as to whether 1334 is really Yellow - Yangtze sediment that has bypassed the shelf without loss of its original textural character, or whether it is a completely different sediment derived from winnowing of old shelf deposits or from an unknown source.

In any case, quartz from the 1334 sediment is quite unlike the other river samples, and clearly justifies further work in the area.

The quartz includes a negligible amount of coarser than 4 phi (64 microns). The 4 phi to 9 phi (64 microns to 2 microns) fraction had a Folk and Ward (1957) mean of 6.78 phi (31 microns) which would place it in a medium to fine silt classification.

A quartz content of 33.2 percent for this sample is near the low end of the range of 30-70 percent for northern hemisphere loess (Rex, 1958) and is much lower than the 44 percent measured in a Manchurian loess by the same author.

The two dominant modes of the East China Sea sample (Figure 9) have means of 8.6 and 17.8 microns (6.82 and 5.77 phi) which contains 48 and 36 percent of the 2-64 micron portion of the quartz. These modes are markedly different from the dominant 20-50 micron size of loess particles (Rex, 1958). Thus, if the loess deposits of China contribute significantly to the sediments of sample 1334, then only the quartz at the fine end of the spectrum is being deposited. The coarsest mode for sample 1334 has a mean of 25.2 microns (5.27 phi), but it contributes only 7 percent to the total area under the frequency curve.

In the absence of other samples, we cannot say whether the unusual size distribution of quartz in sample 1334 is primary (perhaps resulting from eolian transport of fine loess particles) or secondary (due to winnowing of river sediment during the transport across the East China Sea).

Copper River

The suspended solids carried by the Copper River were collected from a surface sample taken during maximum runoff in July of 1971. The sample is from the lower end of the Miles Lake region, just above the delta system of the river. The sample consisted of 60 liters of water which yielded approximately 100 grams of sediment.

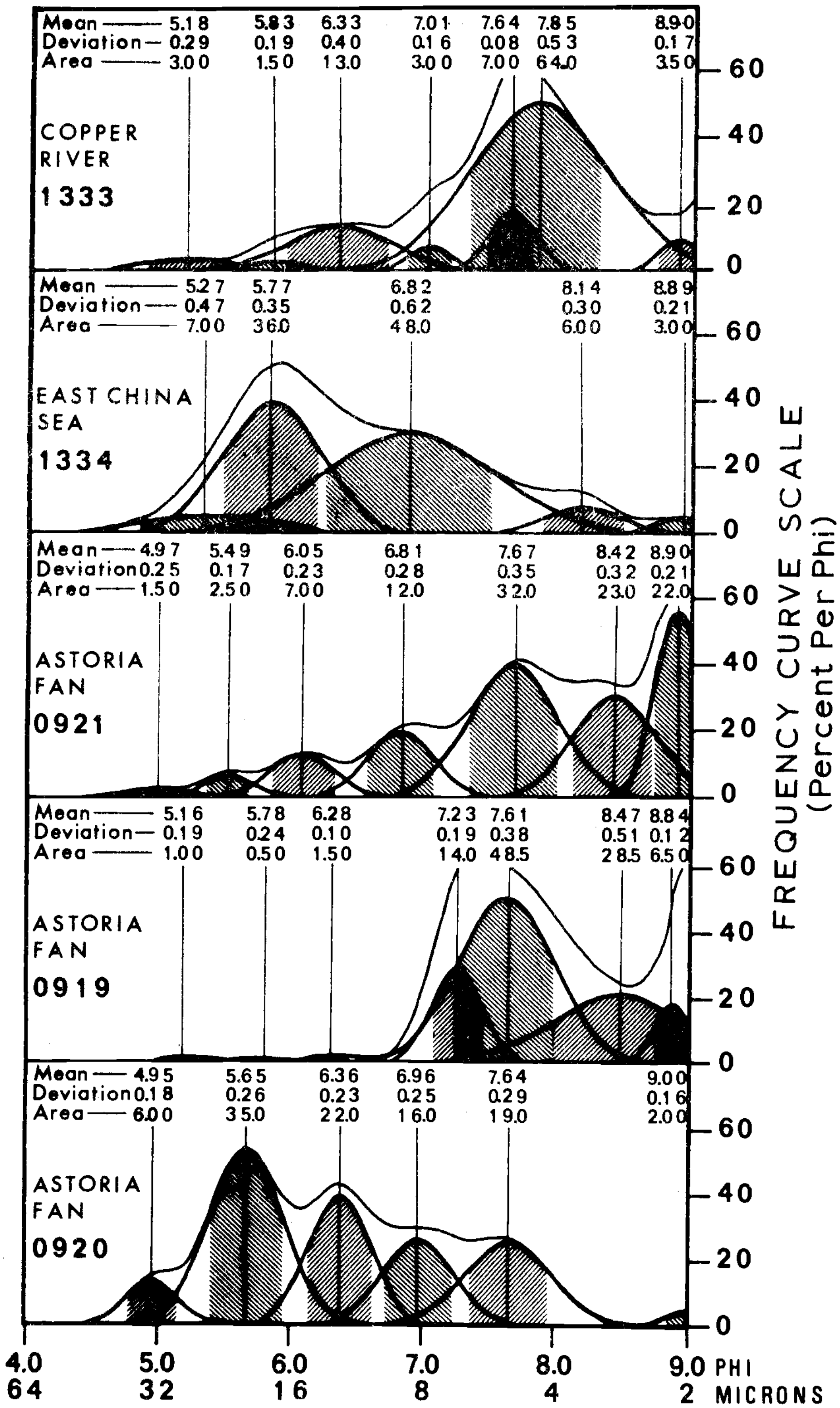


Figure 9. Resolved size frequency surves of samples representing major North Pacific drainage systems. Shaded areas denote one standard deviation about the modal mean.

The Copper River runs primarily from north to south. The eastern part of the Copper River Lowland (Wahrhaftig, 1965) is a relatively smooth plain, 1000-2000 feet in altitude on glacio-lacustrine and glacio-fluvial deposits which are being actively eroded by the Copper River and its tributaries. The western part of the Copper River Lowland is a rolling upland 2200-3500 feet high, with a morainal and stagnant ice morphology. The river discharges approximately 270 million tons of sediment per year (Anon., 1960).

The less than 63 micron material from the Copper River contains 13 percent quartz with a dominant mode at 4.3 microns (7.74 phi, Figure 10) accounting for 64 percent of the 4-9 phi (2-64 microns) fraction of this mineral. This mode falls in the size range of most pelagic quartz (Rex, 1958; Windom, 1968; this study). The next most prevalent mode has a mean of 12.4 microns (6.34 phi) and forms 13 percent of the 4-9 phi quartz.

The important feature of this sample from the Copper River, which must include a large proportion of glacial rock flour, is that the size distribution of its fine-grained quartz is very similar to pelagic quartz. Future studies of fine-grained sediments from the Gulf of Alaska should help define the evolution of the Copper River quartz as it moves from the continent to the deep ocean.

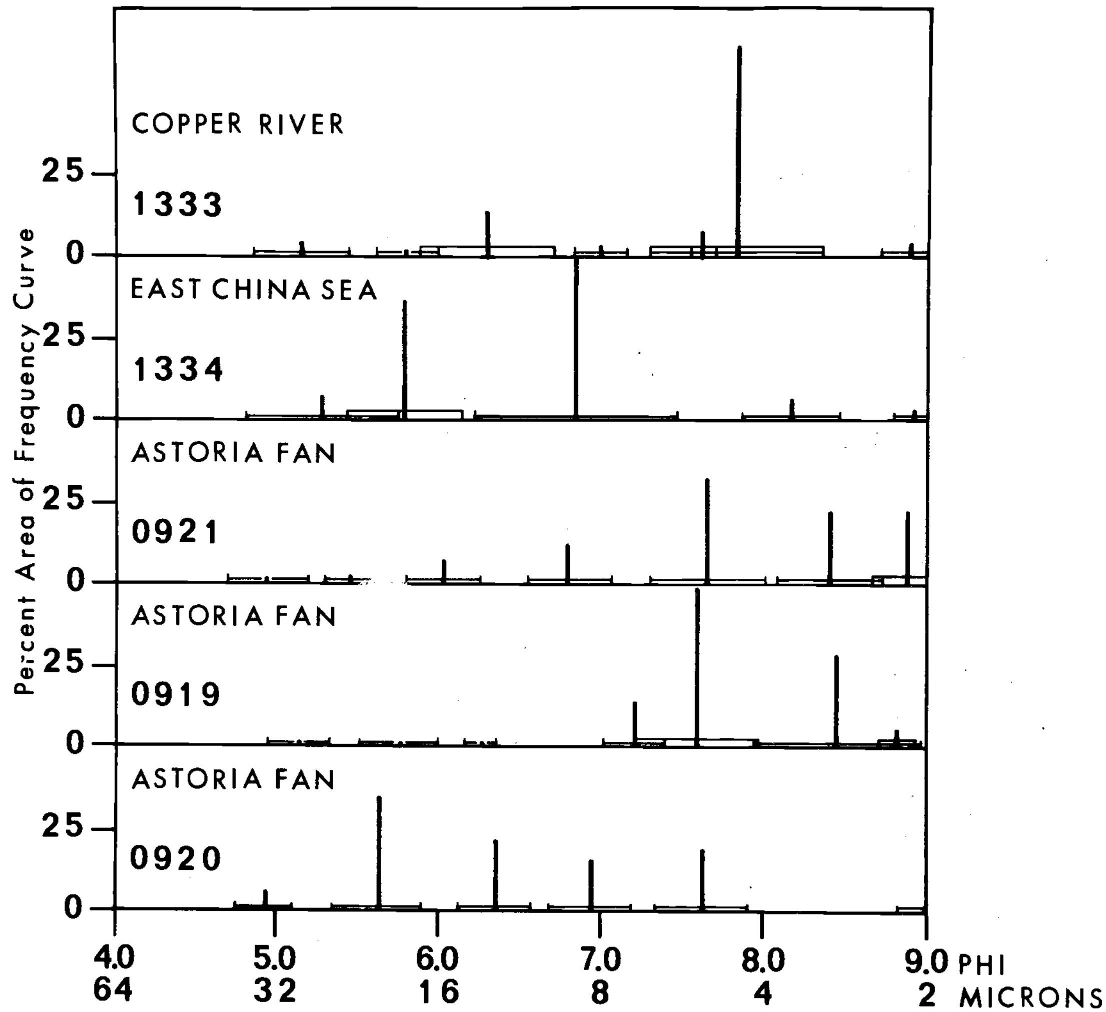


Figure 10. Graphic summary of statistical features of each mode in Figure 9. Height of bars reflect percentage of total area of frequency curves contributed by individual modes.

Columbia River

Samples from three different cores on the Astoria Fan (Appendix I) were chosen as examples of Columbia River sediment. These samples may be more representative of Holocene Columbia River sediments than are modern samples from the river itself because of the numerous dams constructed within the last half century which have impeded and modified the downstream flow of sediment.

Sample 0921 is from upper Astoria Fan, sample 0919 from middle Astoria Fan and sample 0920 from Astoria Channel (Duncan, 1968; Russell, 1967).

Duncan's (1968) studies suggest that the two Astoria Fan samples are about 2.5×10^3 years old, whereas the Astoria Channel sample 1.1×10^3 years old. Although these are not modern samples, they are young enough to represent climatic conditions very much like those of today.

Resolved size frequency curves of the 4-9 phi (64-2 micron) quartz fractions with statistics for each mode are presented in Figure 9. Individual modal statistics are also given in Appendix II. Figure 10 shows a graphic summary of the statistical features of each mode, which are easier to discuss than the raw modal curves. The height of the bars in Figure 10 reflect the percentage of the total area of the frequency distribution curves contributed by individual modes.

The striking feature of the Columbia River samples in Figure 9 is the similarity of their modal positions and number of modes, despite the dramatically different frequency curves. The coarsest mode in all samples has a mean size of 5.02 phi with a standard deviation of the mean of 0.12 phi. Because the raw data were digitized at 0.1 phi intervals, the sizes of the coarsest modes of all three samples are effectively identical. In the same way, the mean sizes and their standard deviations for successively finer modes are 5.64 ± 0.15 phi and 6.23 ± 0.16 phi respectively. The fifth mode of each of the three samples has a mean size of 7.64 ± 0.03 phi. Clearly, the three samples are essentially indistinguishable on the basis of the mean particle sizes of their dominant modes. Apparently the Columbia River supplies a family of modes which may vary in abundance, but not in mean size.

In contrast to their consistent size, the abundance of the modes of the Astoria Channel sample relative to the Astoria Fan samples are highly variable. This difference is particularly noticeable in the three coarsest modes. The Astoria Channel samples has much more coarse quartz than the Astoria Fan samples. Apparently, the higher-energy environment of Astoria Channel results in preferential loss of finer modes, but retention of the overall textural character of the parent sediment.

Further work is necessary to determine whether such changes in the relative abundances of a family of modes can be used to map isoenergetic regions in modern and ancient depositional environments.

Mendocino Escarpment

The Mendocino Escarpment is one of the most impressive topographic features of the northeastern Pacific. It is marked by a regional bathymetric offset of about one kilometer and for most of its length the north block is bounded by an asymetric ridge with a south-facing scarp 1.5 - 3 kilometers high (Bullard and Mason, 1963; Rea and Erickson, 1971; Rea, 1970).

The effect of a topographic barrier such as the Mendocino Escarpment on the distribution and textural characteristics of quartz in the deep sea was tested by examining four samples from cores MEN 25, MEN 26, MEN 27 and MEN 28. These samples are labeled 1335, 1336, 1337 and 1338 respectively. Samples 1335 and 1336 are paired from the high or north side of the scarp and lie opposite 1337 and 1338 on the south side. Appendix I gives precise locations and Figure 8 positions of these samples.

Figure 11 shows the resolved size frequency curves for these four samples and Figure 12, similar to Figure 10 for the Columbia River samples, shows the modal positions, abundances and standard deviations stripped of their envelopes. The striking feature of Figures 11 and 12 is the uniformity of the samples. The mean sizes

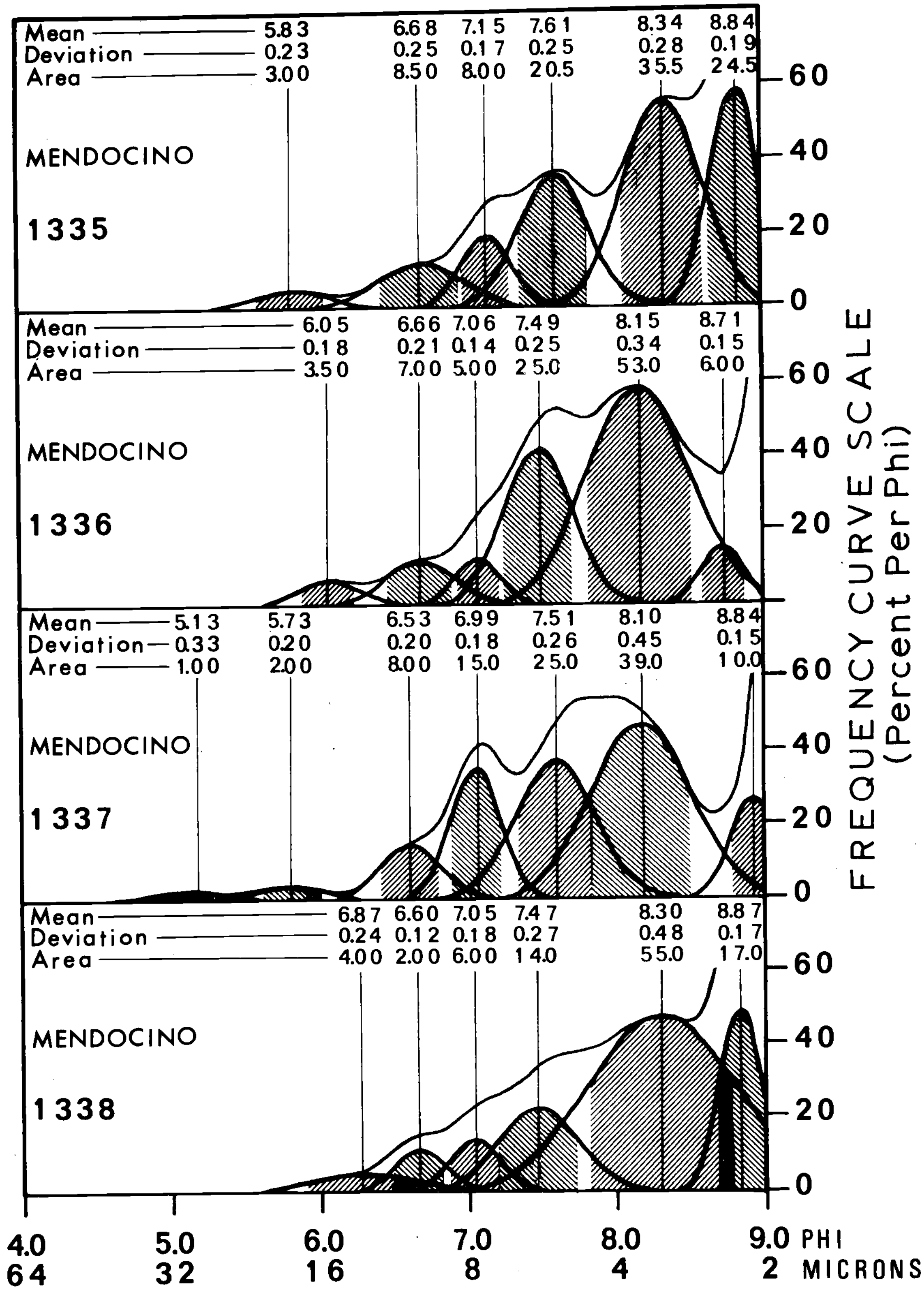


Figure 11. Resolved size frequency curves for Mendocino Escarpment samples.

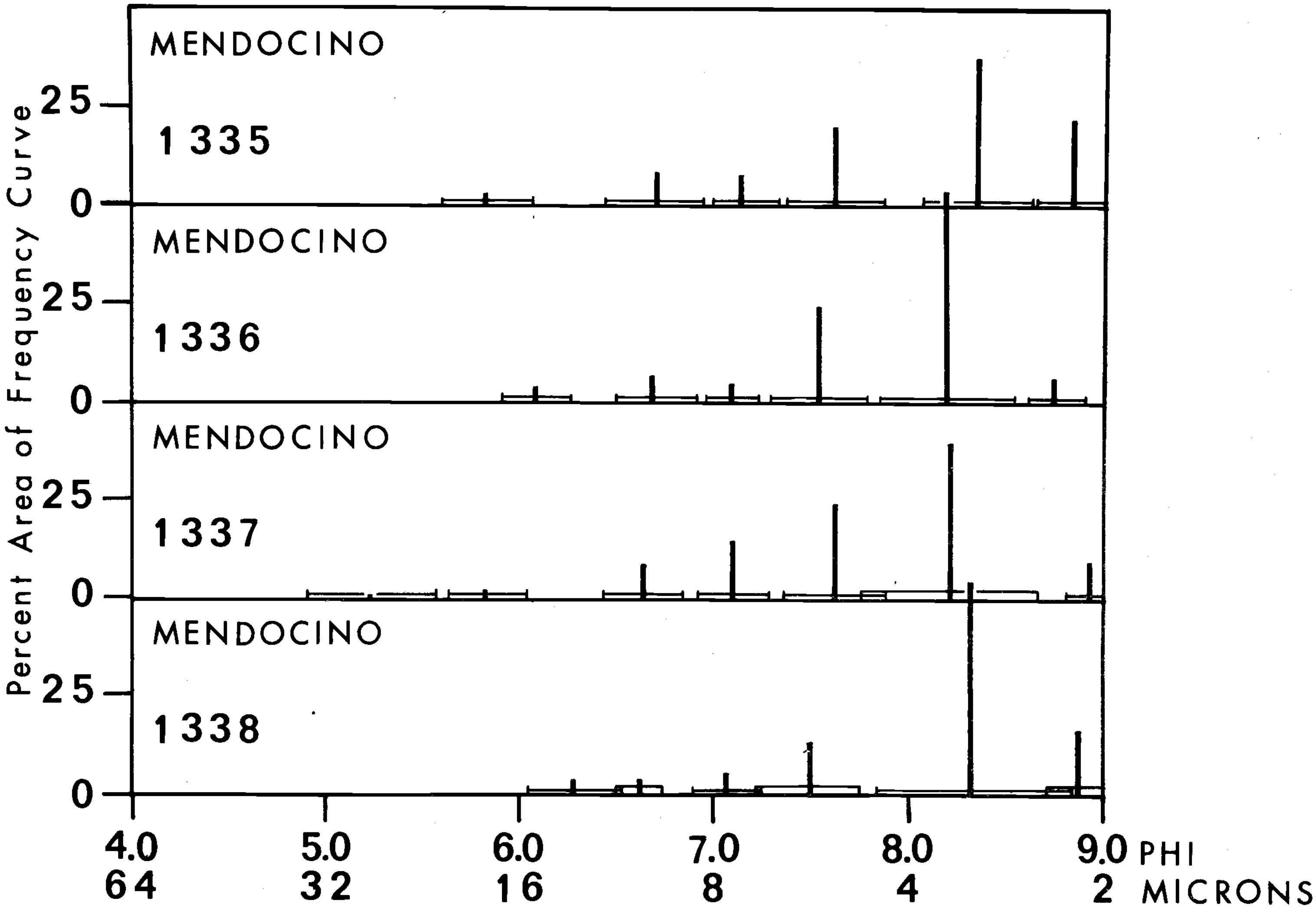


Figure 12. Graphic summary of statistical features of each mode in Figure 11.

of the five modes finer than 6.5 phi (11 microns) are statistically indistinguishable in the four samples. These five modes have the following mean phi sizes and standard deviations of their means: 6.63 ± 0.04 phi, 7.08 ± 0.04 phi, 9.54 ± 0.07 phi, 8.24 ± 0.08 phi and 8.83 ± 0.09 phi.

The uniformity of these samples can only be interpreted in terms of a uniform process of transport and deposition. Clearly, the mechanism responsible for the grain size characteristics of the quartz in these samples is unaffected by topography. It seems unlikely, therefore, that bottom transport, whether of turbidity current or nepheloid layer character, is the transporting mechanism. In view of the fact that these samples were collected 1500 kilometers from the nearest land mass and that they contain relatively coarse modes, dispersal of the quartz in suspension in the ocean at depths above the Mendocino Ridge also seems improbable. The only remaining dispersal mechanism that seems reasonable for the area is eolian transport. Junge (1957) has demonstrated that the size range for natural aerosols is 0.1 to 10 microns - a range which agrees well with the distribution found here as well as in other pelagic sediments studied by Rex (1958) and Windom (1968). The importance of eolian transport of continental detritus to the deep sea has been advocated on other grounds by Radczewski (1937, 1939), Rex and Goldberg (1958), Bonatti and Arrhenius (1965) and Heath (1968).

Although the similarity of the four Mendocino samples is evident from Figure 12 and from the computed modal statistics, the unresolved size frequency distributions (Figure 11) are quite dissimilar. The degree to which the basic character of the size distribution is concealed in unresolved frequency curves, cumulative curves and in statistics commonly applied to grain size distribution (e. g. Folk and Ward, 1957) probably explains the great difficulty that sedimentologists have had in interpreting sedimentary textures of fine-grained materials.

Temporal Variation

In a final test of the method, temporal variations in the texture of fine-grained quartz deposited at a single location were evaluated by analyzing samples from a core, 6910-2, from the east side of the Gorda Ridge, north of the Mendocino scarp (Appendix I).

To ensure that present day surface sediments were sampled, the pilot gravity core as well as the piston core was examined and sampled. The overlap relationship between the two cores was determined by fitting the quartz abundance data (Figure 13). The overlap was then checked using the plotted ratios of foraminiferans to radiolarians and was found to be acceptable (Figure 13).

The gravity core, 6910-2G, which consisted of 60 centimeters of sediment, was sampled at its surface and every 20 centimeters

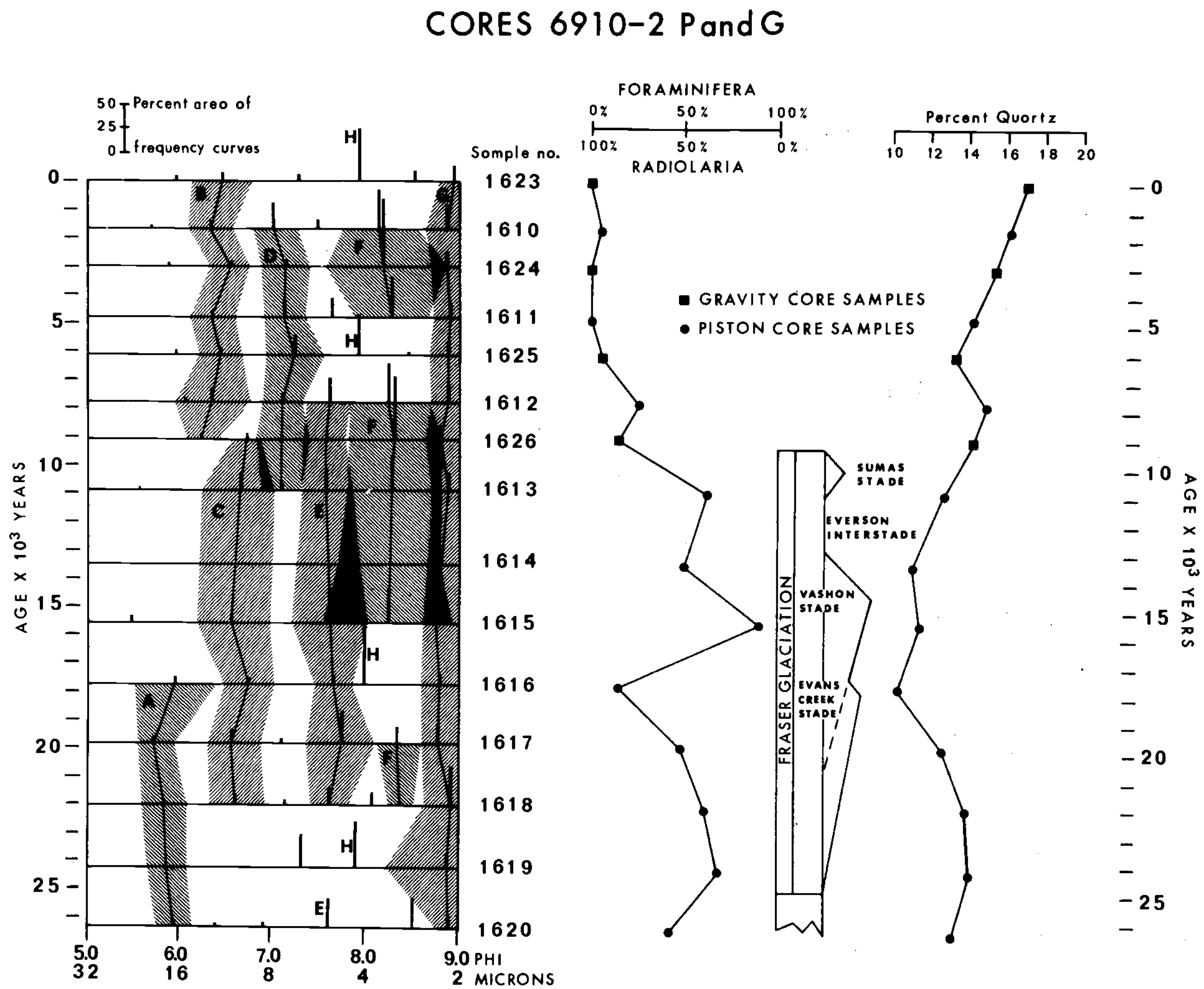


Figure 13. Graphic summary of statistical features of individual modes for samples from cores 6910-2P and G. Also shown is a curve of foraminiferan/radiolarian ratios for the samples from these cores and quartz percentages for these samples.

thereafter. The piston core, 6910-2P, was also sampled at its surface and every 20 centimeters down to 2 meters. The oldest sample (about 26.4×10^3 years) should correspond to the transition period between the Olympia Interglaciation and the Fraser Glaciation (Armstrong et al., 1965) on the basis of two radio-carbon dates in the core (J. Phipps, unpublished research, 1971). Figure 14 shows a sedimentation curve for 6910-2P and G, which were examined in some detail by Phipps (unpublished research, 1971).

Resolved size frequency curves for all samples are shown in Appendix III. The mean size, standard deviation and abundance of the resolved modes in each sample are plotted in Figure 13. Modes which have statistically indistinguishable mean sizes are shown by shaded areas in Figure 13 and are indicated by a letter which is cross-referenced to the calculated mean position and standard deviation of this mean position for each mode in Table 1.

The standard deviation of the position of the mean for all the labeled modes is less than 0.10 phi - at the limit of resolution of the data (as stated earlier, the analog data was digitized at 0.10 phi increments). Clearly, there is no justification for further subdividing the labeled sets of modes.

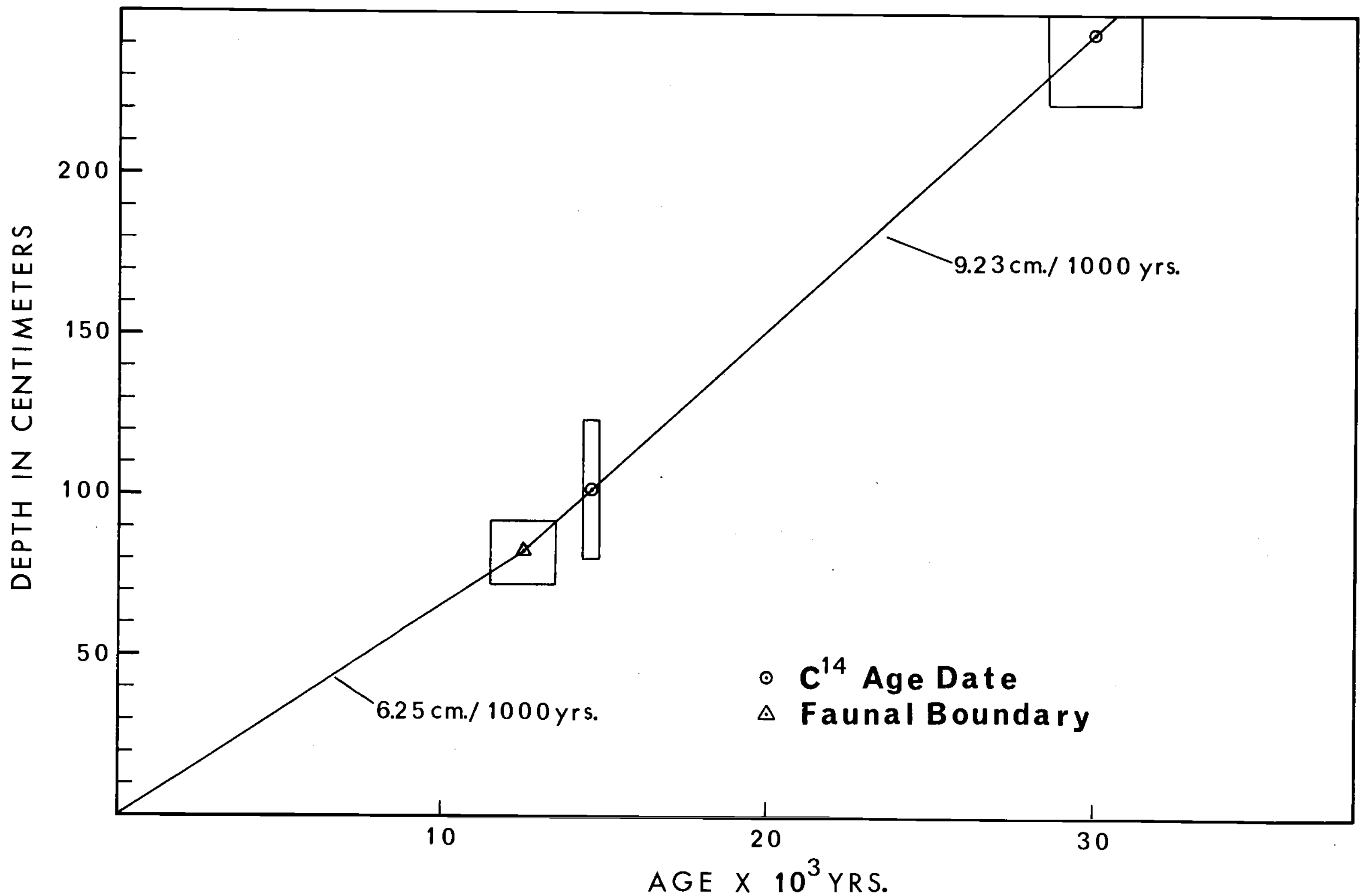


Figure 14. Sedimentation rate curve. Two points controlled by Carbon 14 dates. One point controlled by inflection in foraminiferan/radiolarian curve denoting Pleistocene-Holocene boundary for this area (Duncan, 1968).

Table 1. Statistically similar modes from cores 6910-2P & G.

Mode	Mean Position Phi	Mean Position Microns	Standard Deviation of Mean Position (Phi)
A	5.89	16.9	0.10
B	6.38	12.0	0.10
C	6.66	10.0	0.07
D	7.11	7.2	0.07
E	7.63	5.0	0.07
F	8.26	3.3	0.07
G	8.88	2.1	0.07
H	7.94	4.1	0.04

Mode G which is persistent throughout the interval sampled in cores 6910-2P and G has a mean phi position of 8.88 and a phi deviation of 0.07. A mode in this position also appears in all other samples examined in this study, and may be an "edge effect" resulting from the abrupt termination of the experimental data at 9 phi.

The behavior of two pairs of modes in the sequence are of particular interest. These are the pair labeled C and E and the pair labeled B and D. These two sets of modes cannot be separated hydrodynamically, because the mean sizes overlap (Mode C is straddled by modes B and D). Nevertheless, the mean sizes of these modes are significantly different. Thus, the change from one pair to the other at 8 - 11,000 years must reflect a change in provenance rather than a change in the energy regime between a sediment source and the site of deposition. The transition zone is very close to the Holocene-Pleistocene boundary at about 12,500 years B.P. in this area (Duncan, 1968). This period was marked by a rapid rise in sea level (Curray, 1960, 1961) leading to the drowning of river mouths, reduction of stream gradients and widening of continental shelves. Duncan and Kulm (1970) on the basis of heavy mineral data for sandy sediments deposited in the Late Pleistocene and Holocene show that Columbia River sediments were dominant in Blanco Valley until approximately 8500 years B.P. when sediments from the Klamath Mountains began to dominate. The same conclusion can be drawn from changes in the abundance of various clay minerals in Holocene sediments from this area (Duncan et al., 1970).

Thus, the size distribution of fine-grained quartz from the Gorda Ridge clearly reflects a change in provenance. Because of the ubiquity of quartz and its resistance to the diagenetic changes that can affect other indicators of provenance, this property should be invaluable for distinguishing fine-grained sediments derived from superficially similar source areas.

DISCUSSION

The experiments described here have established that the extraction technique used produces a pure quartz separate without significantly modifying its size distribution.

Textural analysis of the chemically purified quartz reveals the following general features:

1. All the samples examined are polymodal in the 2-64 micron size range. Even sediment largely generated by a single process, such as the glacial debris of the Copper River, is polymodal.

2. The modal character of quartz in a sediment persists in the marine environment and is capable of serving as a provenance indicator.

3. Dispersal processes that act on a fine-grained sediment may change the relative proportions of constituent quartz modes, but do not alter their mean sizes. The way in which the relative proportions of the assorted modes vary within a depositional area may serve as a tool for mapping energy fields at the sea floor.

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APPENDICES

APPENDIX I. Sample location and identification

Sample Identification	Lab. Item	Latitude	Longitude	Water Depth (m)	Type of Sample	Depth in Core (cm)
Copper River	1333	60°43'N	144°36'W	Surface	S. S.	--
East China Sea (BS 49)	1334	25°37'N	124°54'E	2045	G. C.	0- 4
Mendocino (MEN 25)	1335	40°41'N	142°52'W	4700	P. C.	27-29
Mendocino (MEN 26)	1336	40°44'N	139°22'W	4540	P. C.	27-29
Mendocino (MEN 27)	1337	39°05'N	139°26'W	5290	P. C.	27-29
Mendocino (MEN 28)	1338	38°40'N	142°36'W	5270	P. C.	27-29
Astoria Fan (6408-C3)	0919	45°42'N	126°07'W		P. C.	30-36
Astoria Fan (6509-4)	0920	44°57'N	125°47'W	2821	P. C.	30-36
Astoria Fan (6408-Al)	0921	45°31'N	125°40'W	2094	P. C.	30-36
Core 6910-2P	1610	41°16'N	127°01'W	2743	P. C.	0- 2
" "	1611	"	"	"	"	19-21
" "	1612	"	"	"	"	39-41

APPENDIX I (Continued)

Sample Identification	Lab. Item	Latitude	Longitude	Water Depth (m)	Type of Sample	Depth in Core (cm)
Core 6910-2P	1613	41°16'N	127°01'W	2743	P. C.	59- 61
" "	1614	"	"	"	"	79- 81
" "	1615	"	"	"	"	99-101
" "	1616	"	"	"	"	119-121
" "	1617	"	"	"	"	139-141
" "	1618	"	"	"	"	159-161
" "	1619	"	" "	"	"	179-181
" "	1620	"	"	"	"	199-201
" "	1623	"	"	"	G. C.	0- 2
" "	1624	"	"	"	"	19- 21
" "	1625	"	"	"	"	39- 41
" "	1626	"	"	"	"	59- 61

Type of Sample: P. C. = Piston core G. C. = Gravity core S. S. = Surface water sample

APPENDIX II. Sample Statistics

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
1333	7.506	0.868	1	5.18	0.29	3.0
			2	5.83	0.19	1.5
			3	6.33	0.40	13.0
			4	7.01	0.16	3.0
			5	7.64	0.08	7.0
			6	7.85	0.53	64.0
			7	8.90	0.17	3.5
			8	9.09	0.08	5.0
1334	6.822	0.957	1	5.27	0.47	7.0
			2	5.77	0.35	36.0
			3	6.82	0.62	48.0
			4	8.14	0.30	6.0
			5	8.89	0.21	3.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
1335	8.155	0.772	1	5.83	0.23	3.0
			2	6.68	0.25	8.5
			3	7.15	0.17	8.0
			4	7.61	0.25	20.5
			5	8.34	0.28	35.5
			6	8.84	0.19	24.5
1336	7.943	0.714	1	6.05	0.18	3.5
			2	6.66	0.21	7.0
			3	7.06	0.14	5.0
			4	7.49	0.25	25.0
			5	8.15	0.34	53.0
			6	8.71	0.15	6.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
1337	7.842	0.770	1	5.13	0.33	1.0
			2	5.73	0.20	2.0
			3	6.53	0.20	8.0
			4	6.99	0.18	15.0
			5	7.51	0.26	25.0
			6	8.10	0.45	39.0
			7	8.84	0.15	10.0
1338	8.150	0.770	1	6.27	0.24	4.0
			2	6.60	0.12	2.0
			3	7.05	0.18	6.0
			4	7.47	0.27	14.0
			5	8.30	0.48	55.0
			6	8.87	0.17	17.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
0919	7.915	0.714	1	5.16	0.19	1.0
			2	5.78	0.24	0.5
			3	6.28	0.10	1.5
			4	7.23	0.19	14.0
			5	7.61	0.38	48.5
			6	8.47	0.51	28.5
			7	8.84	0.12	6.5
0920	6.408	0.902	1	4.95	0.26	35.0
			2	5.65	0.23	22.0
			3	6.36	0.25	16.0
			4	6.96	0.25	16.0
			5	7.64	0.29	19.0
			6	9.00	0.16	2.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
0921	7.880	1.033	1	4.97	0.25	1.5
			2	5.49	0.17	2.5
			3	6.05	0.23	7.0
			4	6.81	0.28	12.0
			5	7.67	0.35	32.0
			6	8.42	0.32	23.0
			7	8.90	0.21	22.0
1610	8.141	0.829	1	5.68	0.18	1.5
			2	6.32	0.26	8.0
			3	6.98	0.25	29.5
			4	7.45	0.11	11.0
			5	8.11	0.42	43.0
			6	8.83	0.23	27.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
1611	8.053	0.735	1	4.99	0.28	1.0
			2	6.35	0.25	4.0
			3	7.12	0.21	13.5
			4	7.62	0.22	20.0
			5	8.26	0.38	42.5
			6	8.88	0.18	19.0
1612	7.883	0.949	1	4.52	0.32	0.5
			2	6.05	0.24	3.0
			3	6.35	0.41	14.5
			4	7.10	0.20	11.0
			5	7.60	0.25	15.5
			6	8.22	0.42	40.5
			7	8.87	0.18	15.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Relative % of Mode
1613	8.024	1.155	1	4.56	0.29	0.5
			2	5.56	0.18	0.5
			3	6.63	0.40	14.5
			4	7.00	0.22	7.0
			5	7.55	0.26	17.0
			6	8.26	0.41	39.5
			7	8.87	0.18	21.0
1615	7.812	0.913	1	4.97	0.21	0.5
			2	5.49	0.23	4.0
			3	6.58	0.41	10.5
			4	7.63	0.42	37.0
			5	8.26	0.66	39.0
			6	8.77	0.17	8.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Standard % of Mode
1616	7.831	0.776	1	5.98	0.46	5.0
			2	6.77	0.26	5.0
			3	7.67	0.17	6.0
			4	8.00	0.64	72.5
			5	8.81	0.22	9.0
			6	9.01	0.08	4.5
1617	7.951	0.791	1	4.52	0.27	0.5
			2	5.75	0.20	0.5
			3	6.60	0.29	12.0
			4	7.12	0.14	3.0
			5	7.77	0.40	45.0
			6	8.37	0.22	18.0
			7	8.80	0.20	21.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Standard % of Mode
1618	7.975	0.881	1	5.86	0.25	3.0
			2	6.64	0.30	11.0
			3	7.18	0.15	7.0
			4	7.64	0.20	21.0
			5	8.09	0.21	11.0
			6	8.39	0.14	3.0
			7	8.94	0.30	44.0
1619	7.829	0.665	1	5.89	0.21	1.5
			2	7.35	0.28	31.5
			3	7.92	0.45	51.5
			4	8.97	0.72	16.0

APPENDIX II (Continued)

Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Standard % of Mode
1620	7.966	0.891	1	5.98	0.19	5.0
			2	6.45	0.20	5.0
			3	6.95	0.17	6.0
			4	7.65	0.41	33.0
			5	8.55	0.48	37.0
			6	8.92	0.17	14.0
1623	8.055	0.841	1	5.72	0.22	1.5
			2	6.45	0.33	9.5
			3	7.24	0.19	6.0
			4	7.91	0.56	56.0
			5	8.49	0.16	9.0
			6	8.91	0.15	18.0

APPENDIX II (Continued)

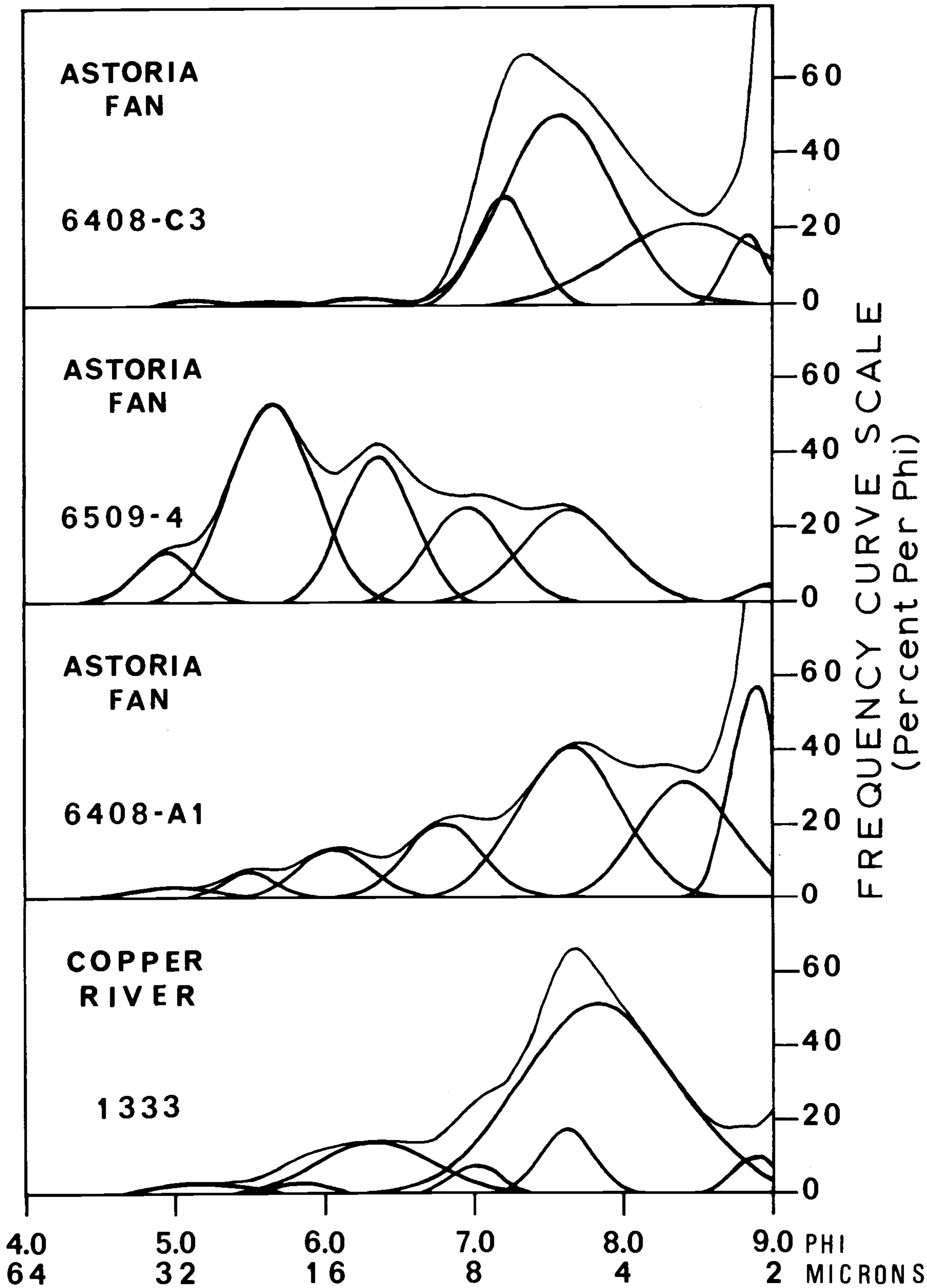
Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Standard % of Mode
1624	8.201	0.750	1	5.88	0.28	1.5
			2	6.55	0.23	3.5
			3	7.12	0.27	6.0
			4	8.18	0.64	72.0
			5	8.85	0.15	17.0
1625	7.991	0.813	1	5.96	0.20	2.0
			2	6.44	0.22	5.0
			3	7.23	0.31	20.5
			4	7.91	0.44	42.0
			5	8.44	0.13	3.5
			6	8.86	0.21	27.0

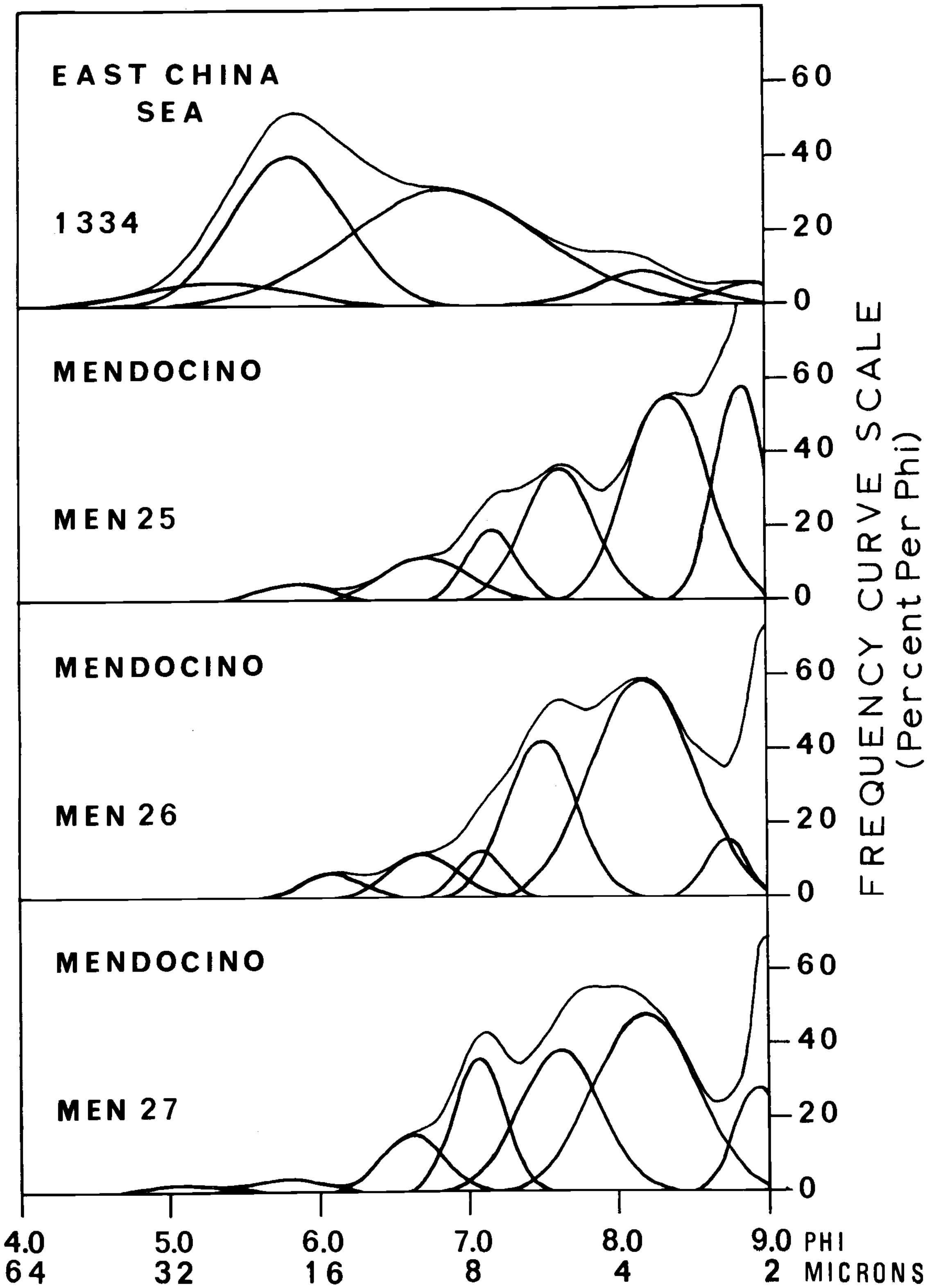
APPENDIX II (Continued)

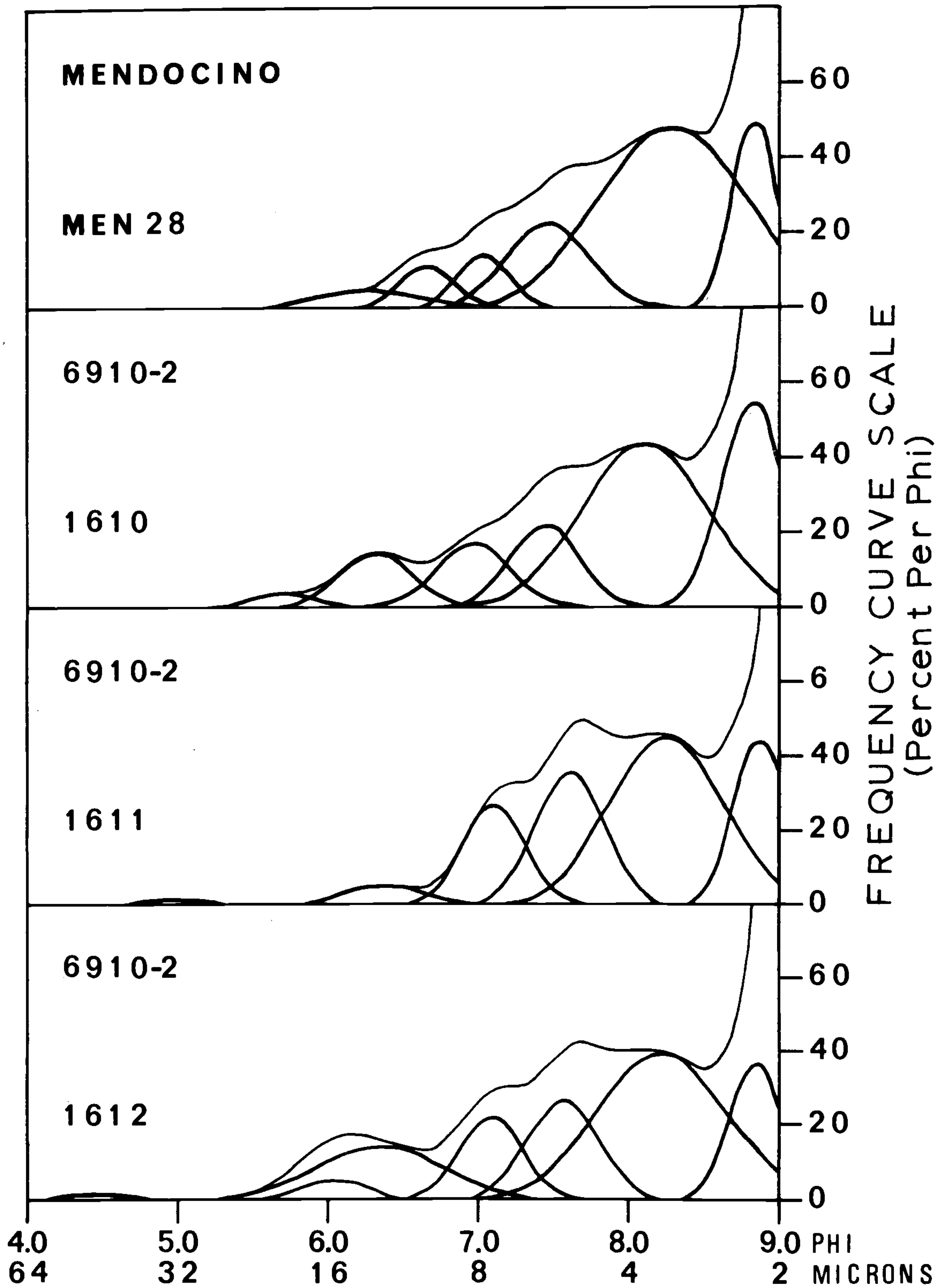
Sample Number	Folk & Ward Mean (Phi)	Folk & Ward Sorting (Phi)	Mode Number	Mode Mean (Phi)	Mode Std. Dev. (Phi)	Standard % of Mode
1626	8.103	0.789	1	6.23	0.17	2.5
			2	6.71	0.16	7.5
			3	7.09	0.28	3.0
			4	7.56	0.25	4.5
			5	8.30	0.54	68.0
			6	8.80	0.18	14.5

APPENDIX III

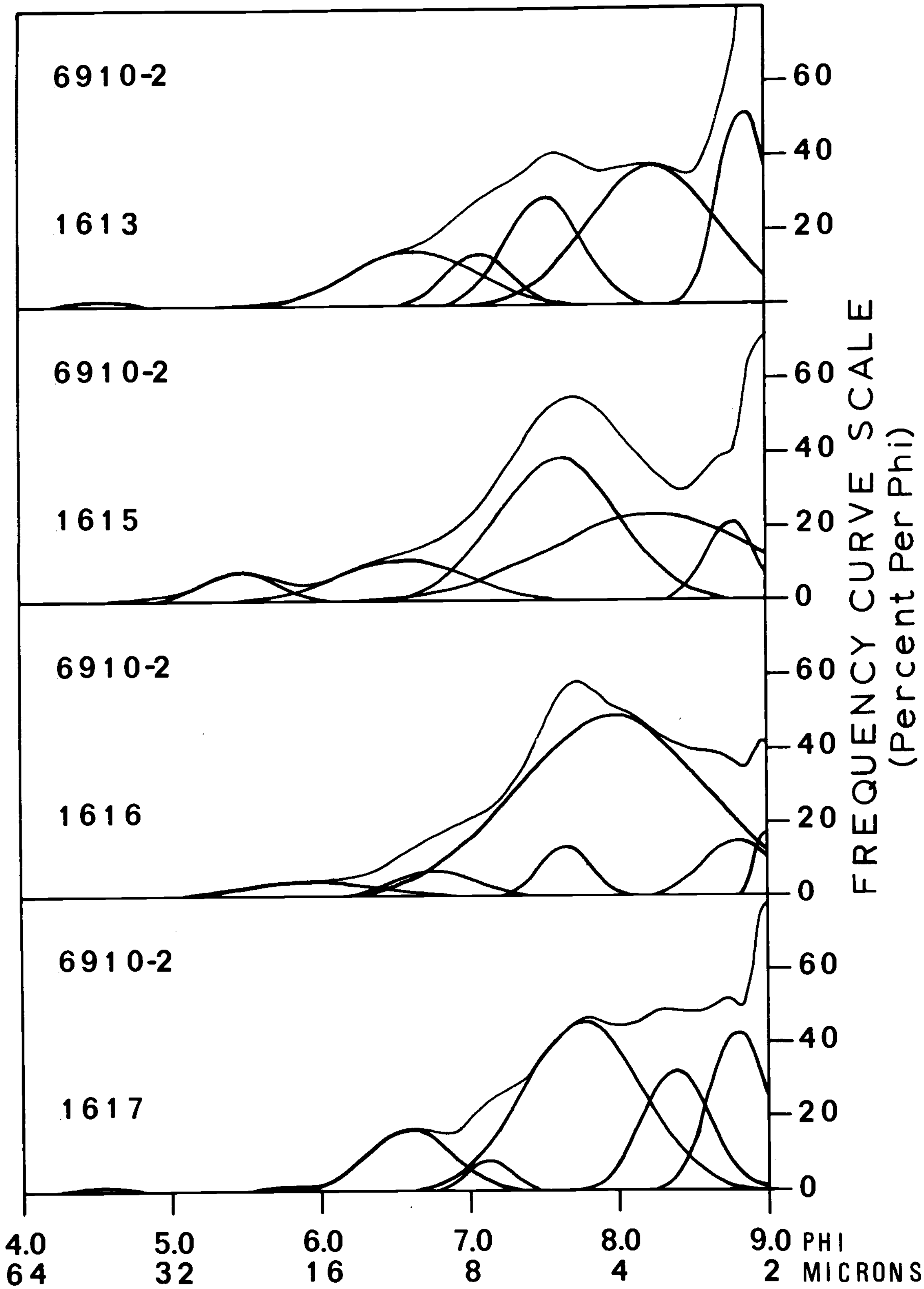
Resolved size frequency curves for all samples texturally analyzed in this study.


ASTORIA
FAN
6408-C3
ASTORIA
FAN
6509-4
ASTORIA
FAN
6408-A1
COPPER
RIVER
1333
60
40
20
0
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
64
5.0
32
6.0
16
7.0
8
8.0
4
9.0 PHI
2 MICRONS

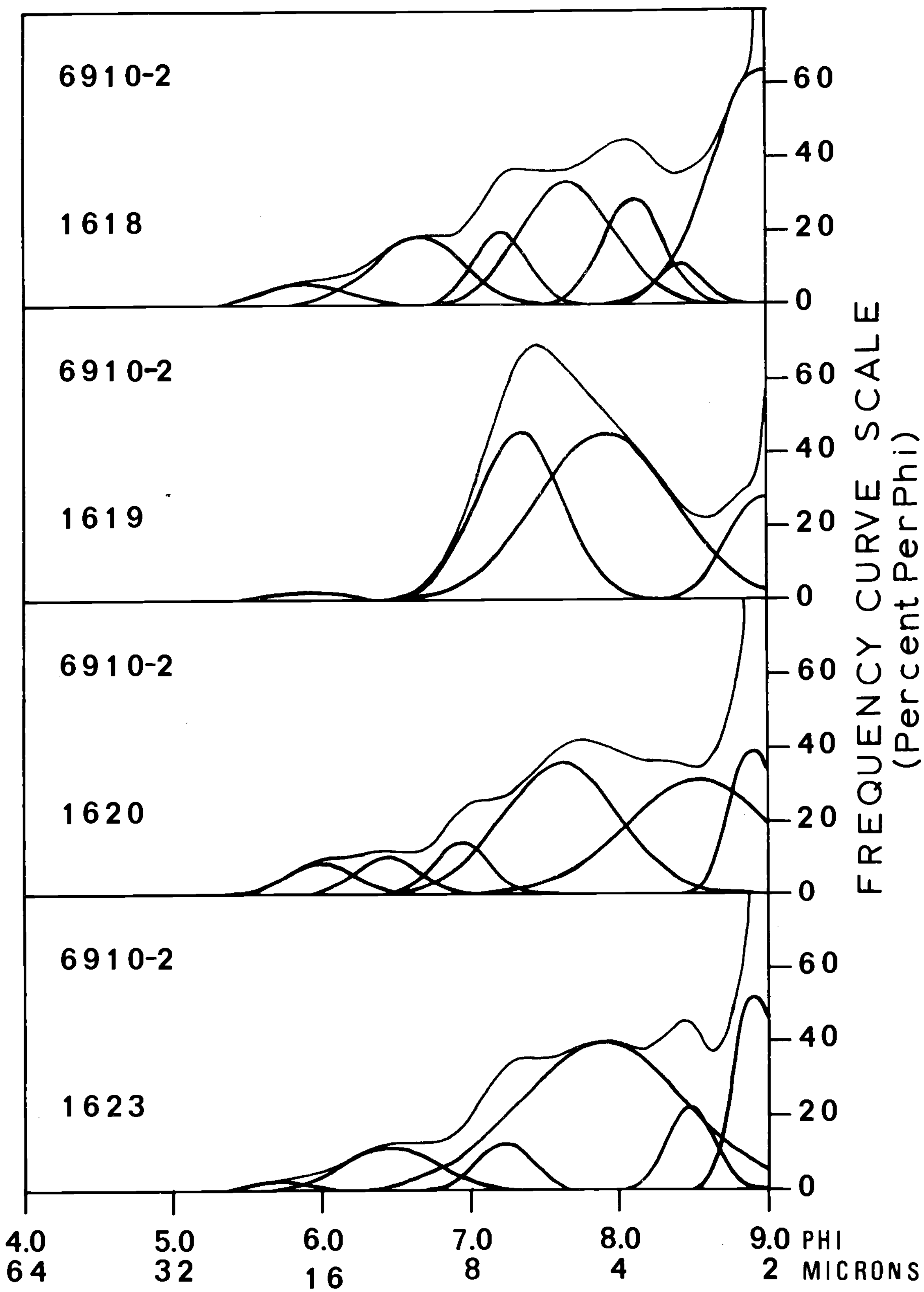

EAST CHINA SEA
1334
MENDOCINO
MEN 25
MENDOCINO
MEN 26
MENDOCINO
MEN 27
60
40
20
0
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
64
5.0
32
6.0
16
7.0
8
8.0
4
9.0 PHI
2 MICRONS



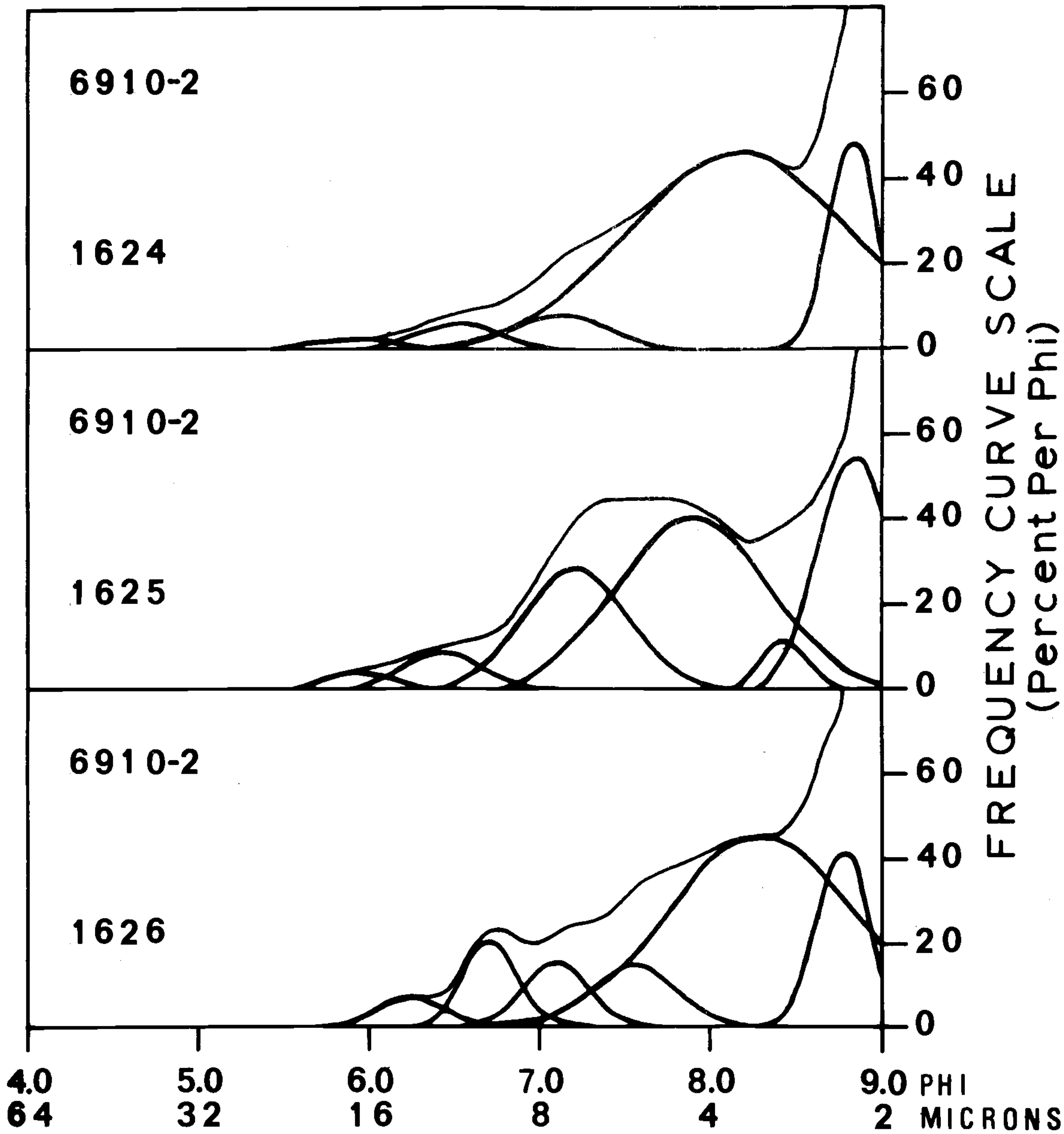
MENDOCINO
MEN 28
6910-2
1610
6910-2
1611
6910-2
1612
60
40
20
0
60
40
20
0
6
40
20
0
60
40
20
0
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
64
5.0
32
6.0
16
7.0
8
8.0
4
9.0 PHI
2 MICRONS



6910-2
1613
6910-2
1615
6910-2
1616
6910-2
1617
60
40
20
0
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
64
5.0
32
6.0
16
7.0
8
8.0
4
9.0 PHI
2 MICRONS



6910-2
1618
6910-2
1619
6910-2
1620
6910-2
1623
60
40
20
0
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
64
5.0
32
6.0
16
7.0
8
8.0
4
9.0 PHI
2 MICRONS


6910-2
1624
6910-2
1625
6910-2
1626
0
20
40
60
FREQUENCY CURVE SCALE
(Percent Per Phi)
4.0
5.0
6.0
7.0
8.0
9.0 PHI
64
32
16
8
4
2 MICRONS