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Harrell, James Anthony

**GRAIN SIZE AND SHAPE DISTRIBUTIONS, GRAIN PACKING, AND PORE
GEOMETRY WITHIN SAND LAMINAE: CHARACTERIZATION AND
METHODOLOGIES**

University of Cincinnati

PH.D. 1983

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GRAIN SIZE AND SHAPE DISTRIBUTIONS, GRAIN PACKING,
AND PORE GEOMETRY WITHIN SAND LAMINAE:
CHARACTERIZATION AND METHODOLOGIES

A dissertation submitted to the
Division of Graduate Studies and Research
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

in the Department of Geology
of the College of Arts and Sciences

1983

by

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February 25 19 83

*I hereby recommend that the thesis prepared under my
supervision by* James A. Harrell

entitled Grain Size and Shape Distributions, Grain
Packing, and Pore Geometry Within Sand Laminae:

Characterization and Methodologies

*be accepted as fulfilling this part of the requirements for the
degree of* Doctor of Philosophy

Approved by:

Wayne A. Rupp
Paul Edmund Potter
John Grover

ABSTRACT

The principal objective of this study was to develop a battery of methodologies for the analysis of texture, grain packing and pore geometry in sands and sandstones. The methodologies developed include: (1) the 'roller micrometer', a machine which sizes grains by their smallest dimension, S; (2) plots of the joint I:S size and S/I form distributions (I is the intermediate grain dimension determined by sieving); (3) a sorting comparator for the visual estimation of sorting in thin sections; (4) 'packing efficiency', the ratio of minimum compactional to depositional porosity; (5) 'floating index', the proportion of grains lacking intergranular contacts; (6) correction of measurement errors in standard thin section packing analyses; (7) transformation, via digitization, of plain sections of samples into matrices of binary (rock vs pore) numbers; and (8) computer processing of the rock-pore matrices using the Fortran IV program PORESTAT which measures numerous parameters including porosity, specific pore surface area, pore size distribution, pore tortuosity, pore orientation, and periodic repetitions in the pore pattern.

Additionally, several new approaches to the hydraulic interpretation of textural data, sampling and sample preparation, and correlation analysis of bivariate data are developed. Two of the more important developments are: a new empirical prediction equation for the settling velocity of nonspherical grains; and a Fortran IV computer program, CORMAT, which produces a correlation matrix describing the strength and character of bivariate curvilinear relationships.

Twenty-eight samples of single laminae were collected from modern and ancient lacustrine and marine beach, eolian dune, and fluvial channel environments. Loose grain fractions and thin sections were obtained for each sample. The loose grains were subjected to textural and packing analyses, and the thin sections were subjected to pore geometry and packing analyses. The samples were collected and analyzed in order to evaluate the methodologies developed in this study. The analyses are too few in number to permit sedimentologic conclusions to be drawn about the sampled depositional environments. The analyses are important, however, in that they represent the first comprehensive characterization of single sand laminae.

DEDICATION

This dissertation is dedicated to my grandparents:
Ethel and Carter Sharp, and Fanny Kate and Jesse Harrell.

ACKNOWLEDGEMENTS

I would like to thank my dissertation committee, Dr.'s Wayne Pryor, Paul Potter and John Grover, for the great patience they have shown during the several years that it has taken to complete this manuscript. I am especially grateful to Dr. Pryor, the dissertation advisor, for allowing me to pursue my unconventional research interests. At the beginning of this research my concern was strictly with sand textures. It was Dr. Pryor who convinced me to consider as well the packing and pore geometry characteristics of sands. For this wise counsel I will be eternally grateful. I would also like to thank Clyde Felix for his moral support during both the laboratory and writing phases of this project. Special thanks are due to Dr. Grover for his careful editing of the manuscript. And finally, I would like to thank Sigma Xi, the University of Cincinnati Research Council, and especially Dr. Richard Moiola and the Mobil Oil Corporation for their financial assistance.

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INTRODUCTION

GENERAL STATEMENT

The world's oil and gas reserves are suffering rapid depletion, and new reserves are becoming increasingly more difficult to find. There is a revitalized interest in clastic sedimentary petrology because of the increasing attention being given to exploration for stratigraphic traps, and secondary and tertiary production from old reservoirs. Much of this interest is centered on texture (grain size and shape distributions), fabric (grain packing—the spacing and arrangement of particles in a granular aggregate, and preferred grain orientation), and pore geometry (porosity, pore size distribution, pore surface area, pore channel tortuosity, etc.). What can these parameters tell us about depositional environments, and what can they tell us about reservoir properties, especially permeability? Although these questions have received a great deal of attention in the past much still remains to be answered.

At the onset of this study my interest was principally in the character of the sedimentologic signature of various depositional environments on terrigenous sand deposits. It was my hope that by

analyzing the size and shape distributions of sand grains within single laminae, instead of the grain size distributions in multi-lamination 'grab' samples (the approach of past investigators), I could improve our ability to discriminate among the many depositional environments. Early in the study I came to the realization that sampling single laminae and employing the conventional methods of textural analysis would not lead to a significant improvement in paleoenvironmental discrimination. What was needed first were new methodologies which provided a fuller description of the physical characteristics of sands and sandstones; methodologies which were at the same time both informative and practical. Accordingly, I redirected my attention to the development of new methodologies and the modification of some existing methodologies. The methodologies subsequently considered were not restricted to those which would be applied in the identification of depositional environments but, at the urging of the principal advisor for this doctoral research (Dr. Wayne Pryor), also included those which would be applied in the description of hydrocarbon (and ground water) reservoir properties.

There is a vast array of analytical procedures in sedimentary petrology. Much of it has been summarized in various manuals (e.g., Krumbein and Pettijohn, 1938; Müller, 1967; and Carver, 1971a). Each month new methodologies are described in the pages of periodicals like *Sedimentology*, and the *Journals of Sedimentary Petrology*, *Sedimentary Geology*, *Geology*, and *Petroleum Technology*. There is still considerable room, however, for improvement in many existing methodologies

as well as for the development of wholly new methodologies. The reader may question this assertion but its veracity will, I believe, be amply demonstrated in the pages which follow.

OBJECTIVES OF THE STUDY

The objective of this study was to develop a battery of methodologies for the analysis of texture, fabric (grain packing only) and pore geometry in sands and sandstones. It is anticipated that these methodologies will improve our ability to deduce sandy depositional environments from textures, and to predict the permeability and enhanced oil recovery characteristics of sandstone reservoirs from packing and pore geometry.

The methodologies developed in this study were applied to 28 quartzose sands and sandstones representing a wide variety of modern and ancient depositional environments (e.g., fluvial point bar, coastal and inland eolian dune, and lacustrine and marine beach). The purpose of the sample analyses was to evaluate the practicality and information quality of the methodologies, and to explore the statistical interrelationships among the measured parameters. The focus of this study was on the development (not the application) of sedimentary petrology methodologies.

SUMMARY

The purpose of this study is to develop a battery of methodologies which can be applied to the problems of paleo-environmental interpretation and hydrocarbon extraction. Many new methodologies are developed and some existing methodologies are modified. These methodologies are used to measure texture, packing and pore geometry in sands and sandstones. A suite of samples is analyzed in order to evaluate the practicality and sedimentologic significance of the methodologies. Twenty-eight single lamina sand samples were collected from modern and ancient lacustrine and marine beach, eolian dune, and fluvial point bar environments. In addition, this study introduces new approaches to sampling and sample preparation, the hydraulic interpretation of textural data, and the correlation analysis of bivariate data. The accomplishments of this study are outlined below.

I. New Methodologies Developed

A. Textural Analyses

1. Roller Micrometer—This batch process machine sizes sand grains by their smallest principal dimension (S). The machine consists of two laterally-adjacent, parallel

cylindrical rollers which revolve in opposite directions (up and away from the intervening slot). Sand grains are fed into the upper elevated end of the slot and are sized as they travel down towards the lower end: thin grains pass through the slot while thicker grains continue to the end of the slot. When the roller micrometer data is combined with that obtained from square-holed sieves, which size grains largely by their intermediate principal dimension (I), the joint I:S grain size and S/I grain form distributions are determined. The roller micrometer results may also be used to obtain the grain size distribution based on the S dimension.

2. Sorting Comparator—This set of five sorting images permits the visual estimation of grain sorting in plane or thin sections. These images simulate plane sections through variously-sorted, lognormally-distributed sphere populations that are randomly packed in three dimensions. The sorting of the sphere populations corresponds to the class boundaries of the Folk (1980) sorting scale: 0, 0.35, 0.50, 1.00 and 2.00 phi. Additional information provided with this comparator makes it possible to also apply it to loose, whole grain samples. Conversely, new information on previously published comparators makes it possible to apply them to thin sections.

B. Packing Analyses

1. Floating Index—This parameter is defined as the percent of all grains counted in a plane or thin section that are not in contact with any other grains. The Floating Index was found to be highly correlated with the conventional measure of grain packing, the Contact Index (the average number of intergranular contacts per grain). The Floating Index is recommended for loosely to moderately compacted sands because it requires less time and effort to measure.
2. Packing Efficiency—This parameter is defined as the ratio of the minimum possible porosity for a sand (estimated from the volumetric porosity of an artificially compacted loose sand) to the actual depositional porosity for the same sand (estimated from a plane section of a sand which was impregnated with epoxy in the field). The Packing Efficiency is a measure of the extent to which a depositional process achieves the maximum possible packing (i.e., minimum porosity).

C. Pore Geometry Analyses

1. Digitization of Pore Space in a Plane Section—The digitization process reduces a tracing of the rock-pore pattern visible in a plane section to a matrix of binary numbers. Each element of the matrix corresponds to a node in a square grid superimposed over the rock-pore pattern.

1

An element is assigned a value of -1 or +1 when the grid node overlies pore space or rock, respectively. The rock-pore matrices analyzed consist of 79 rows and 79 columns. The vertical and horizontal interelement separation (in terms of actual distances on the plane section) are either 0.508 or 0.254 millimeters. The rock-pore matrix is the essential first step in the quantitative description of pore geometry by stereological methods.. The hand-digitization procedure employed in this study is primitive but effective. It is recommended for future studies, however, that the digitization be performed using specially prepared photomicrographs and an automated scanning densitometer.

2. Standard Deviation of the Quadrat Porosity—This parameter provides a good description of the porosity variability within a plane section. The calculation procedure requires the partitioning of a rock-pore matrix into nine square, equal-sized subareas or 'quadrats'. The moment standard deviation is then computed from the porosity values determined for each of the nine quadrats.
3. Double Fourier and Two-Dimensional Autocorrelation Analyses—These techniques are both capable of recognizing periodic repetitions in two-dimensional patterns. Although frequently used in map and areal variation analyses, they have never been used before in pore geometry studies.

Double Fourier analysis is a variety of the statistical technique known as multiple regression. A large number of sinusoidal surfaces are fitted to a binary rock-pore matrix. Each surface differs from every other in its wavelength, amplitude or phase. The wavelength of those sinusoids with high amplitudes indicate the areal repetitions present in a rock-pore pattern. Two-dimensional autocorrelation analysis has the same general objective as double Fourier analysis but is conceptually and mathematically much simpler. In essence, it compares, through successive superimpositions, two copies of the same rock-pore matrix. For each superimposition, the similarity between the overlapping portions of the matrices is measured. The resulting sequence of similarity values indicate the areal repetitions present in a rock-pore pattern. A new measure of pattern similarity was developed for the autocorrelation analyses: the Areal Mismatch Coefficient = one minus the ratio of the number of mismatched matrix elements (rock opposite pore) to the total number of overlapping matrix elements.

4. Pore Orientation—The pore orientation analysis identifies the direction of preferred pore elongation in a rock-pore pattern. A computer creates copies of a rock-pore matrix which are variously oriented with respect to a fixed datum. A measure of the average pore length parallel

to this datum is determined for each copy of a matrix. These averages indicate the direction of preferred pore elongation.

5. Resolution of Individual Pores—Individual pores within a rock-pore matrix are resolved and described in terms of their size and tortuosity. The computer algorithm used to resolve the pores has additional value in that it simulates the movement of a fluid through a two-dimensional pore network.
 - a. Pore Size Distribution—The frequency distribution (histogram and moment mean) of the size of individual pores is determined for four measures of pore size: area, maximum dimension parallel and normal to bedding, and maximum dimension irrespective of direction. All size distributions apparently follow a negative exponential model.
 - b. Tortuosity—This parameter describes the sinuosity of the shortest pathway between the two most widely separated points within an individual pore. The tortuosity is defined as the ratio of the length of the pathway to the maximum dimension of the pore.

6. PORESTAT—Using a digitized rock-pore pattern as input, this Fortran IV computer program performs the following pore geometry analyses.

Measures Based On The Entire Pore Pattern

- a. porosity
- b. standard deviation of the quadrat porosity
- c. specific pore surface area
- d. average Preston-Davis tortuosity (includes map illustrating the 3 pore paths traced)
- e. average pore dimension
 - i. parallel to matrix columns
 - ii. parallel to matrix rows
 - iii. average of i and ii
- f. average rock dimension
 - i. parallel to matrix columns
 - ii. parallel to matrix rows
 - iii. average of i and ii
- g. double Fourier analysis
 - i. power spectrum for the first 20 harmonics
 - ii. frequency distribution of the powers in the power spectrum
 - iii. percentage of the total variance explained by the 400 sinusoid pairs
- h. two-dimensional autocorrelation analysis
 - i. correlogram for lag movement parallel to matrix columns
 - ii. correlogram for lag movement parallel to matrix rows

- i. histogram illustrating the average pore dimension in various directions (analysis of preferred pore elongation orientation)

Measures Based On Individual Pores

- a. number of individual pores
- b. individual pore and weighted average tortuosity
 - i. weighted by pore area
 - ii. weighted by maximum pore dimension
 - iii. map illustrating the individual pore paths
- c. histograms illustrating the frequency distribution of four measures of pore size (the arithmetic mean of each measure is also provided)
 - i. pore area
 - ii. maximum dimension parallel to matrix columns
 - iii. maximum dimension parallel to matrix rows
 - iv. maximum dimension irrespective of direction

II. Existing Methodologies Modified

A. Packing Analyses

It is demonstrated that significant measurement error can occur in the conventional thin section analysis of grain packing due to variations in sample grain size. As grain size decreases, the apparent packing within a thin section increases because there is a greater likelihood that the maximum cross-section of grains will be included within a thin section. Thus thin section-derived packing parameters are not comparable for sands and sandstones of different

average grain size. This measurement error can be avoided, however, if the packing parameters are analyzed in plane sections rather than thin sections.

B. Pore Geometry Analyses

1. Specific Pore Surface Area—This parameter is defined as the ratio of the surface area of the pore walls to the total rock volume. In plane sections this parameter is estimated from the ratio of the length of the pore perimeter to the plane section area. The conventional stereological measure of specific pore surface area is designed for point-counting using a mechanical microscope stage. In order to minimize the considerable time and effort required for the measurement, procedural short-cuts have been adopted by petrologists. In this study the rock-pore matrix traverses are made in two directions (parallel to the matrix rows and columns) instead of the more conventional single direction. This results in a more accurate estimate of specific pore surface area.
2. Average Pore Dimension—The average pore dimension is defined as the mean length of a large number of systematically oriented straight lines spanning pores (i.e., the mean pore chord length). As with specific pore surface area, this parameter is typically determined from rock-pore matrix traverses parallel to either the

rows or columns. An improved measure of average pore dimension is obtained by combining the data for the row and column traverses.

3. Tortuosity—The tortuosity measure proposed (but never used) by Preston and Davis (1976) describes the wanderings of a hypothetical flow path through and between the pores in a rock-pore matrix. The flow path is extended across a matrix in such a way that the most direct route between opposite sides of the matrix is followed. The tortuosity is defined as the ratio of the length of the flow path to the straight line distance between the ends of the path. The Preston-Davis tortuosity measure was modified in the present study in order to improve its reproducibility and to eliminate the element of randomness in the flow path direction. This study is the first to apply the Preston-Davis tortuosity measure to natural porous media.

III. Existing Methodologies Used

A. Textural Analyses

1. Each sand and disaggregated sandstone is sized using three inch diameter, square-holed, wire-mesh sieves. The sieve interval is one quarter phi. From the sieve data the following grain size statistics are computed:
 - a. Moment Measures—mean, standard deviation (sorting), skewness and kurtosis.

- b. Graphical Measures—graphic mean, inclusive graphic standard deviation (sorting), inclusive graphic skewness and graphic kurtosis.
- 2. A cumulative grain size curve (based on the sieve data) is presented for each sample. For each curve three linear segments are identified: a coarse tail, a middle or intertail section, and a fine tail. These segments may correspond, respectively, to the following theoretical grain populations: traction/surface creep, saltation/intermittent suspension, and sustained suspension.
- 3. The roundness range and mode of the loose grains in each sample is estimated using the Powers visual comparator.

B. Packing Analyses

The following packing parameters are measured from a plane section point count of each sample: porosity, contact index, and average number of point, long and concavo-convex contacts per grain.

IV. New Approaches To The Hydraulic Interpretation Of Sand Texture

- A. A genetic classification is proposed for horizontal and cross-bed foreset laminae in sand.
- B. The concept of Standardized Fall Velocity is introduced. This is a useful way of describing the effect of grain shape on settling velocity. The Standardized Fall Velocity of a grain is defined as the ratio of the fall velocity of the grain to the fall velocity of the volume- and density-equivalent sphere.

- C. An empirical prediction equation is developed for the settling velocity of rectangular parallelepipeds (blocks). These regular geometric particles are an adequate model for angular natural sand grains. The equation is valid for sand grains of any size, form and density, and for water of any density and viscosity. The equation incorporates a previously published formula for the settling velocity of spheres along with a newly derived parameter, the Reynolds-Form Factor. This parameter takes into account the effect on settling velocity of grain form and the dynamic character of the fluid immediately adjacent to the falling grain. The expression for the Reynolds-Form Factor was derived by applying multiple regression analysis to previously published experimental data. The prediction equation should be especially useful in hydraulic equivalence studies.
- D. It is shown that the Tabularity Profiles (i.e., the variation in the S grain dimension within a quarter phi sieve (I) fraction) for a suite of samples may be a useful indicator of the hydraulic conditions attending deposition.
- E. A comprehensive description is provided for the three theoretical grain populations: traction/surface creep, C; saltation/intermittent suspension, A; and sustained suspension, B. It is suggested that two other grain populations be recognized: the avalanche/grainflow and grainfall populations. Only these two, and not the A, B and C populations, should be

well-developed on dune and sandwave slipfaces.

V. New Approaches To Statistical Analysis

- A. It is argued that the relationship between variable pairs is more appropriately characterized as being curvilinear than linear. Geologists conventionally use the linear correlation coefficient to describe the strength of bivariate relationships. It seems more likely that natural bivariate trends will be of the simple curvilinear kind (i.e., curves with one bend) and thus the strength of the relationship is described better by the quadratic correlation coefficient. A verbal scale is proposed for the strength of statistically significant quadratic correlations.
- B. CORMAT—This Fortran IV computer program prints a correlation matrix which provides the following statistical and graphical information for all possible pairs of variables:
1. linear, quadratic and cubic correlation coefficients
 2. significance level for the linear, quadratic and cubic regression terms (i.e., results of a F-test of the significance of the regression coefficients)
 3. general shape and orientation of the second degree polynomial curve fitted to the data (Quadratic Curve Type)
- Two sets of results are provided in the matrix for each variable pair. In one set a given variable is treated as the dependent or response variable, and in the other set it is treated as the independent or predictor variable. The

program permits the input of variables having 'missing values.'

VI. New Approaches To Sampling And Sample Preparation

- A. Sampling Single Laminae—Although not new, the sampling of single sediment laminae is still novel. Most investigators collect multi-lamina 'grab' samples. It is argued that only in single laminae will the hydraulic signature of depositional processes be clearly expressed. This study is the first to provide a comprehensive description of the texture, packing and pore geometry of single sand laminae.
- B. Field Impregnation of Unconsolidated Sand—A sampling procedure is developed for the epoxy impregnation of unconsolidated sand in the field. A low-viscosity epoxy is added to the sediment in such a way that the position, spacing and arrangement of the grains is not altered. After the epoxy has hardened, the impregnated sand can be thin-sectioned.
- C. Epoxy Stain—A staining procedure is developed for cured colorless epoxy in thin sections. Conventionally, a color dye is added to the fluid epoxy prior to sample impregnation. It often happens, however, that an investigator impregnates with a colorless epoxy and after preparing the thin section wishes he had used a dye in order to visually enhance the pore space. With the procedure described in this study, it is now possible to stain the thin section epoxy.

D. Plane Sections—Plane sections rather than thin sections should be used in the petrographic analysis of grain packing and pore geometry. If thin sections are used, then the analytical results for samples of different average grain size are not comparable. In this study thin sections are prepared for the sand and sandstone samples but only the upper surface of these sections are analyzed. The upper surface of a thin section represents a plane section view of a sample. This study is apparently the first where the packing and pore geometry of modern and ancient sands are studied in plane section.

VII. Analytical Results

The twenty-eight samples collected were selected so as to provide the widest possible variety of textures, grain packings and pore geometries. The samples are too few in number to adequately represent the depositional environments in which they were deposited. Nevertheless, many of the analytical results of this study are noteworthy. They document the properties of single sand laminae, and they illustrate what appear to be fundamental relationships among sample properties, and between depositional processes and sample properties.

The more important analytical results will be described below for the textural, grain packing and pore geometry analyses. The sections devoted to each of these analyses will begin with a

summary of the measured parameters. In these summaries the parameter mean and range will be given for the following sample groupings:

	<u>Number of Samples</u>	<u>Abbreviations</u>
Modern sands		
Eolian transverse dune foreset	5	M:E
Fluvial point bar sandwave foreset	4	M:FF
Fluvial point bar horizontal	2	M:FH
Marine and lacustrine beach foreshore	4	M:B
Lacustrine washover fan topset and foreset	3	M:W
Ancient sandstones		
Eolian dune foreset	2	A:E
Fluvial channel foreset	4	A:FF
Fluvial channel horizontal	2	A:FH
Marine beach foreshore	2	A:B

A. Textural Analyses

1. Mean and range for some textural parameters

<u>Samples</u>	<u>Moment Statistics</u>	
	<u>Mean</u>	<u>Sorting</u>
M:E	2.53,2.24-2.87	0.29,0.20-0.39
M:FF	2.33,2.16-2.51	0.36,0.30-0.45
M:FH	3.01,2.96-3.06	0.42,0.41-0.42
M:B	1.93,1.39-2.55	0.33,0.26-0.40
M:W	1.20,0.81-1.43	0.37,0.34-0.41
A:E	1.96,1.85-2.08	0.36,0.35-0.37
A:FF	2.48,1.67-2.89	0.48,0.28-0.59
A:FH	2.66,2.65-2.68	0.44,0.41-0.47
A:B	2.57,2.56-2.58	0.41,0.41-0.41

<u>Samples</u>	<u>Moment Statistics</u>	
	<u>Skewness</u>	<u>Kurtosis</u>
M:E	+0.53, (-0.42) - (+1.70)	6.13, 3.75-10.98
M:FF	+1.15, (+0.63) - (+1.53)	9.57, 5.84-12.46
M:FH	+1.15, (+1.11) - (+1.20)	4.86, 4.62- 5.09
M:B	+0.17, (-0.17) - (+0.80)	6.70, 4.89-10.21
M:W	+1.30, (+0.04) - (+1.96)	13.39, 11.41-15.31
A:E	+1.30, (+0.77) - (+1.82)	8.98, 6.65-11.30
A:FF	+1.22, (+0.63) - (+1.61)	6.95, 3.33-14.13
A:FH	+1.48, (+1.43) - (+1.53)	7.48, 7.13- 7.83
A:B	+1.77, (+1.74) - (+1.80)	9.60, 9.53- 9.66

2. The grain size statistics for both the modern and ancient samples are of no value in environmental discrimination but they do show that single laminae consistently have good sorting and a positive (leptokurtic) kurtosis.
3. A comparison of the tabularity profiles for the Cedar Point beach and washover fan samples shows that the fan foreset lamina has a greater proportion of grains with low tabularity (high S/I). This may be due to the winnowing and removal of the flakier, high tabularity grains during suspension above the slipface or reworking of the slipface by reverse currents.

A comparison of the tabularity profiles for the Brazos River point bar samples shows that the trough cross-bed foresets are slightly flakier than the planar cross-bed foresets. This suggests that the ratio of grainfall to grainflow sand on the slipface is greater for the planar cross-bed foresets. The horizontal laminae are substantially flakier than the foreset laminae. This is

to be expected because the horizontal laminae are slack water suspension deposits.

B. Packing Analyses

1. Mean and range for some packing parameters (sections normal to bedding and strike)

<u>Samples</u>	<u>Floating Index</u>	<u>Contact Index</u>	<u>Sample Porosity</u>
M:E	49.3,47.4-52.9	0.68,0.59-0.74	43.6,41.7-46.0
M:FF	55.3,50.3-58.2	0.59,0.54-0.64	44.7,40.8-46.7
M:FH	—	—	46.7,45.0-48.4
M:B	54.9,46.7-60.6	0.57,0.46-0.69	40.3,39.1-42.3
M:W	58.5,53.4-64.7	0.51,0.41-0.60	40.1,36.5-45.4
A:E	1.4, 0.6- 2.3	3.16,3.14-3.17	28.4,27.6-29.1
A:FF	—	—	25.6,24.1-28.0
A:FH	—	—	22.9,21.3-24.5
A:B	—	—	22.2,21.0-23.5

<u>Samples</u>	<u>Compactional Porosity</u>	<u>Packing Efficiency</u>
M:E	37.4,37.0-38.2	0.87,0.83-0.90
M:FF	37.5,36.2-38.4	0.84,0.81-0.88
M:FH	39.4,38.4-40.4	0.84,0.79-0.90
M:B	36.2,35.7-36.6	0.90,0.88-0.93
M:W	36.6,36.1-37.4	0.92,0.83-0.99
A:E	37.4,37.3-37.4	1.32,1.28-1.35
A:FF	38.6,37.1-40.0	1.52,1.43-1.61
A:FH	40.3,39.6-41.0	1.76,1.61-1.92
A:B	38.8,38.5-39.2	1.74,1.67-1.82

2. In plane sections of the modern unconsolidated sands 47 to 66 percent of the grains are floating while the rest of grains have either one or two intergranular contacts which are almost exclusively of the 'point' variety.

3. For ancient indurated sandstones the plane section packing parameters based on numbers and types of intergranular contacts are likely to be invalid. This is because the packing is a product of not only burial compaction but quartz overgrowth cementation as well. A high percentage of 'long' intergranular contacts may be indicative of overgrowth cementation in sandstones.
4. Multiple thin sections of different orientation were prepared for the Cedar Point beach and Mt. Baldy dune samples. The following trend in packing parameters was observed: the sections normal to both bedding and strike had a lower floating index, a higher contact index and a generally higher porosity than the sections parallel to bedding, and the sections normal to bedding and parallel to strike.
5. For the modern sands the porosity of the marine and lacustrine beach foreshore laminae is consistently lower (and hence, the packing is greater) than that for the eolian dune foreset laminae. This difference apparently reflects the mode of deposition: wave reworking on beaches, and grainfall and grainflow sedimentation on dune slipfaces.
6. The packing efficiencies of the modern foreset laminae are less than or equal to the packing efficiencies for the horizontal laminae of foreshore beach and washover fan topset origin.

7. The artificial compaction analyses documented the important role played by grain sorting and roundness in determining minimum compactional porosity: porosity tends to decrease as roundness increases and sorting becomes poorer.

C. Pore Geometry Analyses

1. Mean and range for some densitometric pore geometry parameters (sections normal to bedding and strike)

<u>Samples</u>	<u>Porosity</u>	<u>St. Dev. of Quadrat Porosity</u>	<u>Specific Surface Area (mm⁻¹)</u>
M:E	46.2,43.1-50.3	3.44,2.01-4.27	15.8,12.5-22.1
M:FF	46.9,45.8-47.8	2.30,1.42-3.23	13.3,11.7-14.3
M:B	43.7,40.7-50.8	4.08,3.13-5.06	11.1, 8.9-14.8
M:W	40.1,37.3-42.0	5.36,3.23-9.48	7.8, 6.5- 8.7
A:E	29.3,28.3-30.3	3.58,3.18-3.97	9.8, 9.3-10.3
A:FF	21.8,18.0-26.0	4.62,3.51-7.80	11.1, 7.2-13.5
A:FH	17.6,16.8-18.4	5.04,4.28-5.79	10.3,10.1-10.5
A:B	18.8,18.2-19.5	5.41,5.26-5.56	11.0,10.7-11.3

<u>Samples</u>	<u>Number of Pores</u>	<u>Preston-Davis Tortuosity</u>	<u>Average Pore Dimension (mm)*</u>
M:E	33, 20- 49	1.28,1.23-1.35	0.126,0.079-0.161
M:FF	24, 12- 32	1.33,1.31-1.37	0.142,0.130-0.164
M:B	23, 18- 39	1.37,1.33-1.43	0.163,0.122-0.185
M:W	17, 8- 22	1.41,1.38-1.48	0.209,0.180-0.254
A:E	117,105-129	1.90,1.85-1.95	0.120,0.118-0.122
A:FF	102, 80-123	2.53,2.20-3.04	0.083,0.066-0.120
A:FH	98, 96-101	2.53,2.39-2.67	0.069,0.065-0.073
A:B	84, 83- 86	3.39,3.22-3.55	0.068,0.068-0.069

<u>Samples</u>	<u>Average Maximum Pore Dimension (mm)**</u>	<u>Average Pore Area (mm²)**</u>
M:E	0.278,0.172-0.376	0.179,0.060-0.395
M:FF	0.432,0.306-0.599	0.355,0.234-0.621
M:B	0.450,0.296-0.556	0.315,0.179-0.380
M:W	0.635,0.383-0.933	0.456,0.299-0.805
A:E	0.307,0.290-0.324	0.038,0.035-0.040
A:FF	0.175,0.118-0.252	0.013,0.006-0.025
A:FH	0.120,0.117-0.123	0.007,0.006-0.007
A:B	0.140,0.136-0.145	0.008,0.008-0.008

*Overall average for the entire pore pattern

**Absolute average for individual pores

2. The average pore dimension (based on the entire pore pattern) parallel to bedding is almost always larger than that normal to bedding.
3. The densitometric Preston-Davis tortuosity measure seems to provide values which are comparable to those obtained from three-dimensional sample plugs by electrochemical methods. For both the electrochemical and densitometric approaches, the tortuosity is generally less than 1.5 for unconsolidated sands and greater than 1.5 for indurated sandstones.
4. A consistent difference exists in the principal pore orientation for modern beach foreshore laminae, and fluvial, washover fan and eolian foreset laminae. The beach laminae have pore orientations (elongations) either normal to bedding or inclined away from bedding in a direction opposite from the bedding dip. In contrast, the foreset laminae have pore orientations either parallel to bedding

or inclined in the same direction as the bedding dip. These pore orientations are probably the result of backwash-induced grain imbrication on beaches and down-slope alignment of grains on foreset slipfaces.

5. Based on the negative results of the double Fourier and two-dimensional autocorrelation analyses, it appears that well-developed periodic repetitions do not occur in the sands and sandstones.

SAMPLING

ENVIRONMENTS AND LOCALITIES SAMPLED

The 28 sand and sandstone samples collected for this study came from both modern and ancient beach, river channel and eolian dune environments. The samples were selected so as to provide the widest possible variety of textures, fabrics and pore geometries. It should be kept in mind, however, that the samples are not necessarily representative of their respective environments and that there are far too few samples to allow meaningful generalizations to be made about any particular environment. As mentioned previously, the sample data set was used not to document the sediment characteristics of various depositional environments but rather to evaluate the new methodologies developed in this study.

The environments and localities sampled are as follows:

Foreshore Beach

Modern

Marine: Matagorda Peninsula, Texas
(Samples B1-15 and 16)

Lacustrine: Cedar Point Spit, Lake Erie, Ohio
(Samples B2-1 and 16)

Ancient

Marine: Blackhawk Formation (Upper Cretaceous),
Book Cliffs, Utah
(Samples AB1-1d1 and 1d2)

Washover Fan

Modern

Lacustrine: Cedar Point Spit, Lake Erie, Ohio
(Samples B2-7, 9 and 20)

Eolian Dune

Modern:

Coastal Marine: Padre Island National Seashore, Texas
(Samples D3-15 and 19)

Coastal Lacustrine: Indiana Dunes National Lakeshore,
Lake Michigan, Indiana
(Samples D5-10, 15 and 16)

Ancient

Inland Continental: Navajo Sandstone (Lower Jurassic),
Zion National Park, Utah
(Samples AD2-1e and 1f)

Fluvial Channel

Modern

Meandering/Point Bar: Blasdel Point Bar, Brazos River,
Texas
(Samples R5-21, 23, 25, 27, 29
and 34)

Ancient

Meandering/Point Bar: Kyrock Sandstone (Lower Pennsylvanian),
Nolin Reservoir, Kentucky
(Samples AR1-14, 15a, 18 and 22c)

Braided/Transverse Bar: Kyrock Sandstone as above
(Samples AR1-4c and 5c)

Detailed information on the depositional environments and localities sampled, and the composition and lamina type of the samples is provided in Appendix A.

IMPORTANCE OF SAMPLING SINGLE LAMINAE

All sediment samples collected for this study represent single laminae. This kind of sample consists of texturally and structurally relatively homogeneous sediment deposited under constant hydraulic conditions (Jopling, 1964a) and thus greatly simplifies the interpretation of the analytical results.

A single lamina is a subdivision of a 'sedimentation unit' which was defined by Otto (1938, p. 575) as "that thickness of sediment which was deposited under essentially constant physical conditions." A sedimentation unit may consist of numerous laminae (e.g., a cross-bed set). A single lamina is essentially synonymous with Apfel's (1938, p. 67) 'phase' which is defined as a sediment layer produced by "deposition during a single fluctuation in the competency of the transporting agent." We now recognize, however, that laminae are not necessarily the result of flow competency fluctuations. This point will be discussed at length in the next section. Conceptually, laminae are fairly well defined but their identification in the field can be difficult. Many geologists arbitrarily define a lamina as a sediment layer less than 1 centimeter thick (Blatt et al., 1980, p. 128). In the present study, the more meaningful definition of Hunter (1977, p. 362)

was employed during field sampling: laminae are the "thinnest recognizable internally unstratified sedimentary layers."

Nearly all the past studies dealing with the environmental or hydraulic significance of textures used 'grab' samples consisting of sediment from numerous laminae. Unlike a single lamina, which is deposited under constant hydraulic conditions, a grab sample averages the sedimentologic response to a range of hydraulic conditions. At times grab samples are desirable because they tell us about the average conditions. It seems, however, that the signature of those processes that are unique to the various depositional environments, if they exist, will be found only in single laminae. The mixture of laminae in a grab sample confounds the sedimentologic information and blurs the perhaps subtle differences between environments. Geologists seeking to discriminate among depositional environments on the basis of sediment textures should sample single laminae. To my knowledge, only one study, Tucker and Vacher (1980), has employed such a sampling strategy: these investigators sampled the upper 1 centimeter of active bedding surfaces in modern environments.

CLASSIFICATION AND ORIGIN LAMINAE SAMPLED

The laminae sampled in this study are of two basic types: 'cross-bed foreset' and 'horizontal' laminae. The term 'horizontal', for the latter type, is actually a misnomer because many such laminae are gently inclined (up to 10 degrees). Both types of laminae can be further subdivided into subtypes based on their origin. The numerous lamina types

and their origins are discussed at length below and are summarized in Table 1. Consideration of the depositional processes responsible for the formation of laminae is an essential prerequisite for the interpretation of the textural, packing and pore geometry data gathered in this study.

Cross-Bed Foreset Laminae

Cross-bed foreset laminae represent sediment which was deposited on the slipface of a migrating bedform. The sediment emplacement mechanisms operating on the slipface are essentially the same for both subareal and subaqueous dunes and sandwaves. Excellent discussions of these mechanisms can be found in Jopling (1964b) and Hunter (1977). Under the influence of a current, bedload sediment will travel up the stoss side of a bedform. Upon reaching the bedform crest some of the sediment will be whisked into temporary suspension and much of it will quickly settle out onto the middle and lower slipface surface. Sediment layers formed by this particulate fallout have been called 'grainfall' laminae by Hunter (1977). The bedload sediment that is not carried into suspension accumulates at the bedform crest. Periodically, when the crest becomes over steepened, this sediment avalanches down the slipface. Sediment layers formed by this process are variously known as avalanche, sandflow and grainflow laminae (Hunter, 1977). The latter designation will be used here.

In eolian (Hunter, 1977) and especially subaqueous (Basamallick, 1966) cross-beds the foresets frequently consist of alternating

TABLE 1
CLASSIFICATION AND ORIGIN OF SAND LAMINAE

LAMINA TYPE				ORIGIN		SAMPLES
Cross-bed Foreset Laminae	Grainfall			Upon reaching the crest of a ripple, dune or sand-wave the finer-grained bed load sediment is carried into temporary suspension and subsequently settles out onto the slipface surface.	Both kinds of deposit may be reworked by 1) leeside reverse flow; and 2) secondary currents moving obliquely across the slipface.	AD2-1e and 1f? B2-20 D3-15 and 19 D5-10, 15 and 16
	Grainflow			Coarse-grained bed load sediment accumulating at the crest of a migrating ripple, dune or sandwave periodically avalanches down the slipface.		R5-21, 23, 25 and 34 AR1-4c, 5c, 14 and 15a?
Horizontal Laminae (may be gently inclined; less than 10 degrees dip)	Foreshore Beach	Aggradational		The landward rush of the wave swash deposits bed load sediment and reworks the bed surface. The downslope return of the backwash erodes and redeposits the bed sediment. Lower wave energies.		B1-15 and 16 B2-1 and 16 AB1-1d1 and 1d2?
		Degradational		The wave swash and especially the backwash are primarily erosional. Bed sediment is winnowed to produce lag concentrate deposits of heavy minerals, coarse light minerals and coarse shell hash. Higher wave energies.		
	Unidirectional Currents	Current Competence Variations	Aggradational	A temporary, local decrease in current competence due to turbulence or pulsating flow results in the deposition of bed load sediment.		
			Degradational	A temporary, local increase in current competence due to turbulence or pulsating flow causes winnowing of the bed surface and the formation of lag concentrate deposits.		
		Grain Interactions		Under decelerating flow conditions, those grains which dominate the bed load and are of similar hydraulic behavior are deposited while those grains which are unstable on the bed surface (i.e., are either too large or small, or the wrong shape to fit into the sediment framework) are carried away by the current.		
		Migrating Ripple-like Bed-forms (Psuedo-laminae)	Basal Coarse Layer	Under aggrading bed conditions, a series of migrating ripple-like bedforms, each advancing over the coarse basal slipface deposits of the preceding, will produce a vertical sequence of psuedolaminae.		
			Washed-Out, Low-Amplitude Sandwaves	Under aggrading bed conditions, a series of washed-out, low-amplitude sandwaves, each advancing up the stoss side of the preceding, will produce a vertical sequence of psuedolaminae.		B2-7 and 9?
Grainfall During Slack Water Conditions				During the waning stages of a flood the suspended sediment settles out in the slack water areas and subsequently undergoes little or no traction transport.		R5-27 and 29 AR1-18 and 22c?

coarse- (grainflow) and fine-grained (grainfall) laminae. Lamina cup-lets similar to these can be produced, however, by two other processes. First, the reworking of slipface deposits by reverse flow or oblique currents can form coarse lag or fine-grained climbing ripple deposits. Second, continuous avalanching on subaqueous slipfaces can produce lamina cuplets when the ripples migrating up the stoss side of a larger bedform concentrate the coarsest sediment in their leeside scour pocket. As these ripples reach the crest of the larger bedform the coarsest sediment spills down the slipface and is immediately followed by the finer sediment making up the bulk of the ripple (Smith, 1972).

The B2 (number 20), D3 (numbers 15 and 19) and D5 (numbers 10, 15, and 16) foreset laminae are probably of grainfall origin. The recognition of the eolian D3 and D5 laminae as grainfall deposits was based on the geometric criteria described by Hunter (1977). The heavy mineral layers marking the upper and lower boundaries of these laminae may be lag deposits produced by the winnowing action of wind blowing across the slipface. I observed such lag deposits forming on the active slipface of the Mt. Baldy transverse dune. The washover fan B2 foreset lamina probably has a grainfall origin because it is sandwiched between two much coarser laminae that are undoubtedly avalanche deposits. The fluvial R5 foreset laminae (numbers 21, 23, 25 and 34) are probably of the grainflow variety because they are coarser than the adjacent laminae and display the tongue-like geometry distinctive of avalanche deposits.

It is not clear whether the fluvial AR1 foreset laminae (numbers 4c, 5c, 14 and 15a) are of the grainfall or grainflow variety. However,

sample AR1-4c has bounding laminae consisting of finer-grained sand, and the other three samples had weathered out at the outcrop as resistant slabs of single laminae (suggesting that they too were bounded by finer-grained, more easily weathered sediment). From this evidence it is concluded that these four AR1 samples are probably grainflow laminae. It seems likely that the two eolian AD2 foreset laminae are grainfall deposits because of their thin sheet-like geometry and their textural similarity to the adjacent laminae.

Horizontal Laminae

Beach (Foreshore) Laminae

Sediment laminae on the gently sloping (up to 10 degrees) lacustrine and marine foreshore reflect 1) the differences in the energies of successive waves breaking on a beach, and 2) the differences in competence, for a given wave, of the fast upslope landward rush of the wave swash and the subsequent slower downslope return of the backwash (Clifton, 1969 and Middleton and Southard, 1977, p. 6.45). The swash-backwash process produces laminae both of the primary depositional (aggradational) and winnowed lag concentrate (degradational) variety.

The B1 (numbers 15 and 16) and B2 (numbers 1 and 16) foreshore laminae are probably of the aggradational variety. The upper and lower boundaries of these laminae are marked by heavy mineral and coarse shell hash layers which clearly represent lag deposits.

The two AB1 foreshore laminae (numbers 1e and 1f) are also probably aggradational deposits because their upper and lower boundaries are marked by paper-thin layers of dark chert grains. Although these chert grains are seemingly no denser or larger than the adjacent quartz grains, their concentration could only result from some sort of winnowing action.

Laminae Produced by Unidirectional Currents

Plane bed phase of the transitional flow regime

There are two proposed origins for laminae formed under plane bed flow conditions. The first origin is attributable to hydraulic factors. Turbulence or flow pulsations cause temporary local fluctuations in current competence. A decrease in competence would result in the formation of a primary depositional (aggradational) lamina and an increase in competence would cause winnowing and the formation of a lag concentrate (degradational) lamina (Simons et al., 1965; and Harms and Fahnstock, 1965).

The second origin is due to grain interactions. This is the so-called 'like-accepts-like-and-rejects-unlike' hypothesis of Moss (1962, 1963) and Kuenen (1966). This mechanism was well described by Frostick and Reid (1977, p. 1-2): "... under steadily decelerating flow conditions, the bed becomes dominated by congregations of like particles that offer particles of different hydraulic character little opportunity for permanent deposition. As a result, each lamina exhibits remarkable

homogeneity. Abrupt change in particle character from lamina to lamina results from an exhaustion of the traction carpet supply of any contemporary dominant particle type." A given lamina may be slightly coarser or finer grained than the immediately underlying lamina depending on the new dominant particle type in the bed load. Laminae of this type have been experimentally produced in flumes by Kuenen (1966) and Moss (1972).

Migrating ripple-like bedforms

Two related origins have been proposed for the formation of horizontal laminae by migrating ripples and megaripples. In both cases the laminae formed are actually 'pseudolaminae' because each consists of numerous inclined lamina segments where the interlamina boundaries are not visible. The first origin involves the formation of a coarse-grained lamina at the base of a migrating bedform (Jopling, 1964b; Allen, 1965; Smith, 1971; and Frostick and Reid, 1977). According to this mechanism coarse sediment accumulates at the base of a slip-face where it is then buried under the finer-grained middle and upper foreset sediments of the advancing bedform. During the period of migration, a single bedform can produce an areally extensive, nearly horizontal, thin, coarse-grained basal pseudolamina. Under aggrading conditions, a series of migrating bedforms, each advancing over the basal deposits of the preceding (downcurrent) bedform, will produce a vertical sequence of nearly horizontal laminae.

The second origin for pseudolaminae has been proposed by Smith (1971) and McBride et al. (1975). According to this model, the individual laminae are actually the cross-bed sets deposited by 'washed-out', low-amplitude sandwaves of the lower portion of transitional flow regime. These bedforms resemble sand sheets and have set thicknesses as small as 1 centimeter. The internal cross-stratification is generally poorly developed and indistinct because of the rapid foreset deposition. Under aggrading conditions, a series of migrating low-amplitude sandwaves, each advancing up the stoss side of the next sand-wave downcurrent, will produce a vertical sequence of nearly horizontal laminae.

It is not known with certainty which of the several possible origins for horizontal laminae under unidirectional current conditions was responsible for the deposition of the B2 horizontal laminae (numbers 7 and 9). At present, there are no established criteria for distinguishing among the horizontal lamina varieties. Because the two B2 samples come from the topset laminae of a washover fan that is shallowly submerged or awash at times of severe storm and subareally exposed at all other times, it seems most likely that they are pseudolaminae deposited by low-amplitude sandwaves. This bedform is especially characteristic of high intensity, shallow flows (Smith, 1971; and McBride et al., 1975).

Laminae Produced by Grainfall During Slack Water Conditions

During the waning stages of a fluvial or tidal flood, the suspended

sediment begins to settle out in the areas of sluggishly moving or ponded water. Vertical sequences of fine-grained, horizontally laminated sand are deposited during slack water conditions.

The four R5 (numbers 27 and 29) and AR1 (numbers 18 and 22c) samples came from a thick sequence (up to a few meters thick) of horizontal laminae deposited on an upper point bar surface. These laminae are so fine grained, areally extensive and thin (often 1 millimeter or less) that it seems that this sediment must have been deposited almost directly from suspension without appreciable traction transport.

SAMPLING METHODS

Unconsolidated Sand

Lamina Selection

Three requirements governed the selection of a lamina for sampling. First, the lamina had to be laterally homogeneous in texture, structure and composition across an area of at least 15 square centimeters. This area was sufficiently large to permit the side-by-side collection of two types of samples: 'loose grains' for the textural analyses, and 'epoxy-impregnated grains' for the pore geometry and packing analyses. The line joining the two sampling sites was always parallel to the shoreline or bedform crest, and thus was normal to the flow direction of the depositing current (i.e., parallel to the strike of the

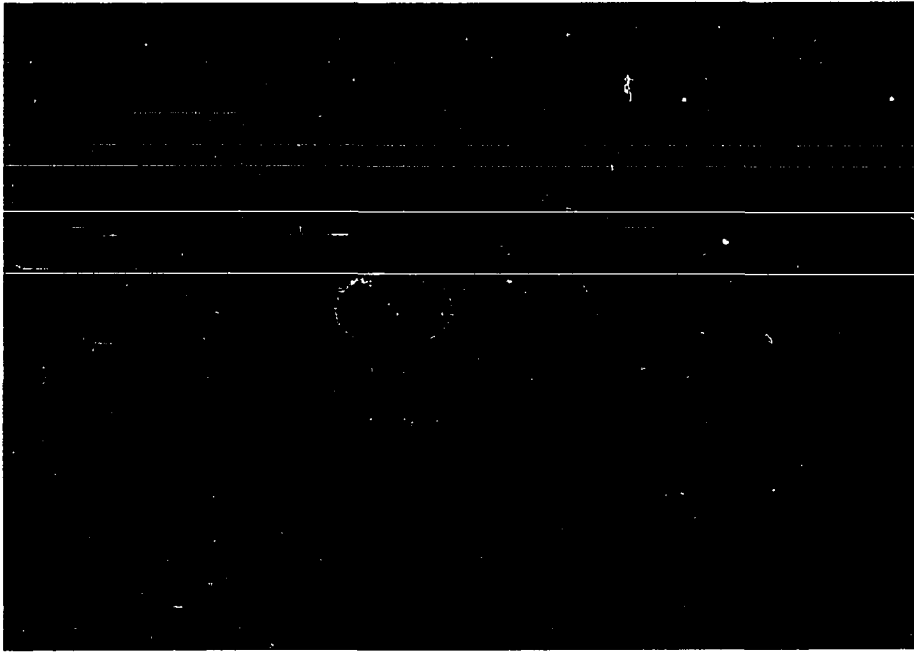


Plate 1 — Collection of loose and impregnated sand samples
(Mt. Baldy, Indiana Dunes National Lakeshore, Indiana).

lamina). Second, the lamina had to be 1 centimeter or less in thickness. The thinner the lamina, the more likely it was deposited under constant hydraulic conditions. The laminae sampled in this study ranged in thickness from 5 to 10 millimeters. Third, for planar and trough foreset laminae, and foreshore beach laminae the samples had to be collected from somewhere within the central two-thirds of the slipface and beachface, respectively. Additionally, for the trough foreset laminae the sampling sites had to be located along the trough axis.

Collection of Loose Sand

The overlying sand was stripped away until the top of the lamina of interest was reached. Using a small artist's trowel (the rectangular blade was 1.6 by 5.1 centimeters in area and 0.2 millimeters thick) the entire thickness of sand in the lamina was carefully removed and placed in a plastic vial (see Plate 1). Approximately 10 to 20 grams of sand was collected, depending on the thickness and lateral homogeneity of the lamina.

Collection of Epoxy-Impregnated Sand

The field impregnation procedure used in this study is notable in that it is apparently the first developed to date that allows the epoxy impregnation of unconsolidated sediment without significantly

disturbing the original spacing, arrangement and position of the grains. The procedural steps are as follows: first, a container with a perforated base is placed on top of the sand; second, a low viscosity epoxy is added to the container; third, the epoxy is allowed to seep into the underlying sand; and fourth, after allowing sufficient time for curing, the mass of impregnated sand is extracted. A more detailed description of this procedure is given in Part I of Appendix P. The impregnated sample can then be thin sectioned and the primary appositional pore geometry and fabric analyzed.

Indurated Sandstone

For the AB1 and AD2 samples, and sample AR1-4c large oriented blocks were quarried. Once suitable laminae were located, they were removed from the block using a rotary saw with a diamond blade or a hack saw with a carbide blade. The cut surfaces of the slabs were scrubbed with a steel-bristle brush in order to remove any broken grains. For the other five AR1 samples, the rocks on the outcrop broke readily along the lamina boundaries and thus thin slabs of single laminae were collected.

The laminae sampled ranged in thickness from 5 to 11 millimeters. The thin section and loose grains were obtained from the same slab.

SAMPLE PREPARATION

Thin Sections

General Considerations

Small 'chips' were cut from the indurated sandstone and the impregnated sand samples. The chips for the sandstone were impregnated under vacuum pressure using Epon 815 epoxy. A standard petrographic thin section (25 to 35 microns thick and lacking cover slip) was prepared from each chip. Thin sections oriented normal to bedding and parallel to the maximum dip or current direction (i.e., normal to strike) were made for all samples.

For both the B2-16 and D5-16 samples four thin sections were prepared: two normal to bedding and parallel to dip, one normal to bedding and parallel to strike, and one parallel to bedding. These multiple thin sections were used to evaluate the reproducibility and variation of the grain packing and pore geometry parameters in different slices through the same lamina. Samples B2-16 (medium-grained lacustrine foreshore beach) and D5-16 (fine-grained eolian dune foreset) were selected for detailed study because 1) their impregnations are of high quality, and 2) they are excellent examples of laminae having very different origins.

Staining Procedure

It is common practice in sedimentary petrology to add a coloring dye to an epoxy (the dye is mixed into the epoxy while it is still fluid) in order to visually enhance the pore space in the thin section prepared from an impregnated sample. Such an enhancement would be useful in any analysis of grain packing or especially pore geometry. No dye was added to the impregnating epoxy in the present study because it was feared that it would interfere with the curing process. What was needed then was a technique which would stain, with any desired color, the colorless epoxy exposed on the outer surface of a thin section. Such a technique has been newly developed for the present study: a thin section is immersed in a weak organic solvent to which a coloring dye has been added. A detailed description of the staining procedure is given in Part II of Appendix P.

Only the thin sections prepared from the sandstones were stained. It was found that the epoxy in the thin sections of the impregnated sands tended to dissolve in the organic solvent. For this reason, these slides were not stained. The tendency for the 'field-cured' epoxy to dissolve is perhaps the result of incomplete curing due to the presence of water.

Loose Grains

The loose sand collected immediately adjacent to the impregnated sand was treated to remove shell and carbonate rock fragments, clay

and fine silt size grains, soluble salts, and heavy mineral grains.

For the indurated sandstones, the portion of the lamina slab immediately adjacent to where the thin section chip was removed was disaggregated to obtain a loose grain sample. During the disaggregation process the samples were treated to remove carbonate grains and cement, iron oxide cement, and clay matrix. The samples contained negligible amounts of heavy mineral grains and thus treatment with a 'heavy liquid' was unnecessary. Some grain breakage was unavoidable during disaggregation. Samples AD2-1e and 1f, and AR1-4c had only minor amounts of quartz cement and so were easily disaggregated without significant alteration of the original grain size distribution. The other seven AR1 and AB1 samples had major amounts of quartz cement and consequently were disaggregated with great difficulty (this is especially true of AR1-18). For these samples a possibly significant amount of the material in the fine tail of the grain size distribution may have been produced by the crushing of larger grains.

The treatment procedures for the unconsolidated sands and indurated sandstones are described in detail in Part III of Appendix P.

METHODOLOGIES FOR THE ANALYSIS OF TEXTURE

GRAIN DIMENSIONS AND SHAPES

Concepts And Definitions

Sediment grains may be considered as having three principal dimensions: a largest or maximum dimension (L), an intermediate dimension (I), and a smallest or minimum dimension (S) where $L \geq I \geq S$. The axes corresponding to these three dimensions are not necessarily mutually perpendicular or even intersecting. Moss (1962), after making measurements on tens of thousands of sand grains, found these axes to be generally nearly mutually perpendicular but seldom mutually bisecting. The three principal grain dimensions will be referred to subsequently simply as the L, I and S dimensions of a grain. These dimensions are approximately those of a rectangular parallelepiped (i.e., a block) which could be circumscribed about a grain (Figure 1).

Following the terminology of Barrett (1980) and Folk (1980), the 'shape' of a sediment grain may be thought of as having four independent aspects: surface texture (the microrelief features of a grain surface), roundness (the angularity of the edges and corners of a grain),

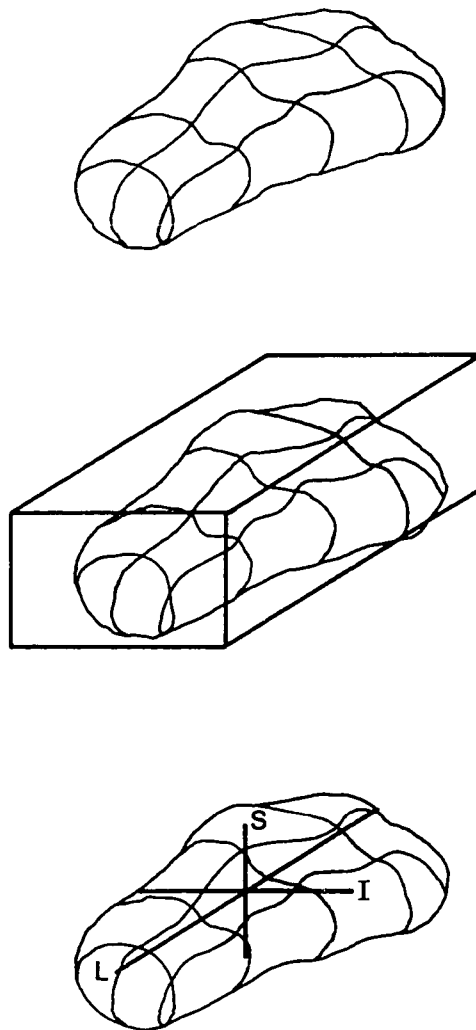


FIG. 1 – The three principal dimensions of a grain and the circumscribing rectangular parallelepiped.

symmetry (the mass distribution of a grain), and form (the relative magnitude of the three principal grain dimensions; the gross or overall 'shape' of a grain). The term 'sphericity' is widely used in geology to describe grain shape. Sphericity should be viewed simply as one measure of grain form. It indicates how nearly equal the three principal dimensions of a grain are. Various measures of sphericity will be considered in a later section dealing with the settling velocities of nonspherical grains.

In this study the focus will be on the overall shape or 'form' of a sediment grain where the form will be conceptually defined by the dimensions of a circumscribed rectangular parallelepiped. Surface texture and symmetry will not be considered here, and roundness will be considered only briefly in a later section dealing with the packing of loose grains.

Any quantification of form should be independent of grain size. In accordance with this requirement numerous form parameters have been proposed utilizing dimensionless ratios of the three principal grain dimensions (Barrett, 1980). Two form parameters, the Zingg elongation (I/L) and flatness (S/I) indices, provide the clearest expression of the full spectrum of grain forms (Zingg, 1935; and Krumbein, 1941). The Zingg Diagram (Figure 2) illustrates the form spectrum. The particles shown in Figure 2 are rectangular parallelepipeds of unit volume (i.e., the product of the three principal dimensions is the same for all particles). The center point on the front face of each particle represents the plot position. If the grain dimensions are measured

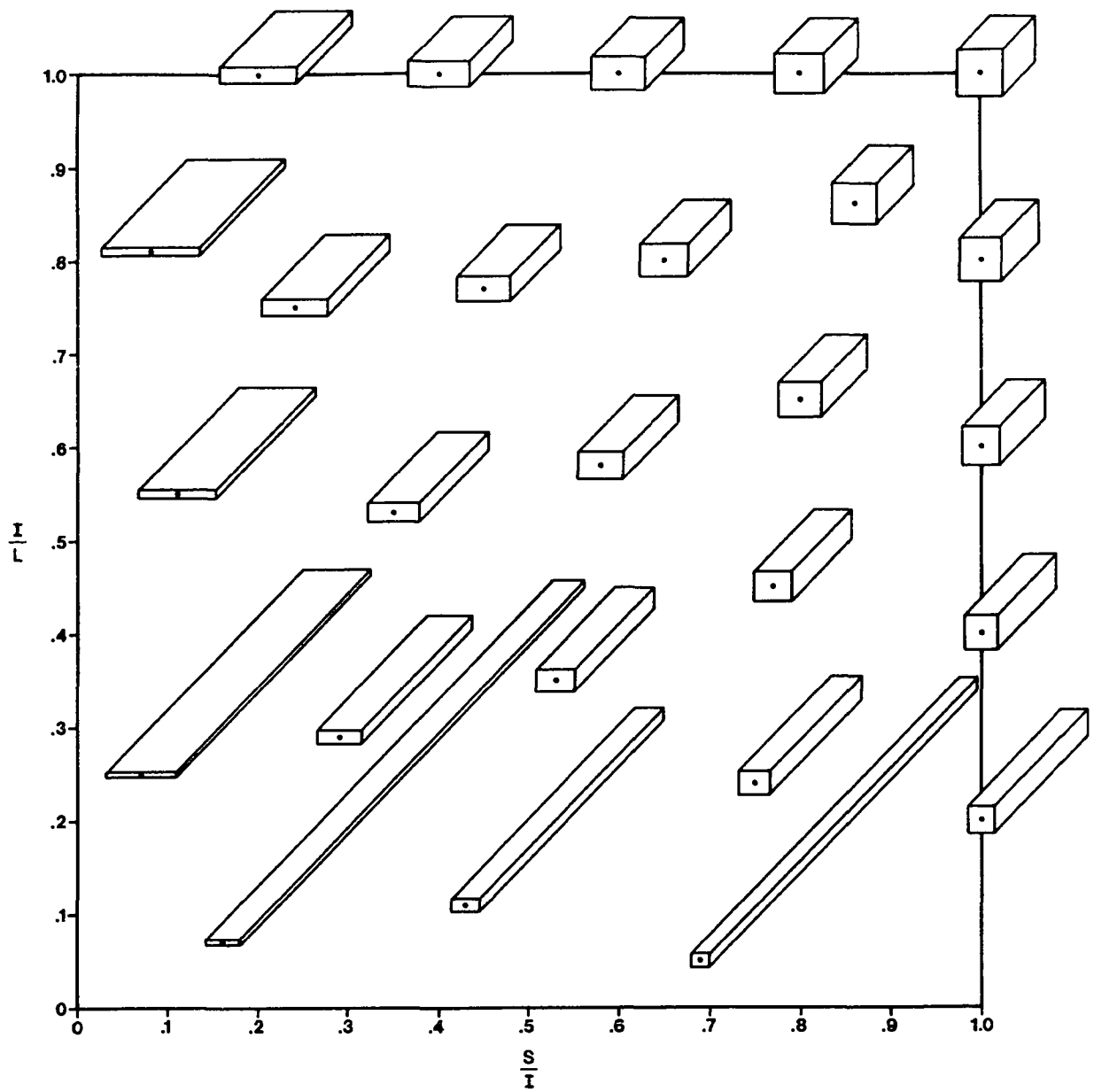


FIG. 2 – The Zingg form spectrum for rectangular parallelepipeds.

in phi units (L_ϕ , I_ϕ and S_ϕ) rather than the more usual millimeter units (L_{mm} , I_{mm} and S_{mm}) then the elongation and flatness indices become, respectively: $I_{mm}/L_{mm} = 2^{(L_\phi - I_\phi)}$, and $S_{mm}/I_{mm} = 2^{(I_\phi - S_\phi)}$. Another useful form parameter is the 'compactness' index (S/L) which is introduced here as a measure of how closely a grain approaches equidimensionality.

General Approaches to Measurement

The description of particle form depends on the method used to measure the three principal dimensions. There are three approaches to measurement of the principal dimensions of sand-sized grains:

- (1) direct measurement of the L, I and S dimensions of individual grains using microscopes fitted with ocular micrometers, or using enlarged images (photographs or projections) of grain outlines (Huitt, 1954; Briggs et al., 1962; Modarresi, 1969; and Wadsworth, 1971);
- (2) rough estimates of the I dimension through sedimentation analysis (Poole, 1957; Ziegler and Gill, 1959; Hulsey, 1961; Kennedy and Koh, 1961; Schlee, 1966; Sengupta and Veenstra, 1968; Gibbs et al., 1971; Gibbs, 1972; Warg, 1973; Brezina, 1979; and Chapman, 1981); and (3)
- rough estimates of the I and S dimensions through sieving (Marwick, 1937; Lees, 1964a; and Ludwick, 1971).

Of the three approaches listed above, direct measurement of individual grains is by far the most accurate but it is extremely tedious and time-consuming, and so is rarely practiced today. The

other two approaches, sedimentation and sieving, both utilize the 'batch process' concept: large numbers of grains are sized simultaneously. The batch process measurements provide, however, only rough estimates of average grain dimension.

Although sedimentation analysis is much more efficient than sieving in terms of both time and effort expended, it has two serious drawbacks from the standpoint of this study. First, sedimentation analysis describes the size distribution of a sediment in terms of a single dimension, the 'sedimentation diameter' (the diameter of a sphere with the same density and settling velocity as an irregular sediment grain). The sedimentation diameter is not necessarily related in any simple fashion to one of the three principal grain dimensions because settling velocity is a behavioristic measure of size which is also a function of grain volume and shape. Second, sedimentation analysis does not physically partition a sandy sediment into discrete size fractions which could then be further analyzed for grain form.

Sieving is the only batch process technique which will physically partition a sediment into size classes based on either the intermediate or shortest dimension. Following Lees (1964a), the three principal grain dimensions can be operationally defined as follows: *S* is the widest dimension of a grain in its narrowest cross-sectional plane and as such is the only dimension that controls the passage of a grain through a rectangular-holed sieve; *I* is the narrowest dimension of a grain in its widest cross-sectional plane and as such is the only dimension that controls the passage of a grain through a round-holed

sieve; and L is the widest dimension of a grain in its widest cross-sectional plane. There is no known batch process technique for measuring L. The three principal grain dimensions as defined above correspond, to a close first approximation, to the lengths of the three mutually perpendicular axes of the circumscribing rectangular parallelepiped (Marwick, 1937; and Lees, 1964a). In the present study, the sieving approach is employed in the determination of the intermediate and smallest grain dimensions. When these two dimensions are measured for a sandy sediment, then an improved description of both the grain size (S as well as I) and shape (S/I) distributions should result. Such a development would significantly enhance our ability to interpret ancient depositional environments.

SIZE DISTRIBUTIONS OF THE INTERMEDIATE AND SMALLEST GRAIN DIMENSIONS

Measurement Of The Intermediate Grain Dimension (Sieve Analysis)

Introduction

It is well known that the largest and smallest principal dimensions of a grain have no effect whatsoever on its passage through a round hole (Ludwick, 1971). Only the intermediate grain dimension controls the sizing action of round-holed sieves. Sieves with round-holed openings

are rarely used, however, because of their excessively high cost. There is apparently only one manufacturer of round-holed sieves in North America, the Buckbee-Mers Company of Saint Paul, Minnesota. The opening diameters of the sieves sold by this company do not conform to the U.S. Standard Series used by geologists. The company will, however, custom-make 3 and 8 inch diameter electroformed sieves with openings of any size. The cost for this service is prohibitive. First, a 'master' must be made for each sieve at a cost of \$2000 or more per sieve. Second, once the master is made the cost for each 3 and 8 inch sieve is about \$100 and \$300, respectively.

Instead of round-holed sieves, the much more affordable and readily available square-holed woven-wire sieves are generally used to size sediment. Because the sieve openings are square, however, the passage of grains is controlled not only by the intermediate dimension but also, to a small extent, by the smallest dimension (Marwick, 1937; Rittenhouse, 1943; Sahu, 1965; and Ludwick and Henderson, 1968). The length of the diagonal of a square is 1.414 times that of the side. It is the length of the side of a square aperture which is referred to as the 'nominal sieve opening'. From the above it is clear that a platy grain with an intermediate dimension up to 1.4 times the nominal sieve opening may pass diagonally through a square aperture. The smaller the S/I ratio of the grain, the greater the magnitude of the sizing error (Figure 3). If the sieve interval is the standard $\frac{1}{2} \phi$ (i.e., the ratio of nominal openings for adjacent sieves, measured in millimeters, is 1.189) and if we define N_0 to be the nominal opening

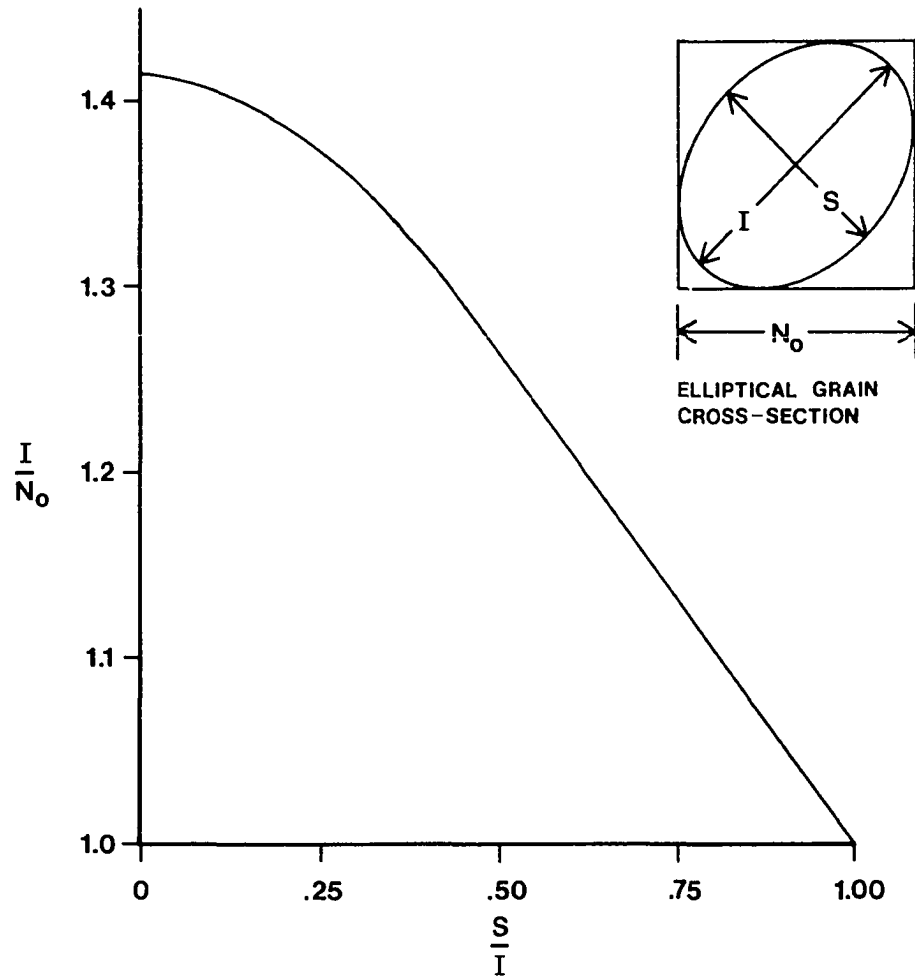


FIG. 3 – Relationship between the grain flatness index (S/I) and the magnitude of the sizing error for square-holed sieves.

of the sieve on which a grain with dimension I should ideally be caught (i.e., $I \geq N_0$), then sufficiently platy grains with an I/N_0 ratio greater than 1.19 can accumulate on the next sieve below, and those with an I/N_0 ratio between 1 and 1.19 can accumulate on the second sieve below the one on which they should have been caught. For grains of elliptical cross-section in the plane of the sieve and an I/N_0 ratio greater than 1, the flatness index (S/I) must be less than 0.84 in order for the grains to pass through the sieve on which they would ideally be caught. Unfortunately, grains with S/I ratios less than 0.84 are common in natural sands. Deducing the magnitude and character of the sizing error for the so-called square-holed sieves is made more difficult by the fact that most sieve apertures are actually slightly rectangular (Ludwick and Henderson, 1968).

Another source of inaccuracy when sizing with sieves is the variation in the nominal sieve opening introduced by the manufacturing process. Because the sieves are woven-wire screens it is inevitable that there will be a range of dimensions for the openings in a given sieve and that the average dimension of the openings will not correspond exactly to the size of the nominal opening for the sieve. The most accurate sieves are those which comply with the ASTM Standard E11-70 (ASTM, 1977a). The permissible variation under this standard for the average and maximum sieve openings is given in Table 2. It is interesting to note in this table that the average nominal sieve openings do not correspond exactly with the boundaries of the quarter phi Udden-Wentworth sand size classes, and that the difference in the

TABLE 2
 UDDEN-WENTWORTH GRAIN SIZE SCALE AND PERMISSIBLE VARIATION IN THE
 OPENINGS OF THE U.S.A. STANDARD SERIES SIEVES

Udden-Wentworth ¹ Grain Size Scale						U.S.A. Standard Series Sieves ²			
Sand Size Class	Code for ¼ Phi Size Class	Size Class Boundaries		Nominal Sieve Opening		Difference in Size of Opening for Adjacent Sieves (phi)	Permissible Variation Relative to the Nominal Sieve Opening (ASTM Standard E11-70)		
		mm	phi	mm	phi		Average Size of Openings (±)	Maximum Size of Openings (+)	Maximum Size for Not More than 5 of Openings (+)
granules		2.0000	-1.00	2.000	-1.000		3.5	10.8	6.8
	VC1					0.234			
very		1.6818	-0.75	1.700	-0.766		3.5	11.2	7.1
	VC2					0.280			
coarse		1.4142	-0.50	1.400	-0.485		3.6	11.8	7.5
	VC3					0.247			
sand		1.1892	-0.25	1.180	-0.239		3.8	12.7	7.6
	VC4					0.239			
—		1.0000	0	1.000	0		4.0	13.5	8.0
	C1					0.234			
coarse		0.8409	0.25	0.850	0.234		4.1	14.1	8.8
	C2					0.260			
sand		0.7071	0.50	0.710	0.494		4.2	14.8	9.2
	C3					0.243			
		0.5946	0.75	0.600	0.737		4.2	15.8	10.0
	C4					0.263			

TABLE 2 (continued)

		0.5000	1.00	0.500	1.000		4.0	17.0	10.0
	M1					0.234			
		0.4204	1.25	0.425	1.234		4.5	18.1	10.8
	M2					0.260			
medium		0.3536	1.50	0.355	1.494		4.5	19.7	11.5
	M3					0.243			
sand		0.2973	1.75	0.300	1.737		4.7	21.0	12.3
—	M4					0.263			
		0.2500	2.00	0.250	2.000		4.8	22.4	13.2
	F1					0.238			
		0.2102	2.25	0.212	2.238		4.7	24.1	14.2
	F2					0.236			
fine		0.1768	2.50	0.180	2.474		5.0	26.1	15.0
	F3					0.263			
sand		0.1487	2.75	0.150	2.737		5.3	28.0	16.0
—	F4					0.263			
		0.1250	3.00	0.125	3.000		5.6	30.4	17.6
	VF1					0.238			
very		0.1051	3.25	0.106	3.238		5.7	33.0	18.9
	VF2					0.236			
fine		0.0884	3.50	0.090	3.474		5.6	35.6	20.0
	VF3					0.263			
sand		0.0743	3.75	0.075	3.737		6.7	37.3	21.3
—	VF4					0.263			
silt		0.0625	4.00	0.063	4.000		6.3	41.3	22.2

¹From Folk (1980, p. 23).

²Based on information in Table 1 of ASTM (1977a).

nominal openings for adjacent sieves is not constant when measured in phi units. It must be kept in mind that Table 2 reports only the inherent inaccuracy of the sieves at the time of manufacture, and that with use the size distribution of the sieve openings will change unpredictably. One aspect of the size distribution of the sieve openings which is especially worrisome is the presence of 'over-sized' openings (i.e., openings substantially larger than the nominal opening).

The net effect of the presence of over-sized sieve openings and the diagonal passage of grains through the openings is that within a given sieve fraction: 1) the grain size distribution is skewed towards the coarser sizes, and 2) the coarser grains tend to be more platy and the finer grains, more equidimensional. It is clear then that the simple-minded interpretation of sieving results strictly in terms of intermediate grain dimensions is unwarranted. Ludwick and Henderson (1968, p. 233) were being perhaps overly cynical when they said that the "accurate estimation of [a] particle-size frequency distribution by sieving requires that [the] particle-shape frequency distribution be known."

There are other sources of error in sieving that can be largely controlled by the investigator (Müller, 1967, p. 75; Ludwick and Henderson, 1968; and Ingram, 1971, p. 64): 1) overloading (too much sediment on a sieve inhibits the sizing processes), 2) oversieving (the longer the sieving duration the more likely grains will pass through over-sized openings or diagonally through nominal-sized openings), 3) hygroscopicity (humid air causes the smaller grains to adhere to the sieve

surfaces), 4) electrostaticity (electrostatic charges cause the smaller grains to adhere to the sieve surfaces), and 5) the method employed to shake the sieves ('Ro-Tap' sieve shakers do a better job of sizing than vibratory sieve shakers).

Even though sizing with square-holed woven-wire sieves may involve significant measurement error, it is the only batch process that is both financially feasible and capable of sizing sand grains, to a reasonable first approximation, by their intermediate dimensions.

Procedure

Sediment from the unconsolidated sand and disaggregated sandstone samples was sieved using a set of twenty-one square-holed, woven-wire three-inch diameter U.S. Standard Series sieves. The sieve interval was constant throughout the sand size range and corresponded to a quarter phi increment in the size of the nominal opening for adjacent sieves (see Table 2). The smaller diameter sieves were used instead of the more traditional 8 inch sieves because of the small sample sizes: 8 to 25 grams. The sieves were new and were manufactured by the Dual Manufacturing Company (Chicago, Illinois) in conformance with the ASTM Standard E11-70 (ASTM, 1977a). Using a binocular microscope equipped with an ocular micrometer, each sieve was checked for obvious defects and conformance with the ASTM standard. Approximately 100 openings were randomly selected and measured on each sieve. All sieves were found to be within the limits of permissible variation (see Table 2).

According to McManus (1965) the optimal sieving time for 3 inch sieves is 10 minutes when a Ro-Tap sieve shaker is used and the maximum sediment load is 5 grains per sieve opening. When translated into weight, the maximum sediment load varies from about 18 grams for a sieve with a 2.000 millimeter nominal opening to about 0.7 grams for a sieve with a 0.0625 millimeter nominal opening. The 10 minute sieving time is said to be optimal because it minimizes the sum of the inaccuracies caused by the finer grains ($I < N_0$) not passing through a sieve and by the coarser grains ($I > N_0$) passing through over-sized openings or diagonally through nominal openings. A Ro-Tap sieve shaker which would accomodate 3 inch sieves was not available. The following alternative procedure was thus adopted in this study with McManus' recommendations in mind. The entire sediment sample was poured into a nest of sieves having a quarter phi interval. The sieves were then placed on a small vibratory ('throw') sieve shaker for 10 minutes (the sieve shaker was manufactured by Sepor Laboratory Supply in Wilmington, California and is pictured along with the sieves in Plate 2). In contrast to a Ro-Tap sieve shaker, the vibratory variety is notoriously inefficient and inaccurate (Müller, 1967, p. 69). The up-and-down motion of the vibratory sieve shakers causes sediment to pile up around the outer edges of the sieve screen and thus overloads this portion of the sieve surface. The vibratory sieve shaker was used in this study only to obtain a first 'rough split'. Additional sieving, this time by hand, was necessary. The sediment fraction caught on each sieve, after sizing with the vibratory sieve shaker, was split up into

subfractions weighing no more than about 1 gram. Each of these subfractions was then sieved by hand for 5 minutes. The hand sieving technique closely resembled the actions of a Ro-Tap sieve shaker: a circular swishing motion with frequent light taps was employed. Hand sieving each sample required from 45 to 75 minutes. After sieving, the quarter phi size fractions were weighed to the nearest one-thousandth gram. The raw data for the sieve analyses are tabulated in Appendix B.

Size Statistics

Moment and graphical versions of the following four grain size statistics were computed for each sample (Appendix C): mean (the average grain size), standard deviation or sorting (the spread of the size distribution about the mean), skewness (the asymmetry of the size distribution about the mean), and kurtosis (the relative spread of the central and outer portions of the size distribution about the mean; or, for nearly symmetrical distributions, the 'peakedness' of the size distribution). These statistics were calculated using grain size expressed in phi units. For grain sizes expressed in phi (d_ϕ) and millimeter (d_{mm}) units, the following relations hold: $d_\phi = -\log_2 d_{mm}$; $d_\phi = -(\log_{10} d_{mm})/(\log_{10} 2)$; and $d_{mm} = 2$ to the $-d_\phi$ power (Krumbein and Pettijohn, 1938, p. 85). In order for grain size statistics to be strictly valid it is necessary that the sieve fractions represent contiguous and mutually exclusive size classes. Because of the inherent

inaccuracies of sieves these ideal conditions are never met. It will be assumed in this study, however, that the necessary conditions are approximately met and that the statistics are sufficiently robust to give a meaningful description of the grain size distributions.

Many formulas have been proposed for the four graphical statistics (for a review see McCammon, 1962; and Folk, 1966). However, only the formulations of Folk and Ward (1957) have met with widespread acceptance: Graphic Mean, Inclusive Graphic Standard Deviation, Inclusive Graphic Skewness and Graphic Kurtosis (Table 3, part II). These graphical statistics have been adopted in the present study. Preparatory to the calculation of these statistics a cumulative frequency curve with an arithmetic abscissa and a probability ordinate was drawn for each sample using the raw data in Appendix B. The plot points for each sieve fraction were located on the 'fine side boundary' (i.e., the lower limiting size) of each quarter phi size class and were joined by straight lines to form a linear-segmented curve. The use of straight-line segments is not intended to imply that a sediment is log-normally distributed between size classes. It was felt that the linear-segmented curve provided a sufficiently accurate representation of a size distribution to justify the convenience of its use. The plotted cumulative grain size curves are illustrated in Appendix E.

The four moment statistics computed in this study (Table 3, part IB; McBride, 1971) do a better job of describing a grain size distribution than do the graphical statistics. Moment statistics utilize information from the entire distribution rather than just portions

TABLE 3
CALCULATION FORMULAS FOR MOMENT AND
GRAPHICAL STATISTICS

I. Moment Statistics

A. For 'Ungrouped' Data¹

$$\text{Mean} = \frac{\sum X_i}{n} = \bar{X}$$

$$\begin{aligned}\text{Standard Deviation} &= \sqrt{\frac{\sum (X_i - \bar{X})^2}{n - 1}} = S \\ &= \sqrt{\frac{\sum X_i^2 - \bar{X}^2}{n - 1}}\end{aligned}$$

where n = the total number of observations
 X_i = one of the n individual observations
 Σ = indicates the summation of a quantity for all n observations

$$\text{Coefficient of Variation} = \frac{S}{\bar{X}} \cdot 100$$

B. For 'Grouped' Data¹

$$\text{Mean} = \frac{\sum (f \cdot m)}{100} = \bar{X}$$

$$\begin{aligned}\text{Standard Deviation} &= \sqrt{\frac{\sum (f \cdot [m - \bar{X}]^2)}{100}} = S \\ &= \sqrt{\frac{\sum (f \cdot m^2)}{100} - \bar{X}^2}\end{aligned}$$

$$\text{Skewness} = \frac{\sum (f \cdot [m - \bar{X}]^3)}{100 \cdot S^3} = SK$$

$$\begin{aligned}&= \frac{\frac{\sum (f \cdot m^3)}{100} - 3 \cdot \bar{M} \cdot \frac{\sum (f \cdot m^2)}{100} + 2 \cdot \bar{X}^2}{S^3}\end{aligned}$$

TABLE 3 (continued)

$$\text{Kurtosis} = \frac{\sum(f \cdot [m - \bar{X}]^4)}{100 \cdot S^4}$$

$$= \frac{\frac{\sum(f \cdot m^4)}{100} - 4 \cdot M \cdot \frac{\sum(f \cdot m^3)}{100} + 6 \cdot \bar{X}^2 \cdot \frac{\sum(f \cdot m^2)}{100} - 3 \cdot \bar{X}^4}{S^4}$$

where m = the midpoint (in phi units) of a size class
 f = the weight percent or frequency ($0 \leq f \leq 100$)
for a size class
 Σ = indicates the summation of a quantity for
all size classes

II. Graphical Statistics²

$$\text{Graphic Mean} = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} = M_G$$

$$\text{Inclusive Graphic Standard Deviation} = \frac{(\phi_{84} - \phi_{16})}{4} + \frac{(\phi_{95} - \phi_5)}{6.6} = S_{IG}$$

$$\text{Inclusive Graphic Skewness} = \frac{(\phi_{16} + \phi_{84} - 2 \cdot \phi_{50})}{2 \cdot (\phi_{84} - \phi_{16})} + \frac{(\phi_5 + \phi_{95} - 2 \cdot \phi_{50})}{2 \cdot (\phi_{95} - \phi_5)}$$

$$= SK_{IG}$$

$$\text{Graphic Kurtosis} = \frac{(\phi_{95} - \phi_5)}{2.44 \cdot (\phi_{75} - \phi_{25})} = K_G$$

where ϕ_i = the size (in phi units) corresponding to
the i^{th} percentile of a cumulative grain
size curve.

¹Croxtan (1953, p. 82-106) and McBride (1971)

²Folk and Ward (1957) and McBride (1971)

of it as is the case with the percentiles used in graphical statistics. Moment statistics are superior in all cases except when the distribution is 'open-ended' (i.e., contains a 'pan fraction'). In order to calculate the moment statistics for open-ended distributions it is necessary to estimate the modal grain size of the pan fraction. When the weight percent of the pan fraction is greater than a few percent and the assumed modal size of the pan fraction is wrong, substantial computational errors can occur for the moment statistics, especially skewness and kurtosis (McBride, 1971, p. 118; and Folk, 1980, p. 46). Of the 28 samples analyzed in this study only 8 have pan fractions exceeding 1 weight percent of the sediment. Among these 8 samples the largest pan fraction (sample AR1-14) amounts to only 3.46 weight percent and the other 7 are all below 2.4 weight percent.

For lognormal grain size distributions the graphical statistics, with the exception of graphic kurtosis, give results which are identical to those of the corresponding moment statistics. The moment and graphical kurtosis equal 3 and 1, respectively, for this type of distribution. For non-lognormal (i.e., natural) grain size distributions the means and standard deviations for the moment and graphical statistics are generally very close but the corresponding values for skewness and especially kurtosis are generally quite different (Friedman, 1962a; Davies and Ehrlich, 1970; and Appendix C of the present study). The usually great discrepancy between the moment and graphical skewness and kurtosis is explained by the fact that, unlike the mean and standard deviation, these two statistics are heavily influenced by the outer

portions (i.e., the 'tails') of a distribution. Because moment statistics take into account all the information in the tails whereas graphical statistics either ignore the tails altogether or at best characterize them with a couple of percentiles, there is often a substantial difference between computed values for the two types of statistics.

Measurement Of The Smallest Grain Dimension (Roller Micrometer Analysis)

Introduction

It has long been recognized that rectangular-holed (i.e., 'slotted') sieves size grains by their smallest principal dimension (Coghill et al., 1928; Marwick, 1937; Lacabanne and Thiel, 1950; Lees, 1964a; Matschinski, 1964; and Ludwick, 1971). The only requirement is that the long side of the rectangular slot have a dimension several times greater than that of the short side. The slot length must be at least as long as the largest intermediate dimension of any grain with a smallest dimension less than the slot width. If this condition is met, the largest and intermediate principal dimensions of a grain will have no effect on the sizing process. For example, in order for grains with a S/I ratio greater than 0.10 to pass through a nest of slotted sieves uninhibited by the slot length, the slot length to width ratio must be at least 10. The slot length to width ratios for the three commercially available slotted sieves used by Ludwick (1971) had values of 5.4, 6.9 and 10.1.

There are two problems associated with the use of slotted sieves for the measurement of the smallest principal grain dimension. First, woven-wire and perforated slotted sieves probably have a greater inherent inaccuracy than the woven-wire square-holed sieves. Unlike for the square-holed sieves, there is no rigid ASTM Standard for slotted sieves which specifies the maximum permissible variation in the slot width. Second, and more serious, slotted sieves are not commercially available in the quarter phi U.S. Standard Series that sedimentary petrologists are accustomed to using. The only manufacturer of slotted sieves in North America is apparently the Buckbee-Mers Company of Saint Paul, Minnesota. This company will custom-make highly accurate 3 and 8 inch diameter electroformed rectangular-holed sieves. The cost is the same as for the round-holed sieves which they also manufacture: \$2000 for each sieve 'master'; and \$100 and \$300, respectively, for each 3 and 8 inch sieve made from a master. The cost of these sieves is clearly prohibitive.

The Roller Micrometer

Principle

As an alternative to slotted sieves, Perry (1949) developed a new batch process device for sizing granule- and pebble-sized sapphire crystals according to their smallest principal dimension. The device consisted of two laterally-adjacent, parallel cylindrical rollers which

were revolving in opposite directions (i.e., the rollers rotated up and away from the intervening slot). The slot width could be varied by setting the spacing between the rollers with a thickness gauge. The two rollers were inclined and the sapphire crystals were fed into the elevated end of the slot. The slot slope and the turning motion of the roller caused the crystals to ride smoothly down the slot with each crystal turning over until it presented its smallest dimension to the slot. If this dimension was less than the slot width, the crystal passed through the slot into a collection bin below. Those crystals having S dimensions larger than the slot width continued down the slot and were discharged at the lower end into a second collection bin. Perry did not name his device and so in the present study it will be referred to as a 'roller micrometer'.

The sizing action of a roller micrometer is identical to that of a slotted sieve, but roller micrometers need not have the sizing error associated with sieves. Because the slot between the rollers is very long and the inter-roller spacing can be exactly set, a roller micrometer can accurately size particles by their smallest principal dimension. Although roller micrometers similar to the one described by Perry (1949) have been used in industry to size seed, lead shot, bottle cap inserts and pills, they have apparently never been used to analyze sediment grain size or shape distributions. Roller micrometers are apparently not commercially available today; where they are in use, they had to be custom-built by the user.

Design and operation

1) Overview

The roller micrometer which was built by the author for this study is illustrated in Figures 4 and 5, and Plates 2 through 6. Its general design is similar to that for the device described by Perry (1949) but its design details are substantially different. The roller micrometer used in the present study is powered by a 30 rpm, 1/10 hp electric motor. Only one of the two rollers is movable or mobile; the other is permanently fixed in its position. Using a micrometer head, the mobile roller can be moved backwards in the pillow block slide tracks to obtain the desired slot width. The slot widths used corresponded to the quarter phi size class boundaries of the Udden-Wentworth grain size scale. The two rollers are turned in opposite directions through the use of spur gears. The spur gear and roller shafts are connected by a sprocket-and-chain drive. Because the sprockets on the 30 rpm spur gear shafts have a diameter 1.21 times larger than that of the sprockets on the roller shafts, the rollers revolve at 36.3 rpm. Located on the spur gear shaft closest to the mobile roller is a variable-pitch pulley sheave. As the slot width is increased the sheave pitch is decreased (i.e., the pulley groove is narrowed) in order to keep the drive chain taut. An idler pulley (i.e., a fixed-pitch pulley sheave) on the drive chain for the fixed roller serves a similar purpose by taking the slack out of the chain. The motor, fixed roller, mobile roller pillow block slide tracks, and

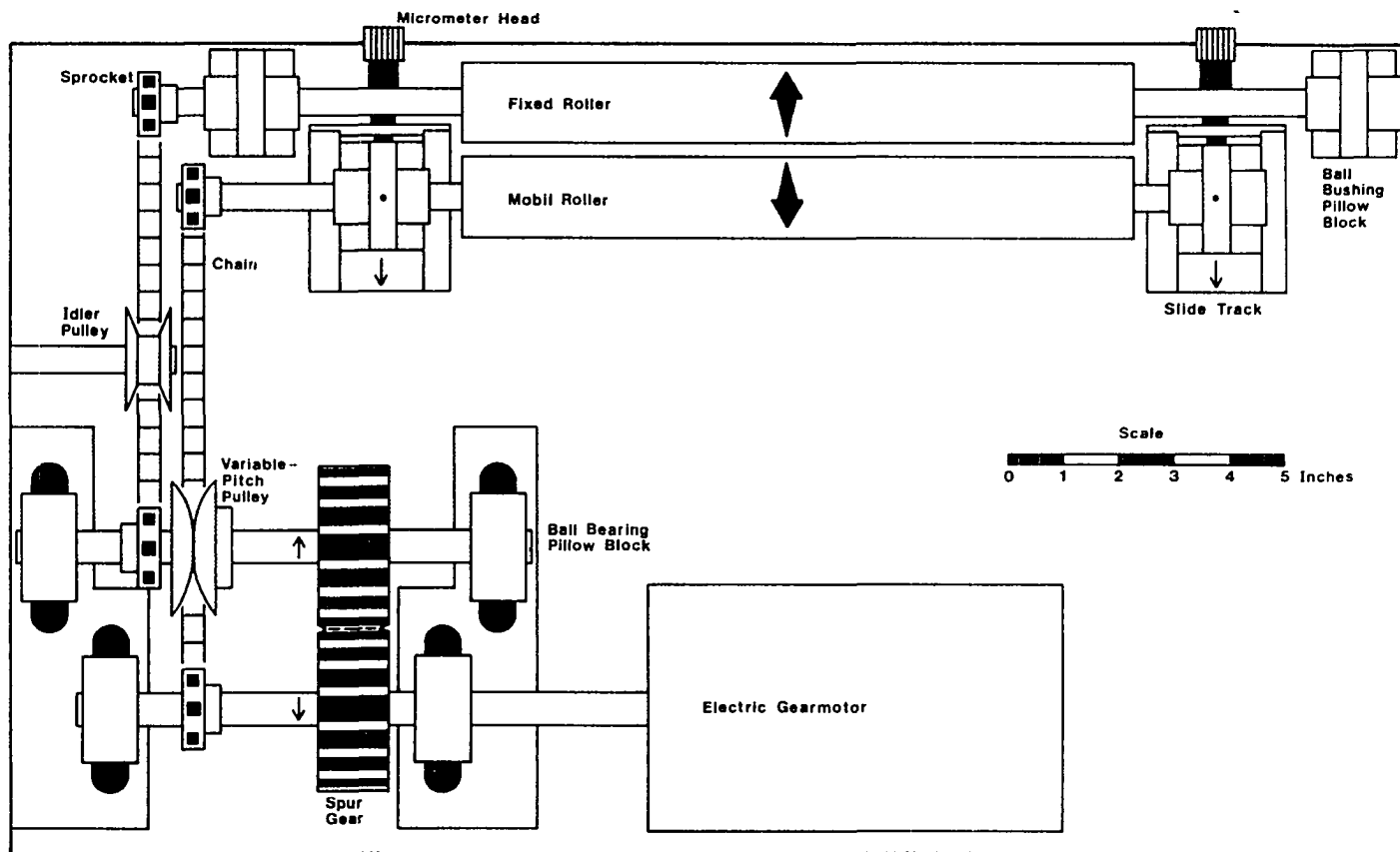


FIG. 4 - Schematic illustration of the roller micrometer.

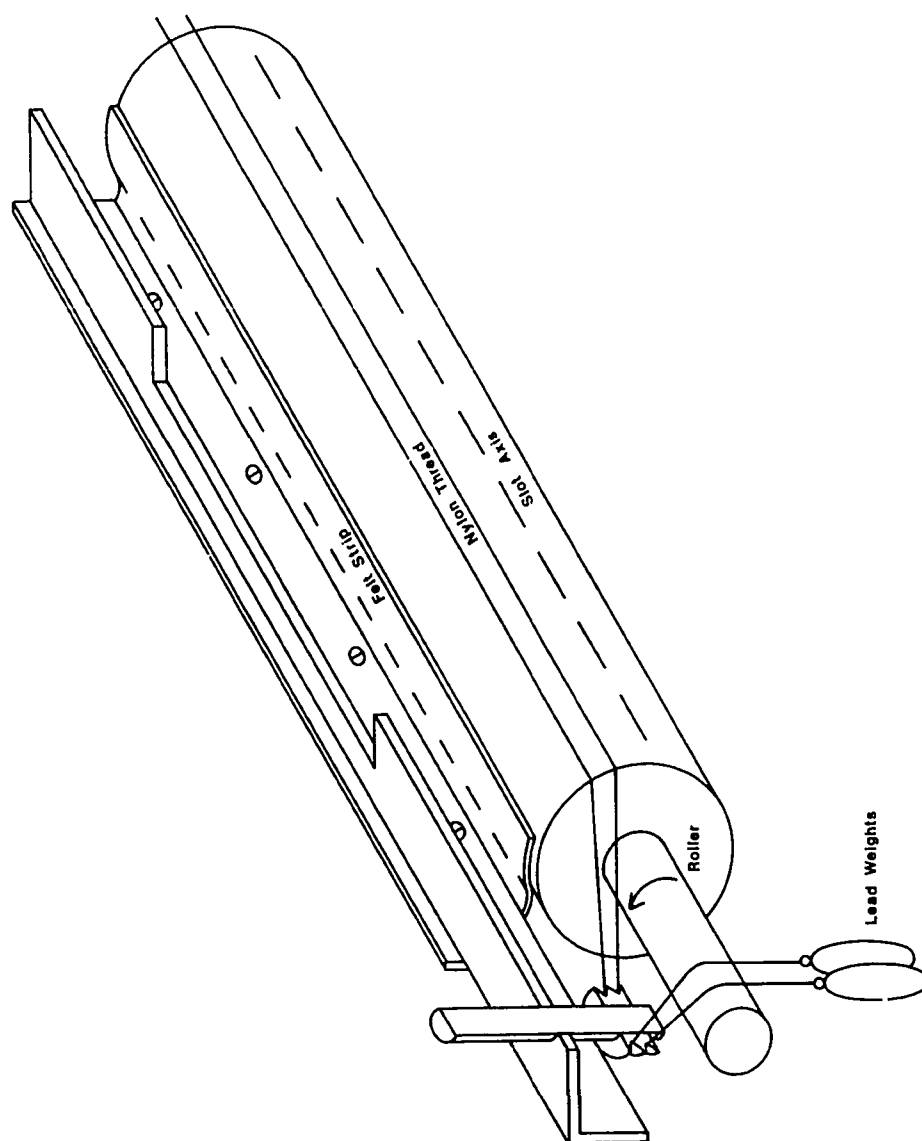


FIG. 5 – Schematic illustration of the roller micrometer grain guard (interior view).

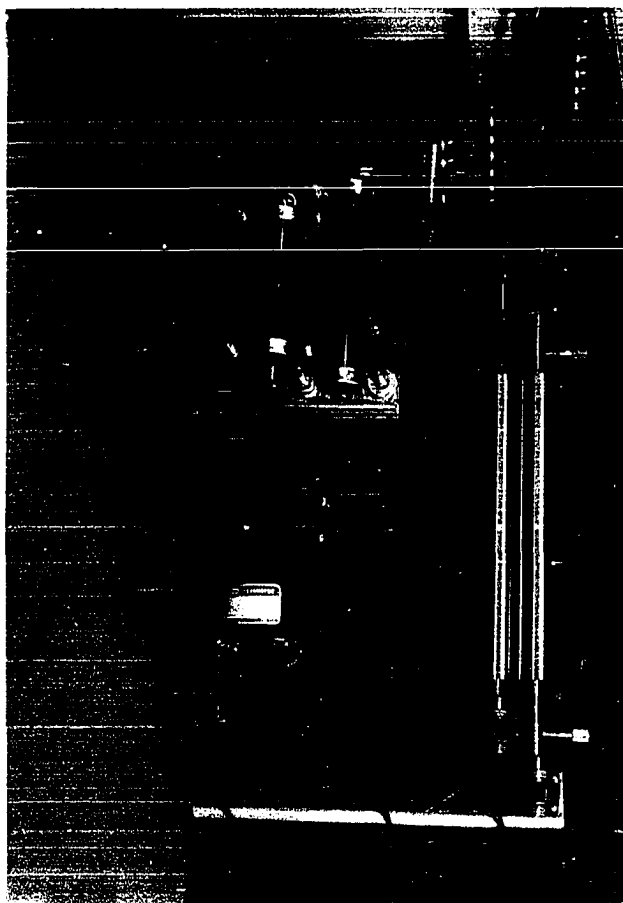


Plate 2 – Top view of the roller micrometer.

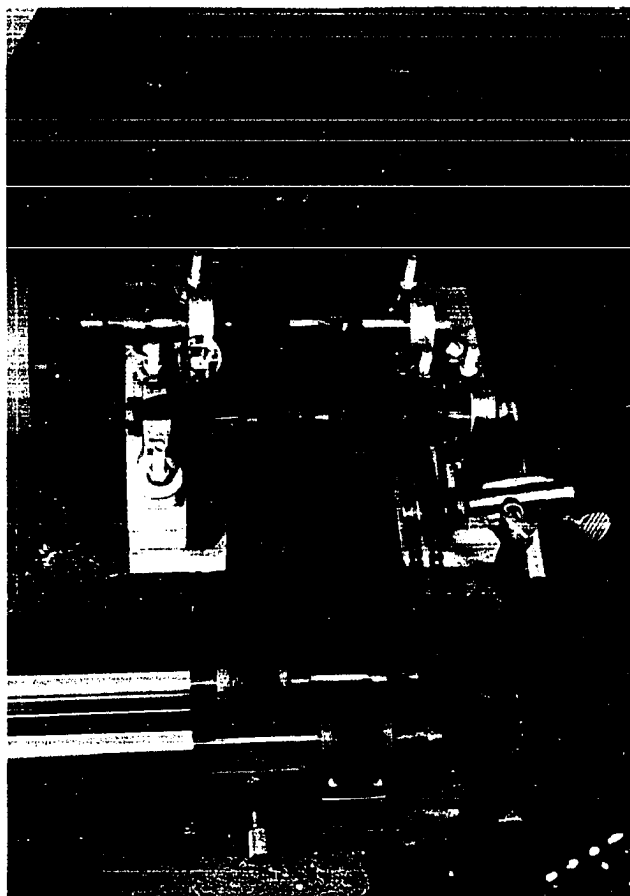


Plate 3 — Close-up view of the roller micro-meter's motor drive assembly.



Plate 4 – Oblique top view of the roller micrometer showing the collection cups, grain-guard, and feed chute set-up for a 9 inch slot length.

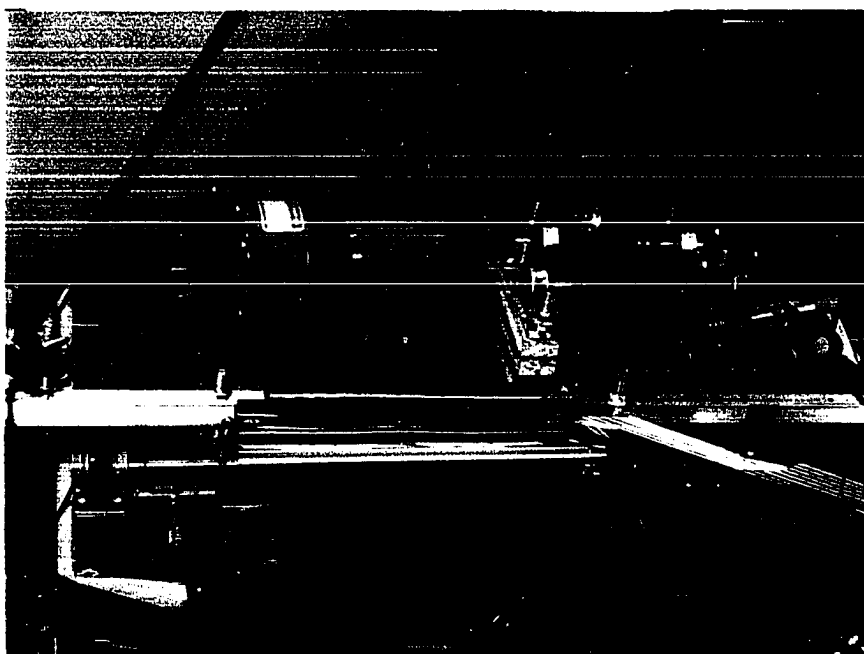


Plate 5 – Oblique front view of the roller micrometer showing the collection cups, grain-guard, and feed chute set-up for a 9 inch slot length.

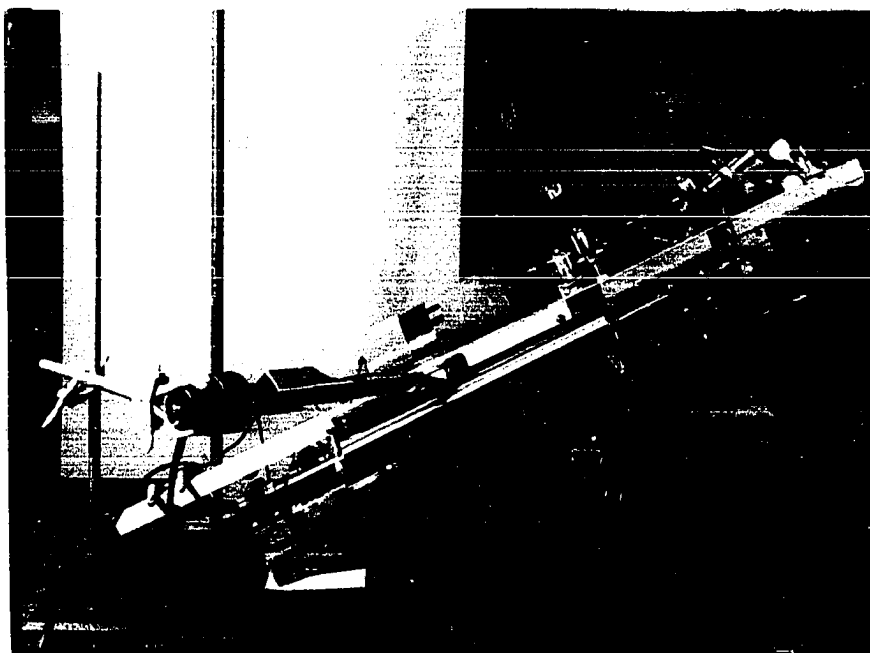


Plate 6 – Front view of the roller micrometer showing the collection cups, grain-guard, and feed chute set-up for a 4 inch slot length.

drive shaft foundations are bolted to a $1\frac{1}{2}$ inch thick steatite slab. Visible in the plates but not illustrated in Figure 4 is a non-functional ornament (the object topped with a clear glass knob). The ornament is located on the drive shaft foundation near the spur gear closest to the mobile roller. During operation, collection cups are placed under the rollers, a 'grain-guard' is placed on top of the rollers, and the whole assembly is tilted. Grains are added to the upper, elevated end of the slot through a 'feed chute'. Grains having dimensions less than the slot width fall through the slot into the long collection cup. Thicker grains continue on to the lower end of the slot where they spill into the short collection cup. The grain-guard catches grains adhering to the roller surface and so prevents them from being thrown out of the slot or crushed when approaching the slot from below.

There are really only six 'critical' aspects to the roller micro-meter design: (1) the roller axis must be straight, (2) the roller diameter must be constant along the length of the axis and radially around the axis, (3) the two rollers must be parallel to one another (i.e., the slot width must be constant), (4) the sediment grains should proceed down the slot in more-or-less single file (i.e., sediment in the slot should be about one grain deep), (5) the turning of the rollers should be slow enough that grains will not be lifted out of the slot (the accuracy of the sizing process decreases with increasing roller speed), and (6) the rollers must be long enough to allow sufficient travel time for sizing of the grains to occur.

2) Roller specifications

a) Straightness, Circularity and Material

The rollers were precision ground by the Cincinnati Milacron Company (Cincinnati, Ohio) from hardened 60 case stainless steel bar stock. The scratch hardness of the rollers exceeds that for quartz. The axis of both rollers deviates from a straight line by no more than 0.0001 inches (2.54 microns) along the entire length. For both rollers, the circularity (i.e., the variation in the diameter radially around the axis) does not vary by more than 0.001 inches at any point along the length.

b) Diameter

Both rollers should have similar diameters. The larger the diameter of the rollers, the more nearly vertical the L•I axial plane of a grain within the slot and thus the more readily a grain will present its S dimension to the slot. It was observed during the analyses that grains tended to orient themselves with their longest dimension parallel to the roller axis. According to Perry (1949), the minimum practical diameter for the rollers is about six times the I dimension of the largest grain being sized. The greater the roller/grain diameter ratio the more effective the sizing process. In the present study, the ratio of the roller diameter (1.5 inches or 38.1 mm) to the maximum intermediate grain dimension (about 2 mm) is 19.

c) Length

Perry (1949) recommends that the length of the rollers should be at least 4 to 8 times the roller diameter when grains proceed down

the slot in a single file. Such a length should allow ample time for the sizing action to occur. In the present study the length (12 inches, not including the shafts at each end) to diameter (1.5 inches) ratio was 8. It was observed that grains were completely sized after only a couple of inches of travel down the slot. This is a distance amounting to about 1/6 of the roller length. The rollers should only be long enough to allow complete sizing to occur. Longer rollers are undesirable for two reasons. First, the longer the roller, the more difficult and expensive it is to machine it to the desired straightness. Second, the longer the roller, the more likely it is to warp under its own weight.

3) Slot slope

Because grains must move down the slot in single file it takes longer, for a given slot slope, to size smaller grains than it does an equal weight of larger grains. Any slope will move grains down the slot from one end of the rollers to the other, but adjustment of the slope to regulate the roller capacity (i.e., the number of grains sized per unit of time) is necessary when dealing with a wide range of grain sizes. Perry (1949) varied the slot slope between 20 and 35 degrees, and recommended 25 degrees as a good starting value. In the present study the slot slope was varied with the slot width (i.e., the narrower the width, the steeper the slope): for slot widths 0.420 mm and wider, slope = 7 degrees; for slot widths 0.354 to 0.250 mm, slope = 14 degrees; and for slot widths 0.210 mm and narrower, slope = 28 degrees. Even with the

increase in slope, the sizing time for the finer sediment was almost prohibitively long: about 1 minute per 1 gram of sand for the 0.50-0.75 phi sieve fraction and a slot width of 1.00 phi; and about 15 minutes per 1 gram of sand for the 1.5-1.75 phi sieve fraction and a slot width of 2.00 phi.

4) Roller speed

The roller speed should be kept as low as possible while still being sufficient to cause grains within the slot to turn over until they present their thin edge to the opening. Too high a roller speed would prevent close-fitting grains (i.e., grains with the S dimension slightly less than the slot width) from dropping through the slot and it would also cause the finer grains in frictional contact with the rollers to be lifted out of the slot and carried away on the rising roller surface. The optimal relation between roller speed and grain size has not yet been worked out, but it is clear that the finer the grains being sized, the lower the roller speed should be. Perry (1949) used a constant roller speed of 60 rpm, and in the present study, a constant speed of 36 rpm was used. It was later realized after the analyses that 36 rpm was too high a speed for the fine and very fine sand fractions (see the discussion on 'design flaws').

5) Sediment feed

The sediment to be sized was first poured into an aluminum feed chute (Plates 4, 5 and 6). Attached to the chute was a vibration generating device. The sediment was next fed into the elevated end of

the roller slot in a more-or-less continuous stream. The feed rate was adjustable through a rheostat (visible in Plates 4 and 6) which controlled the vibration intensity of the feed chute. It was necessary for the operator to continuously monitor the movement of the grains down the slot. By constant adjustment of the chute vibration intensity it was possible to maintain a steady stream of sediment into the slot and a single file migration of grains down the slot. Occasionally, the sediment would surge out of the feed chute, causing a piling-up of grains in the upper end of the slot. When this happened the feed was briefly stopped, and, as the sediment gained forward momentum, the grains quickly broke out of the pile and organized themselves into a single file.

6) Grain guard

One particularly acute problem encountered during the analyses was the tendency of grains, especially those finer than medium sand, to adhere to the roller surface. The adhering grains were lifted up out of the slot and were either thrown off or, if they continued to adhere, were crushed when the revolving rollers brought them back into the slot from below. There are three factors which might cause grains to stick to the roller surfaces: friction, electrostatic charges, and hygroscopic water. Although the roller surfaces are highly polished, there is probably sufficient micro-roughness (and hence, frictional contact) to propel the finest grains upwards and out of the slot. The

importance of friction seems to be discounted, however, by the observation that the grains with the roughest surface texture (frosted grains in samples AD2-1e and 1f) showed no greater tendency to adhere to the rollers than the smoother grains of similar size in other samples. Because both the motor and rollers were electrically grounded, it seems unlikely that electrostatic charges could develop with sufficient strength to cause grains to adhere to the roller surfaces. Probably the principal cause of the problem is hygroscopic water on the roller surfaces. This speculation is supported by the observation that the tendency for grains to adhere could be largely eliminated for a period of a few minutes by simply wiping the roller surface with a cloth moistened with acetone. Apparently the rapid evaporation of the acetone also caused the hygroscopic water to evaporate.

It is, of course, not practical to swab the rollers every few minutes with acetone. Even if it could be done, the tendency for grains to stick to the roller surfaces would not be totally eliminated. Clearly then it is not possible to prevent grain sticking, but it is possible to prevent the grains adhering to the roller surfaces from being thrown off or crushed. Accordingly, a 'grain-guard' was built and placed over the rollers (Figure 5 and Plates 4, 5 and 6). This device presses a felt strip and two taut nylon threads flush against each roller. The threads are kept taut by the lead weights attached to their ends. Most grains adhering to a roller are caught on the first thread. The few that work their way underneath this thread are generally caught on the second thread. Occasionally, grains will get by both threads but

they are always stopped by the final line of defense, the felt strip. Grains caught on the threads can be dislodged and thrown back into the slot by 'plucking' the threads with a dental probe (care should be taken to not lift the threads off the roller surface). Using the same probe, any grains which have collected along the edge of the felt stripes can be scrapped back into the slot.

7) Sizing distance

As was pointed out earlier, grains moving down a slot in single file are completely sized after only a couple of inches of travel. This is certainly true of the coarser sand grains, and for the finer sand grains it seems that the bulk of the sizing is actually accomplished during the first inch of travel. With these considerations in mind, the following two sizing distances (i.e., the distance from the point of sediment input to the lower end of the rollers) were employed in this study: 9 inches for slot widths 2.00 phi (0.250 mm) and wider (Plates 4 and 5); and 4 inches for slot widths narrower than 2 phi (Plate 6; a collection cup, at the lower end of the rollers, narrower than the one shown in the plates was used during the analyses). The sizing distance was decreased for the smaller slot widths in order to reduce the number of grains adhering to the roller surfaces. This approach is justified by two observations. First, the longer the travel distance, the more opportunity grains have to stick. Second, grains seldom adhere to the rollers during the first few inches of travel. The shorter sizing distance markedly improved the operation of the roller micrometer.

for the fine sand grains but for the very fine sand, the widespread adherence of grains to the roller surfaces made the roller micrometer inoperable.

8) Setting the slot width

The separation between the rollers was set using micrometer heads (for slot widths 2.00 phi and wider) and thickness gauges (for slot widths less than 2.00 phi). Perry (1949) used thickness gauges to set the slot widths.

Micrometer heads are mounted on the front of each of the two pillow block slide tracks for the mobile roller (see Plates 2 and 3). The micrometer heads have an extendable shaft on one end that can be set and adjusted by turning a graduated thimble on the other end. The shaft has an extension range between 0 and 12 millimeters, and can be set to within ± 0.0001 inch (± 2.54 microns) of the desired extension. To set the slot width, the set screws in the pillow block slide tracks are loosened and the mobile roller is then pushed up against the fixed roller. The two rollers are pressed tightly together and the micrometer head shafts are extended until they firmly abut against the base of the mobile roller pillow blocks. The two rollers are then released, and the mobile roller is 'pushed' backwards by further extending both micrometer shafts (the thimbles must be turned simultaneously). Once the mobile roller has been pushed back far enough to obtain the desired slot width (check the shaft extension readings on the micrometer heads), the set screws in the pillow block slide tracks are tightened against the pillow block foundations.

When the above procedure was attempted for slot widths narrower than 2.00 phi (0.250 millimeter) considerable difficulty was encountered. The narrower slot widths came late in the roller micrometer analysis. By this time the portions of the pillow block foundations opposite the set screws had become slightly indented. They had originally been perfectly smooth and flat. When tightened against these surfaces, the set screws were slightly deflected by the indentations and as a result, the mobile roller underwent a visually imperceptible but nevertheless damaging shift. The end result was that the slot width could no longer be accurately set to within a few microns. In some cases the shift in the mobile roller amounted to a few tens of microns. Through experimentation it was determined that the narrower slot widths could be accurately set (± 10 microns) using thickness gauges (i.e., metal stripes with a fixed uniform thickness varying by no more than 0.0001 inches).

To set the slot width using thickness gauges, the two rollers were pressed tightly together with a thickness gauge placed between them at each end. The set screws in the pillow block slide tracks were then tightened while pushing the rollers against one another. The chief disadvantage of the thickness gauges was that, unlike the micrometer heads, they did not allow the slot widths to be set exactly to the nominal sieve openings corresponding to the boundaries of the quarter phi size classes. This is because the gauges used come in a limited number of thicknesses: 0.0015 inch (0.0381 millimeter), 0.002 inch (0.0508 millimeter), 0.003 inch (0.0762 millimeter), 0.004

inch (0.1016 millimeter), 0.006 inch (0.1524 millimeter), 0.008 inch (0.2032 millimeter), 0.010 inch (0.2540 millimeter), 0.012 inch (0.3048 millimeter), and 0.015 inch (0.3810 millimeter). By using one gauge or combining two gauges, the slot widths could be set to the following millimeter values (the corresponding nominal sieve openings are given in parentheses): $0.0508 + 0.1524 + 0.00254$ spacing = 0.206 (0.212), $0.0762 + 0.1016 + 0.00254$ spacing = 0.180 (0.177), 0.152 (0.149), and $0.0508 + 0.0762 + 0.00254$ spacing = 0.129 (0.125). When two gauges are combined the aggregate thickness is slightly greater than the sum of the individual thicknesses. The spacing between the two gauges was arbitrarily assumed to be 0.0001 inch or 0.00254 millimeter.

Apart from the measuring device used to set the slot width, the accuracy of the slot width setting is contingent upon two other factors: 1) the amount of play in the mobile and fixed roller pillow blocks, and 2) the amount of play between the pillow block slide track and foundation. To satisfy the first requirement, 'zero-play bushing' pillow blocks were used. These pillow blocks allow a roller to pivot about a point centered on its axis, but prevent the roller from shifting laterally from its pivot point. Satisfying the second requirement was more difficult. The pillow block slide tracks and foundations were constructed from machined tool-steel bar stock. Because this bar stock was machined and not extruded, the edges of the bar were 90 degrees and the opposite surfaces were flat and parallel. The pillow block slide track assembly was constructed then of closely-fitting pieces of bar stock and consequently has no discernable play in it.

9) Motor drive assembly

In the original version of the roller micrometer built for this study, the rollers were turned by the electric motor using a system of pulley sheaves and belts. Both adjustable round- and v-belts were tested. It was found that there were two serious problems with the use of belts. First, the belts tended to slip on the pulley sheaves even after the application of belt dressing. This slippage resulted in an uneven, jerky motion in the rollers. Second, in order to minimize slippage, the belts had to be kept fairly taut and this resulted in a strong backwards pull on the end of the mobile roller nearest the motor. This pull had the potential for overcoming the holding effect of the set screws in the pillow block slide track. If this were to happen, the slot width would of course be altered. Both of these problems were avoided by using sprockets and chains in place of the pulley sheaves and belts.

Cost

A complete list of the roller micrometer components is given in Table 4. Also provided are the 1978-79 prices for these components. If one were to add to the \$475 of actual expenditures the value of the other supplies, parts, equipment and services which were obtained at no cost, the total cost of the roller micrometer in 1978-79 dollars would probably be close to \$1000. Most of the additional expense would be for the precision grinding of the two rollers. The cost of building a roller micrometer seems high but when compared to the cost of a quarter

TABLE 4

COMPONENT AND PRICE LIST FOR THE ROLLER MICROMETER

I. Components Purchased

<u>Items</u>	<u>1978-79 Price¹</u>
1) 2 rough-ground 60 case stainless steel rollers (Thompson brand)	\$158
2) 4 'zero-play' ball bushing pillow blocks (Thompson brand)	\$ 72
3) 2 micrometer heads with .0001 inch graduations (Starrett brand)	\$ 51
4) 1 30 rpm, 1/10 hp electric gearmotor (Dayton brand)	\$ 44
5) 2 1.5 feet bars of ground tool steel flat stock (Brown and Sharpe brand)	\$ 37
6) 2 spur gears (Martin brand)	\$ 22
7) 4 chain sprockets (Browning brand)	\$ 18
8) 4 ball bearing pillow blocks (Dayton brand)	\$ 16
9) 2 sets of thickness gauges (9 leaves per set) (Starrett brand)	\$ 14
10) 4 feet of no. 25 stainless steel chain (Hart brand)	\$ 12
11) 1 variable-pitch pulley sheave and 1 fixed-pitch pulley sheave (Browning brand)	\$ 6
12) miscellaneous (nuts, bolts, washers, short lengths of steel bar stock, and other minor items)	\$ 25
Total Expenditures:	\$475

TABLE 4 (continued)

II. Components Acquired, Equipment Borrowed and Services Obtained at No Cost

- 1) ring stands, clamps, rheostat, and vibrator for the feed chute (borrowed from the Geology Dept.)
- 2) steatite slab (donated by the Geology Dept.)
- 3) precision grinding of the two rollers (the work was done by the Cincinnati Milacron Company during a trial demonstration of a newly developed milling machine)

¹The components were purchased over a two year period spanning 1978 and 1979. The prices have been rounded off to the nearest dollar.

phi set of slotted sieves for the sand size range, it is only 1/2 to 1/3 as expensive. Roller micrometers are apparently not commercially available. They must, therefore, be built by the investigator, and this constitutes the single greatest drawback to their use.

Reproducibility

The results of the reproducibility experiments for the roller micrometer are summarized in Table 5. Although not exhaustive, the experiments do adequately document the strengths and weaknesses of the roller micrometer. The experiments show that the sizing process is highly reproducible when the grains travel down the slot in single file (i.e., 'normal feed') and the slot width is not reset between analyses. At higher feed rates the sizing process is understandably less accurate. If the slot is two or more grains deep, the grains towards the top will have difficulty in working their way down to the slot where they can be sized. The most alarming result of these experiments is the apparent inability to reset the slot to the same width. The fault lies not with the micrometer heads but probably with the design of the pillow block slide track assembly. It seems this assembly was unable to maintain the roller separation set by the micrometer heads. Upon tightening the set screws the mobile roller may have undergone a slight repositioning. It is also possible that the backward pull of the drive chain on the mobile roller may have caused some slight slippage in the slide track nearest the motor.

TABLE 5
RESULTS OF THE ROLLER MICROMETER
REPRODUCIBILITY EXPERIMENTS

Sample	Phi Sieve Fraction ¹	Slot Width (phi)	Slot Width Reset Policy ²	Sediment Feed Rate ³	Number of Runs	Single Analysis	Oversize/Undersize Weight Ratio		
							Multiple Analyses		
							Mean	Standard Deviation	Coefficient of Variation
B2-20	C3	1.00	Not Reset	normal	4		0.8198	0.0013	0.161
			Reset	fast	1	0.8253			
			Reset	normal	1	0.6771			
AD2-1f	M3	2.00	Not Reset	normal	4		2.1330	0.0143	0.671
				fast	1	2.4794			
				very fast	1	2.6822			

¹C3=0.50 to 0.75 phi coarse sand sieve fraction
M3=1.50 to 1.75 phi medium sand sieve fraction

²The slot width was not reset to 1.00 phi for sample B2-20 prior to each of the first five runs. It was reset, however, prior to the sixth run. The slot width was set to 2.00 phi for sample AD2-1f prior to the first run and was not reset prior to the next five runs.

³Normal: the slot was one grain deep with the grains traveling in single file.
Fast: the slot was about two grains deep.
Very Fast: the slot was several grains deep.

⁴Ratio of the weight of sand not passing through the slot to weight of sand passing through the slot.

In all the roller micrometer analyses performed in this study a normal sediment feed rate was used, and the slot width was set once and left unchanged until after all the samples had been processed. Further, the slot widths set with the micrometer heads (2.00 phi and wider) were always checked with the thickness gauges, and the two measuring devices were found in all cases to be in 'good' agreement. From this agreement and the results of the reproducibility experiments, it is concluded that the roller micrometer sizing process is highly precise and reasonably accurate.

Design flaws

The roller micrometer built for this study should be viewed as a primitive prototype. It was the best that could be done given the financial resources and mechanical skills of the builder. The design was sufficiently sound, however, to amply demonstrate the potential usefulness of this approach to sizing sand grains. There are several design flaws that need to be corrected in order to improve the reliability and practicality of the roller micrometer. Each of these flaws is discussed below along with the recommended design changes.

- 1) The use of a single roller speed (36 rpm) probably contributed to the problem of the finer sand grains being carried out of the slot on the rising roller surfaces. The roller speed needs to be adjustable. The smaller the grains being sized, the lower the roller speed should be. It is recommended that the rollers be turned with a variable speed motor having a rpm range of 0 to 30. A rpm higher

than 30 should not be necessary for the coarsest sand grains.

2) The slot slope should be more easily adjustable. In the present device, the desired slope was obtained by piling wood slats and masonry blocks under one end of the steatite foundation. It is recommended that this foundation be elevated instead with a hydraulic or screw jack which will permit a range of slopes between 0 and 45 degrees.

3) The drive chain exerts a backwards pull on the mobile roller. Although it is believed that this pull never caused significant slippage in the pillow block slide track assembly, the potential exists in the present design for accidental widening of the slot width. It is recommended that the motor drive assembly be rebuilt so that the mobile roller is turned either with a spur gear or a drive chain that exerts only a downwards pull.

4) The sediment feed chute requires the constant attention of the operator in order to maintain a constant feed rate. For the 28 samples analyzed in this study the sizing process required a few hundred hours. During an analysis the operator must adjust the vibrator rheostat at least once a minute. The task of the operator is thus extremely tedious and time consuming. What is needed is a self-regulating feed chute that will maintain a constant feed rate and require minimal operator control. Doubtless such a device could be built, but it is not at all clear to the author how this could be done.

5) As previously discussed, the use of set screws to fix the position of the mobile roller made it difficult to set the slot width

accurately. In the pillow block slide track assembly as it now exists, the mobile roller is 'pushed' back by the micrometer heads to the desired slot width. This design feature should be retained but an improved method is needed for locking the mobile roller into place. Perhaps a clamping device built into the walls of the slide track would work well enough. Other design options need to be investigated, however, before an adequate solution to the problem is found.

Concluding Remarks

If the design flaws are corrected, the roller micrometer will be an excellent alternative to slotted sieves for sizing very coarse through medium sand grains by their smallest dimension. The device does seem, however, to be impractical for fine and very fine grained sand. There are two reasons for this. First, the time required to size the sand at normal feed rates is excessive, and second, the widespread adherence of grains to the roller surfaces inhibits the sizing process. While the second problem is potentially solvable, the first is not.

An adjustable roller micrometer should be at least as accurate as a set of electroformed slotted sieves but has the advantages of much lower cost and no limitation on the widths and boundaries of the size classes. The roller micrometer does admittedly have some disadvantages: it must be designed and built whereas the sieves can be purchased ready made; and it takes several times longer than sieves to size equal weights of the same sediment.

Size Distributions Based On The
Intermediate Grain Dimension

Grain Size Statistics

Introduction

The differentiation of depositional environments using textural parameters has been an elusive goal of sedimentologists for many years. Published studies on this subject are legion. A review of the results and problems for many of these studies can be found in Pettijohn et al. (1972, p. 86-88), Reineck and Singh (1973, p. 115-119), Amaral and Pryor (1977), Friedman (1979), Blatt et al. (1980, p. 72-74), Tucker and Vacher (1980), and Sedimentation Seminar (1981). Most of these studies achieved some success by demonstrating that there existed clearly discernable textural differences among the sampled modern depositional environments. There can be no doubt that hydraulic sorting according to grain size does occur. However, when other workers have applied the recommended discriminatory equations or plots to ancient sediments or to the same modern environments but at different localities the results were usually disappointing. Why this general lack of success in environmental discrimination? In the case of the ancient sediments the diagenetic alteration of the original grain size distribution (especially the fine 'tail') is a major factor. For both modern and ancient sediments there are several reasons why no textural 'fingerprinting' of depositional environments should be expected. Most important among these is the effect

of source. The distal source (i.e., the source rock), abrasion history and proximal source (i.e., the last depositional environment the sediment passed through) may all cause excesses or deficiencies in certain size ranges which the final depositional environment is unable to mask through hydraulic sorting. Added to this is the fact that similar erosion, transport and deposition processes may operate in many different environments. Thus hydraulic sorting is not necessarily 'fundamentally' different for each environment. Another complication stems from the way samples have generally been collected in the past. Most samples have contained sediment from numerous laminae and, as a consequence, reflect average hydraulic conditions. Perhaps the examination of individual laminae may lead to the recognition of subtle but meaningful differences between environments.

The grain size statistics which seem best to reflect the hydraulic sorting tendencies of beaches, river channels and eolian dunes (the environments sampled in this study) are the moment mean, standard deviation and skewness (Blatt et al., 1980, p. 72; and Sedimentation Seminar, 1981, Table 1). It is generally believed that kurtosis has no hydraulic significance (Friedman, 1978; and Blatt et al., 1980, p. 53). Except for the fact that eolian sands rarely have a mean grain size coarser than medium sand (Ahlbrandt, 1979), grain size is of little value in discriminating among environments. It simply reflects the general energy level, which has similar wide variation in all three environments. It has been demonstrated with bivariate scatter plots that standard deviation (i.e., sorting) and skewness are by far the two most useful

statistics for environmental discrimination (Friedman, 1979). These parameters may reflect the range and asymmetry, respectively, of the velocity fluctuations in the depositing fluid (Sahu, 1964). Both also may reflect the extent of reworking and winnowing.

Discussion of results

The grain size statistics for the modern and ancient sands analyzed in this study are tabulated in Appendix C and are also shown graphically in Figures 6 and 7. According to conventional wisdom, when beach, river channel and eolian dune sands are compared: the beach and dune sands will both have good sorting with the river sands being less well sorted; the river and dune sands will be positively skewed while the beach sands are negatively skewed; and the dune sands will be finer-grained than the beach sands with the river sands being highly variable in grain size (Reineck and Singh, 1973, p. 119; Friedman, 1978; and Blatt et al., 1980, p. 72-73).

An examination of Figure 6 shows that the above generalizations do not hold for the modern sands. One striking feature of this plot, however, is that all the samples are either 'very well' or 'well' sorted (see Table 8 for definition of the verbal sorting scale). Even the ancient sands in Figure 7 exhibit good sorting. This result would be unexpected for multi-lamina grab samples but not for single lamina samples (Walger, 1962; Seibold, 1963; and Davies and Ehrlich, 1970). The ancient sands are notable for their high positive skewness.

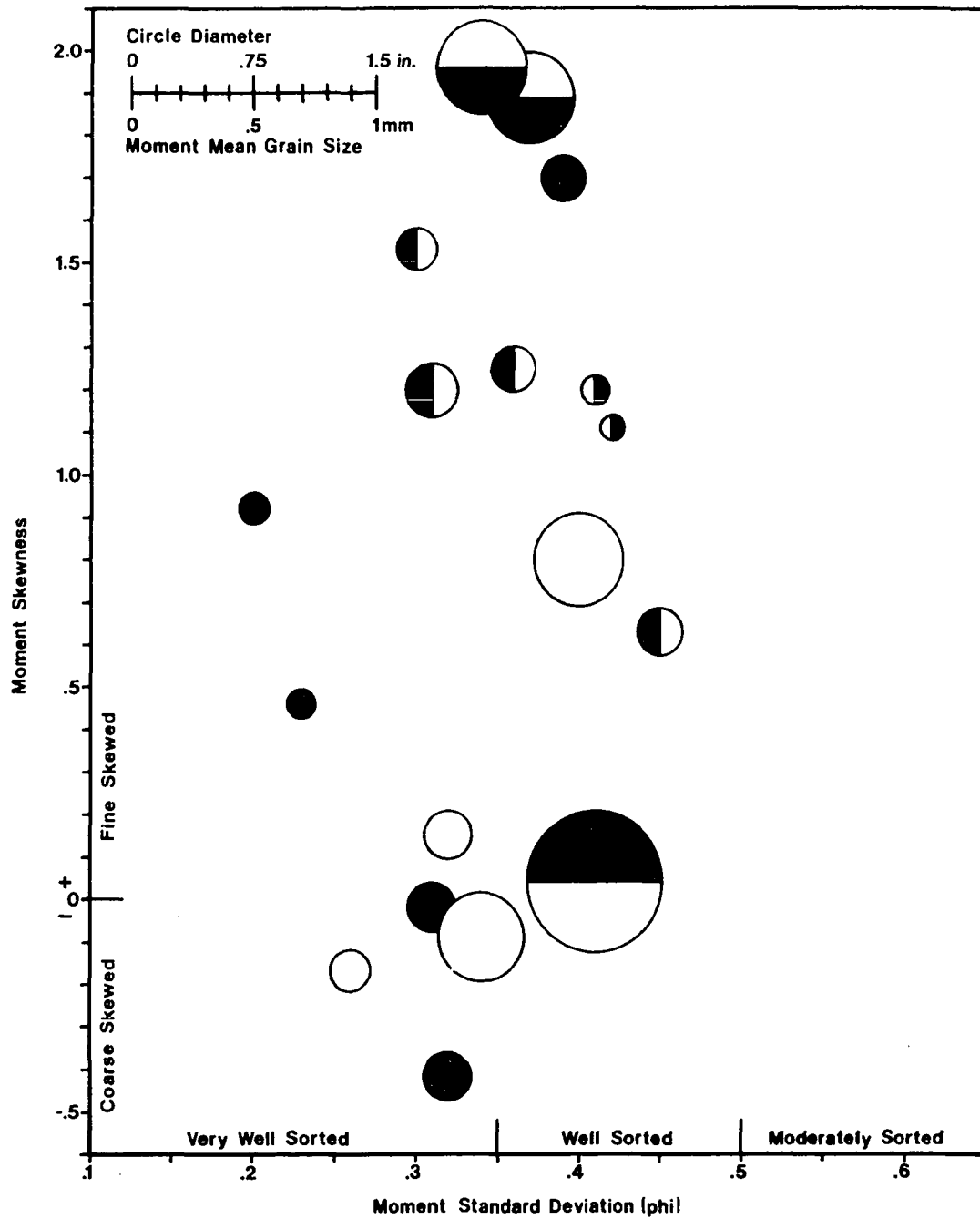


FIG. 6 – Trivariate plot for modern sands: moment mean, standard deviation and skewness (see Figure 7 for definition of plot symbols).

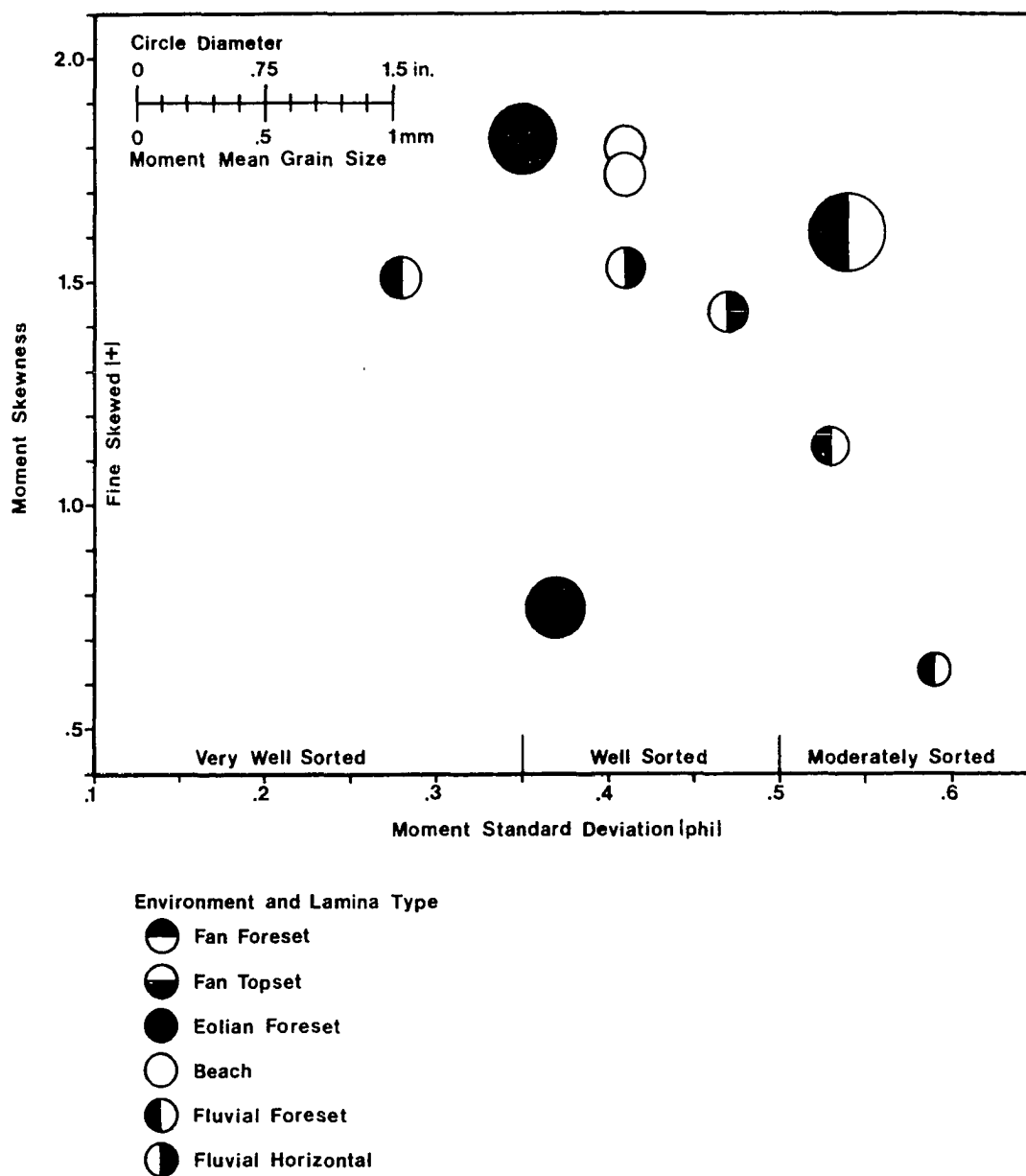


FIG. 7 – Trivariate plot for ancient sandstones: moment mean, standard deviation and skewness.

This characteristic is probably the result of the creation of an artificial fine tail during the disaggregation of these quartz-cemented sands. Appendix C shows that, in terms of moment kurtosis, all samples are leptokurtic (i.e., $K > 3$ and the sample distribution frequency curve is more 'peaked' than the corresponding frequency curve for a lognormal distribution having the same mean and standard deviation). Further, there appears to be no consistent relationship between the kurtosis and depositional environment of the samples. The leptokurtic character of the samples suggests an interesting correlation between kurtosis and individual laminae: it may be the nature of single laminae to be leptokurtic. This would be expected if laminae were deposited by the mechanism proposed by Moss (1962, 1963) and Kunen (1966), the so-called 'like-accepts-like-and-rejects-unlike' hypothesis discussed earlier.

In summary, the grain size statistics for the samples analyzed in this study were found to be of no value in environmental discrimination, but they do show that single laminae consistently have good sorting and a leptokurtic character. A comprehensive summary of the statistical intercorrelations among the textural, packing and pore geometry parameters will be provided in a later section.

The 'Grain Population' Concept

Introduction

When cumulative grain size distributions are plotted on paper with an arithmetic abscissa and probability ordinate the resulting curves commonly show discontinuities separating nearly straight-line segments. Typically up to three such segments are observed. Moss (1962, 1963 and 1972) recognized discontinuities in curves for L versus L/I which corresponded to the discontinuities in the cumulative grain size (I) curves for the same sediment. Visher (1969) popularized the notion that the linear segments on the cumulative curves represent lognormal subpopulations of grains which were sorted and deposited by different mechanisms of sediment transport. It was Visher's interpretation that each depositional environment contains the same grain subpopulations but that each differs in the relative proportions, sorting and size limits of the individual subpopulations. It follows that differentiation among depositional environments may be possible through an analysis of the characteristics of the grain subpopulations.

Theoretical grain populations

Three theoretical grain populations have been proposed for wind- and water-laid deposits. The transport mechanisms and textural characteristics for the three populations are summarized in Table 6. The

TABLE 6

CHARACTERISTICS AND ORIGINS OF THE
THEORETICAL GRAIN POPULATIONSC Population

- 1) Grain size: coarsest of the populations; represents the coarse tail of the distribution.
- 2) Sorting: poorer than A, comparable to or better than B.
- 3) Occurrence: may be absent.
- 4) Transport mechanism: traction/surface creep.

The bed material is transported in traction (i.e., in contact with the bed). Movement of the grains is by rolling and sliding under the influence of fluid drag. Some grains are propelled forward by the impact of salting grains.

- 5) Hydraulic significance:

The maximum grain size is determined by flow competence (or, in some cases, the maximum grain size available in the sediment). The minimum grain size is determined by the intensity of the turbulent eddies impinging on the bed.

- 6) Grain interactions:

The population consists of grains too large to fit into the predominant sediment framework (i.e., the A population), but which come to rest on and are eventually buried by the A population.

A Population

- 1) Grain size: intermediate between C and B; represents the central part of the distribution.
- 2) Sorting: better than C and B.
- 3) Occurrence: always present; constitutes the bulk of the sediment.
- 4) Transport mechanism: saltation/intermittent suspension.

The bed material is transported just above the bed. Movement of the grains is by saltation (grains propelled along a ballistic

TABLE 6 (continued)

path by hydrodynamic lift and fluid drag forces) and intermittent suspension. The two causes of intermittent suspension recognized are: 1) temporary suspension of bed material by turbulent eddies impinging on the bed, 2) rheological motion — a concentrated suspension of grains maintained just above the bed by internal dispersive pressure.

5) Hydraulic significance:

The maximum grain size is determined by the intensity of the turbulent eddies impinging on the bed. The minimum grain size corresponds roughly to that grain size in the suspended load where all grains finer remain in more-or-less continuous suspension.

6) Grain interactions:

The population consists of exactly selected grains which constitute the sediment framework. The texture of the framework is a reflection of the fact that a grain will be most difficult to entrain when it is the same size as the neighboring grains. Grains which are larger are reentrained because they project above the bed into the higher velocity flow zone where they are subjected to higher fluid drag. Grains which are smaller are reentrained because they tend to be dislodged and thrown above the bed by the micro-turbulence around the larger neighboring grains. Thus "by repeated grain emplacement and subsequent removal of those in less stable positions, a well-packed sediment framework is built of particles of almost equal size" (Moss and Walker, 1978, p. 85).

B Population

1) Grain size: finest of the populations; represents the fine tail of the distribution.

2) Sorting: poorer than A, comparable to or poorer than C.

3) Occurrence: may be absent.

4) Transport mechanism: sustained suspension.

The bed material is transported in the main body of the flow (i.e., well above the bed). The grains are held in more-or-less continuous suspension by turbulent eddies.

5) Hydraulic significance:

The maximum grain size is determined by the upward velocity component of turbulent eddies. The minimum grain size is controlled by the sediment source and not fluid hydraulics.

TABLE 6 (continued)

6) Grain interactions:

The population consists of grains which settled out of suspension onto the bed composed principally of the A population sediment framework. Most of these finer grains are immediately reentrained but some become trapped in the interstices of the sediment framework. The maximum grain size for the B populations corresponds to the maximum size of the interstices in the sediment framework composed of A population grains.

Note

- i) The grain size, sorting, occurrence and transport mechanism information is summarized from Moss (1962, 1963 and 1972).
- ii) The hydraulic significance information is summarized from Middleton (1976).
- iii) The grain interaction information is summarized from Moss (1962, 1963 and 1972) and Moss and Walker (1978).

information in this table represents the full spectrum of the 'classical' views on grain populations. The three principal proponents of the grain population concept, Moss (1962, 1963, 1972), Visher (1969) and Middleton (1976), are not entirely in agreement on the origins of the grain populations. Visher ascribes the existence of the populations to deposition by three transport mechanisms: traction/surface creep, saltation/intermittent suspension and sustained suspension. Middleton largely agrees with Visher's interpretation but feels the populations are more directly related to the hydraulics of the depositing fluid, especially the flow competence and the intensity of the turbulence. The transport mechanisms are viewed more as a consequence of the fluid mechanics than a cause of the populations. Moss admits to the importance of the transport mechanisms and fluid hydraulics but feels the grain-to-grain interaction occurring on the bed is the main factor controlling the development of the populations.

There seems to be one serious omission in the classical view of grain populations. Implicit in the concept is the assumption that deposition takes place only from one of the three transport mechanisms. This would be true for all depositional surfaces except the slipfaces of eolian and subaqueous dunes and sandwaves. On these surfaces the traction/surface creep and saltation/intermittent suspension mechanisms should be largely inoperative. Grain emplacement on slipfaces is by one of two processes: avalanching (or grainflow) and grainfall. The bed load sediment moving up the stoss side of a bedform towards the crest should be deposited largely by the traction/surface creep and saltation/intermediate suspension mechanisms. Upon reaching

the crest, the finer portion of the bedload (i.e., part of the A population) is whisked into temporary suspension but immediately settles out through the zone of flow separation to accumulate on the lower and middle portions of the slipface. The rest of the bedload avalanches down the slipface surface. The avalanching sand probably includes all of the C and part of the A stoss side grain populations. Both modes of emplacement, avalanching and grainfall, resort the sediment. It therefore seems that there should be added to the traditional three grain populations two others, the avalanche and grainfall populations. Both of these, but especially the avalanche, represent sediment which has been deposited by transport mechanisms substantially different from the three described in Table 6.

Problems with the grain population concept

Linear segments have been observed in the cumulative grain size curves for single laminae (Walger, 1962; Seibold, 1963; Basamallick, 1966; Moss, 1972; Glaister and Nelson, 1974; Grace et al., 1978; and the present study), conventional multi-lamina 'grab' samples (Doeglas, 1946; Visher, 1969; and many others), and the averages of many samples (Shea, 1974). Clearly, the linear segments on these curves cannot all be explained in terms of the 'classical' grain populations. For averages of many samples, the linear segments probably largely reflect the size characteristics of the sediment source or, if the samples all come from the same locality, the average sorting tendencies of

the environment. For multi-lamina grab samples, the linear segments may represent the average characteristics of the three grain populations, or they may represent different fine and coarse laminae, each consisting largely of an A population but deposited by currents of different strength. Only in individual laminae is there any chance that each linear segment may actually correspond to a single distinct grain population. There are still, however, interpretive problems associated with the individual laminations. It would be inappropriate to interpret the linear segments of a cumulative grain size curve in terms of the conventional A, B and C populations for foreset laminae, or laminae exhibiting vertical (current strength varied temporally) or lateral (current strength varied spatially) textural grading.

From the above arguments, it is concluded that the linear segments observed on cumulative grain size curves do not necessarily bear any relation to the theoretical grain populations. Even sampling single laminae does not assure their recognition. The grain populations undoubtedly exist but we probably seldom see their unaltered expression in the curves. Nevertheless, curve dissection is still a useful exercise. It will provide additional textural information and it may aid in the interpretation of depositional environments.

Grain subpopulations in the samples analyzed

Linear segments were identified from the cumulative grain size curves (Appendix E) for the samples analyzed in this study. The

corresponding grain subpopulations were assigned the following codes: CT—coarse tail, may correspond to the C population; IT—middle (inter-tail) section, may correspond to the A population; and FT—fine tail, may correspond to the B population. The relative proportion of the three subpopulations are given in Appendix C.

Joint Size Distribution Based On
The Intermediate and Smallest
Grain Dimensions

Procedure

By combining the sizing actions of the square-holed sieves and the roller micrometer it becomes possible to separate a sediment into fractions containing grains with similar I dimensions and similar S dimensions. Sediment fractionation of this kind was also achieved in previous studies where round-holed sieves were used in conjunction with rectangular-holed sieves (e.g., Matschinski, 1964; and Ludwick, 1971). This approach to sizing provides the size distribution of a sediment in terms of either the I or S dimension, and the 'joint' size distribution of the I and S dimensions. This joint size distribution records the simultaneous variations in I and S, and as such also records one aspect of the grain form distribution: S/I, the Zingg grain flatness index. S/I will hereafter be referred to simply as the 'tabularity ratio'.

The joint I:S size distribution was determined using the following procedure. All samples were first sieved into quarter phi (I dimension) size fractions. These fractions were stored separately in plastic vials. The slot width of the roller micrometer was initially set to 1.700 millimeters, the lower size limit of the coarsest quarter phi sieve fraction encountered in this study (i.e., VC1 or -1.00 to -0.75 phi). Note that the slot width was not set to 1.682 millimeters as required by the Udden-Wentworth grain size scale but rather to the nominal opening of the corresponding U.S. Standard Series sieve (see Table 2). All the VC1 sieve fractions from the various samples were sized by the roller micrometer at the above slot width. The 'oversized' grains, those not passing through the slot, were collected in a cup at the lower end of the slot and weighed. These grains represent the I-VC1, S-VC1 subfraction. Within this subfraction both the I and S dimensions of the grains range between -1.00 and -0.75 phi but the S dimension is always less than or equal to the I dimension. The 'undersized' grains which passed through the slot are collected in another cup. These grains are stored in a separate vial for reanalysis at a narrower slot width.

After all the I-VC1 sieve fractions had been analyzed by the roller micrometer, the slot width was reset to 1.400 millimeters, one quarter phi less than the previous setting. All I-VC2 fractions and residual I-VC1 fractions (i.e., undersized grains from the previous slot width) were then sized using this new slot width. As before, the oversized grains (i.e., the I-VC2, S-VC2 and I-VC1, S-VC2 subfractions) were

collected and weighed. The undersized grains were stored in vials for reanalysis at a narrower slot width.

Next, the slot width was reset to 1.180 millimeters, again one quarter phi less than the previous setting. The I-VC3 and residual I-VC1 and I-VC2 fractions of the samples were then processed. As before, the oversized grains were collected and weighed, and the undersized grains were stored for further analysis. This procedure was repeated for the many original and residual I fractions using a series of slot widths, each narrower than the preceeding one by a quarter phi. The results of these analyses for the 28 samples are tabulated in Appendix D. In Figure 8 the results for one sample, B2-20, are shown. This figure illustrates well the 'structure' of the data in the joint size distribution of the intermediate and smallest grain dimensions. In Figure 9 the same data are shown graphically with circle areas proportional to weight percents.

Figure 8 also shows the relation between the tabularity ratio (S/I) and the joint I:S distribution. If S/I values are computed using the I and S midpoints (expressed in millimeters) of each subfraction, it will be found that the tabularity ratio is the same for all subfractions falling on a given diagonal (each diagonal is indicated by a set of tick marks oriented with their ends pointing to the upper left and lower right). The S/I value for each diagonal set of I:S subfractions is given in the lower right portion of the figure. Because each I:S subfraction consists of grains with a range of I and S dimensions, the S/I values for the grains will range both above and below

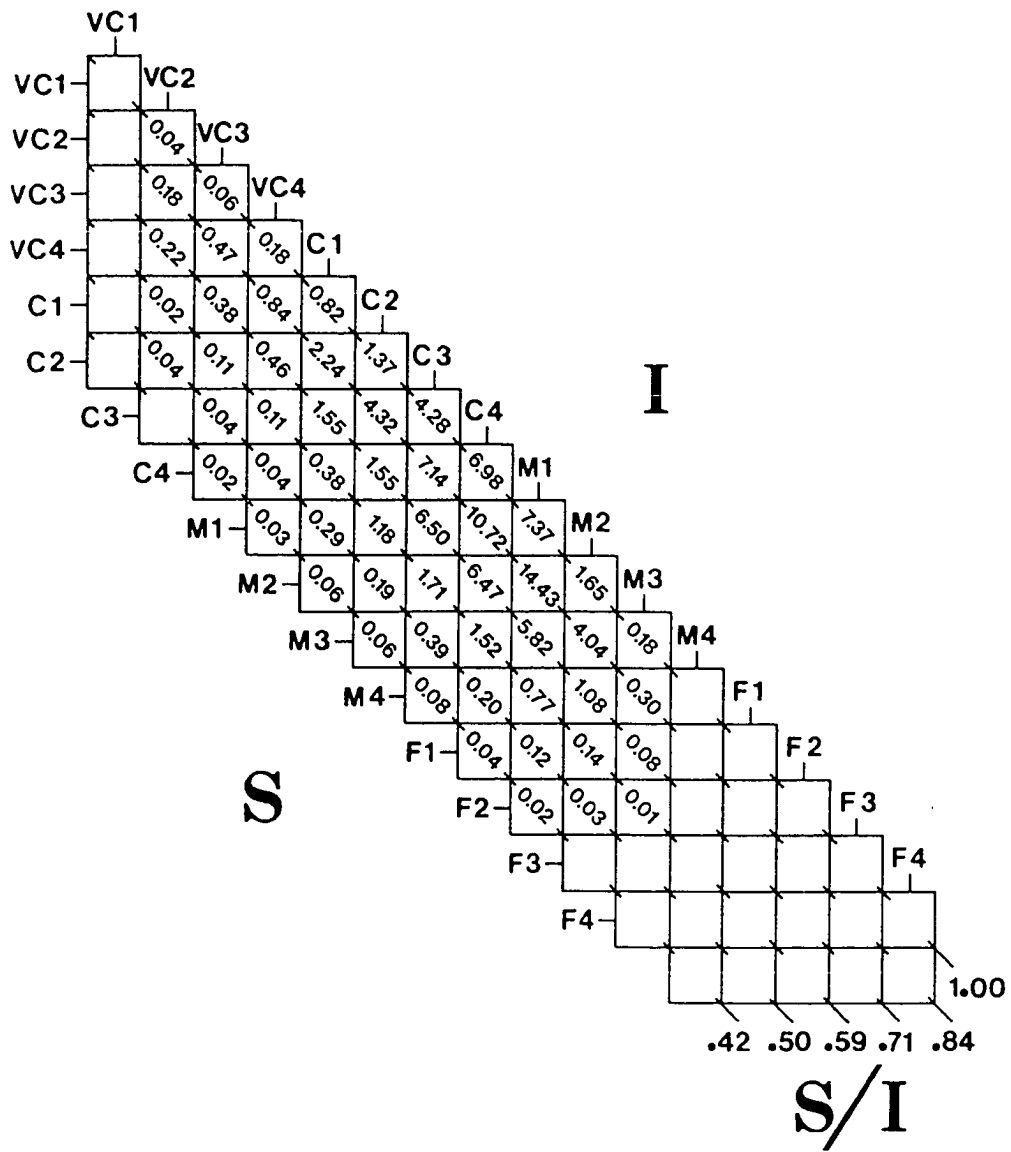


FIG. 8 – Raw data (weight percents) for the joint I:S grain size distribution for sample B2-20.

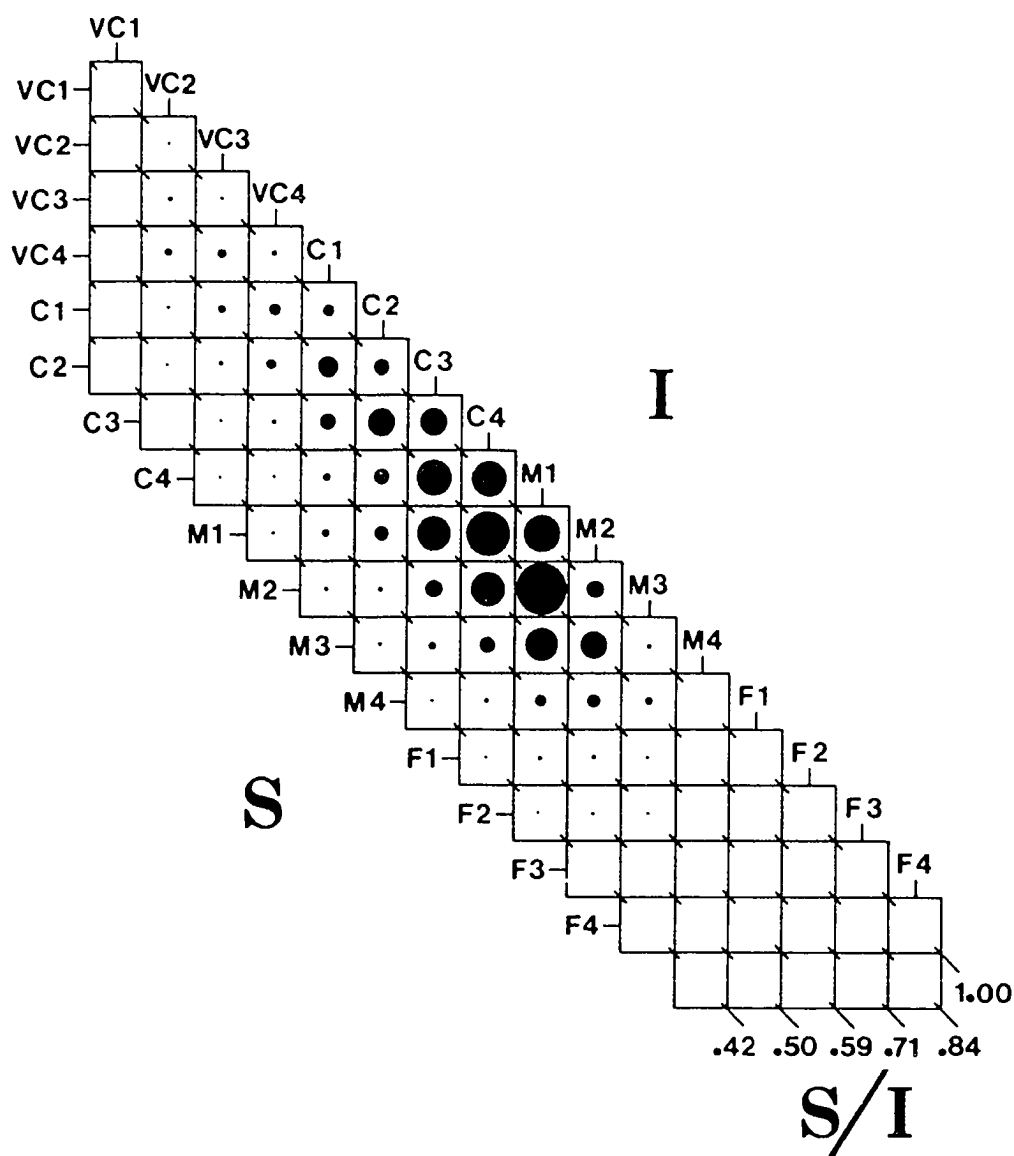


FIG. 9 – Graphical representation of the joint I:S grain size distribution for sample B2-20.

the value for the I and S midpoints. The S/I values for the subfraction midpoints and the corresponding range of S/I values for the grains within the subfractions (in parentheses) are as follows: 1.00 (1.00 to 0.84), 0.84 (1.00 to 0.71), 0.71 (0.84 to 0.59), 0.59 (0.71 to 0.50), 0.50 (0.59 to 0.42) and 0.42 (0.50 to 0.35). Those grains with an I dimension smaller and a S dimension larger than the midpoint will have S/I values greater than that for the midpoint. The reverse would be true for those grains having an I dimension larger and a S dimension smaller than the midpoint. It is apparent that the I:S subfractions are not mutually exclusive with respect to the S/I values of their grains but rather overlap by a considerable amount. This overlap is unavoidable when each subfraction allows a range of I and S dimensions. The actual overlap is probably somewhat greater when the sizing error for the square-holed sieves is taken into account. It is, of course, desirable to keep the tabularity ratio overlap to a minimum. A reduced overlap could have been obtained by using a smaller sizing interval (e.g., one-eighth phi) for the roller micrometer.

Determination of the joint I:S size distribution was subject to three limitations. (1) Original I fractions containing less than 0.25 grams were not analyzed with the roller micrometer. (2) Residual I fractions containing less than 0.10 grams were not further analyzed with the roller micrometer. (3) The narrowest slot width used in the roller micrometer analyses was 0.125 millimeter. This corresponds to the lower boundary of the fine sand size class. Sizing below this

limit was not attempted because of the adherence of the finer grains to the roller surfaces and the inability to accurately set the slot width.

Discussion of Results

Analytical problems

The joint size distribution of the I and S grain dimensions cannot be meaningfully summarized by statistics. There are two reasons for this. First, for a given I fraction, the S subfractions overlap by a substantial amount. Descriptive statistics for grouped data assume mutually exclusive size classes and negligible sizing errors. These conditions are approximately met by the I size classes but not by the S size classes. Second and more important, the character of the sizing action changed with the slot width. This is amply demonstrated by the data in Appendix D. For the I-M3 and coarser sieve fractions the amount of sediment in the second S subfraction (i.e., the subfraction where $S/I = 0.84$) is always greater than the amount in the first S subfraction (i.e., the subfraction where $S/I = 1.00$). In the I-M4 and I-F1 sieve fractions there is an increasing number of cases where the first S subfraction contained more sediment than the second. For the I-F2 and finer sieve fractions the amount of sediment in the first S subfraction is always greater than the amount in the second S subfraction. This result is clearly anomalous because the expectation

would be that sand grains become flakier, not more equant, with decreasing grain size. The results suggest then that the sizing action for the narrower slot widths was fundamentally different from that for the wider ones.

For slot widths wider than 0.250 millimeter (i.e., 2.00 phi, the boundary between the medium and fine sand classes), and slot widths equal to or less than 0.250 millimeter the test conditions differed in three respects.

- (1) The narrower slot widths were set with thickness gauges rather than micrometer heads. It would seem that any error which might occur in setting the slot width would cause the slot to be too wide. Such an error would have resulted in the first S sub-fractions being under-represented but just the opposite occurred. Thus the use of thickness gauges could not have been responsible for the change in the sizing action.
- (2) For the narrower slot widths the length of the slot was reduced from 9 to 4 inches, and the slope of the slot was increased from 14 to 28 degrees. As previously discussed, the purpose of these changes was to decrease the time required to size individual grains. It was observed that the grains traveled in more-or-less single file and were apparently fully sized within about one inch of travel. These observations, however, may be in error. If in fact the grains were not completely sized because of bunching in the slot or too short a travel distance then the result would be an under-representation of the second S subfraction.

- (3) The tendency for grains to adhere to the roller surfaces increased markedly for grains finer than medium sand. The net effect of this tendency would be under-representation of the second S subfraction.

From the above it is concluded that the sizing action of the roller micrometer for slot widths equal to or less than 0.250 millimeter was inaccurate because of incomplete sizing resulting from too much sediment in the slot and a tendency for grains to adhere to the rollers. The effect of this sizing error is probably largely restricted to the fine sand I fractions. Although it is true that some of the medium sand I fractions contained S subfractions which were sized at slot widths less than or equal to 0.250 millimeter, because of their larger size, these grains would not have been subject to bunching in the slot or adherence to roller surfaces to the same extent as the smaller grains. Hence, it is believed that the sizing results are reasonably accurate for these S subfractions.

Tabularity profiles

Even with the overlapping I:S subfractions and the sizing errors for the narrower slot widths, the joint size distribution of the I and S grain dimensions still contains important information. The data in Appendix D can, for example, be used to produce 'tabularity profiles' for samples. These profiles may say a great deal about the shape sorting mechanisms attending deposition. Tabularity profiles are constructed as

follows. A single I sieve fraction common to all samples of interest is selected. For each sample, the relative frequencies of the S sub-fractions are plotted in histogram form. The relative frequencies are weight percents which have been recalculated to sum to 100 percent. Examples of this kind of plot are given in Figures 10 and 11. These plots are useful when dealing with a suite of samples from the same locality, where it is likely that the grains in a given I fraction in all samples belong to a single population. The erosional, transportational and depositional processes select grains from this population for inclusion in a deposit. If the samples come from different microenvironments, then their tabularity profiles should differ because the kind and intensity of the sorting mechanisms operating in each microenvironment differ. Tabularity profiles should be relatively unaffected by the sizing problems associated with the roller micrometer: if the sizing action is not the same for all I fractions, for a given I fraction it is the same for all samples; and if the sizing process is inaccurate, I fractions sized on the same basis can still be compared.

As examples of the kind of comparative analysis advocated above, suites of samples from two localities will be considered: the B2 barrier island samples, and the R5 point bar samples.

Figure 10 shows the tabularity profiles for the I-M1 sieve fraction of the B2 samples. This is a good I fraction to use in the comparison because it is large and located near the center of the I size distribution in each sample. The character of the profiles for the beach (samples B2-1 and 16) and topset (samples B2-7 and 9) laminae is variable; no

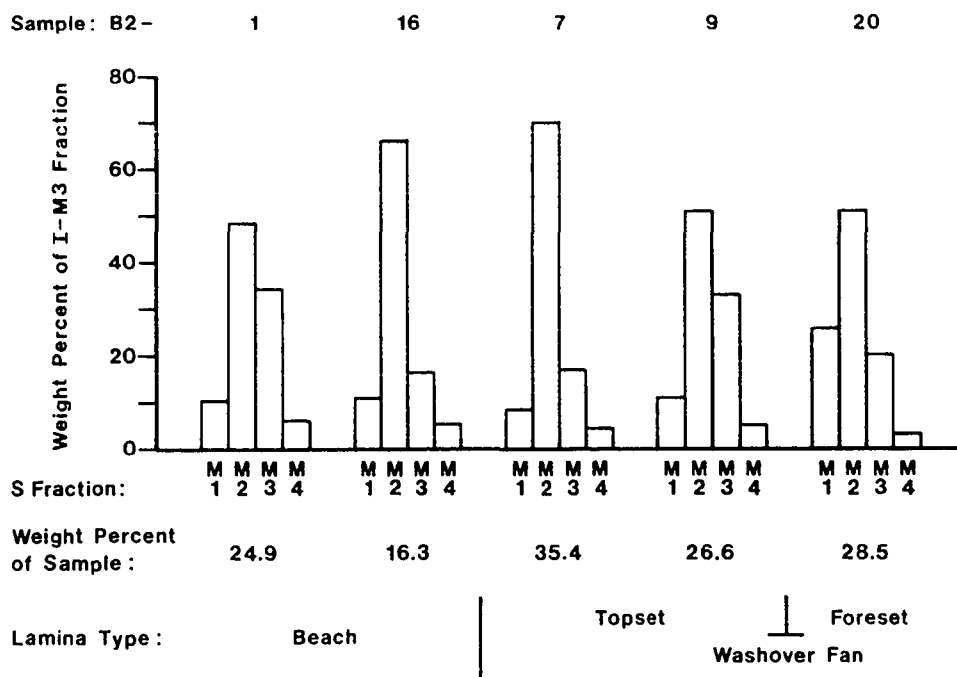


FIG. 10 – Tabularity profiles for the I-M1 sieve fraction of the Cedar Point Spit (B2) samples.

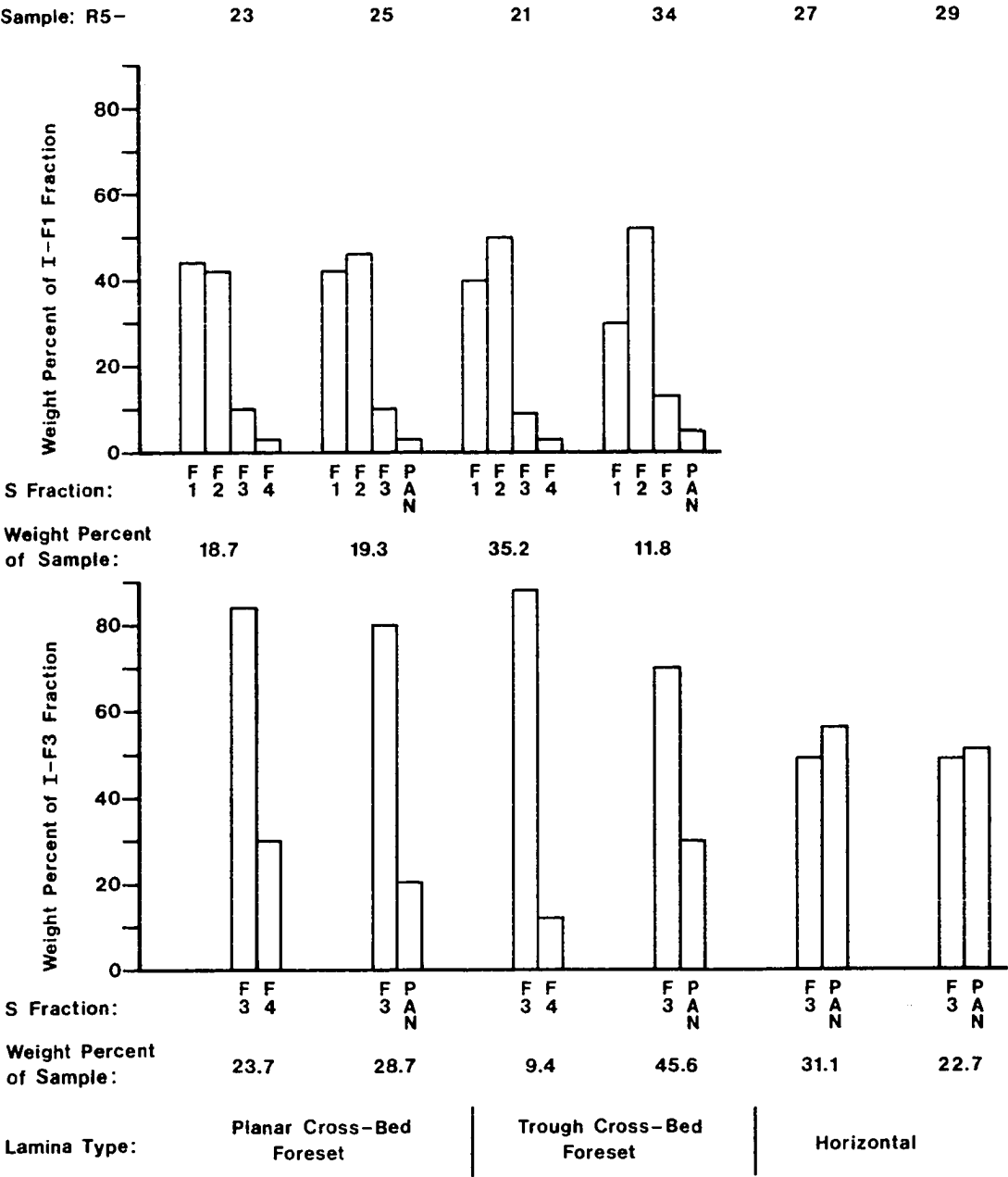


FIG. 11 - Tabularity profiles for the I-F1 and I-F3 sieve fractions of the Brazos River (R5) samples.

consistent differences are apparent. The profile for the foreset lamina (sample B2-20) does differ markedly from the other four laminae in one important respect; there is a far greater proportion of grains with low tabularity (i.e., high S/I). Note that in sample B2-20 the first S subfraction (S-M1) is larger than the third (S-M3), whereas the opposite is true for the other four samples. This difference could be interpreted as follows. The beach and topset laminae are traction deposits whereas the foreset lamina is composed of grains which were emplaced by avalanching and grainfall on a slipface. Apparently the flakier grains in the I-M1 fraction were not preferentially winnowed during traction transport, but upon coming to the crest of the washover fan and being thrown into temporary suspension above the slipface were carried away by the current. Only the most equant grains with the higher settling velocities would have fallen back onto the slipface. An alternative interpretation would be that the flakier grains were preferentially winnowed from the slipface by powerful reverse currents generated on the lee side of the washover fan.

Figure 11 shows the tabularity profiles for the I-F1 and I-F3 sieve fractions of the R5 samples. The I-F1 fraction of the four foreset laminae are compared in the upper part of the figure. There is only one conspicuous difference in the tabularity profiles for the two types of foresets. The relative amounts of sediment in the first (S-F1) and second (S-F2) S subfractions of the planar foreset laminae (samples R5-23 and 25) is variable but very similar. In contrast, for the trough foreset laminae (samples R5-21 and 34) the amount of

...

sediment in S-F2 is substantially greater than that in S-F1. Put simply, the trough foreset sediment is slightly flakier than the planar foreset sediment. At first consideration this result seems to contradict the general belief that trough cross-beds represent higher flow intensity conditions than do planar cross-beds. One would think that the stronger the depositing current, the more readily the flaky grains would be winnowed out of a sediment. One possible explanation for this apparent contradiction is that the ratio of the amount of grainfall to grainflow sediment should be higher in the planar cross-beds, and thus the planar foreset laminae are supplied through grainfall with the more equant grains (i.e., those with the higher settling velocities). The trough foreset laminae, in contrast, may receive most of their grains from grainflow because the stronger currents carry the suspended sediment beyond the slipface.

In the lower part of Figure 11, the I-F3 fractions of all six R5 samples are compared. Even though we are seeing for four of the samples a pan fraction rather than the S-F4 fraction, it is still very obvious that the two horizontal laminae (samples R5-27 and 29) are much flakier than the foreset laminae. This result is not unexpected because at this locality the horizontal laminae represent slack water suspension deposits formed during the waning stages of a flood. For grains of a given size, sediment traveling in suspension invariably tends to be flakier than sediment traveling in the bedload.

Before leaving the subject of tabularity profiles, one other result of the analyses needs to be mentioned. The two Padre Island

dune sands (the D3 samples) along with R5-27 and 29 are highly unusual in that they are the only samples where the I-F3 sieve fraction has more sediment in the S-F4 and finer fractions than the S-F3 fraction. These samples thus appear to be extraordinarily flaky. The peculiar nature of the D3 samples is further documented by the artificial packing analyses which will be described in a later section. It has already been pointed out that the high proportion of flaky grains in R5-27 and 29 is not surprising. The great flakiness of D3-15 and 19 is also readily explained. Field studies have shown that the less equant grains are more readily entrained and transported by wind because of their greater form drag (Mattox, 1955; and Winkelmoen, 1971). Because the sampled dunes are located on the lagoon side of the barrier island, about two miles from the beach (their sediment source), eolian shape sorting occurred over a considerable distance; and consequently, the more equant grains were left behind.

I:S size distribution plots

A plot for sample B2-20 of the joint size distribution of the I and S grain dimensions is shown in Figure 9. The data on which this plot is based are given in Figure 8 and Appendix D. Similar plots have been made for the other samples analyzed in this study. Because of the coarseness of the grains in B2-20, Figure 9 is probably the most accurate and complete of the 28 plots. An examination of the plots yielded no new information on the textural differences between

different types of sand deposits, or the existence and character of grain subpopulations. However, if I:S size distribution plots could be produced which are largely free of sizing errors then the plots would no doubt prove to be a useful tool for interpreting sediment textures.

Size Distributions Based On The Smallest Grain Dimension

The use of slotted sieves or a roller micrometer makes it possible to obtain the size distribution of the S grain dimension. Sedimentary petrologists are conventionally concerned only with the I distribution but perhaps the S distribution can provide additional textural information which will contribute to our understanding of the hydraulic sorting of sediment. The I distribution will no doubt continue to be the most important of the two because the I grain dimension is a better estimate of the nominal diameter (i.e., the diameter of a sphere having the same volume as the grain) which is the 'ideal' measure of grain size. Because of the excessive time required for the analyses, it is impractical to use the roller micrometer strictly for the determination of the S distribution. If, however, the roller micrometer is used in conjunction with sieves for the purpose of determining the joint I:S distribution then the S distribution can also be obtained.

The procedure for determining the S distribution using the raw data from the I:S distribution is as follows. The total weight percent for a given S subfraction is obtained by adding the individual weight

percents for that subfraction in all I fractions in which it occurs. One problem does arise when doing this. What should be done with the 'pan fractions' which exist below the last S subfraction in each I fraction? It can probably be safely assumed that the bulk of the sediment in a pan fraction consists of grains with S dimensions falling within the S subfraction immediately below the last one for which actual sizing was conducted. This assumption will lead to negligible error provided the pan fraction is small (i.e., less than one weight percent?). If this condition is met, then the pan fractions are added to those S subfractions for which the bulk of the grains is assumed to fall.

An example of a cumulative grain size curve based on the S dimension is shown in Figure 12. B2-20 is one of the few samples analyzed in this study for which curves of this kind could be constructed. The other samples were unsuitable because of large pan fractions, or large amounts of sediment in the I-F1 and finer sieve fractions where the S sizing was inaccurate. The cumulative grain size curve for B2-20 based on the I dimension is shown in Figure 13. The graphical size statistics for both the I and S cumulative curves were computed for all five B2 samples. Not surprisingly, the mean grain size for the I curves was always larger than that for the corresponding S curves. The sorting of the S curves was always slightly poorer than that of the corresponding I curves. The I and S curve relationships for skewness and kurtosis showed no consistent pattern. These last two statistical measures are highly sensitive to the tails of a size distribution where most of the analytical error is located. Apparently there was

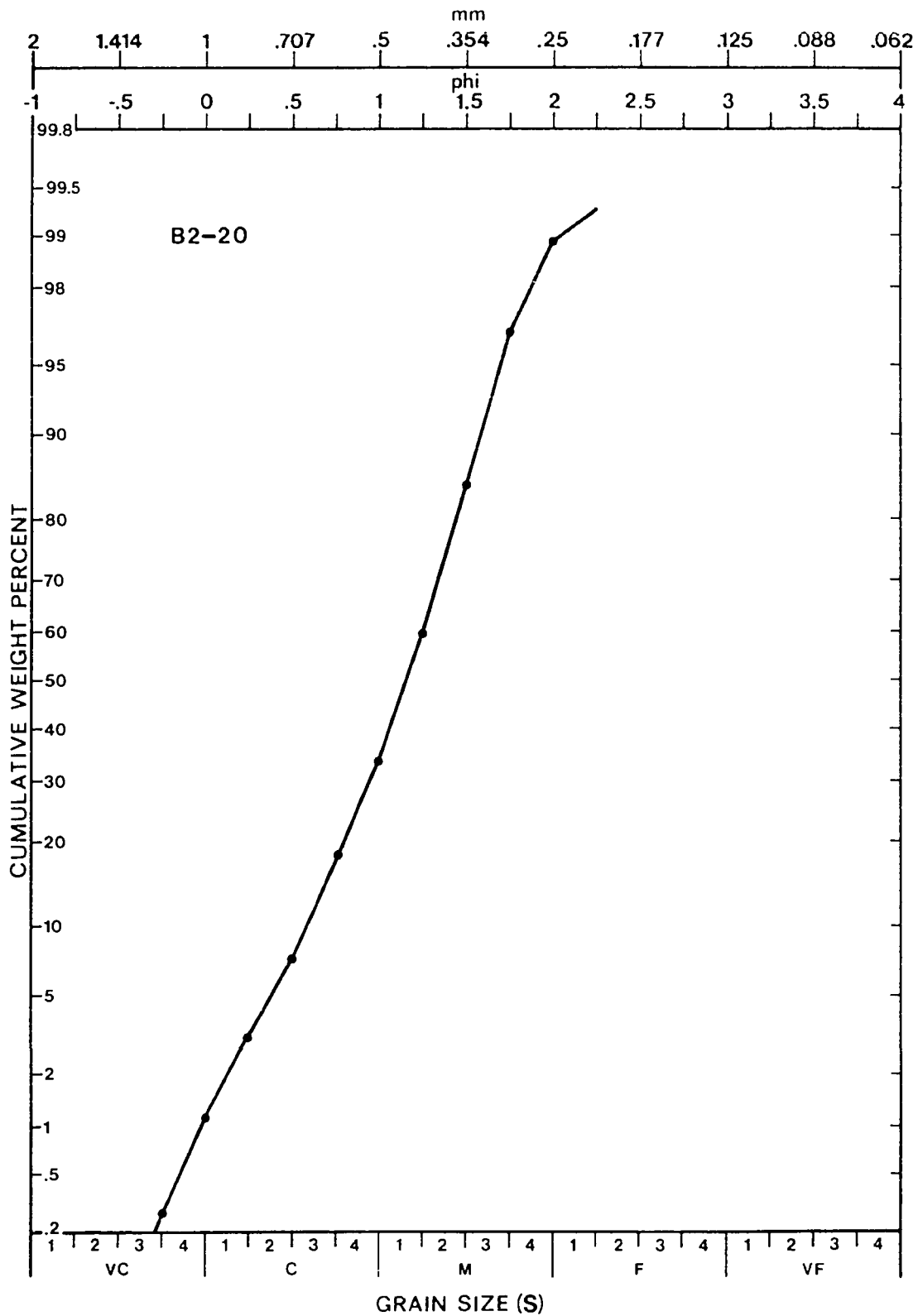


FIG. 12 – Cumulative grain size (S dimension) curve for sample B2-20.

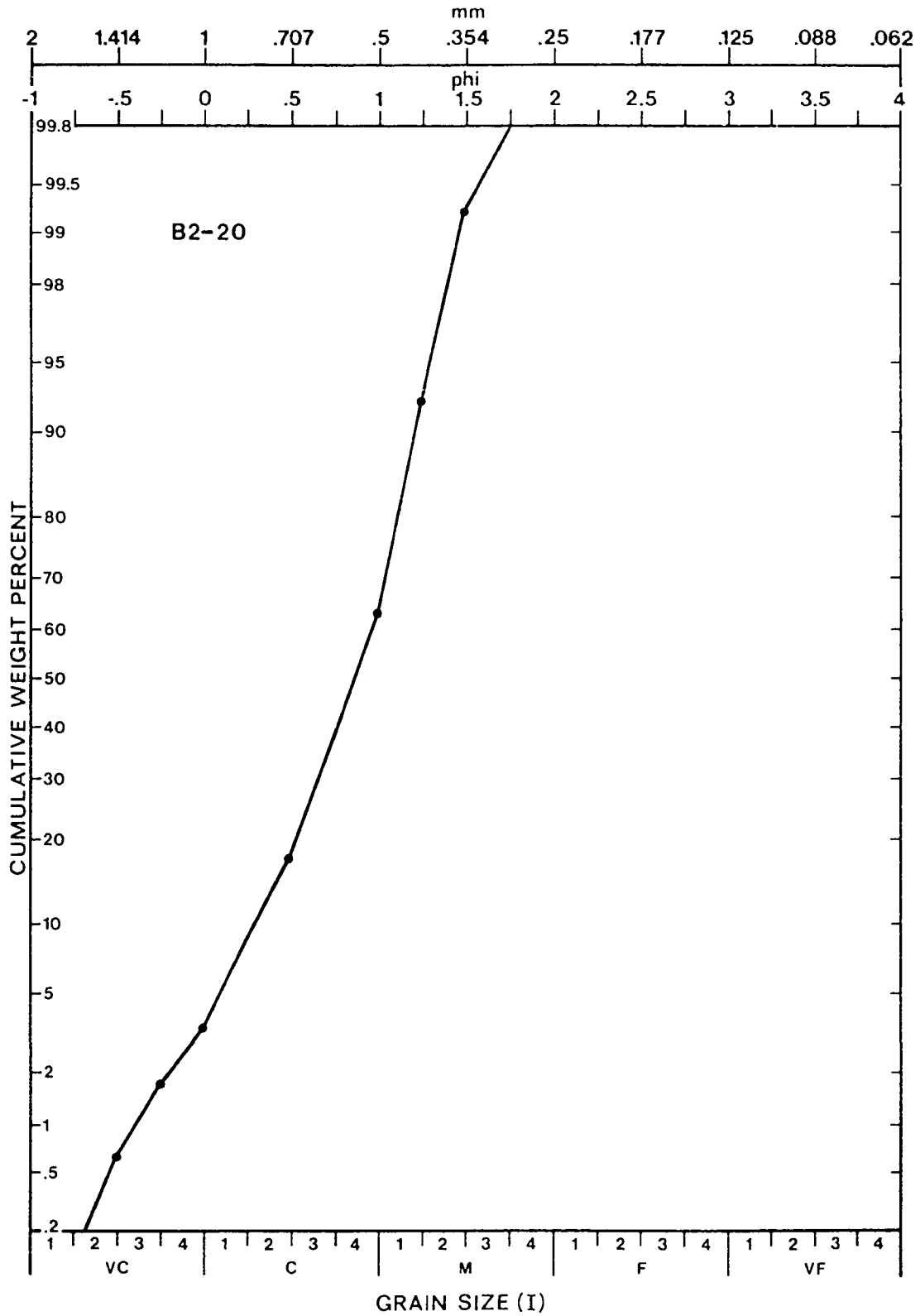


FIG. 13 – Cumulative grain size (I dimension) curve for sample B2-20.

a lack of consistency in the error for the I and S curves. In their overall form, the I and S curves were not notably different. At present, it is not possible to evaluate the usefulness of the S distribution but it is anticipated that future research will demonstrate that it provides environmentally significant information.

VISUAL COMPARATOR FOR SORTING IN THIN SECTIONS

Introduction

Disaggregation and sieving are often not possible for well-indurated sandstones, especially those with quartz or hematite cements. In such cases descriptive statistics for the grain size distribution may be obtained from thin section analysis by either of two approaches. The first approach is the more accurate but is also the most time-consuming. It involves the measurement of the longest dimension of a few hundred grains in a thin section. Moment statistics may be calculated directly from the grain dimensions, or graphical statistics may be calculated if the size measurements are grouped into, say, quarter phi classes and then plotted as a cumulative curve. The problem with size statistics obtained in this manner is that they can be substantially in error because with random sectioning the observable dimensions of grains in thin section differ from the true dimensions. Many conversion equations have been proposed which correct the statistics derived from thin section analysis to the statistics that would have been

obtained had it been possible to sieve the grains (Friedman, 1958 and 1962b; Adams, 1977; and Harrell and Eriksson, 1979). From these studies it is apparent that only the average grain size can be reliably estimated. The average grain size based on the maximum observable grain dimensions in thin section is generally about 0.15 phi coarser than the average grain size obtained from a sieve analysis.

The second approach to obtaining grain size statistics from thin sections involves the use of 'visual comparators'. The idea here is that by comparing a rock or sediment sample with a set of pictures illustrating variations in grain size, a visual estimate of a grain size distribution parameter can be obtained. Descriptive statistics based on visual comparators are, of course, less accurate than those based on actual grain size measurements. They have an overwhelming advantage, however, in that they provide rough estimates of statistical parameters in a matter of seconds rather than hours. In many cases these estimates are sufficiently accurate to meet the needs of the study. Visual comparators for estimating average (modal) grain size and sorting in loose grains and hand specimens are in widespread use. Apparently no visual comparators for skewness and kurtosis have been developed.

Most modal grain size comparators in use are either 'home-made', or are made by petroleum exploration or service companies exclusively for their employees. Only two companies in the United States are engaged in the public sale of modal grain size comparators (American Stratigraphic, Inc., Denver, Colorado; and Forestry Suppliers, Inc., Jackson Mississippi).

The only sorting comparators available to the public have been published in textbooks (Pettijohn et al., 1972, p. 585; Folk, 1980, p. 102; and Tucker, 1981, p. 15). All three describe sorting in phi units and conform to the sorting scale of Folk (1980, p. 103). Of the three, only the comparator of Pettijohn et al. (1972) is widely used. The problem with all of these sorting comparators is that they contain substantial errors. In Table 7 the reported and 'actual' sorting for the three comparators is tabulated. The actual or true sorting was established in the following manner. The diameters of the circular grains were measured to the nearest tenth of a millimeter using an optical micrometer. The moment standard deviation was then computed for the ungrouped measurements. It is apparent in Table 7 that as the sorting value increases so to does the error. That such errors occur is not surprising because to illustrate accurately a sorting of 1 or 2 phi requires that the ratio of the maximum and minimum circle diameters be 32 and 512, respectively. In the preparation of these comparators the tails of the size distributions were apparently truncated.

It is common for modal grain size and sorting comparators designed for loose grains to be applied to thin sections. The use of modal grain size comparators need not result in significant error if it is remembered that the average size of the longest grain dimension in thin section is about 0.15 phi less than the 'true' average size that would be obtained by sieving. Additional compensation may be necessary, however, if the eye perceives grain size in terms of the intermediate

TABLE 7

ACTUAL AND REPORTED SORTING FOR PUBLISHED VISUAL COMPARATORS

Reported Sorting ¹	Actual Sorting ²		
	Pettijohn et al. (1972)	Folk (1980)	Tucker (1981)
0.25	—	0.22	—
0.35	0.34	0.30	0.38
0.50	0.54	0.40	0.60
1.00	0.77	—	0.75
2.00	1.14	—	1.05

¹The sorting measure used by the cited authors was never specified but there is little doubt that it was the moment standard deviation for ungrouped data.

²The moment standard deviation for ungrouped data was computed. The circle diameters were measured to the nearest tenth of a millimeter using an optical micrometer.

rather than the longest grain dimension. Thus the modal grain size determined from thin section may be somewhat more than 0.15 phi smaller than the 'true' average grain size. Given the errors inherent in existing sorting comparators, these measuring aids cannot be reliably used for loose grains or thin sections. Even if error free, sorting comparators designed for loose grains cannot be used with thin sections. This is true for two reasons. First, the discrepancy between the apparent and actual sorting is not constant for different degrees of sorting but rather is small for poorly sorted grains and large for well sorted grains. Second, the discrepancy between the apparent and actual sorting decreases with decreasing average grain size. Thus there is maximum discrepancy for coarse well-sorted sediment and minimum discrepancy for fine poorly-sorted sediment. The cause of these discrepancies will be discussed in a later section.

A sorting comparator designed specifically for thin sections was published by Beard and Weyl (1973). The comparator consists of six black-and-white thin section photomicrographs of artificially textured, lognormally distributed sand. Unfortunately this comparator has two serious flaws. First, the photomicrographs were taken using crossed-polarizers and thus the grains vary in visibility from black (when extinct) to white and all shades of gray in between. Second, the photomicrographs conform to a sorting scale which differs considerably from the Folk (1980, p. 103) sorting scale generally preferred by sedimentary petrologists (Table 8).

There seems to be little need of a modal grain size comparator

TABLE 8
COMPARISON OF THE FOLK, AND THE
BEARD AND WEYL SORTING SCALES

Folk (1980) ₁ Sorting Scale (phi units)	Beard and Weyl (1973) Sorting Scale ²	
	Sorting Classes (dimensionless)	Corresponding Phi Value on the Folk Sorting Scale
0	1.00	0
very well sorted	extremely well sorted	
0.35	1.10	0.21
well sorted	very well sorted	
0.50	1.20	0.38
moderately sorted	well sorted	
1.00	1.40	0.71
poorly sorted	moderately sorted	
2.00	2.00	1.48
very poorly sorted	poorly sorted	
	2.57	2.00
	very poorly sorted	

¹Sorting is computed using the moment standard deviation or the inclusive graphic standard deviation of Folk and Ward (1957). Grain size data is expressed in phi units.

²Sorting is computed using the 'Trask sorting coefficient' (Krumbein and Pettijohn, 1938, p. 230-231). Grain size data is expressed in millimeter units.

designed specifically for thin section work. A comparator like the one marketed by American Stratigraphic can be laid directly on the thin section and both the comparator and slide can be viewed simultaneously. If the 0.15 plus phi correction is applied then a reasonably accurate estimate of the modal grain size can be obtained. It is probably not possible to develop workable visual comparators for estimating skewness and kurtosis in thin sections because these two statistical parameters describe highly complex attributes of grain size distributions which could not be adequately represented in images or visually perceived by the investigator. It seems that the primary need today is for a sorting comparator which can be used with thin sections. The development of such a comparator is one of the principal objectives of this study.

Design

General Considerations

Five different computer-generated sets of spheres were used in the development of the sorting comparator. Each set consisted of 100 (or, in one case, 101) spheres with a lognormal size distribution. The mean sphere size for each set was the same but the standard deviations were different: 0, 0.35, 0.50, 1.00 and 2.00. The standard deviation values correspond to the boundaries of the Folk (1980, p. 103) sorting scale (Table 8).

Because the sphere sets were going to be used to simulate natural sediment, the choice of the type of size distribution was of critical importance. The lognormal distribution is a popular one with sedimentary petrologists because many natural grain size distributions approach lognormality and because the properties of this distribution are easily treated mathematically and graphically. For these reasons the lognormal distribution is perhaps the best 'model' with which to compare natural grain size distributions (Blatt et al., 1980, p. 68-71). If d_ϕ and d_{mm} correspond to grain dimensions in units of phi and millimeters, respectively, then a sediment is said to be lognormally distributed (with respect to d_{mm}) when d_ϕ is 'normally' distributed.

Histograms showing the size distributions of four of the sphere sets are displayed in Figure 14. The fifth sphere set, which is not displayed, has a sorting value of zero. It consists of spheres which are all of the same size (a special case of the lognormal distribution). The spheres in each set are organized into half phi size classes, and all spheres within a given class have a diameter equal to the class midpoint. The sorting value for each sphere set was calculated using the formula for 'ungrouped data' moment standard deviation (Section IA of Table 3). It should be recognized, however, that because the distributions are lognormal the computed sorting values would be the same regardless of whether the grouped or ungrouped moment, or graphical statistics were used.

Two series of computer experiments were conducted using the sphere sets. In the first series, the 'plane section experiments', the computer

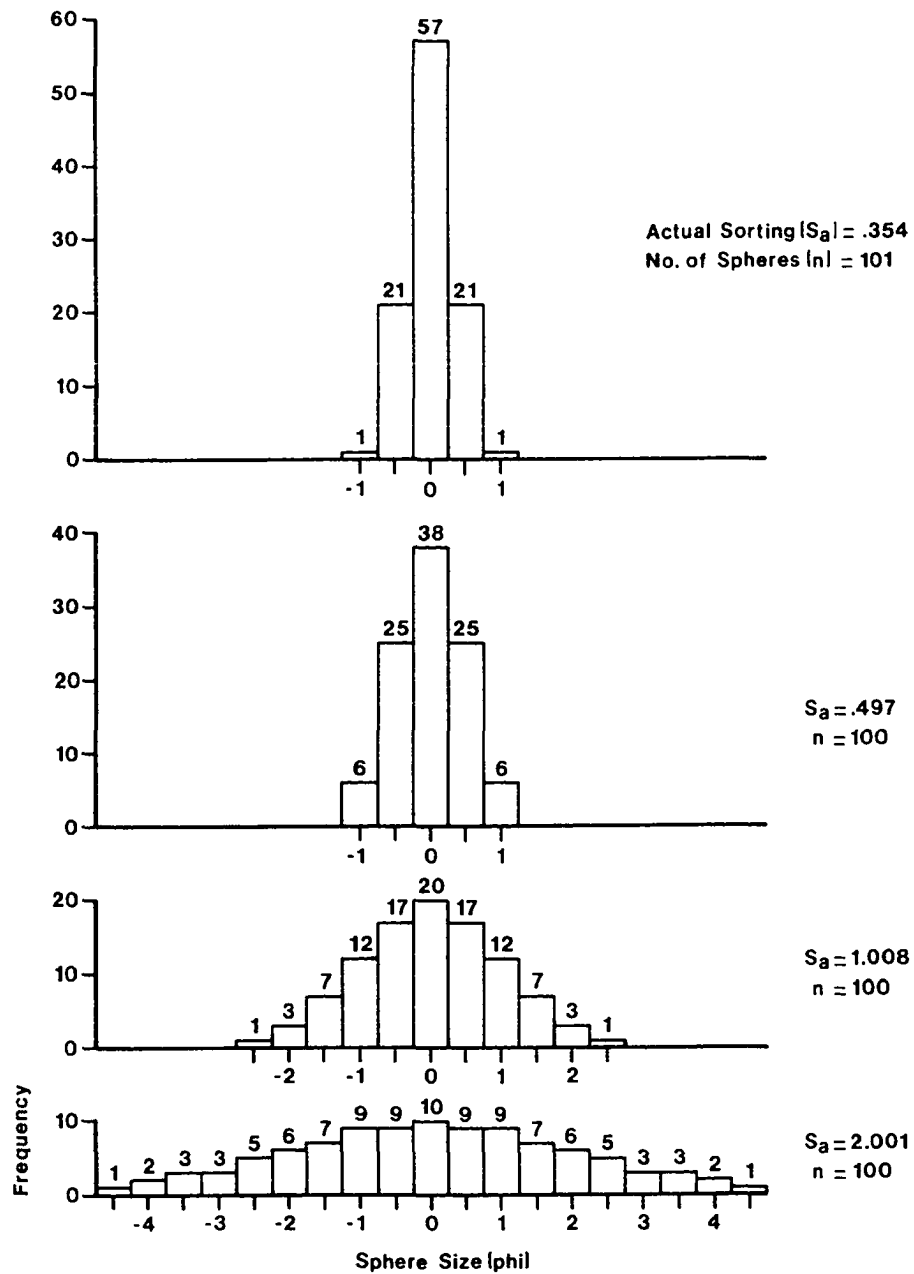


FIG. 14 – Histograms of the lognormally distributed sphere sets.

generated random plane sections through the spheres. These plane sections were used to construct the sorting comparator. The individual images making up the sorting comparator simulate plane sections through different lognormally-distributed sphere populations that are 'randomly packed' in three dimensions. In the second series, the 'thin section experiments', the computer generated random slices of finite thickness through the sphere. By varying the mean size of sphere sets, the effect of grain size on the 'apparent' sorting in 30 micron-thick thin sections was determined. Computer programs were written by the author to perform all the above operations.

Plane Section Experiments

The following operations were performed for each of the five sphere sets.

- 1) Each sphere within a set was cut by a random plane section (i.e., a randomly positioned plane with zero thickness). The random cut was achieved using a 'uniform random number generator'. This computer subroutine produces uniformly distributed random numbers between 0 and 1. By multiplying the diameter of each sphere by one of these random numbers a point on the axis passing through the sphere center was randomly selected. The 'random plane section' for a sphere would be then the circular trace of the sphere on the plane which is normal to the axis and passes through the randomly selected point on the axis.

- 2) The moment standard deviation was calculated for the plane

section diameters (i.e., the diameters of the circular outlines of the spheres visible in the random plane sections). This standard deviation constitutes the 'apparent sorting' of a sphere set.

3) Steps 1 and 2 above were repeated for each sphere set a total of 25 times, each time using a different set of uniform random numbers to section the spheres.

4) The moment mean and standard deviation were computed for the 25 apparent sorting values for each sphere set (Table 9).

5) The results for the one plane section experiment yielding an apparent sorting value closest to the sphere set's mean apparent sorting value were used in the preparation of the 'sorting image' for the sphere set. The sorting image illustrates the 'apparent sorting' of a set of lognormally distributed spheres having an 'actual sorting' corresponding to one of the class boundaries of the Folk sorting scale (Table 8). The diameters of the circular outlines of the 100 randomly sectioned spheres were rescaled so that all would fit in a square six inches on a side with 60 percent of the total area within the square taken up by the sphere cross-sections.

The sorting images for the five sphere sets are shown in Figures 15, 16, 17, 18 and 19. A plot of the actual sorting values versus the mean apparent sorting values for the five sphere sets is provided in Figure 20. Note that the apparent sorting is always higher (i.e., poorer) than the actual sorting but that the discrepancy between actual and apparent sorting decreases (asymtotically?) with increasing sorting values.

TABLE 9
RESULTS OF THE COMPUTER EXPERIMENTS ON THE APPARENT
SORTING IN THIN AND PLANE SECTIONS¹

	Mean Size (phi)	Sphere Sets ⁵									
		0 ²		0.35		0.50		1.00		2.00	
		mean ³	std dev ⁴	mean	std dev	mean	std dev	mean	std dev	mean	std dev
Thin Section Experiments	-2	0.606	0.089	0.690	0.086	0.792	0.083	1.184	0.061	2.082	0.060
	-1	0.603	0.084	0.699	0.080	0.744	0.069	1.172	0.056	2.089	0.085
	0	0.604	0.095	0.704	0.075	0.797	0.098	1.168	0.084	2.058	0.062
	1	0.591	0.073	0.682	0.071	0.777	0.095	1.166	0.106	2.031	0.050
	2	0.608	0.104	0.698	0.076	0.767	0.115	1.119	0.075	2.003	0.050
	3	0.569	0.092	0.668	0.083	0.730	0.069	1.104	0.065	2.000	0.042
	4	0.542	0.090	0.629	0.086	0.692	0.092	1.072	0.055	2.000	0.049
	5	0.467	0.098	0.569	0.098	0.630	0.074	1.069	0.062	2.000	0.062
Plane Section Experiments		0.587	0.093	0.688	0.078	0.767	0.080	1.166	0.064	2.083	0.060

¹All means and standard deviations (sortings) were computed using the moment measures for grouped data in Part 1B of Table 3.

²Actual sorting of sphere set.

³Mean of 25 apparent sorting values.

⁴Standard deviation of 25 apparent sorting values.

⁵All sets contained 100 spheres except the set with 0.35 phi sorting which contained 101 spheres.

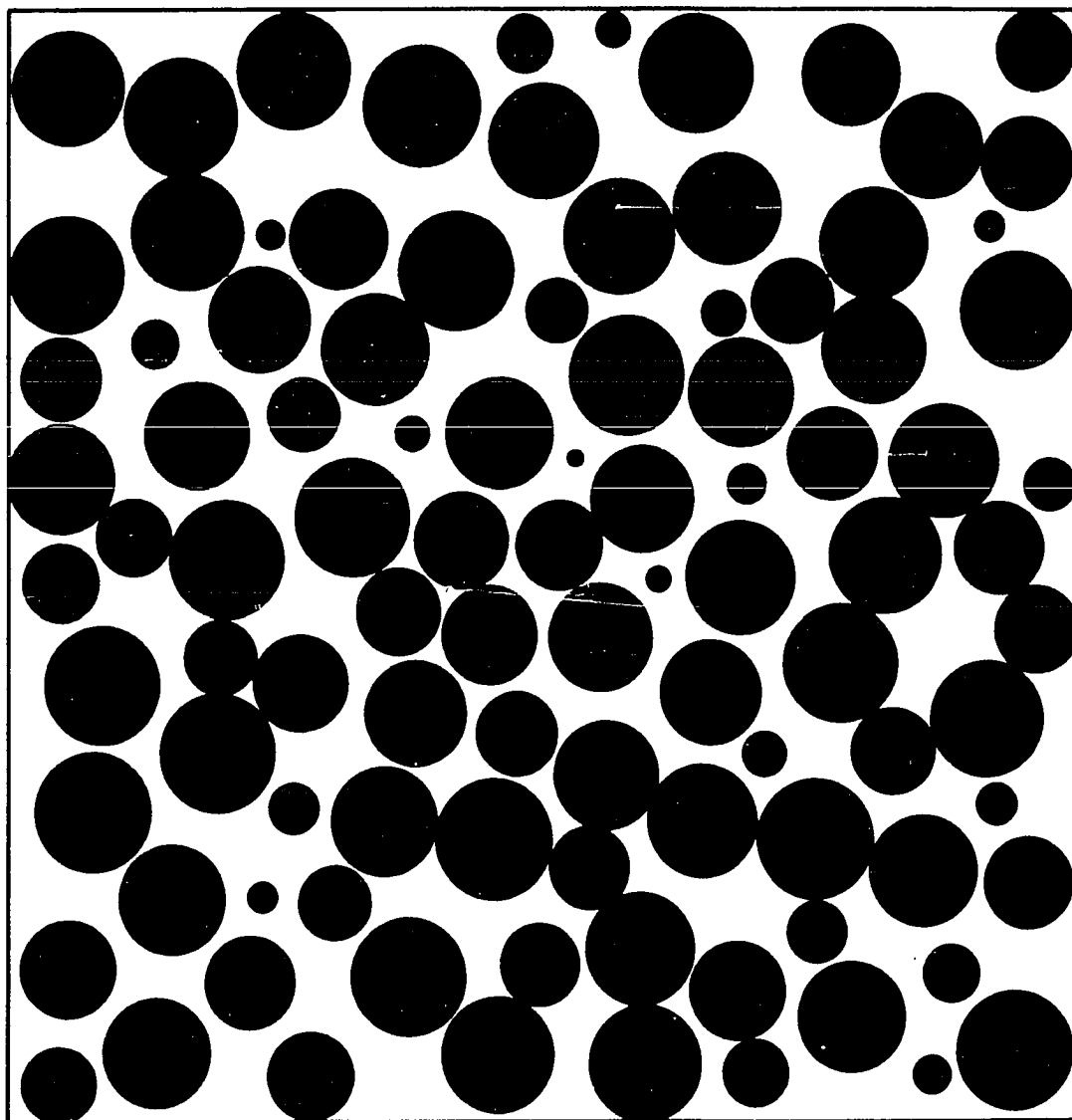


FIG. 15 — Sorting image for a random plane section through a lognormally distributed set of spheres having an 'actual' sorting of 0 phi.

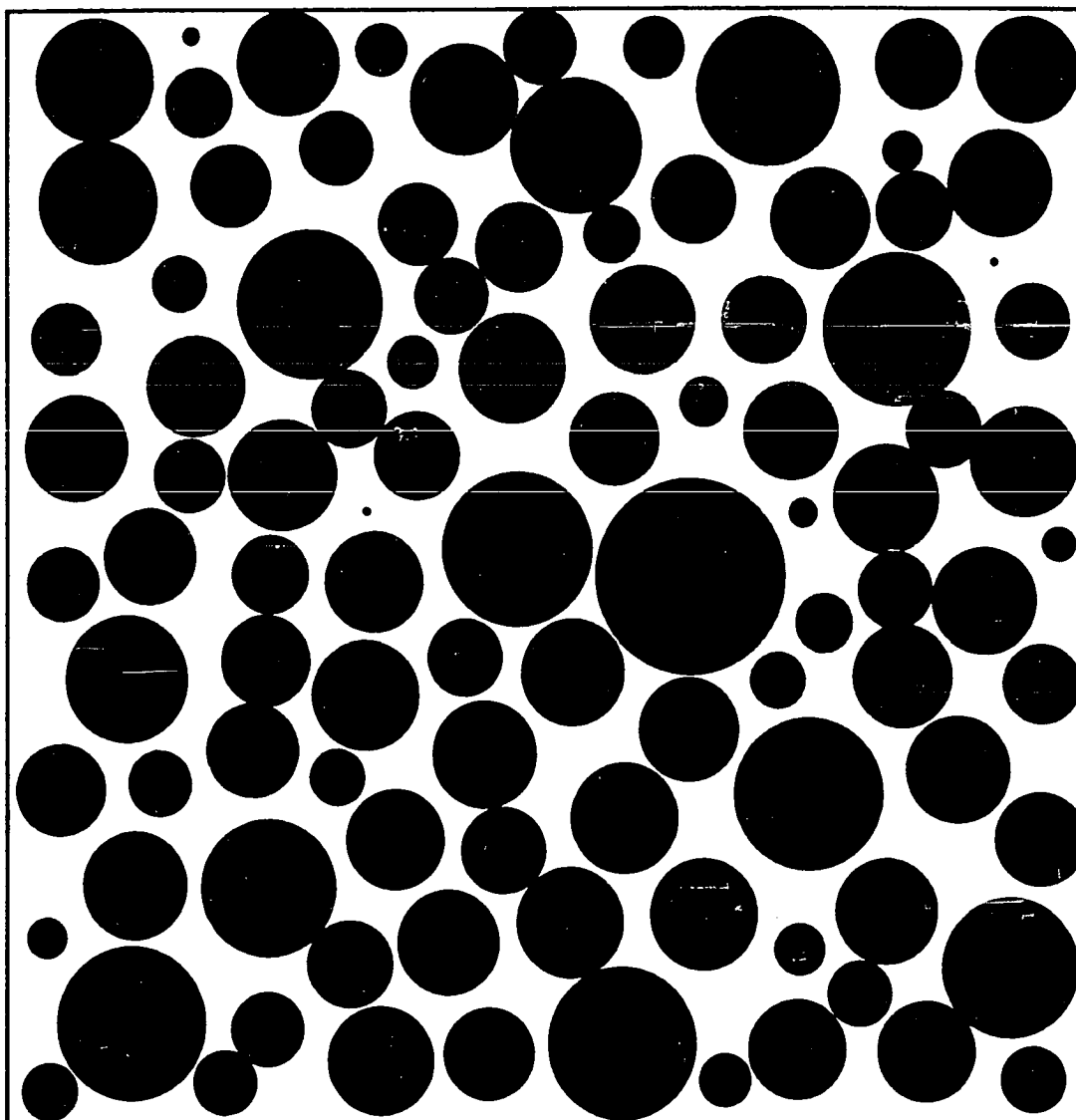


FIG. 16 – Sorting image for a random plane section through a lognormally distributed set of spheres having an 'actual' sorting of 0.35 phi.

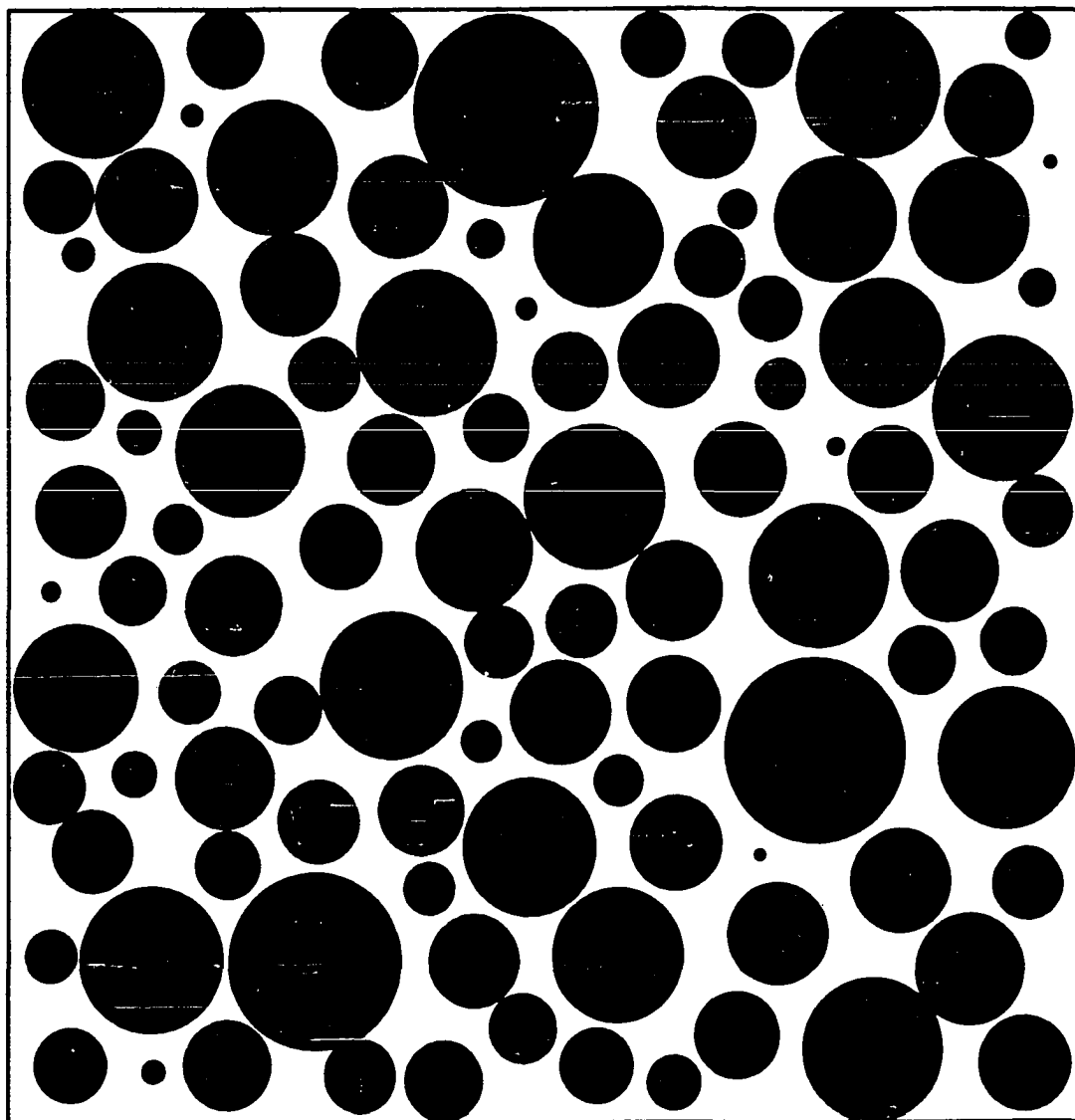


FIG. 17 – Sorting image for a random plane section through a lognormally distributed set of spheres having an 'actual' sorting of 0.50 ϕ .

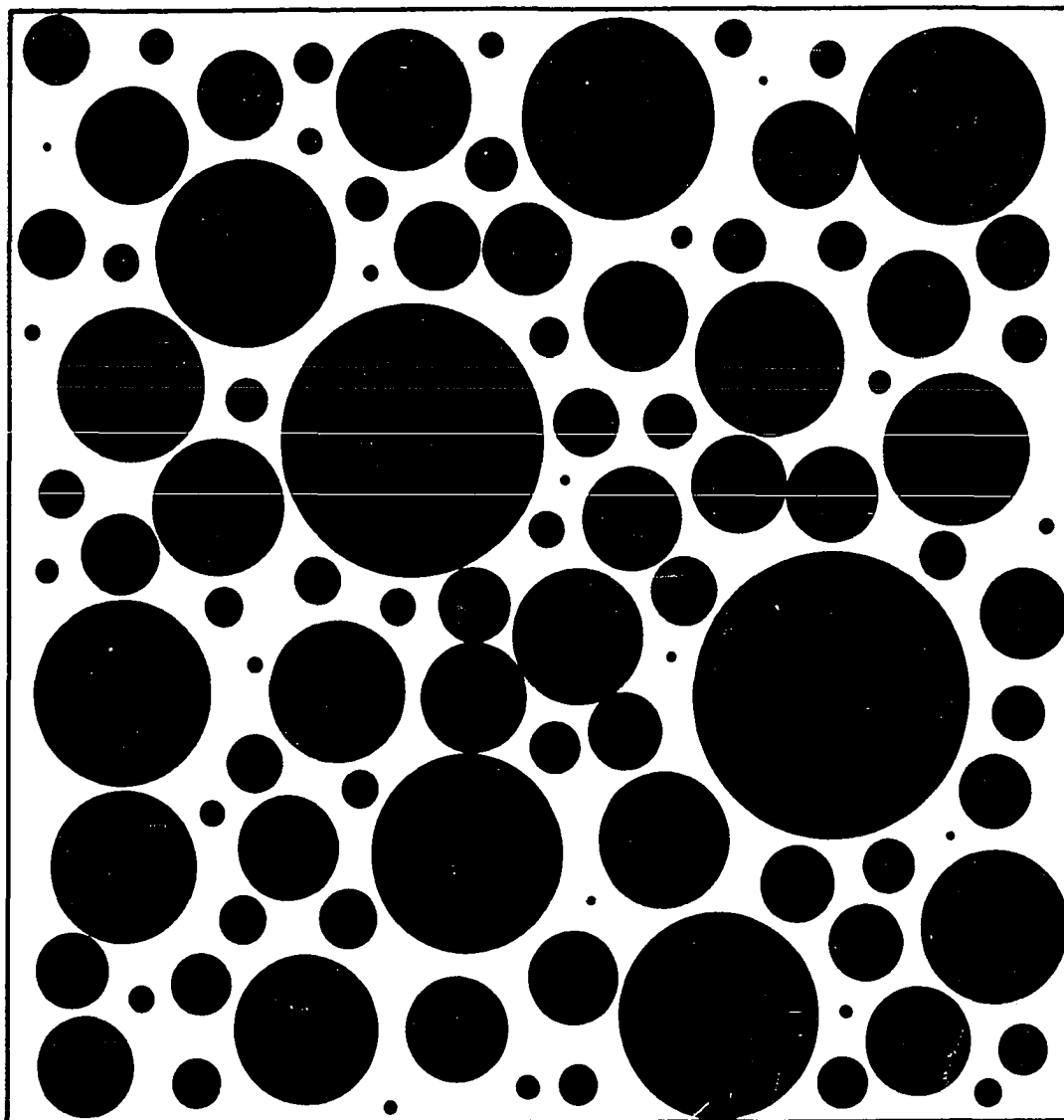


FIG. 18 – Sorting image for a random plane section through a lognormally distributed set of spheres having an 'actual' sorting of 1.00 ϕ .

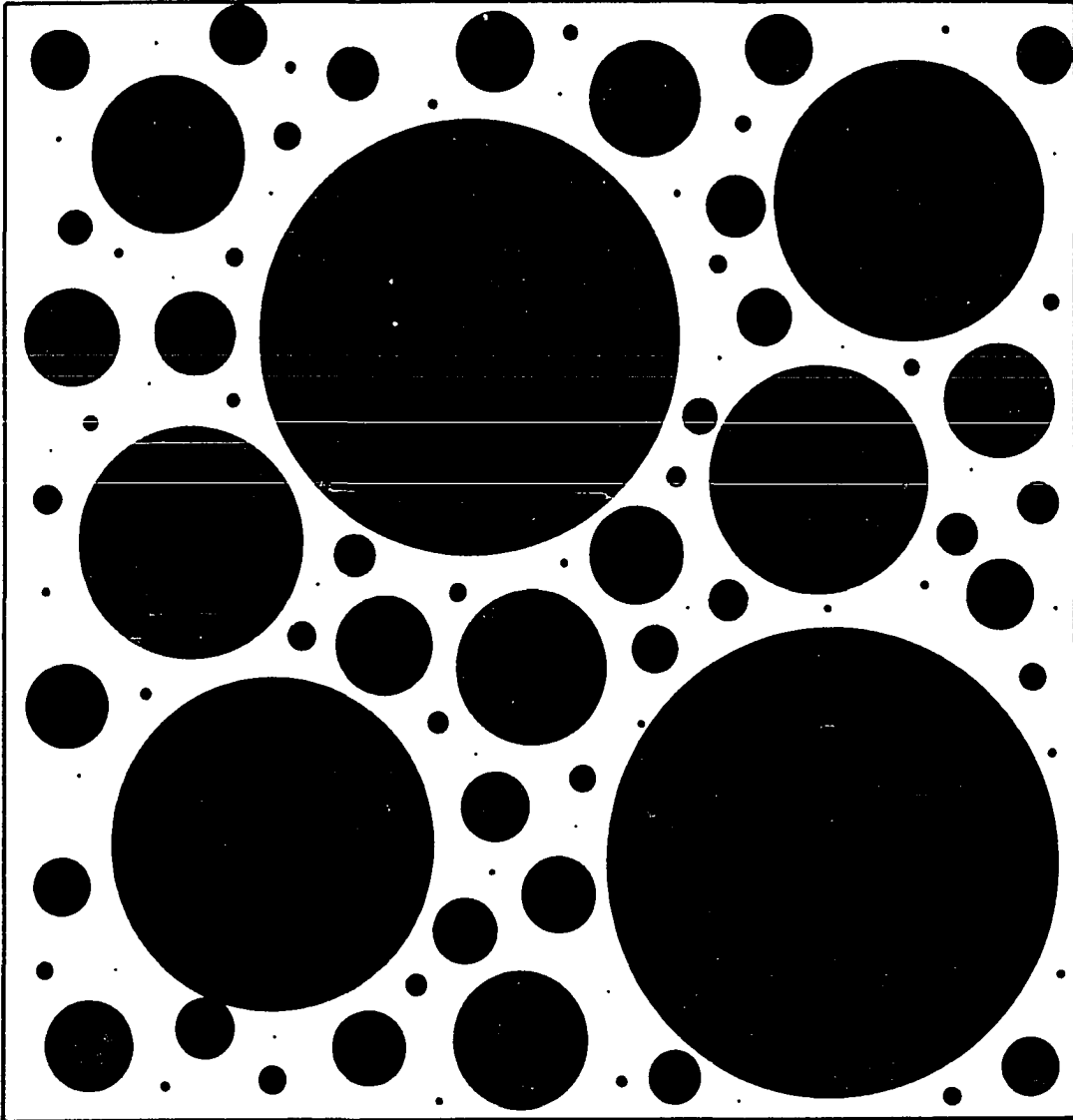


FIG. 19 — Sorting image for a random plane section through a lognormally distributed set of spheres having an 'actual' sorting of 2.00 ϕ .

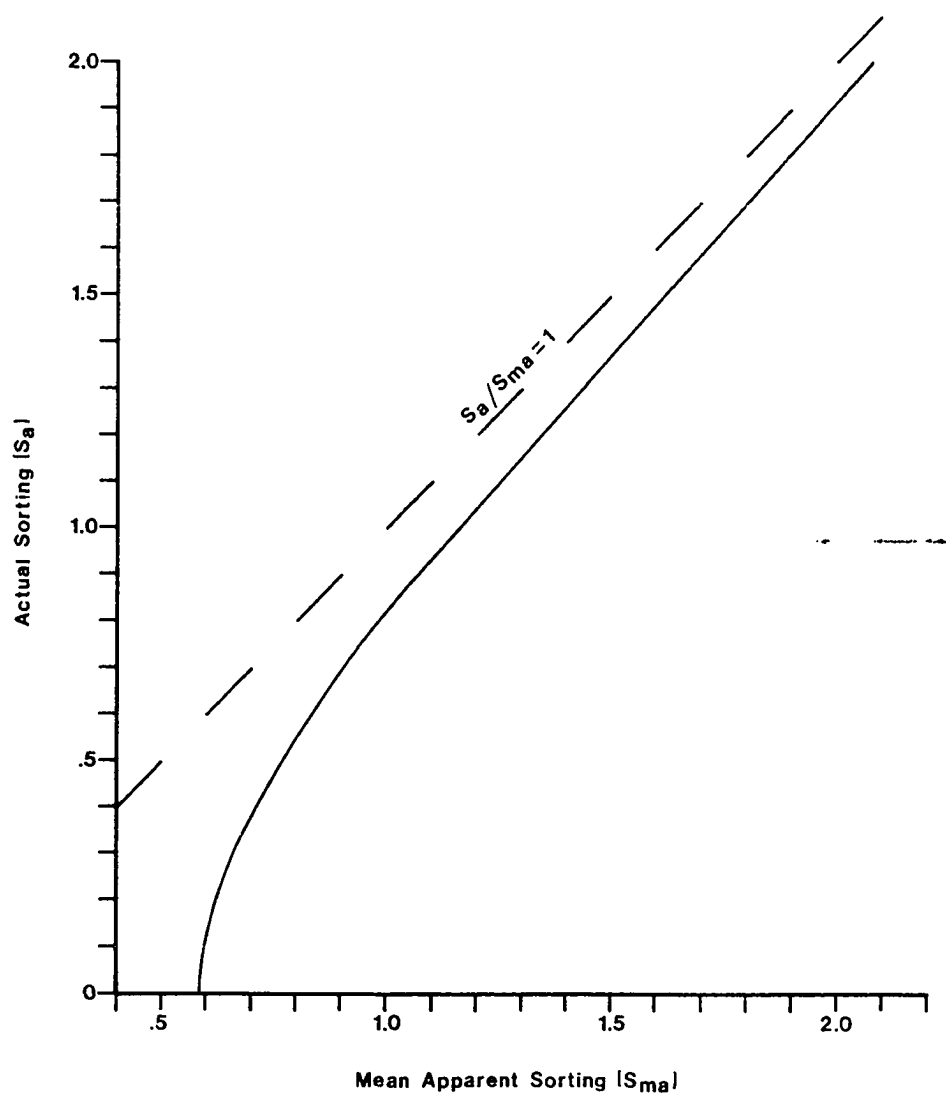


FIG. 20 — Plot of 'actual' versus 'mean apparent' sorting for plane-sectioned sphere sets.

Thin Section Experiments

Because thin sections, unlike plane sections, have a finite thickness (normally 30 microns) the discrepancy between the actual and apparent sorting is a function not only of the magnitude of the sorting but the size of the grains as well. This is because when looking through a thin section we see a three-dimensional slice through a grain (Figure 28). The smaller the grains are relative to the thin section thickness, the more likely the slice is to contain the intermediate dimension of some of the grains. Thus, the apparent sorting in thin section for a very fine sand would be closer to the actual sorting (as measured by sieving) than would be the case for a very coarse sand. If one wanted a sorting comparator based on thin sections rather than plane sections, then for each sphere set a series of sorting images would be required for the different mean sphere sizes. Clearly, this is impractical. It is also unnecessary as will be shown shortly. It is maintained here that the random plane sections, which are independent of sphere size, provide a sufficiently accurate basis for the design of a sorting comparator. The purpose of the thin section experiments described below is to document 1) the magnitude of the effect of grain size on apparent sorting in thin section, and 2) the relation between apparent sorting in plane and thin sections.

The following operations were performed for each of the five sphere sets.

- 1) Seven replicate sphere sets were created, each having the same

sorting but different mean size: -2, -1, 0, 1, 2, 3, 4 and 5 phi. This range of mean sphere sizes completely brackets the sand size range (-1 to 4 phi).

2) It is recognized that thin section slices through a sphere can take any of several forms depending upon the sphere dimension and the position of the sphere center. The latter may lie within the thin section, or above or below the thin section at a distance between zero and the sphere radius (Figure 21). For each sphere within a replicate set, the quantity $2 \cdot r + t$ was computed (r is the sphere radius and t is 30 microns, the thin section thickness). This quantity was then multiplied by a uniform random number between 0 and 1. The resulting product (c) located the position of the sphere's center relative to the top and bottom of the thin section. From Figure 21 it is clear that if $c < r$ or $c > (r + t)$, the maximum sphere dimension ($2 \cdot r$) lies outside the thin section; and if $r \leq c \leq (2 \cdot r + t)$, the maximum sphere dimension lies within the thin section. The 'apparent' sphere diameter in the thin section is in the first case less than $2 \cdot r$, and in the second case is equal to $2 \cdot r$. From a knowledge of the actual sphere diameter, the position of the sphere center and the thin section thickness, the maximum dimension of the sphere slice within the thin section can be determined.

3) The moment standard deviation was calculated for the thin section diameters (i.e., the diameters of the circular outlines of the sphere slices visible in a random thin section). This standard deviation constitutes the 'apparent sorting' of a replicate sphere set.

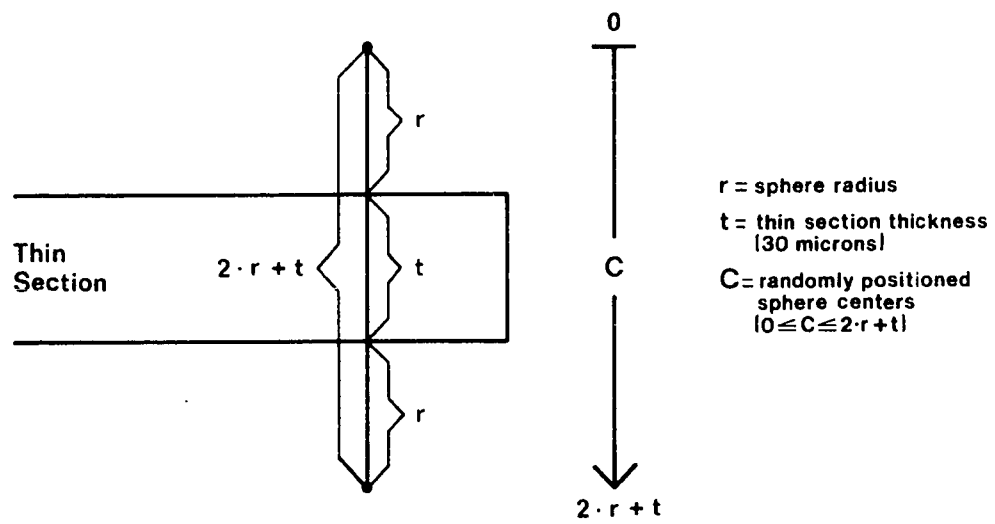


FIG. 21 – Geometrical considerations for sphere slices in the thin section experiments.

4) Steps 2 and 3 above were repeated for each replicate sphere set a total of 25 times, each time using a different set of uniform random numbers to slice the spheres.

5) The moment mean and standard deviation were computed for the 25 apparent sorting values for each replicate sphere set (Table 9).

The results of the plane and thin section experiments are compared in Figure 22. From the plots in this figure three observations can be made. First, for sphere sizes of 2 phi or smaller, and actual sorting values of 1.00 phi or less, the apparent thin section sorting becomes nearly constant and approaches in value the apparent plane section sorting. Second, as expected, the apparent thin section sorting approaches in value the actual sorting with decreasing mean sphere size. Third, the maximum difference between the apparent plane and thin section sorting for mean sphere sizes within the sand size range is only about 0.1 phi.

Concluding Remarks

A visual comparator has been developed for estimating the sorting of a clastic sediment in thin section. Although the sorting images are based on plane sections, Figure 22 shows that the apparent sorting in plane and thin sections is very nearly the same (within 0.1 phi) for mean grain sizes within the sand range. The intervals for the Folk sorting scale are sufficiently broad that use of this visual comparator should permit the accurate determination of the 'true' sorting class of a sediment.

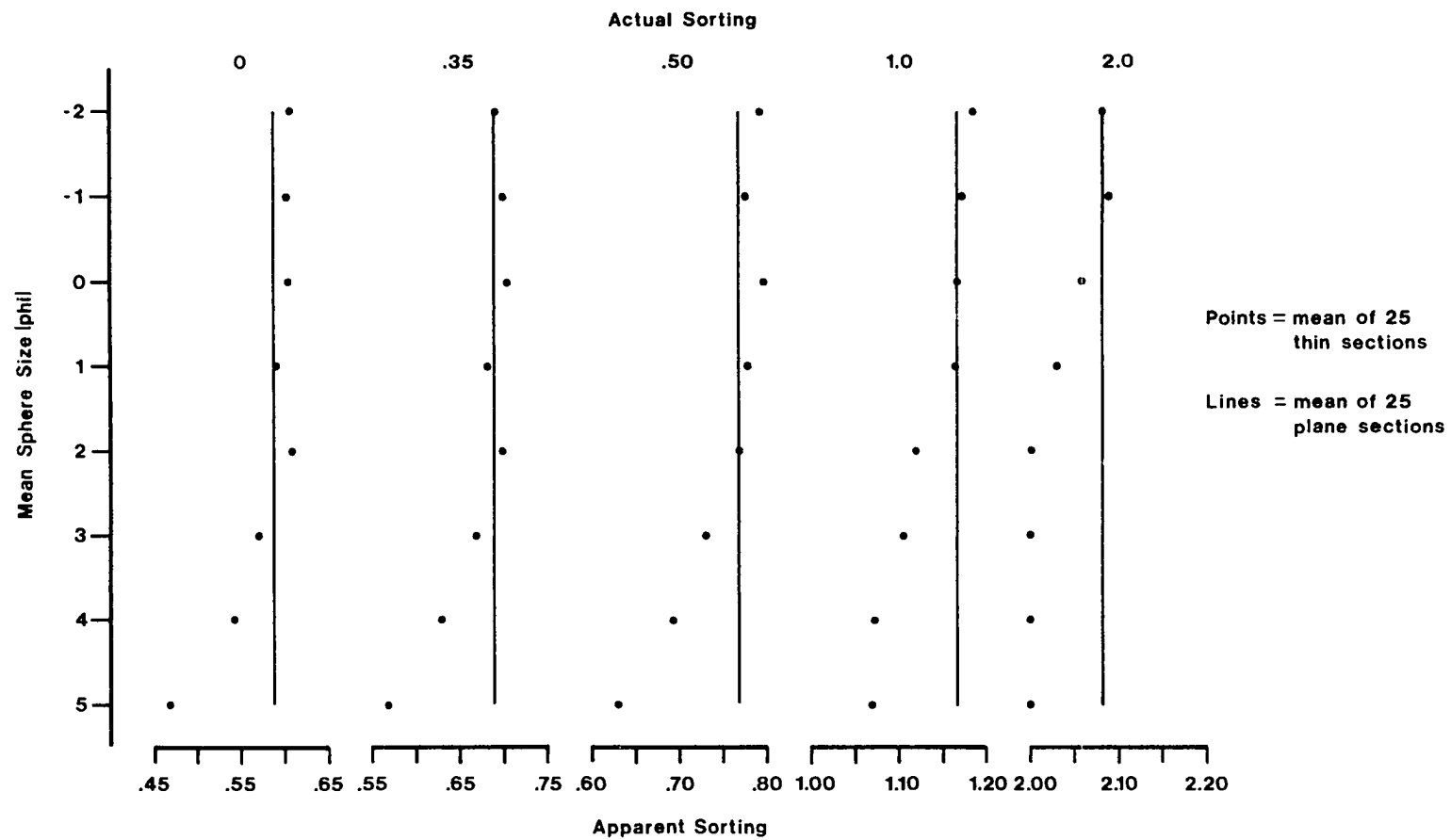


FIG. 22 — Comparison of the results for the plane section and thin section experiments.

Using the actual sorting values for previously published comparators (Table 7) and the apparent sorting values for the comparator developed in this study, a set of sorting images could be compiled and used for estimating sorting in loose grains and hand specimens.

The previously published comparators can be put to still another use. If we let the sorting images in these comparators represent random plane sections through spheres rather than outlines of whole loose spheres, the actual sorting for these images in Table 7 would correspond to the plane section sorting. The sorting of hypothetical sets of spheres can be determined using these plane section sorting values and Figure 20. For those sorting images in Table 7 with an actual sorting (S_a) in excess of 0.585 (the minimum possible apparent sorting for plane sections) the actual sorting of the corresponding sphere sets (S_s) are: $S_a = 0.60$, $S_s = 0.05$; $S_a = 0.75$, $S_s = 0.46$; $S_a = 0.77$, $S_s = 0.50$; $S_a = 1.05$, $S_s = 0.86$; and $S_a = 1.14$, $S_s = 0.97$. These results make it possible to use published sorting comparators to augment the set of plane section sorting images developed in this study.

SEDIMENTOLOGIC SIGNIFICANCE OF GRAIN FORM

Introduction

The hydraulic sorting of grains traveling by saltation and intermittent or sustained suspension is primarily a function of their settling

velocity. The sorting of grains traveling in traction on the bed is controlled by the ease of sliding or rolling ('rollability'), a behavioral property not necessarily related to settling velocity. In a decelerating current, grains deposited from saltation and suspension generally undergo a period of movement on the bed by traction. Thus at some point during their transport history virtually all sediment grains experience traction and, except perhaps for the coarse sand and larger grains, saltation and suspension as well. Because grains are subjected to innumerable cycles of reentrainment, transport and deposition, and because grains that are deposited together are not necessarily reentrained together, it is important for sedimentary petrologists to understand how the physical properties of grains affect their settling velocity and rollability, and hence their sorting.

Mass (i.e., size and density) is the most important grain property controlling settling velocity and rollability. Of secondary but still considerable importance is grain shape. Studies on the hydraulic effects of grain size and density are legion. Relatively few studies have addressed the hydraulic effects of grain shape. This study will focus on the effect of grain 'form' on settling velocity. The other two aspects of grain shape, roundness and surface texture, will be shown to have a comparatively small influence on settling velocity. The settling behavior of grains is important not only because it controls sorting during saltation and suspension transport but also because it can have a high positive correlation with rollability (Krumbein, 1942 and; especially, Winkelmoen, 1971).

A New Empirical Equation For Predicting
The Effect Of Grain Form On
Settling Velocity

Statement of the Problem

It would be useful in sedimentology to have a concise, straightforward set of equations which accurately relates the form of sand-sized grains to their terminal settling velocity in water. Surprisingly, such a set of equations does not exist. Instead, there are currently two alternative approaches. The first is a highly involved procedure proposed by Janke (1963, 1966 and 1979) which requires the use of a series of empirical equations, plots and tables. The complexity of the approach is well illustrated by the flow chart in Figure 1 of Janke (1979). Although the predicted fall velocities are very accurate, the procedure is not a popular one because it requires considerable time and effort to perform the calculations. The second approach utilizes tables or curves (USIACWR, 1957; Zeigler and Gill, 1959; and ASCE, 1962) that are based on the experimental work of Schulz et al. (1954). These authors used natural sediment grains in their experiments. There are two problems with this approach: only very rough estimates of settling velocity are provided, and the data is limited to a small variety of grain forms. Grain form in these curves and tables is expressed in terms of the Corey 'shape factor' ($S/\sqrt{L \cdot \bar{I}}$) and typically is provided only for shape factors of 0.3, 0.5, 0.7, 0.9 and 1.0.

The approach developed in this study for calculating the settling velocity of a nonspherical grain can be symbolically represented by the following equation:

$$V_n = V_s \cdot RFF \quad (1)$$

where V_n is the settling velocity of a nonspherical grain; V_s is the settling velocity of the equivalent sphere (i.e., a sphere having the same volume and density as the nonspherical grain); and RFF is the Reynolds-Form Factor, a parameter that takes into account the grain form and the dynamic character of the fluid immediately adjacent to the falling grain. For a given volume and density, a smooth sphere settles at a higher velocity than grains of any other shape (Kunkel, 1948; Malaika, 1949; McKnown et al., 1951; and Briggs et al., 1962). The settling velocity of the equivalent sphere serves then as a useful reference datum. If the Reynolds-Form Factor varies between 0 and 1, then V_n can be obtained by multiplying V_s by RFF and thus, in a sense, V_s is 'corrected' for the braking effects of grain form and fluid character. In the present study, V_s was obtained from a published set of equations and RFF was calculated from an equation derived here.

Calculation of the Settling Velocity of a Sphere

There are only two calculation procedures which accurately predict the settling velocity of sand-sized spheres (Janke, 1965; and Gibbs et al., 1971). Both utilize empirical equations. Of the two, the one developed by Janke is superior because of its greater generality.

It can be applied to particles of any density, and fluids of any density and viscosity. In contrast, the procedure of Gibbs et al. is applicable only to particles with a density near that of quartz and to fluids with densities and viscosities within the range of fresh and marine waters. Both procedures give comparable results for sand-size quartz spheres settling in water and both have a maximum error in predicted velocity of about one percent. It should be kept in mind that the computed velocity is only for a single sphere settling through a quiescent fluid. The two calculation procedures are summarized below.

1) Janke (1965)

$$A = \frac{4 \cdot ([\rho_s/\rho_f] - 1) \cdot d_n^3 \cdot g}{3 \cdot (\mu/\rho_f)^2}$$

$$B = 10(0.0293 \cdot \log_{10} A - 0.000785 \cdot [\log_{10} A]^2 + 0.008)$$

$$R_n = 10([\log_{10} A - 1.435]/B) \quad (2)$$

$$V_s = \frac{R_n \cdot \mu}{d_n \cdot \rho_f} \quad (3)$$

where ρ_s and ρ_f are the sphere and fluid densities, respectively (gm/cm^3); d_n is the 'nominal diameter' of the particle (cm) and is equal to the diameter of the sphere having the same volume as the particle of interest; g is the gravitational acceleration (980.6 cm/sec^2); and μ is the dynamic viscosity of the fluid (in units of poise, $\text{gm}/[\text{cm} \cdot \text{sec}]$). The Reynolds Number, R_n , is calculated in equation 2. More will be said about this parameter

in a later section. If V_s is calculated for a nonspherical particle of unknown volume, the nominal diameter can be estimated by assuming that the particle shape can be approximated by either a rectangular parallelepiped ($d_n = \sqrt[3]{(6/\pi) \cdot L \cdot I \cdot S}$) or, more realistically, a triaxial ellipsoid ($d_n = \sqrt[3]{L \cdot I \cdot S}$).

2) Gibbs et al. (1971)

$V_s =$

$$\frac{-3 \cdot \mu + \sqrt{9 \cdot \mu^2 + (g/4) \cdot d_n^2 \cdot \rho_f \cdot (\rho_s - \rho_f) \cdot (0.015476 + 0.099205 \cdot d_n)}}{\rho_f \cdot (0.011607 + 0.074405 \cdot d_n)} \quad (4)$$

where V_s , μ , g , ρ_f , ρ_s and d_n are as previously defined for Janke (1965).

Derivation of the Reynolds-Form Factor

Introduction

The value of the Reynolds-Form Factor for a given particle and fluid is a function of the Reynolds Number for the equivalent sphere (R_{ne}) and some measure of the particle's form (PF). Equation 1 can then be rewritten as:

$$V_n = V_s \cdot f(R_{ne}, PF) \quad (5)$$

What is needed now is an equation describing $f(R_{ne}, PF)$. It is

clear that the value of $f(R_{ne}, PF)$ should ideally equal the ratio of V_n to V_s . This ratio, which is the square root of the 'dynamic shape factor' of Briggs et al. (1962), will be referred to here as the 'standardized fall velocity' of a particle. It is also clear that R_{ne} and PF should individually have the strongest possible correlation with V_n/V_s . For PF , one of the several form measures proposed in the literature will be used in the Reynolds-Form Factor equation. But for R_{ne} a problem is encountered. As will be demonstrated in a later section, R_{ne} has a nongeometric inverse relationship with V_n/V_s . Thus some function of R_{ne} which is maximally correlated with V_n/V_s will have to be derived. It is this function (RF) that will be used in the Reynolds-Form Factor equation. The coefficients for PF and RF in this equation will be determined using experimental data and standard multiple regression.

The Reynolds Number Concept

The Reynolds Number is a dimensionless parameter that describes the dynamic character of the fluid immediately adjacent to a settling particle. It can be calculated by rearranging equation 3: $R_n = (V_s \cdot d_n \cdot \rho_f) / \mu$. At Reynolds Numbers below about 0.5 (the 'Stokes range') the fluid flow around a falling particle is said to be fully laminar: the fluid moves along smooth, regular streamlines which are essentially parallel to the surface of the particle (Middleton and Southard, 1977, p. 2.9 and 3.9). The effect of this fluid condition

is that all particle orientations are stable during settling regardless of particle shape. Thus the settling velocity will vary with the orientation of a particle, being greatest when the minimum surface area is exposed on the side of the particle facing the direction of fall (Janke, 1966).

The Reynolds Number increases as the flow separation and turbulence generated by a falling particle increases. Flow separation refers to the divergence of streamlines away from the particle surface on the side opposite the direction of fall. Turbulence is the term applied to the irregular, random fluid motions behind the particle in the zone of flow separation. At Reynolds Numbers within the Stokes range most of the drag on a settling particle is due to the 'viscous shear stress' applied to the particle surface. At higher Reynolds Numbers, however, the drag results principally from the development of the zone of flow separation with its accompanying turbulent wake. The pressure within this zone is generally negative relative to the ambient fluid pressure. This negative pressure acts as a 'suction brake' and further retards the downward movement of a particle (Middleton and Southard, 1977). The higher the Reynolds Number, the greater this retardation.

At Reynolds Numbers above the Stokes range, falling particles tend to have only one stable orientation because of the presence of a zone of flow separation. The most stable orientation is that in which the plane of the maximum cross-sectional area is approximately normal to the direction of fall (Krumbein, 1942; and McNown and Malaika, 1950). At Reynolds Numbers above about 100, nonsymmetrical particles

(e.g., natural sediment grains) become unstable and rather than falling vertically in a single orientation may experience an oscillating or side-to-side glide-tumble ('falling leaf') type of motion (Alger and Simons, 1968; Stringham et al., 1969; and Middleton and Southard, 1977, p. 4.6). For symmetrical regular geometric particles the fall instability begins at Reynolds Numbers between 400 and 500 (Stringham et al., 1969).

All particles, regardless of shape, experience fluid drag but non-spherical particles experience more than spheres because of their greater surface area per unit volume and less streamlined shape (Middleton and Southard, 1977, p. 4.5). Thus the settling velocity of a nonspherical particle will always be less than that for the equivalent sphere because of its greater 'form drag'. The role of the Reynolds-Form Factor is now clear. This parameter will measure the form drag of a nonspherical particle. Its formulation will incorporate information on the particle's form and the Reynolds Number for the particle's equivalent sphere.

The maximum and minimum Reynolds Numbers for sand-size quartz spheres settling in distilled water at 20°C are, respectively, 550 ($d_n = 2.000\text{mm}$) and 0.2 ($d_n = 0.063\text{mm}$) (calculated from equations 3 and 4). According to Briggs and Middleton (1962) most natural quartz sand grains that experience saltation or suspension transport settle through water with a Reynolds Number of less than 100, the value for a coarse, sand-sized quartz sphere.

Experimental data

Formulation of the empirical Reynolds-Form Factor required the use of experimental data. The geological and especially the civil engineering literature abounds with the results of settling velocity

experiments which used variously shaped test particles. Some of these studies used natural sand, granule or pebble clasts: Corey, 1949; Albertson, 1953; Wilde, 1952; Schulz, 1953; Schultz et al., 1954; Briggs et al., 1962; Alger, 1964; Alger and Simons, 1968; Komar and Reimers, 1978; and Baba and Komar, 1981. In addition, Maiklem (1968) and Braithwaite (1973) have performed settling experiments using carbonate skeletal clasts. Still other studies have used regular geometric particles (all particles are machined metal or plastic unless otherwise stated): Krumbein, 1942—hand-molded clay rectangular parallelepipeds, cylinders and triaxial ellipsoids; Kunkel, 1948—sphere aggregates with various geometries; Pettyjohn and Christiansen, 1948—rectangular parallelepipeds (cubes only) and a variety of other isometric ($I/L = S/I = 1$) particles; Malaika, 1949—rectangular parallelepipeds, cylinders, double cones and spheroids (the latter are also known as prolate and oblate ellipsoids of revolution); Pramanik, 1950—rectangular parallelepipeds and octahedral double pyramids; Janke, 1963—rectangular parallelepipeds; Stringham, 1965 and Stringham et al., 1969—cylinders and spheroids; Williams, 1966—cylinders; Komar, 1980—cylinders. All of the studies just cited for regular geometric particles contain a listing of the raw experimental data. Other references which merely discuss the results of some of these experiments but present no raw data are: McNown and Malaika, 1950; McNown et al., 1951; and Janke, 1966.

In selecting experimental data from the literature two factors had to be considered: 1) the type of particle—natural sediment clasts or any of several varieties of machined regular geometric particles;

and 2) the Reynolds Number of the particle. Only experimental data for test particles settling within the Reynolds Number range for sand-sized grains (about 0.1 to 500) were considered. The use of natural sediment clasts was ruled out because these particles vary not only in form but in roundness, surface texture and symmetry as well. Further, the experimental data for these clasts was considerably less reliable than that for the regular geometric particles. It was decided then to use the data for one variety of regular geometric particle. Only one variety could be used because it was desired that the Reynolds-Form Factor depend only on particle form. Inclusion of other particle varieties in the data set would introduce another factor, roundness. Of the several varieties of regular geometric particles, the rectangular parallelepipeds had by far the widest range of forms. All other varieties had a very limited form range because two of their three principal dimensions were always equal (i.e., S/I or $I/L = 1$). Next to the tri-axial ellipsoid the rectangular parallelepiped is probably the most appropriate type of geometric solid for representing the shape of natural sediment grains. Interestingly, the hydraulic behavior of both particle varieties is apparently quite similar. According to McNown et al. (1951, p. 512), ". . . tests with biaxial particles indicated that there was little difference between the performances of prismatic and ellipsoidal particles of the same proportions".

The experimental data for rectangular parallelepipeds used in this study were constituted as follows: Pettyjohn and Christiansen (1948)—6 particles and 7 analyses; Pramanik (1949)—8 particles and 39 analyses;

Mailaika (1950)—6 particles and 19 analyses; and Janke (1963)—10 particles and 20 analyses. The raw data from these studies have been tabulated in Appendix F. Among the 30 test particles there are actually only 17 different forms (Figure 23). Although the test particles are generally larger than 2 millimeters and made of metal, the investigators were able to obtain a range of Reynolds Numbers comparable to that for sandy sediment by varying the fluid density and viscosity. The range of Reynolds Numbers for the above data is 0.1 to 450. All of the data in Appendix F represent analyses where the test particles maintained a single stable orientation and a vertical fall path. The individual settling velocities are the result of a single 'drop' rather than the average of several drops. Except for the data from Pettyjohn and Christiansen (1948), none of the data in Appendix F has been published outside of the original Masters and Doctoral theses.

Reynolds number and the standardized fall velocity

Figure 24 illustrates the relationship between the equivalent sphere Reynolds Number and the standardized fall velocity for rectangular parallelepipeds of a given form (based on data for particles P1A, P1B, P4A, P4B, P14A and P14B in Appendix F). Note that for each of the three forms V_n/V_s decreases with increasing R_{ne} . The figure also shows that the amount of decrease in V_n/V_s with increasing R_{ne} is greater for the less equant forms (P4 and P14) and that the decrease is greatest for the elongate form (P14). This same pattern of behavior is repeated

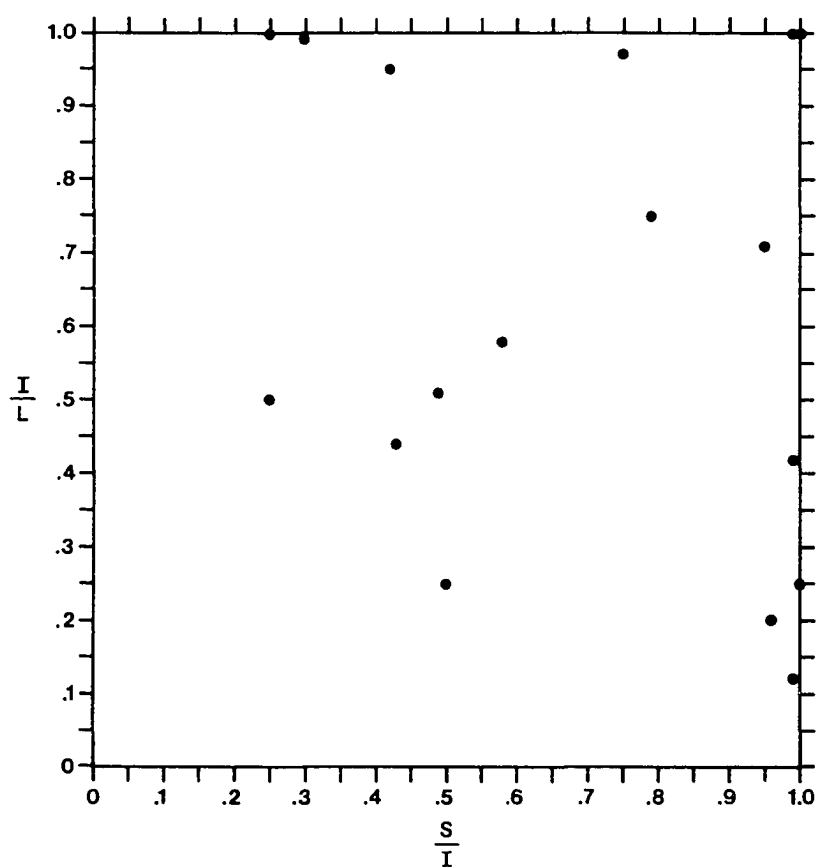


FIG. 23 – Zingg form plot for the rectangular parallelepipeds used in the derivation of the Reynolds-Form Factor.

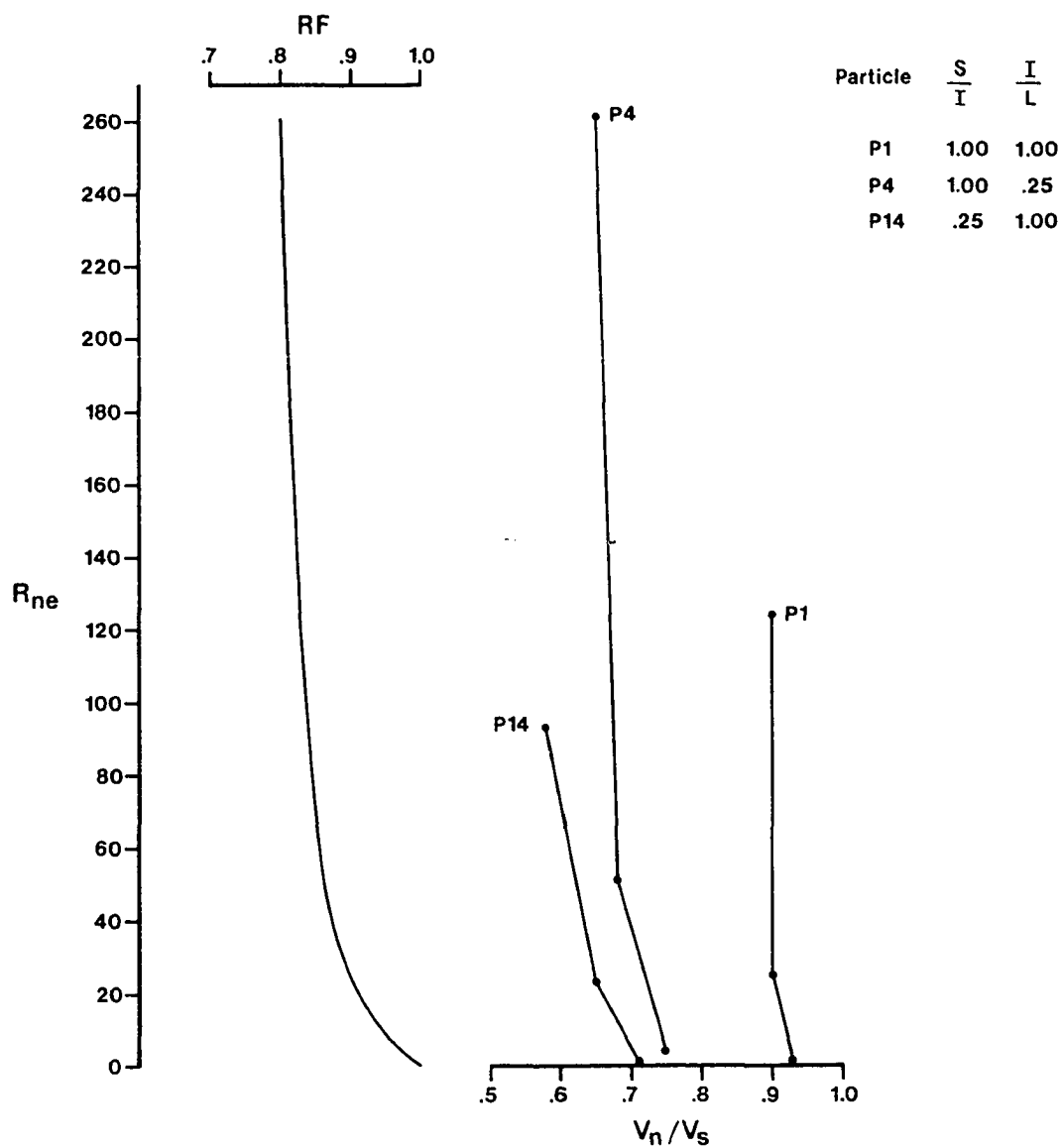


FIG. 24 — Relationship between the equivalent sphere Reynolds number (R_{ne}) and 1) the Reynolds number function (RF), and 2) the standardized fall velocity (V_n/V_s).

for the other forms in Appendix F, and has also been recognized by McNown and Malaika (1950), McNown et al. (1951) and Stringham et al. (1969).

Through a trial-and-error evaluation of numerous functions of R_{ne} , the function described by equation 6 was found to be the best at matching the nongeometric inverse relationship between R_{ne} and V_n/V_s (Figure 24).

$$f(R_{ne}) = RF = 1 / \sqrt[4]{\log_{10}(R_{ne} + 10)} \quad (6)$$

The Pearson Product-Moment linear correlation for RF and V_n/V_s is 0.239 when computed from the 85 analyses in Appendix F. Employing the 't test' to evaluate the statistical significance of this correlation, the correlation was found to be barely significant at the 95 percent confidence level (Crow et al., 1960, p. 159 and 241). The correlation is quite small but this should be expected because the bulk of the variation in V_n/V_s is due to the particle form and not the Reynolds Number.

Particle form and the standardized fall velocity

There are many dimensionless measures of particle form which are based on the three principal grain dimensions. For a general review of these measures see Fleming (1965), Pryor (1971) and Barrett (1980). Some of these measures were developed strictly from geometrical considerations while others were formulated with the interrelationship between settling velocity and particle form in mind. Obviously, a

form measure of the latter type would be most appropriate for inclusion in the Reynolds-Form Factor equation. Several such form measures were evaluated in this study. Each is briefly discussed below.

(1) Intercept Sphericity (Krumbein, 1941)

The 'sphericity' of a particle was originally defined by Wadell (1932) as the ratio of the surface area of a particle to the surface area of a sphere of equal volume. Because the surface area of an irregular particle could not be readily measured, Wadell (1933) introduced the 'practical' or 'operational' sphericity measure where sphericity was defined as the cube root of the ratio of the particle volume to the volume of the circumscribing (not equivalent) sphere. Krumbein (1941) later developed the Intercept Sphericity as an approximation to Wadell's (1933) Operational Sphericity. In Krumbein's form measure the volume of the nonspherical particle is assumed to be approximately equal to that of a triaxial ellipsoid with the same L, I and S dimensions (triaxial ellipsoid volume = $(\pi/6) \cdot L \cdot I \cdot S$). The volume of the circumscribing sphere would be equal to $(\pi/6) \cdot L^3$. The cube root of the ratio of these two volumes reduces to the familiar Intercept Sphericity formula:

$$\text{Intercept Sphericity} = \sqrt[3]{\frac{I \cdot S}{L^2}} \quad (7)$$

The Intercept Sphericity form measure was derived using strictly geometrical considerations. It was considered here, however, because it has been used in the past as an indication of the effect of particle form on settling velocity (e.g., Krumbein and Sloss, 1963, p. 107).

(2) Corey Shape Factor (Corey, 1949; and McNown and Malaika, 1950)

Although this form measure was independently derived by both Corey (1949) and McNown and Malaika (1950) it is almost universally referred to as the Corey Shape Factor. Its formulation is as follows:

$$\text{Corey Shape Factor} = S / \sqrt{L \cdot I} \quad (8)$$

The derivation of this formula was based on the observation that particles tend to settle with their maximum cross-sectional area (i.e., the plane of the L and I dimensions) normal to the direction of fall. The denominator of the formula reflects the importance of maximum cross-sectional area on settling velocity. Both investigators found that this form measure had a high positive linear correlation with V_n/V_s . The Corey Shape Factor is probably the most widely used form measure in the world today.

(3) Maximum Projection Sphericity (Sneed and Folk, 1958)

Recognizing the importance of a particle's maximum cross-sectional area on settling velocity, Sneed and Folk based their form measure on the ratio of the maximum cross-sectional area of a particle ($[\pi/4] \cdot L \cdot I$ for a triaxial ellipsoid) to the maximum cross-sectional area of the equivalent sphere ($[\pi/4] \cdot [\sqrt[3]{L \cdot I \cdot S}]^2$). This ratio reduces to the following formula:

$$\text{Maximum Projection Sphericity} = \sqrt[3]{S^2 / (L \cdot I)} \quad (9)$$

This form measure is, however, not fundamentally different from the Corey Shape Factor because it is equal to the latter taken to the two-thirds power. Interestingly, it was shown by Gray (1971) that the Maximum Projection Sphericity of a particle is approximately equal

to the average width to length ratio of randomly oriented plane sections through a triaxial ellipsoid having the same L , I and S dimensions as the particle. The Maximum Projection Sphericity was also referred to as the 'effective settling sphericity' by Sneed and Folk.

(4) Sphericity Factor (Janke, 1963 and 1966)

Janke's form measure is similar in design to the Corey Shape Factor. It places S in the numerator and the denominator contains a 'representative shape length' which has a strong influence on the settling behavior of a particle. The formulation of the Sphericity Factor is as follows:

$$\text{Sphericity Factor} = S / \sqrt{(L^2 + I^2 + S^2)/3} \quad (10)$$

A variety of denominators were evaluated experimentally by Janke and he found the one in equation 10 had the highest correlation with settling behavior. Janke further justified the choice of this denominator by pointing out that it closely approximates the moment of inertia for rotating bodies. In the published formulation of the Sphericity Factor, Janke used not L (the maximum dimension normal to the I and S dimensions) but rather the absolute maximum dimension irrespective of particle symmetry (for rectangular parallelepipeds this dimension, $L_{\max}$, is the distance between the two most widely separated corners: $L_{\max} = \sqrt{L^2 + I^2 + S^2}$). In order to be consistent with the other form measures previously described which utilize L rather than $L_{\max}$, L was used in equation 10. In his settling experiments with cylinders, Komar (1980) similarly used L rather than $L_{\max}$ in Janke's Sphericity Factor.

Selection of one of the above form measures for inclusion in the Reynolds-Form Factor equation was based on the strength of the Pearson Product-Moment linear correlation between the form measure and V_h/V_s . The correlation coefficients (r) were computed from the 85 analyses in Appendix F. The values of the square of the correlation coefficient (r^2 , the 'coefficient of determination') for the various form measures are, in order of increasing correlation: Intercept Sphericity, $r^2 = 0.679$; Maximum Projection Sphericity, $r^2 = 0.746$; Corey Shape Factor, $r^2 = 0.749$; and Sphericity Factor, $r^2 = 0.777$.

From these results it is clear that Janke's Sphericity Factor is the form measure most sensitive to settling behavior and, as a consequence, will be included in the Reynolds-Form Factor equation. The Sphericity Factor is admittedly only slightly better than the Corey Shape Factor and the Maximum Projection Sphericity. As expected, the Intercept Sphericity was the weakest of the form measures but it still proved to be nearly as sensitive to settling behavior as the Sphericity Factor. The validity of the above correlations is substantiated by the results of two other studies. Komar (1980) in his settling experiments with glass cylinders found the Sphericity Factor to have a higher correlation with settling behavior than the Corey Shape Factor. Briggs et al. (1962) in their settling experiments with grains of 15 common heavy minerals ranked the various form measures as follows, in increasing order of correlation with settling behavior: Intercept Sphericity, Maximum Projection Sphericity and Corey Shape Factor.

In Figure 25 the Sphericity Factor is plotted against the elongation (I/L) and flatness (S/I) ratios of the Zingg diagram. For a very rough first approximation, the Standardized Fall Velocity (V_n/V_s) can be estimated directly from Janke's Sphericity Factor.

Regression analysis

Standard multiple regression procedures were used to develop an equation for the Reynolds-Form Factor. This equation was to be based upon the Reynolds Number function (RF, equation 6) and the Janke Sphericity Factor (SF, equation 10). The first regression model evaluated was the following:

$$(V_n/V_s) = a + (b \cdot RF) + (c \cdot SF) + (d \cdot RF^2) + (e \cdot SF^2) + (f \cdot RF \cdot SF)$$

This model is a full second degree or quadratic polynomial equation with two predictor variables, RF and SF. The response variable, (V_n/V_s), represents the expected value of the Reynolds-Form Factor (RFF, equation 1). The unknown intercept constant (a) and regression coefficients (b, c, d, e and f) were determined using the experimental data in Appendix F and the SAS (Helwig and Council, 1979, p. 237-264) computer program for regression analyses (the General Linear Models Procedure).

As part of the program output, the statistical significance of the regression coefficients was evaluated using a conventional 't test' (for a description of this test see Crow et al., 1960, p. 179-181). Each regression coefficient was tested separately under the null hypothesis that the population value of the coefficient equaled zero. As a result of these tests two of the regression terms, $d \cdot RF^2$ and

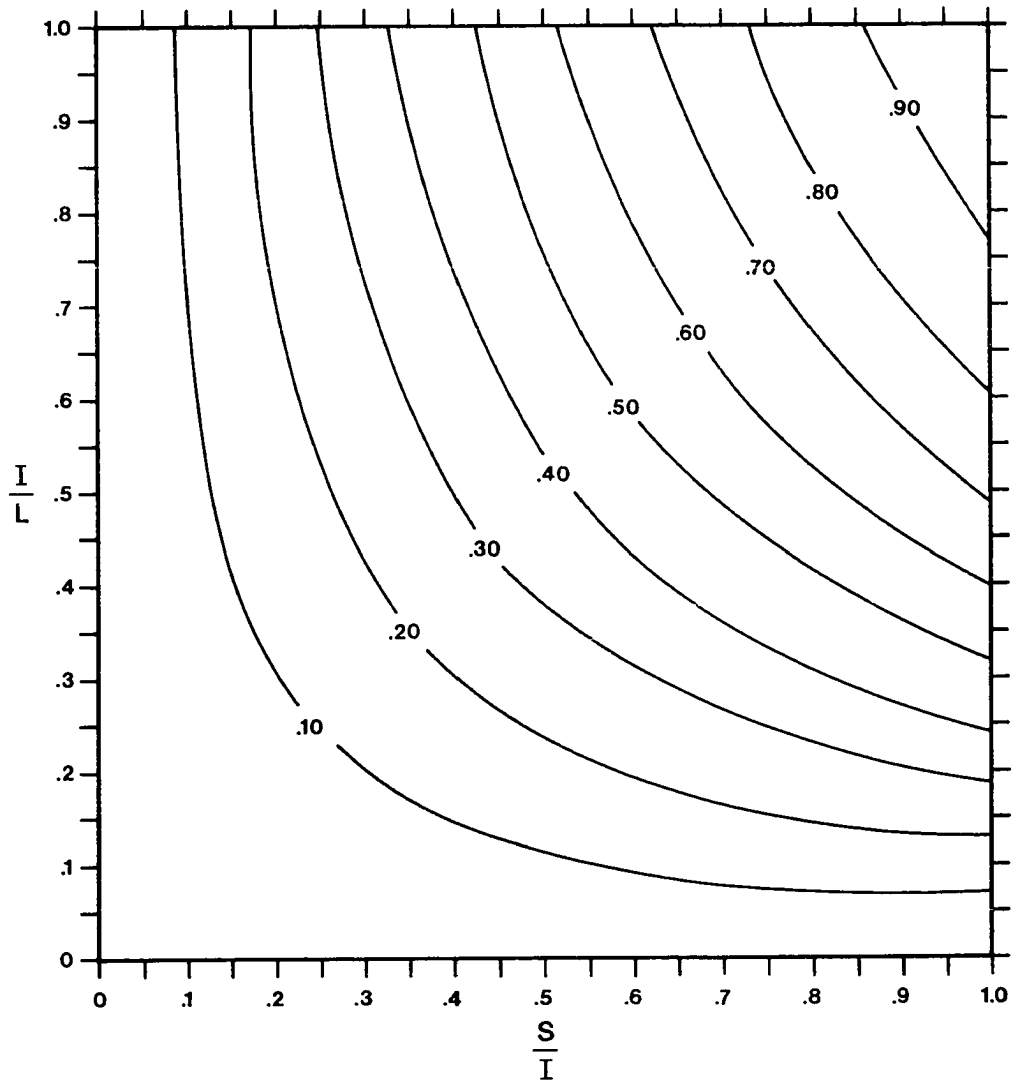


FIG. 25 – Zingg form plot for Janke's (1963) 'Sphericity Factor'.

$e \cdot SF^2$, were found not to contribute significantly to the explanation of the variation in V_n/V_s . These terms were significant at the 24 and 29 percent confidence levels, respectively. The other three regression terms were all significant at the 99 percent confidence level. The lack of significance for the RF and SF squared terms is not surprising because both RF and SF were specifically formulated to vary linearly with V_n/V_s .

From the above results it was clear that the most appropriate regression model would lack the RF and SF squared terms. Accordingly, the second model evaluated was:

$$(V_n/V_s) = a + (b \cdot RF) + (c \cdot SF) + (d \cdot RF \cdot SF)$$

All regression terms were found to be significant at the 99.9 percent confidence level. The linear correlation coefficient (r) and corresponding coefficient of determination were 0.905 and 0.819, respectively. Interestingly, these values are essentially the same as those for the first model and thus further substantiate the nonsignificance of the RF and SF squared terms. The regression equation derived for the second model is as follows:

$$RFF = (V_n/V_s) = -0.58629 + (1.2193 \cdot RF) + (1.9978 \cdot SF) - (1.7824 \cdot RF \cdot SF) \quad (11)$$

Evaluation of the Settling Velocity Prediction Equation

Rectangular parallelepipeds

The settling velocity of rectangular parallelepipeds (V_n) can be

estimated from equation 1 when V_s and RFF are obtained from equations 3 (or 4) and 11, respectively. Using equation 1, the standardized fall velocities have been computed (Figure 26) for rectangular parallelepipeds settling in pure water at 20°C, and having a nominal diameter of 0.250 millimeters (corresponds to the fine/medium sand size boundary) and a density equal to that of quartz (2.65 gm/cc). For larger particles, the curves in Figure 26 would be slightly displaced towards the upper right; and for smaller particles, the displacement would be to the lower left. The reason for these displacements has been previously explained: for a given particle form, the standardized fall velocity decreases with increasing Reynolds Number (and, hence, increasing particle size).

The question now arises, how good are the settling velocity estimates provided by equation 1? The linear correlation coefficient for the actual settling velocities (V_n in Appendix F) and the estimated settling velocities obtained from equations 1, 3 and 11 is 0.991. This correlation is gratifyingly high but it should be kept in mind that the value of a correlation coefficient is not necessarily a good indication of the quality of a prediction equation. This is evident from the fact that the linear correlation for V_n (actual) and V_s (estimated) is 0.917. This correlation is quite high but obviously V_s would provide an estimate of V_n which is much too high.

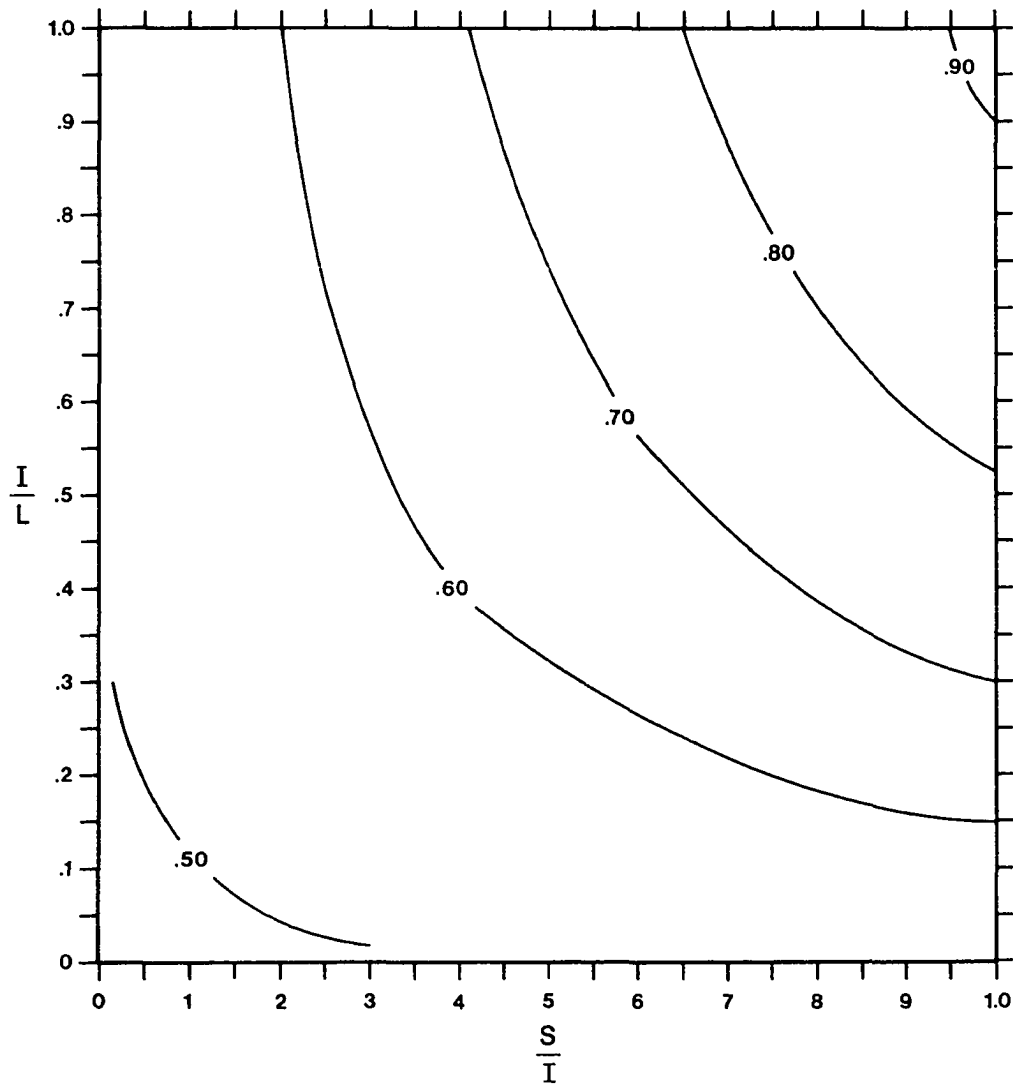


FIG. 26 — Zingg form plot and estimated standardized fall velocities for quartz rectangular parallelepipeds of unit volume ($d_n=0.250$ mm) settling in pure water at 20°C .

The proper way of evaluating the accuracy of a prediction equation is to compute the 'percentage mean and standard error of the estimate' (Janke, 1979). These two statistics are obtained as follows: multiply by 100 the ratio of V_n (estimated) to V_n (actual) for all particles in the data set; and then compute the mean and standard deviation for these modified ratios using the appropriate equations in Part IA of Table 3. These statistics correspond then to the so-called percentage mean estimate and percentage standard error of the estimate. The latter statistic may be thought of simply as the average percentage deviation of the predicted velocity from the observed velocity.

For the experimental data in Appendix F, the mean estimate for V_n (estimated)/ V_n (actual) is 100.58 and the standard error is 7.43. If we are willing to assume that the distribution of values for this ratio is Gaussian (i.e., 'normal') then 68 percent of the test particles deviate from the predicted velocities by up to plus-or-minus one standard error, and 95 percent deviate up to plus-or-minus two standard error (Crow et al., 1960, p. 229). With this in mind, a standard error of 7.43 seems rather large. The alternative to predicting settling velocities with equation 1 would be to use the estimated velocity of the equivalent sphere. However, when the percentage mean and standard error of the estimate are computed for V_s (estimated)/ V_n (actual)—145.71 and 14.18, respectively—the corresponding values for V_n (estimated)/ V_n (actual) do not seem so bad in comparison. The percentage mean and standard error for the equivalent spheres indicate that the predicted settling velocities would be about 50 percent too high on the

average and twice as variable as the estimates obtained from equation 1.

In the past, form measures have been used in conjunction with the settling velocity of the equivalent sphere to estimate the settling velocity of a nonspherical particle (i.e., $V_n \cong V_s \cdot PF$). Such a practice has been advocated by Sneed and Folk (1958) who refer to their Maximum Projection Sphericity form measure as the Effective Settling Sphericity. Even the Janke Sphericity Factor which has a hydraulic sensitivity superior to that of Maximum Projection Sphericity cannot adequately substitute for the Reynolds-Form Factor in equation 1. This is amply demonstrated by the percentage mean and standard error for $(V_s \cdot SF)/V_n$ (actual): 62.27 and 28.62, respectively.

Magnetite grains

It has been shown in the preceding section that the settling velocity of rectangular parallelepipeds can be fairly accurately predicted using equation 1. The critical question now is, how well does this equation predict the settling velocities of irregular sediment grains? Ideally, to answer this question, experimental data for quartz sand grains settling in water should be analyzed. However, the only experimental data for variously shaped irregular grains available in the literature appears to be that of Briggs et al. (1962). These authors used heavy mineral grains rather than quartz grains.

The accuracy of equation 1 was evaluated using the experimental

data of Briggs et al. (1962) for 20 magnetite grains (Appendix G). Briggs et al. also performed settling experiments on other varieties of heavy minerals but the data for magnetite were selected for the present study because these grains had the greatest range of forms (Figure 27). The grains were produced by crushing magnetite crystals and then rounding the fragments in a tumbling mill. The final roundness of the grains ranged from 0.2 to 0.5 (angular to subangular, respectively) on Krumbein's (1941) visual comparator for roundness and sphericity (this comparator has been reproduced in Krumbein and Sloss, 1963, Figure 4-10; and Pryor, 1971, Figure 3). The L and I dimensions of each grain were measured from the projected grain outline (it was assumed that the grains oriented themselves with their L • I plane approximately parallel to the underlying flat microscope stage). The S dimension of each grain was taken to be thickness of the grain measured normal to the microscope stage. The grains were settled in pure water at 20°C. The range of Reynolds Numbers for the grains was 5 to 54, essentially the same as that for fine to very fine sand-sized quartzose sediment.

Using equations 1, 3 and 11, and the data in Appendix G the predicted settling velocity for each magnetite grain was computed. The percentage mean and standard error of the estimate for V_n (estimated)/ V_n (actual) were found to be 97.06 and 6.12, respectively. The linear correlation coefficient for V (estimated) and V (actual) was 0.986. From these results it can be concluded that the settling velocity of irregular sediment grains can be accurately predicted using equation 1.

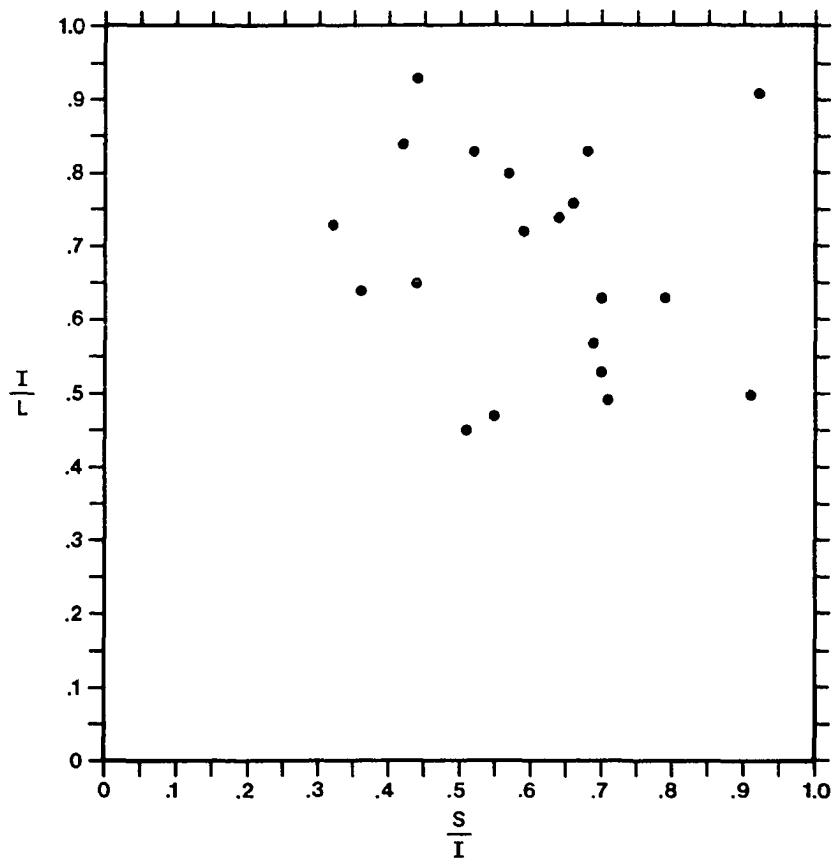


FIG. 27 - Zingg form plot for the magnetite grains used in the test of the settling velocity prediction equation for nonspherical particles.

The slight underestimation apparent in the percentage mean settling velocity is probably due to the fact that the rectangular parallelepipeds, on which the equation for RFF is based, are more angular than the magnetite grains. In general, it can be expected that equation 1 will underestimate settling velocities by a few or several percent on the average. The greater the roundness of the grains, the greater the underestimation.

Concluding Remarks

According to Briggs et al. (1962, p. 653) the ". . . differences in the shape of heavy minerals can produce about the same difference in size distributions as can the usual differences in specific gravities." From this statement and Figure 26 it is clear that particle form has a profound effect on hydraulic behavior. Admittedly, it is probably true that the vast majority of sediment grains (especially those composed of quartz) would plot in the upper right one-fourth of the Zingg Diagram ($I/L > 0.5$ and $S/I > 0.5$ in Figure 2). Within this quarter of the diagram the standardized fall velocities vary between 1 and 0.65. Although this range is only moderate in extent, it is still probably large enough to warrant the consideration of the effect of grain form when interpreting the hydraulic sorting of sandy sediment. Equation 1 should prove useful for 1) computer simulation studies of sedimentation processes; 2) interpreting the textural data for a sediment where both the grain size and shape distributions

have been determined; and 3) calibrating the 'recording sedimentographs' (i.e., automated settling columns) now widely used to determine the grain size distribution of a sediment.

Other Factors Affecting Settling Behavior

Up to this point we have only considered the effect of grain mass and form on the settling velocity of single grains falling through a quiescent fluid. It should be kept in mind that grain roundness, surface texture and symmetry also may have a significant, albeit lesser, effect. Of these three properties, only grain symmetry has yet to be studied experimentally. This is unfortunate because it may be quite important. It seems likely that the stability of a settling particle will be largely determined by its departure from geometric symmetry. Apart from the effects of the grain properties, the settling velocity of a particle is also affected by two other factors: flow turbulence and concentrated sediment suspensions.

Roundness

Williams (1966) established that when all other particle properties except roundness are held constant (e.g., density, volume, form and surface texture), the settling velocities of sharp-edged cylinders and discs were reduced by 8 to 28 percent relative to the settling velocities of their well-rounded counterparts for Reynolds Numbers

greater than 250. The lower the Reynolds Number, the smaller the percentage reduction. Only very coarse quartz sand grains would settle with Reynolds Numbers of 250 or more. For finer sand grains the retarding effect of angular edges and corners may be slightly less.

Williams' findings are in agreement with the results of the present study. In Figure 26 it can be seen that a cube settles with a velocity about 9 percent less than that of its equivalent sphere. Both the sphere and cube have the same isometric form; they differ only in their roundness.

Williams' experimental results come as no surprise. The presence of angular edges and corners increases the turbulence generated by a falling particle. As the turbulence increases, the 'suction breaking' and consequent retardation in settling velocity also increases.

Surface Texture

Williams (1966) established that when all other particle properties except surface texture are held constant, the presence of 'deep' grooves and pits on discs and spheres reduced their settling velocity by 0 to 5 percent of that for their smooth-surface counterparts at Reynolds Numbers greater than 230. For the smaller Reynolds Numbers and the lower relief surface textures typical of settling sand grains the reduction in fall velocity should be less. Janke (1963) similarly found that a shallowly grooved and pitted surface reduced the settling velocities of rectangular parallelepipeds by about 8 percent for Reynolds

Numbers over 2790.

From these experimental results it may be concluded that the settling velocities of sand sized grains may be reduced by a few percent in cases of extreme surface roughness. Surface roughness, like particle angularities, generates turbulence and thus increases 'suction braking'.

Flow Turbulence

Particles are maintained in suspension by the upward velocity component of turbulent eddies or cells. Such particles, of course, have 'effective' settling velocities which are much smaller than those for the same particles falling through a quiescent fluid. The retarding effect of flow turbulence differs with the size, density and shape of the particles. According to Murray (1970), suspended particles are subjected to 'oscillating accelerated motions' arising from the waxing and waning, and migration of turbulent cells. He demonstrated experimentally that there is a net downward fluid acceleration. Because of the greater inertia of the larger and denser grains, these grains are less susceptible to the fluid accelerations. Thus for the smaller and less dense grains, the retardation of settling velocity due to turbulence is less.

Concentrated Suspensions

In flows with high concentrations of suspended sediment the effective settling velocity of particles is generally reduced. The 'hindered settling' conditions of concentrated suspensions results from three factors (Coulson and Richardson, 1955; and Thorpe, 1965). First, larger particles settling through a suspension of finer particles are hindered in their fall because the suspension has a higher effective density and viscosity than the pure fluid. Second, there is a net upward flow of fluid which has been displaced by the settling particles. This upward flow hinders the fall of all particles but it has its greatest effect on the finer particles which may actually be swept upwards by the fluid rising through the spaces between the larger settling particles. Third, when two settling particles pass close-by to each other, the resulting fluid perturbations hinders the fall of both. There is one situation where concentrated suspensions actually result in the increase in settling velocity for some particles. This occurs when smaller particles become entrapped in the turbulent wake of larger particles, and thus are dragged downwards by the more rapidly settling particles.

Effect of Grain Form On Other Aspects of Grain Behavior

Rollability

It has been demonstrated experimentally that grains of high

sphericity (i.e., compact form) roll down a smooth inclined surface more readily than grains of lesser sphericity, all other particle properties being equal (Krumbein, 1942; Shepard and Young, 1961; Glezen and Ludwick, 1963; Kuenen, 1964; and Winkelmoen, 1971). This behavioral property of grains has been referred to as 'rollability' or 'pivotability'. For grains of the same size and density, rollability is principally a function of particle form with roundness having a significant but much subordinate effect (Kuenen, 1964). It has been shown that one aspect of particle form, the flakiness or tabularity, is responsible for the rollability characteristics of a grain (Krumbein, 1942; Glezen and Ludwick, 1963; and Kuenen, 1964). This is so because grains tend to roll with their longest dimension oriented normal to the direction of travel (Rusnak, 1957). It is the relative lengths of the smallest and intermediate dimensions which determines the ease with which a grain pivots about its center of gravity. Regardless of the value of the I/L ratio, the grains with the higher S/I ratio have the greater rollability.

In field and laboratory studies of selective pebble sorting it has been shown that a downcurrent increase in S/I (and presumably, rollability) indicates traction transport whereas a downcurrent decrease in S/I indicates that the pebbles were transported primarily in suspension (Kuenen, 1964; Einstein, 1972; Orford, 1975; and Spalletti, 1976). Although this is perhaps true for pebbles, it is apparently not true for sand grains. Winkelmoen (1971) argues convincingly that the

more tabular, less rollable sand grains are preferentially transported in traction as well as in saltation and suspension. He cites two arguments in support of this point of view. First, because the more tabular, less rollable grains have a greater surface area per unit weight, they have greater 'form drag'. They are thus more susceptible to the viscous drag forces of an eroding current. Second, the less rollable grains tend to have L dimensions which are larger than those of the more rollable grains of the same volume. Thus they do not sink as far into the interstices of the sediment framework. The effect of this is that the less tabular, more rollable grains are hindered more by bottom roughness. The more tabular, less rollable grains 'feel' the bed less and are, as a consequence, more readily transported across it. Only in the case where the entrained grain is substantially larger than the bed roughness will the more rollable grain be preferentially transported in traction. This is often the situation with pebbles but for sand deposits, the sorting is usually good enough that it is the less rollable grains which are selectively transported (Winkelmolen, 1971).

Many field studies have documented a downcurrent increase in the tabularity or rollability of sand grains (Pettijohn and Lundahl, 1943; Glezen and Ludwick, 1963; Winkelmolen, 1971; Winkelmolen, 1972; Winkelmolen and Veenstra, 1974; Poché and Goodell, 1975; Veenstra and Winkelmolen, 1976; and Winkelmolen, 1978). Exceptions to these findings should be rare if, as Winkelmolen maintains, it is true that greater

tabularity is more favorable to the transport of sand in traction, saltation and suspension. Thus it appears that the joint grain size and tabularity distributions obtained using the roller micrometer in conjunction with sieves may provide valuable information on the hydraulic sorting characteristics of a depositing current.

Engineering Properties

The tabularity of the grains in concrete and asphalt aggregate is of utmost importance. Whereas high grain angularity is deemed advantageous, high tabularity is considered to be detrimental to the strength of the final product because it reduces the internal friction (Marwick, 1937; and Lees, 1964a and 1964b).

METHODOLOGIES FOR THE ANALYSIS OF PACKING

INTRODUCTION

Definition

The literature abounds with definitions of grain 'packing'. Nearly all of these definitions are consistent with the American Geological Institute definition adopted in this study: packing refers to ". . . the manner of arrangement or spacing of the solid particles in a sediment or sedimentary rock" (Bates and Jackson, 1980, p. 449). Thus packing may be conveniently thought of as simply the spacing and arrangement of grains.

Standard Approaches to Measurement

Grain packing is easily treated as a concept, but reduction of the concept to operational procedures has been difficult. No one measurement procedure has succeeded in describing both the spacing and arrangement of the grains. Because of this it is necessary to

apply two or more measurement procedures in order to adequately describe packing. Each of the standard measurement procedures for packing will be briefly described below. All except one of these procedures utilizes thin sections.

Measurements Utilizing Unconsolidated Sediment

Fraser (1935), Gaither (1953), Krumbein (1959) and Beard and Weyl (1973) used porosity as a measure of packing in unconsolidated sand. The porosity was computed from the volume, weight and assumed density of the sediment.

Measurements Utilizing Thin Sections

1) Minus-Cement-Matrix Porosity

Kahn (1956) introduced the popular 'Packing Density' which is equal to one hundred minus the percent minus-cement-matrix porosity (i.e., $100 - [\% \text{ cement} + \% \text{ authigenic matrix} + \% \text{ pore space}]$).

2) Average Number of Intergranular Contacts Per Grain

a) Packing Proximity (and Packing Index)

The 'Packing Proximity' of Kahn (1956) and the 'Packing Index' of Masson (1951), Rosenfeld (1953) and Winsauer et al. (1952) are equal to one hundred times the ratio of the total number of grain-to-grain contacts for grains encountered in traverses to the total number of grains encountered (a given grain can have only one grain-to-grain

contact and to be counted it must occur on the left side of the grain immediately beneath the horizontal cross-hair of the microscope ocular).

b) Contact Index

Taylor (1950) and Gaither (1953) introduced a packing measure which was equal to the total number of grain-to-grain contacts for grains encountered in a point count to the total number of grains encountered (a given grain can have any number of grain-to-grain contacts). This measure was never named by these two authors but it has been referred to as the 'Contact Index' by Pettijohn et al. (1972, Table 3-4).

c) Condensation Index

The 'Condensation Index' of Allen (1962) is equal to the ratio of the percent of 'fixed' grains encountered in a point count or traverse to the percent of 'free' grains encountered. In this measure a 'fixed' grain is a grain with 50 percent of its margin in contact with other grains (contact with cement or authigenic matrix is not counted). A grain is said to be 'free' if less than 50 percent of its margin is in contact with other grains. The Condensation Index is especially well suited for those sandstones with abundant squashed rock fragments.

d) Packing Index

The 'Packing Index' of Emergy and Griffiths (1954) is equal to the product of the total number of quartz-to-quartz intergranular contacts for grains encountered in a traverse and the average length of the traverse line crossing the quartz grains (i.e., the sum of the lengths of line segments in quartz grains divided by the total number of quartz grains encountered), divided by the total length of the

traverse (this length includes the line segments in matrix, cement and pores as well as grains). These authors gave to their packing measure a name given earlier by Masson (1951) to a related but different parameter.

3) Frequency of Different Types of Intergranular Contacts

a) Contact Types

Taylor (1950) recognized that intergranular contacts can take any of five forms: floating, tangential (called 'point' by others), long, concavo-convex (called 'complete' by others), and sutured (called 'serrated' by others). Illustrations of each of these contact types can be found in Taylor (1950, Plates 1-4), Gaither (1953, Figure 4), Griffiths (1967, Table 8.5), Pettijohn et al. (1972, Figure 3-10), Bell (1978, Figure 4) and Blatt et al. (1980, Figure 12-1). The terminology and definitions for the contact types recognized in the present study are given in Table 10. The frequency of each of the five contact types is determined as follows. The number of intergranular contacts of each type is determined for each of the grains encountered in a point count or line traverse. A given grain may have any number of intergranular contacts. Floating grains, which lack intergranular contacts, are counted as one floating contact. The absolute frequency of each contact type is then divided by the total number of intergranular contacts of all types to obtain the relative frequency, or it can be divided by the total number of grains encountered to obtain the average number of contacts of a given type per grain.

TABLE 10
CLASSIFICATION OF INTERGRANULAR CONTACTS

GEOMETRICAL AND SPATIAL RELATIONSHIP			CONTACT TYPE	ILLUSTRATION
Not Touching			Floating	
Touching	No Occlusion	Tangential Contact	Point	
		Straight or Curvilinear Nontangential Contact	Long	
	Occlusion	Angular or Curvilinear Interpenetration	Concavo-Convex	
		Serrated or Ragged Interpenetration	Sutured	

b) Contact Strength

Füchtbauer (1967) defined the 'Contact Strength' as:

$$\frac{PC + (2 \cdot LC) + (3 \cdot CCC) + (4 \cdot SC)}{(PC + LC + CCC + SC)}$$

where the terms in the equation correspond to the relative frequencies (or percentages) of point (PC), long (LC), concavo-convex (CCC) and sutured (SC) contacts. Inherent in the Contact Strength concept is the assumption that with increasing burial compaction, the relative proportions of the contact types changes in a systematic way. Representing increasing degrees of compaction, from left to right, the contact types are floating, point, long, concavo-convex and sutured.

Füchtbauer (1974) also proposed an abbreviated version of the Contact Strength which is supposed to be more suitable for the less compacted and diagenetically altered sandstones:

$$\frac{PC + (2 \cdot LCSC)}{PC + LCSC}$$

where PC is as previously defined and LCSC is the combined relative frequency (or percentage) of the long, concavo-convex and sutured contacts.

c) Consolidation Factor

The 'Consolidation Factor' proposed by Bell (1978) is very similar to Füchtbauer's (1967) Contact Strength. It differs primarily in its inclusion of floating grains. The formula is as follows:

$$\frac{FC + (2 \cdot PC) + (3 \cdot LC) + (4 \cdot CCC) + (5 \cdot SC)}{500} \cdot 100$$

where FC is the percentage of all intergranular contacts which are floating, and PC, LC, CCC and SC are the percentage values for the

contact types previously defined for Füchtbauer's (1967) Contact Strength. The percentages for the five contact types must sum to one hundred.

Only one other measure of particle packing has been devised in recent decades but it has not yet been applied to sands or sandstones. The measure is generally known as the Radial Distribution Function, and it has been used to describe the packing of gravel (Smalley, 1964) and sets of spheres (Scott, 1962; Finney, 1970; and Norman and Maust, 1971). This measure characterizes the frequency of occurrence of particles with increasing radial distance from an arbitrarily selected central particle.

Of the many packing measures described above the minus-cement-matrix porosity, contact index and the average number of intergranular contacts of a given type per grain are, in the authors opinion, probably the best because they are both highly informative and easily determined. None of these individually, however, comes close to expressing the full scope of packing. All three must be used to adequately characterize packing. It should be kept in mind though that these three measures are not necessarily independent of one another. One would expect with decreasing minus-cement-matrix porosity that the contact index will increase, and that the number of long and concavo-convex contacts will increase at the expense of the floating and point contacts.

A comprehensive description of grain packing is not always a necessary objective. Measures like the packing proximity, packing index or contact index should be useful in assessing the petroleum transmissibility (i.e., permeability) characteristics of a rock. It is well known

that as the number of intergranular contacts increases, so too does the 'irreducible water saturation' (Brooks and Purcell, 1952; Winsauer et al., 1952; and Morrow, 1971). The irreducible water saturation refers to the water that cannot normally be displaced by petroleum. This water is tightly held in the vicinity of intergranular contacts by surface tension and meniscus forces. The permeability generally decreases as the irreducible water saturation increases. In typical reservoir sands the irreducible water saturation is on the order of 20 to 30 percent of the total pore space (Nakayama and Van Siclen, 1968; and Morrow, 1971).

In all of the ancient sandstones analyzed in this study quartz overgrowths are present. Because the original grain boundaries are generally not visible, no meaningful packing analysis can be performed on these samples. Grain packing is supposed to be a measure of compaction and not the extent of quartz cementation, and thus it should never be measured in indurated sediments where the original boundaries of the framework grains are not fully visible. Packing analyses performed in this study were essentially restricted to the modern sands (the two lightly cemented AD samples were also analyzed). The parameters measured from the thin sections were total porosity (no cement or matrix was present in any of the samples), contact index and the frequency of occurrence of the different types of intergranular contacts.

MEASUREMENT ERRORS IN THE THIN SECTION ANALYSIS OF GRAIN PACKING

Introduction

Because the packing parameters described above are conventionally measured from a thin section (normally 30 microns thick) and not from a plane section (a planar surface of zero thickness), the observed values will be dependent upon the grain size as well as the grain packing. The thin section thickness is thus the cause of a potentially large measurement error, one which increases with decreasing grain size. An article based on a preliminary draft of this section was previously published by the author (Harrell, 1981).

Porosity Measurement

Halley (1978) described the effect of grain size on porosity determination in thin sections. It is well known that the area percent of pore space in a randomly chosen plane section provides a valid estimate of the volume percent of pore space in a rock (Chayes, 1956, p. 12-15). In thin sections, however, the actual porosity may be underestimated by a substantial amount. Figure 28 illustrates the problem. When looking through a thin section, we see portions of grains not exposed on the planar upper surface (e.g., the blank areas enclosed by the dotted lines). Thus we would see a greater area percent of

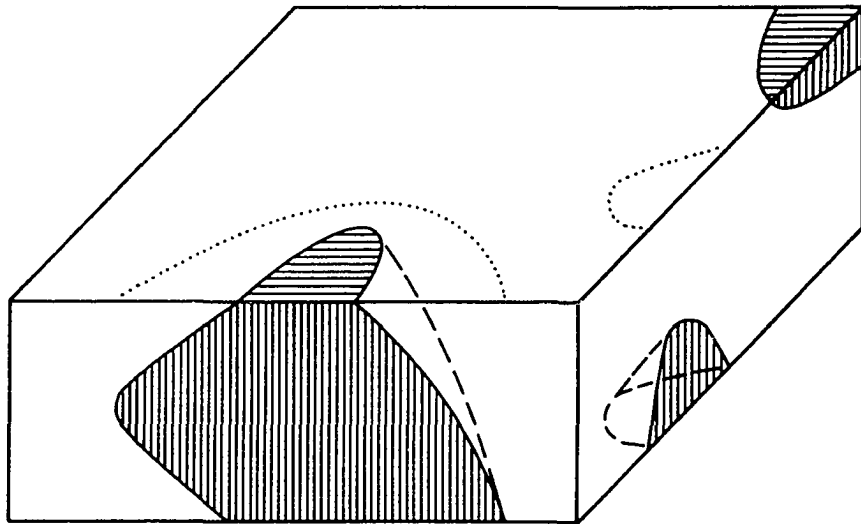


FIG. 28 – Hypothetical thin section showing the differences in grain outlines between the plane section view of the upper surface (edges of horizontally-ruled areas) and the thin section view of the entire thickness (dotted lines).

grains than would actually exist in a plane section. The porosity would be correspondingly underestimated. The measurement error for porosity determinations based on thin sections increases with decreasing grain size and is especially serious when the grains are fine sand size or smaller (Halley, 1978, Figure 5).

Intergranular Contact Measurement

The other two approaches to packing analysis, numbers and types of intergranular contacts, also have measurement errors resulting from the effect of grain size. Figure 29 illustrates the grain size effect. Figure 29A depicts two spheres of the same size and which are separated by a distance equal to one-tenth their diameter. Figures 29B and 29C show these same spheres when viewed parallel to the X and Y axes, respectively. Notice that on the Z axis in Figures 29B and 29C there are three pairs of tick marks, each pair being of a different length. If the distance between the two shortest tick marks represents the thickness of a 30 micron thick thin section then the diameter of the spheres would correspondingly equal 250 microns. Let the two shortest tick marks then indicate the position of a thin section which cuts through the spheres parallel to the XY plane. On viewing the thin section, the spheres would appear as floating grains with an apparent separation which is less than the actual distance between them (Figure 29D). Next, let the pair of tick marks of intermediate length represent the thickness of a 30 micron thick thin section with the spheres having

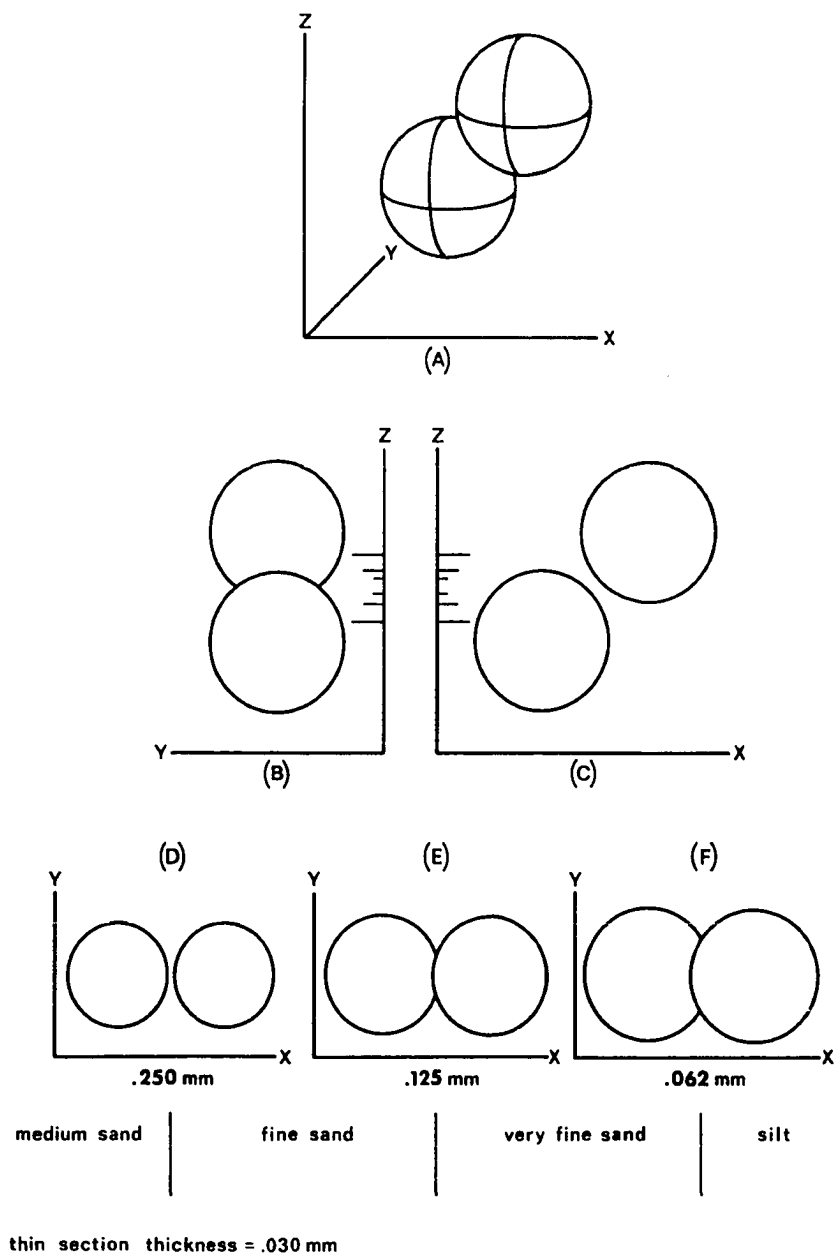


FIG. 29 – Illustration of the effect of grain size on the apparent character of intergranular contacts.

a corresponding diameter of 125 microns. On viewing the thin section we see what appears to be two interpenetrating grains with a concavo-convex contact (Figure 29E). Finally, let the longest pair of tick marks represent a 30 micron thick thin section with the spheres having a corresponding diameter of 62 microns. The thin section shows an even more pronounced concavo-convex contact between the spheres (Figure 29F).

From Figure 29, it is clear, for a constant thin section thickness and grain packing but decreasing grain size, that: (1) the average number of contacts per grain will increase; and (2) the frequency of concavo-convex and long contacts will increase at the expense of the point and floating contacts. This phenomena was first recognized by Gaither (1953). There will be no change in the frequency of sutured contacts as these require an actual intergrowth or interpenetration of grains. It is important to stress that the packing parameter values for thin sections of texturally dissimilar sediment are not comparable because of the grain size-related measurement error. It is probably not possible to devise an adequate correction factor for this error because grain sorting and shape as well as average grain size must be taken into account. For example, the contact index should increase as the sorting decreases because the poorer the sorting for a given mean grain size, the greater the number of grains in a unit volume of sediment. With decreasing grain sphericity and roundness there is an increasing opportunity for contacts between grains with angular corners and edges, and large surface areas per unit volume.

Long and especially concavo-convex contacts in sandstones are sometimes considered evidence of pressure solution. Petrographic observations (Heald, 1956; and Adams, 1964), experimental results (Renton et al., 1969; and Sprunt and Nur, 1976) and theoretical considerations (Weyl, 1959) indicate that pressure solution increases with decreasing grain size. Figure 29 suggests that some of the evidence for the occurrence and textural control of pressure solution may simply be an artifact of thin sectioning. Interestingly, Sippel (1968, p. 534), who dispelled the myth of widespread pressure solution in quartz arenites with his cathodoluminescence petrography, attributed concavo-convex contacts between the detrital cores of grains to pressure solution. In many cases Sippel may have been looking at overlapping rather than interpenetrating grains.

Comparison Of Thin And Plane Sections

Figure 30 illustrates the differences in apparent grain packing between a thin section and a plane section. The figure shows two tracings of grain outlines for the same area in a 35 micron-thick thin section of sample D5-16. Figure 30A depicts grain outlines as seen under crossed polarizers (thin section view) and Figure 30B depicts grain outlines as seen on the upper surface of the thin section under uncrossed polarizers (plane section view). The mean grain size of the sand is 193 microns. The differences between the two tracings in Figure 30 are striking. Figure 30A is characterized by a smaller porosity (27 percent

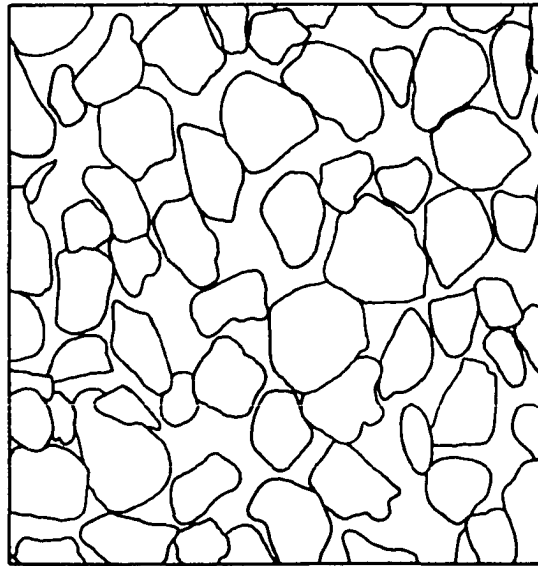
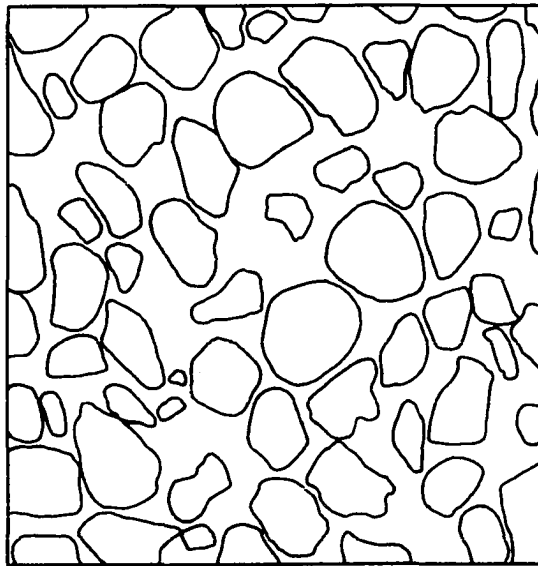
**A****B**

FIG. 30 – Thin section and plane section views of sample D5-16: A) thin section view of the entire thickness, and B) plane section view of the upper surface.

as opposed to 36 percent for Figure 30B), a larger number of intergranular contacts, and a higher frequency of concavo-convex and long contacts.

Recommendations

When interpreting grain packing from thin sections of sedimentary aggregates, one must consider the texture (principally grain size) as well as the actual spacing and arrangement of the grains. The texture-related measurement error may be avoided entirely, however, by measuring the packing parameters from a plane section. Accordingly, one should not view a thin section through crossed polarizers, because only maximum grain outlines will be seen. Instead, one should focus on the upper surface of the thin section and view with uncrossed or half-crossed polarizers. To enhance grain outlines, the thin section surface can be abraded or chemically etched, or the pore space can be impregnated with colored epoxy. Oils and cover slips should not be used.

PLANE SECTION ANALYSES

Procedure

Following the recommendations of the preceeding section, the packing parameters (porosity, and numbers and types of intergranular contacts) were measured from plane sections (i.e., the upper surface of

the thin sections). In analyses of this kind it is desirable to have the maximum possible contrast between the rock (i.e., the grains, cement and matrix) and the epoxy-filled pores. A good contrast was achieved with the procedure described below.

1) The thin sections were viewed using a standard petrographic microscope with transmitted light and half-crossed polarizers. Fully crossed polarizers would have caused the grains at or near extinction to blend imperceptibly into the dark isotropic epoxy. Partially crossed polarizers had the advantage of avoiding this problem while still causing some grains to exhibit subtle interference colors which clearly distinguished them from the adjacent epoxy.

2) The upper surface of the thin sections was not covered with a glass 'cover slip' or a coating of oil. Immediately prior to viewing, the surface was thoroughly cleansed with acetone to remove any skin oils or moisture that might have gotten onto the thin section during handling. When the upper surface of a thin section was brought into focus the grains and other rock components had a very rough, fractured appearance while the epoxy was very smooth in comparison and stood in higher relief.

3) The epoxy in the pore space of all but the B2 samples was uncolored. In the case of the B2 samples, a red dye was added to the epoxy used in the field impregnations. This practice was discontinued for the other sampling localities because the presence of the dye seemed to interfere with the curing of the epoxy. Although coloration in the epoxy was not necessary for locating the pore boundaries it was found to be useful.

All of the packing parameters were measured for 16 of the 18 modern sands (R5-27 and 29 excluded) and 2 of the 10 ancient sands (AD2-1e and 1f included). For the remaining 10 samples only porosity was determined. As pointed out earlier, the presence of quartz cement in the ancient sands made the measurement of grain packing in these samples meaningless. For the two modern sands, R5-27 and 29, a poor epoxy impregnation and cure caused the grain-pore boundaries to be indistinct and thus made it impossible to determine reliably the types and numbers of intergranular contacts.

The raw data for the packing analyses are given in Appendix H. Tabulated in Appendix I are the following computed plane section packing parameters: 1) percent of all grains which are floating (hereafter referred to as the 'floating index'); 2) contact index; 3) average number of point, long and concavo-convex contacts per grain (no sutured contacts were encountered); and 4) porosity.

Discussion Of Results

Comparison with the Literature

Porosity is the only packing parameter for which published data are available for modern unconsolidated sands. Two studies, Pryor (1973) and Schenk (1981), report percent porosities computed from the following relation:

$$\text{Porosity} = [1 - (\text{grain volume}/\text{sediment volume})] \times 100 \quad (12)$$

where the sediment (grain plus pore) volume is measured directly and the grain volume is estimated from the ratio of dry sediment weight to an assumed density equal to that of quartz. Porosity computed in this way is comparable to the porosity determined from plane sections. The porosity determinations for the present study and Pryor (1973) are compared in Table 11. When the small number of samples analyzed in this study is taken into account, there seems to be reasonably good agreement between the two sets of porosity values. Schenk (1981) documented the average porosity for three different types of eolian laminae: grainflow foresets (47 percent), grainfall foresets (43 percent), and climbing ripples (39 percent). All of the eolian laminae analyzed in this study are believed to be of grainfall origin. Their average porosity of 43 percent is in excellent agreement with Schenk's findings.

Gaither (1953) performed compaction analyses using well-sorted, medium-grained St. Peter sand. He loaded the dry sand into a cylinder and then applied a 25 pound dead weight to the top of the sand. Compaction was achieved by repeatedly tapping the side of the cylinder. Gaither considered the compaction results comparable to the natural packing in unconsolidated, well-sorted, medium grained sand. Utilizing thin sections of his artificially compacted sands, Gaither measured the same packing parameters considered in the present study. His results are compared to those of the present study in Table 12. It is readily apparent in this table that all the packing parameters measured from a thin section indicate a higher degree of compaction than do their plane section counterparts. As previously discussed, the interaction

TABLE 11
COMPARISON OF THE POROSITY DETERMINATIONS FOR
MODERN UNCONSOLIDATED SAND: PRYOR (1973)
AND THE PRESENT STUDY¹

Data Set	This Study ²			Pryor (1973) ³		
	Mean	Range	Number of Samples	Mean	Range	Number of Samples
Beach	39.2	36.5-41.4	6 ⁴	49	39-56	480
Fluvial Point Bar	45.4	40.8-48.4	6 ⁵	41	17-52	348
Eolian Dune	43.2	41.7-45.6	5 ⁶	49	42-54	164
All Three Environments Combined	42.6	36.5-48.4	17	49	17-56	992

¹All porosities are expressed as percent of bulk sediment volume.

²Porosity was computed from a point count of plane sections perpendicular to bedding and parallel to dip (or current).

³Porosity was computed from the bulk sediment volume and dry weight.

⁴Samples included are B2-1, 7, 9 and 16; and B1-15 and 16.

⁵Samples included are R5-21, 23, 25, 27, 29 and 34.

⁶Samples included are D5-10, 15 and 16; and D3-15 and 19.

TABLE 12

COMPARISON OF THE RESULTS OF THIN AND PLANE SECTION
PACKING ANALYSES FOR UNCONSOLIDATED SAND:
GAITHER (1953) AND THE PRESENT STUDY

		This Study ¹ (plane sections)		Gaither (1953) ² (thin sections)
		Mean	Range	Mean
Porosity		42.7	36.5 - 48.4	37
Contact Index		0.60	0.41- 0.74	0.85
Floating Index		53.7	46.7 - 64.7	46
Percent of Grains with	1 contact	34.3	28.2 - 39.5	31
	2 contacts	10.7	5.7 - 15.0	16
	3 contacts	1.3	0 - 3.3	6
	4 or more contacts	0.1	0 - 0.6	1
Percent of Contacts which are	point	93.4	87.2 - 98.2	77
	long	6.3	1.8 - 12.8	17
	concavo-convex	0.3	0 - 1.6	6

¹The samples used are very well to well sorted, fine to medium grained sand. The parameters were measured from a point count of plane sections perpendicular to bedding and parallel to dip (or current). Porosity is based on 18 samples, and all other packing parameters are based on 16 samples.

²These 'suggested' averages are based on numerous thin section analyses of artificially compacted well-sorted, medium grained St. Peter sand. The data is tabulated on pages 181 and 194 of Gaither (1953).

between grain size and thin section thickness will always result in an overestimation of compaction. If Gaither's values could be slightly adjusted to correct for the thin section effect, the two sets of figures would be in reasonably good agreement.

Generalizations for Unconsolidated Sands

In the modern unconsolidated sands analyzed here a little over half the grains visible in plane sections are floating while the rest of the grains have either one or two intergranular contacts which are almost exclusively of the 'point' variety (see Table 12). The small number of contacts of the 'long' variety are probably entirely attributable to contacts between grains with long, relatively flat surfaces rather than to compaction. Essentially no concavo-convex or sutured contacts were observed. This is to be expected because such contacts in plane sections could only be produced by compaction severe enough to cause actual interpenetration of grains through pressure solution or grain squashing.

A correlation analysis reveals, not surprisingly, that the floating index has a very high inverse linear correlation with the contact index ($r = -0.966$, where r is the Pearson Product-Moment Correlation Coefficient). This indicates simply that as the number of intergranular contacts decreases, the number of floating grains increases. In this study the contact index is nearly equal to the average number of point contacts per grain because the other contact types are either zero or

negligible in number. Even if the other contact types were more abundant the same high correlation between the floating and contact indices should still hold. This point is significant because of the two parameters, the floating index is by far the easiest and quickest to measure. The two parameters are equally good indicators of compaction but the floating index is more practical and thus probably should be used in place of the more conventional contact index.

One would reasonably expect porosity to generally increase as the floating index increases and the contact index decreases. The linear correlation coefficients, however, are: $r = 0.092$ for porosity versus floating index; and $r = 0.011$ for porosity versus contact index. These results are surprising. They are perhaps partially explained by the fact that the packing parameters do not vary over a wide enough range for a strong trend to develop. Apart from this, one could speculate that the expected relationship is masked by the textural differences (especially size sorting and grain shape) among the samples.

The results for the two AD2 (Navajo Sandstone) samples show what can happen to the packing parameters when even relatively small amounts of quartz cement are present. Some of the differences between these samples and the unconsolidated sands are no doubt due to their greater compaction but most of the differences are probably attributable to the presence of quartz overgrowths. The evidence for this assertion is the unusually high proportion of long intergranular contacts: on the average, 66 percent for the two samples.

Effect of Environment and Thin Section Orientation

For the two samples with multiple thin sections of different orientation, B2-16 and D5-16, the following trend in packing parameters was observed: the sections normal to bedding and strike had a lower floating index, a higher contact index and a generally higher porosity than the sections parallel to bedding, and normal to bedding and parallel to strike (see Appendix I). No consistent difference in packing parameters existed for the latter two orientations.

When the packing parameters for the three sampled environments are compared, with one exception, no consistent differences are apparent. The exception is the porosity difference between the foreshore beach and eolian dune sands: porosity range for beach sands = 39.1 to 41.4 (samples B1-15 and 16; and B2-1 and 16); and porosity range for dune sands = 41.7 to 44.9 (samples D3-15 and 19; and D5-10, 15 and 16). These results could be anticipated by recognizing two conventional wisdoms: 1) foreshore beach sands are among the most highly compacted sediments because of the incessant pounding of the surf (Krumbein, 1959); and 2) eolian dune sands are among the least compacted sediments because of the mode of sedimentation and the generally low sphericity of the grains (Fraser, 1935; Mattox, 1955; Sohn and Moreland, 1968; Winkelmoen, 1971; Riley and Mann, 1972; and Beard and Weyl, 1973). Pryor (1973), in his study of several hundred beach and dune sands, found no difference in the porosities for the two environments.

When the packing parameters for the three subenvironments at the B2 sample locality are compared the following differences are observed. The foreshore and topset laminae do not differ significantly in their floating and contact indices, and porosity; but the foreset lamina has overall the lowest contact index, the highest floating index and the highest porosity. Although these results are based on very few analyses, they are still consistent with the expectations that foreset laminae should have relatively loose packing. The reason for this is the sedimentation mode: grainfall transport for the washover fan foreset lamina, and traction transport (augmented by pounding surf) for the foreshore beach and washover fan topset laminae. No consistent differences in the packing parameters were observed for the three subenvironments at the R5 sample locality.

A comparison of the packing parameters for the different lamina types sampled (see Table 1) reveals little new information. Only porosity shows some systematic variation. In order of increasing porosity the lamina types are (with porosity range and numbers of samples given in parentheses): horizontal, unidirectional current (36.5 to 38.3, 2); horizontal, foreshore beach (39.1 to 42.3, 4); foreset, grainflow (40.8 to 46.7, 4); foreset, grainfall (41.7 to 46.0, 6); and horizontal, slack water grainfall (45.0 to 48.4, 2). As expected, the traction transported sands deposited on horizontal bedding surfaces by unidirectional currents and waves are the most tightly packed whereas the suspension transported sands deposited by grainfall are the most loosely packed.

A comprehensive summary of the statistical intercorrelations among the textural, pore geometry, and plane section and other packing parameters will be provided in a later section.

COMPACTION ANALYSES

Introduction

The packing observed in sands and sandstones is controlled by five factors: 1) the size and shape distributions of the grains, 2) the manner in which the grains were deposited, 3) the mechanical rearrangement of grains due to overburden weight, 4) the interpenetration of grains via pressure solution due to overburden weight, and 5) the squashing of weak grains due to overburden weight. In many quartz-cemented sands where the original grain boundaries are not visible, the 'apparent' tight packing is the result of the presence of secondary overgrowths and not compaction. The packing of deeply buried sediments and sedimentary rocks is controlled almost entirely by the last three factors. It is only the first two factors, of course, which determine the original or appositional packing of newly deposited sediments. Although the literature is mute on the subject, it seems likely that the final deep burial packing is largely independent of the appositional packing. Nevertheless, the origins of appositional packing are still of considerable academic interest. Accordingly, the focus of this section will be on the two factors which control the packing of newly deposited sand:

texture and sedimentation mode.

In the previous section porosity was found to be the only packing parameter which seemed to be sensitive to differences in sedimentation mode. With this in mind a new measure of packing was devised: the Packing Efficiency. This measure is equal to the ratio of the minimum possible porosity for a sand (estimated from the volumetric porosity of an artificially compacted loose sand) to the actual depositional porosity for the same sand (estimated from a plane section of a sand impregnated with epoxy in the field). It was hoped this measure would reflect the efficiency with which the various depositional processes packed the sandy sediment. A highly efficient depositional process would be one which would be able to pack a sand close to the minimum possible porosity (i.e., the value of the Packing Efficiency would approach one). Because the depositional and compactional porosities are both determined from the same sediment, the ratio of the two porosities is essentially independent of texture. Thus two or more environments with sands of different texture can be directly compared in terms of their packing efficiencies.

The effect of sediment texture on depositional porosity has already been well documented in previous studies. In these studies variously textured sands were artificially compacted. When all other textural parameters were approximately equal it was found that the minimum compactional porosity decreases as 1) the sorting of the sediment gets poorer (Rogers and Head, 1961; Sohn and Moreland, 1968; and Beard and Weyl, 1973); and 2) the sphericity and roundness of the grains increases

(Lamar, 1928; Fraser, 1935; White and Walton, 1937; Tickell and Hiatt, 1938; Sohn and Moreland, 1968; Koerner, 1970; Riley and Mann, 1972; and Beard and Weyl, 1973). The explanation of the decrease in porosity with poorer sorting is fairly obvious: as the sorting worsens, an increasing number of finer grains are able to fill the interstices between the coarser grains. The explanation of the effect of roundness and sphericity on porosity is somewhat less obvious: it is believed that the internal friction of a sediment increases as the sphericity and roundness of the grains decreases (i.e., the more angular edges and corners, and greater grain surface areas inhibits the mechanical rearrangement of the grains during compaction; Riley and Mann, 1972).

Theoretically, when all other textural parameters are equal, the minimum compactional porosity should be independent of average grain size. It has been demonstrated experimentally, however, that the minimum compactional porosity does increase very slightly with decreasing average grain size owing to the increased surface cohesive and friction forces (Westman and Hugill, 1930; and Beard and Weyl, 1973).

The minimum compactional porosities reported for natural sediment ranges from a high of about 45 percent for well-sorted sand to about 25 percent for poorly-sorted sand (Fraser, 1935; Gaither, 1953; Sohn and Moreland, 1968; and Beard and Weyl, 1973). The minimum porosity for systematically packed equal-sized spheres is 26 percent (Graton and Fraser, 1935; and Scott, 1960). In contrast, the minimum porosity for 'randomly' packed equal-sized spheres is about 37 percent (Westman and Hugill, 1930; White and Walton, 1937; Scott, 1960; and

Norman and Maust, 1971). For a systematic packing of selected sizes of spheres a minimum porosity of 4 percent has been obtained (White and Walton, 1937).

Procedure

There have been many experimental procedures proposed for the artificial compaction of sand. In all of these procedures the sand was loaded into a cylinder. The sand was either left dry, or wetted with water or methanol. The compaction of the sand was achieved either by tamping the upper surface of the sand with a piston-like rod, vigorously tapping the outside cylinder wall, dropping the base of the cylinder onto a hard surface, or vibrating the cylinder with a conventional or ultrasonic vibrator. No comparative study has yet been made which assesses the efficiency, effectiveness and reproducibility of the various procedures. It is clear, however, from studies like that of Beard and Weyl (1973) where the same sand was compacted both water wet and dry, that greater compaction is achieved when the grains are wet. This is true because the internal friction forces which inhibit the mechanical rearrangement of grains are greatly reduced when the grain surfaces are wet. Although the presence of water promotes compaction, a liquid with a greater 'wettability' should prove to be even more effective. It was with this in mind that Wilson (1977) employed methanol as the wetting agent in his compaction analyses.

Preliminary experiments were conducted by the author to determine the most effective compaction procedure. For a given method of 'jarring' the sand within a cylinder, it was found that saturating the sand with methanol resulted in the greatest compaction. Water-wetted sand was somewhat less compactable, and dry sand was by far the least compactable. For sand saturated with methanol, the relative effectiveness of the jarring methods evaluated were (in order of decreasing effectiveness): ultrasonic vibration, conventional vibration (the small sieve shaker in Plate 2 was used), and tamping with a rod.

The compaction procedure ultimately adopted in this study was similar to that of Wilson (1977). The sand sample to be compacted was first homogenized by a process of splitting and recombination using a small sample splitter (the sample was split and recombined a total of 12 times). The sample was then poured into a methanol-filled 'certified, class A' 25 milliliter glass cylinder graduated with 0.2 milliliter increments (Kimax brand). The cylinder was 13 centimeters deep in its graduated portion and had a 16 millimeter inside diameter. Because the cylinder was a 'class A' variety, it had high volumetric accuracy: the graduations were accurate to within 0.18 milliliters of the true volume. After loading the cylinder with sand, the cylinder was lightly tapped until a level upper sediment surface was obtained. The initial bulk sediment volume was read from the graduations and recorded. The cylinder was next placed into an ultrasonic bath. The water level in the bath was always above the top of the sand in the cylinder. The sand was subjected to 15 minutes of ultrasonic vibration. It was

observed that the bulk of the sediment volume reduction occurred within the first several seconds of vibration and that no additional volume reduction was discernable after the first couple of minutes. After the ultrasonic vibration was completed, the cylinder was removed from the bath and lightly tapped until a level upper sediment surface was obtained. The bulk sediment volume was read from the graduations and recorded. The ultrasonic vibration tended to dilate the uppermost part of the sand framework and because of this it was necessary to further compact the sand by tamping with a snug-fitting aluminum rod. Prior to tamping, a circular piece of felt with the same diameter as the inside of the cylinder was placed on top of the sand. This caused the tamping rod to hit the top of the sand in a 'dead fall', thus reducing to a minimum the amount of sediment rebound. About 100 tamps were delivered to the sand over a 2 minute period. The final bulk sediment volume was read and recorded.

From the known sediment weight, an assumed grain density of 2.65 grams per cubic centimeter, and the final bulk sediment volume the minimum compactional porosity was computed from equation 12 (note that 1 milliliter equals 1 cubic centimeter). Using this equation and the initial bulk sediment volume the maximum porosity was also calculated. And finally, the Packing Efficiency was computed utilizing the minimum compaction porosity and the plane section porosity from Appendix I.

The raw data for the compaction analyses as well as the results of the above calculations are tabulated in Part I of Appendix J. In Part II of this appendix, the reproducibility of the compaction procedure

is documented. It can be seen that the minimum porosities are highly reproducible. For the three sand samples tested, the standard deviation did not exceed 0.3 percent porosity.

Discussion Of Results

Packing Efficiency

The relationship between Packing Efficiency and sedimentation mode (i.e., lamina type and depositional environment) is illustrated in Figure 31. The most striking result in this figure is the high packing efficiency for samples B2-7 and 9. It appears that the depositional processes responsible for the washover fan topset laminae were able to achieve a near maximum packing of the sand grains. This result would be expected if these horizontal laminae originated from Mossian grain interactions rather than the low-amplitude sandwaves as earlier suggested by the author. The four beach laminae can be seen to have roughly similar packing efficiencies which are all lower than the washover fan topsets. One would ordinarily expect that the opposite would be true.

The packing efficiencies for two of the D5 samples are perhaps higher than they should be. The D5 samples differ from all other samples collected in this study in that they may have experienced some compactional porosity reduction. Whereas the other samples were collected at or very near the active depositional interface (and thus suffered little or no burial compaction), the D5 samples were taken from near

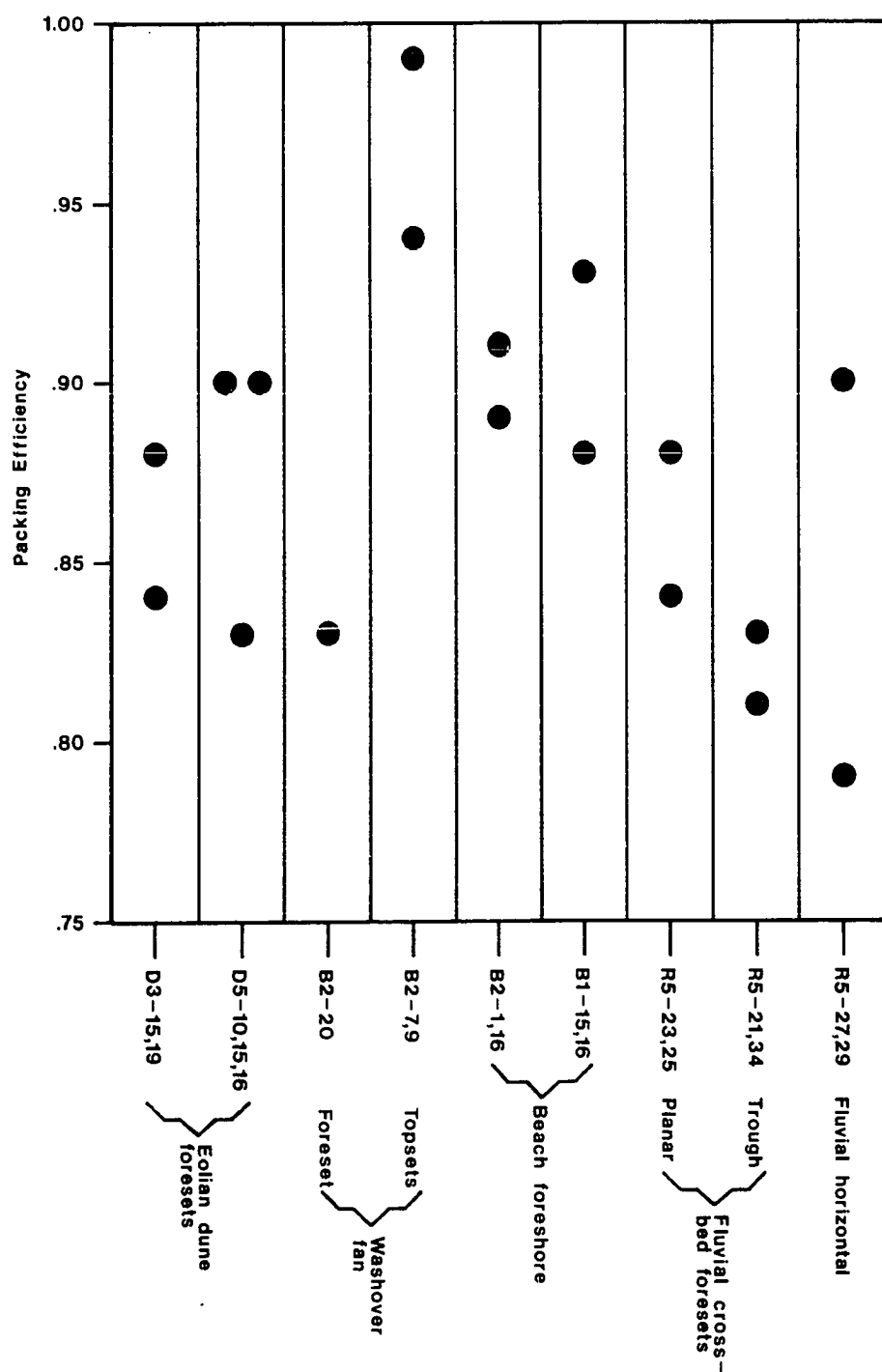


FIG. 31 – Results of the packing efficiency analyses for modern sands.

the center of a large dune and at some point in the past may have had a few tens of feet of overburden. If some porosity reduction due to burial compaction is taken into account for the D5 samples, the beach laminae can be seen to have a somewhat higher packing efficiency than the eolian dune foreset laminae. This would be the expected result. For the R5 fluvial sands, the planar foresets are more efficiently packed than the trough foresets. Perhaps this is a reflection of the higher energy flow conditions accompanying the deposition of the trough cross-beds.

Interestingly, the packing efficiencies for all ten foreset laminae analyzed are broadly similar (R5-21, 23, 25 and 34; D3-15 and 19; D5-10, 15 and 16; and B2-20). Their packing efficiencies are generally less than or equal to those for the six horizontal beach and unidirectional current laminae (B1-15 and 16; and B2-1, 7, 9 and 16). Apparently grains deposited via grainfall or grainflow on slipfaces are not as efficiently packed as those deposited by traction processes on horizontal surfaces. The two horizontal laminae (R5-27 and 29) which were deposited by grainfall during slack water conditions seem to have anomalous packing efficiencies.

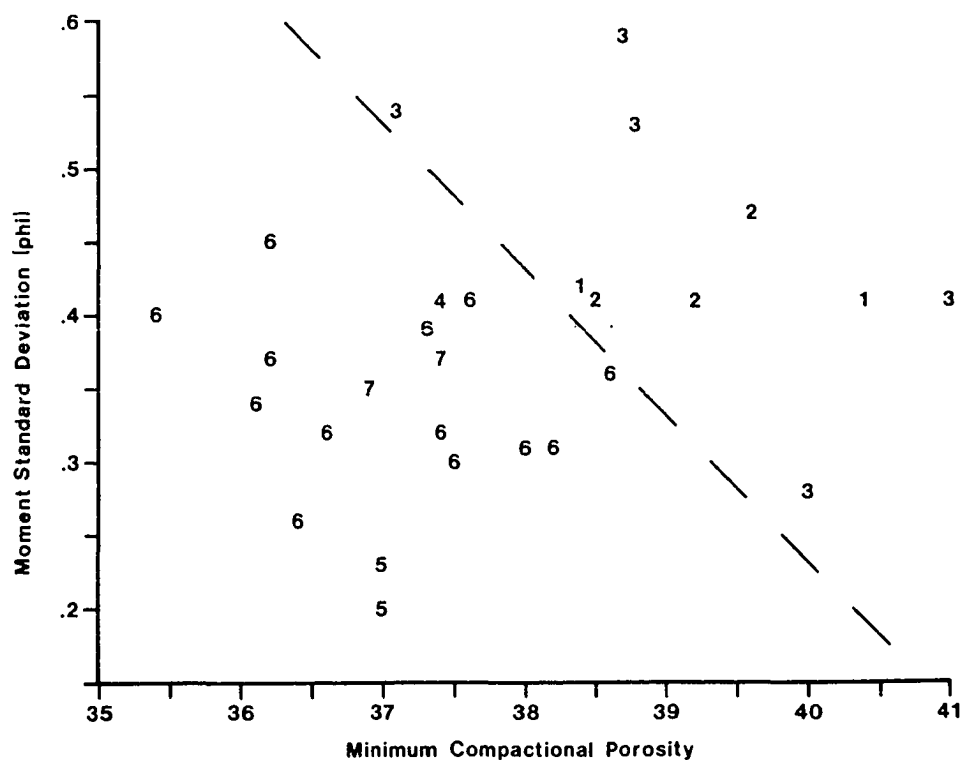
The limited number of samples analyzed in this study does not permit an adequate evaluation to be made of the usefulness or significance of the packing efficiency measure. As can be seen in Figure 31, the total range of packing efficiency for the 18 samples is rather small. The analytical error associated with the determination of this measure may be large relative to this range. If so, the apparent differences

among the lamina types and environments may be more fortuitous than real. The moderately high quadratic or simple curvilinear correlation between the plane section and minimum compactional porosities ($r_Q = 0.830$) does suggest, however, that the depositional processes tend to achieve near maximum packing. Thus the packing efficiencies for the various environments should in general be both similar and high.

In Appendix J it can be seen that the packing efficiency of the ancient sandstones has also been determined. In all cases it is greater than the theoretical maximum of one. Although the packing efficiency is totally lacking in environmental significance when applied to these samples, it is interesting to note that a value of greater than one for this measure is a good indication of deep burial compaction and/or quartz cementation.

Effect of Sediment Texture

In Figure 32 minimum compactional porosity is plotted against sorting (i.e., grain size moment standard deviation). The sample points on this plot are coded according to the roundness rank (based on the Powers roundness range and mode) of the sand grains. Higher rankings indicate greater degrees of rounding. It can be seen in this figure that if grain roundness is not taken into account then there is no significant relationship between sorting and porosity. The linear correlation coefficient for the two variables equals +0.275 and thus indicates that there is a very weak tendency for minimum porosity to increase as sorting



Powers Grain Roundness

Rank	Min.	Mode	Max.
1	VA	A	SA
2	VA	A-SA	SA
3	A	A-SA	SA
4	VA	A-SA	SR
5	A	SA	SR
6	A	SA-SR	R
7	SA	SR-R	WR

VA-very angular A-angular SA-subangular SR-subrounded
 R-rounded WR-well rounded

FIG. 32 — Plot of minimum compactional porosity versus sediment sorting and Powers roundness.

gets poorer. This is just the opposite of the relationship that one would expect when all other textural parameters are held constant. When the grain roundness is taken into account, however, the plot takes on considerable significance. It is evident that the more angular sand is clearly separated from the more rounded. Thus we see, as expected, that for a given sorting the lesser grain roundness results in higher minimum porosity. Furthermore, for both the more rounded sands (ranks 5, 6 and 7) and especially the more angular sands (ranks 1, 2, 3 and 4) the expected trend of decreasing porosity with poorer sorting is reasonably well developed.

In Figure 33 minimum compactional porosity is plotted against mean grain size. As in Figure 32, the sample points are coded according to the roundness rank of the sand grains. The linear correlation coefficient for the two variables is +0.586 and thus indicates what is already visibly apparent: there is a moderate tendency for the minimum porosity to increase as the mean grain size decreases. This relationship is consistent with the previously stated theoretical expectation that, when all other textural parameters are held constant, the increase in porosity with decreasing grain size is caused by the increased internal friction of the sediment. To interpret the plot in these terms, however, would be wrong. An examination of the roundness codes shows that the more angular sands have the higher porosities. The relationship exhibited in Figure 33 is then in reality between roundness and porosity with the roundness being controlled by the grain size. This is as it should be because it is widely recognized by geologists that the finer

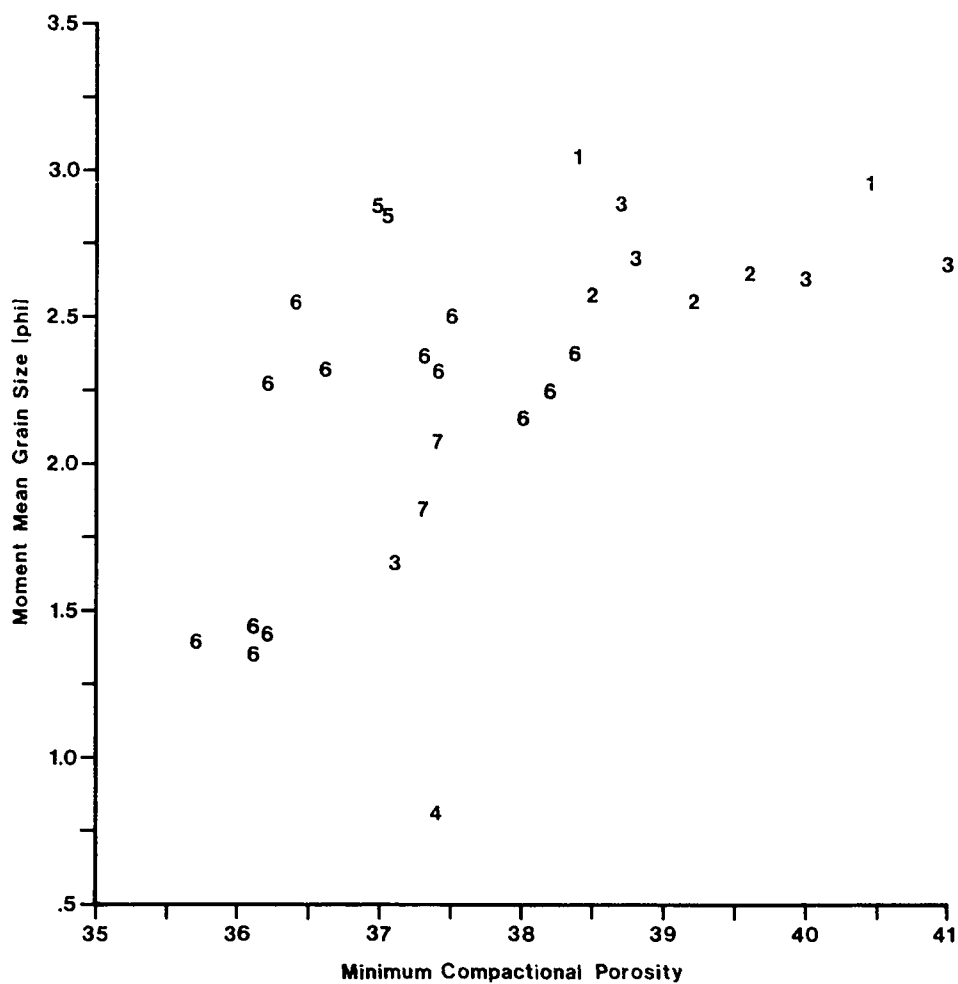


FIG. 33 – Plot of minimum compactional porosity versus mean grain size and Powers roundness (see Figure 32 for definition of Powers roundness rank).

sediments are more angular. It should be kept in mind, however, that perhaps a substantial portion of the grains for the sandstones are angular because of breakage during disaggregation or the presence of crystal-faceted quartz overgrowths.

Figures 32 and 33 strongly suggest that grain roundness is much more important than either grain form or size in determining minimum compactional porosities. The evidence for this is three-fold. First, in Figure 32 sorting and roundness adequately explain the variations in porosity. The consideration of other factors like grain form and size seems to be unnecessary. Second, in Figure 32 the two samples (D3-15 and 19; the two rank 5 points) with the least spherical or compact grains of any sample analyzed in this study seem to have anomalously low minimum porosities. As pointed out in the discussion of the tabularity profiles, these samples have an unusually high proportion of flaky grains. If grain form were really an important factor, these samples should have higher minimum porosities. Third, in Figure 33 the increase in minimum porosity is adequately explained by grain roundness alone. Although mean grain size may contribute to the trend, its effect cannot be very important. The strong relationship between grain roundness and minimum compactional porosity was recognized by Lamar (1928) who used this type of porosity as a measure of grain roundness for samples of medium grained sand.

A comprehensive summary of the statistical intercorrelations among the textural, pore geometry, and compactional and other packing parameters will be provided in a later section.

METHODOLOGIES FOR THE ANALYSIS OF PORE GEOMETRY

INTRODUCTION

Concepts And Definitions

The 'pore geometry' of a sediment or sedimentary rock refers to the amount and configuration of the pore space. The more widely recognized aspects of pore geometry are as follows (Scheidegger, 1972, p. 5-10).

1) Pore Volume

Pore volume is expressed as either the 'fractional porosity' (ratio of pore volume to total bulk rock or sediment volume) or the 'percent porosity' (percent of the total bulk rock or sediment volume occupied by pore space; equals the fractional porosity times 100). The term 'porosity' unfortunately has two very different meanings. It can refer simply to some measure of the pore volume, or it can be used in a more general sense as a synonym for 'pore space'. In the present study, porosity will always be used in reference to pore volume. Note

that porosity may be thought of as both a packing and a pore geometry parameter. Two basic types of fractional or percent porosity are recognized: 'total porosity' (the total volume of the pore space) and 'effective porosity' (the volume of the interconnected pore space which is in open communication with the sample boundaries). It is the effective porosity, of course, which is most important in considering the fluid transmissibility of a sample. In unconsolidated, matrix-free sand, all pore space is probably interconnected. In sandstones, the effective porosity is usually only slightly less than the total porosity (Blatt et al., 1980, p. 412).

2) Pore Size Distribution

The size distribution of the pores within a rock or sediment can be described by any of several kinds of summary statistics and plots but typically it is characterized only by some measure of the average pore dimension or a cumulative pore size distribution plot.

3) Pore Surface Area

The surface area of the pore walls is usually expressed as the 'specific pore surface area' which is the internal surface area of the pore space divided by the total bulk rock or sediment volume.

4) Pore Tortuosity

The tortuosity of a series of interconnected pores is a measure of the average sinuosity of the paths which would be followed by a fluid flowing through a rock or sediment. More specifically, tortuosity is

defined as the length of the actual fluid flow path divided by the length of the sample in the direction of fluid flow. From this definition it is clear that tortuosity is both a kinematical concept as well as a geometrical property.

The four pore geometry parameters just described are the ones of principal interest to geologists but other geometrical aspects of pores are recognized (e.g., the shape, orientation and spatial arrangement of pores).

At the time of deposition, the pore geometry of a sediment is largely a reflection of the texture and fabric, and hence, the sedimentary environment. After burial, however, the pore geometry is modified by compaction and authigenesis, and so may bear little or no resemblance to the pore geometry at the time of deposition.

Relation Between Pore Geometry And Permeability

There has always been substantial interest in pore geometry because it alone determines the fluid transmissibility or 'permeability' characteristics of a rock or sediment. Permeability is defined by the AGI glossary as "the property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure" (Bates and Jackson, 1980, p. 468). An understanding of the pore geometry is of critical importance in the production of hydrocarbons and water from sedimentary rocks. The porosity determines how much of a fluid is present, and all the pore

geometry parameters combined determine the permeability, and hence, the rate at which a fluid will flow or can be pumped out of a rock. The Kozeny Equation, which will be discussed in a later section, describes the intimate relationship between permeability and pore geometry. With the increasing use of secondary and tertiary recovery methods to increase the production of oil, an understanding of pore geometry is more important than ever. Its consideration is essential in the development of any recovery strategy. According to Stegemeier (1977, p. 64) ". . . the nature of the pore network largely controls the amount of trapping and the ease of release. Important parameters are the pore size distribution, pore body/pore neck [size] ratio, and the degree of interconnection between pores".

In the past, workers have attempted to deduce the inherent permeability characteristics of a rock not from the four principal pore geometry parameters but rather from one of these parameters, effective porosity, in combination with two textural parameters, mean grain size and sorting. It has been demonstrated repeatedly from theoretical considerations (Berg, 1970; and Pettijohn et al., 1972, p. 525 and Table 11-9), and from studies of experimental sands (Krumbein and Monk, 1942; and Beard and Weyl, 1973) and natural sands (Chilingar, 1964, p. 71-75; Davis, 1969; Pryor, 1973; and Hsü, 1977) that permeability tends to increase in unconsolidated sands as porosity and mean grain size increase, and as sorting improves. It is true, of course, that the geometry of the pore space is largely a reflection of the geometry of the bounding surfaces, i.e., the grains. The interrelationship between the grains and pore geometry rapidly breaks down, however, when cements

and matrix are present, or the pore space is partly derived from fractures or dissolution of original detrital components. If one's interest is in the inherent permeability characteristics of sedimentary rocks, it should prove more fruitful to consider only the geometry of the pore space and to essentially ignore the solid part of the rock. This will be the approach adopted in the present study.

Measurement Of Pore Geometry

Nonstereological Approaches

There are basically eight nonstereological approaches to the measurement of pore geometry. These approaches are called nonstereological because they do not involve the quantitative description of plane or thin sections. Each of these approaches will be briefly discussed below. For an excellent general review of the methodologies available see Dullien and Batra (1970), Scheidegger (1972, p. 10-24), and Dullien (1979, p. 75-155).

1) Volumetric and Bulk Density Determinations

As previously shown by equation 12, the total porosity can be calculated if the rock density and bulk volume are known. Several methods for determining the total rock volume are described by Curtis (1971). The effective porosity can be calculated from the difference

between the weight of a rock when completely saturated with a liquid and the weight of the rock when dry (WD), the density of the liquid (LD), and the total rock volume (TRV) (fractional effective porosity = $(WD/LD)/TRV$; Curtis, 1971).

2) Gas Expansion

The effective porosity can be determined using a pycnometer which directly measures the volume of a gas contained in the pore space of a sample of known bulk volume (Beeson, 1950).

3) Mercury Intrusion Porosimetry

The amount of mercury injected into a porous rock at various pressures can be used to obtain rough estimates of the effective porosity, the pore surface area, and the pore size distribution (Orr, 1969; Curtis, 1971; Dullien and Dhawan, 1974; Wardlaw, 1976; and Pittman, 1979). The size distribution determined is not really for the 'pores' but rather for the 'pore throats'. The pore throats are the smaller openings connecting pore spaces of greater dimension.

4) Gas Adsorption

The pore surface area can be determined from the amount of nitrogen or other gas adsorbed by a porous rock (Brunauer, Emmett and Teller, 1938; and Nelsen and Eggertsen, 1958).

5) Electrical Resistivity and Ion Transit Time

Rough estimates of pore tortuosity can be obtained from the electrical resistivity of a brine-saturated porous rock (Jackson et al., 1978). If the effective fractional porosity (P) and the 'formation factor' (FF; also called the 'resistivity factor') are known, the tortuosity (T) can be computed from Archie's Law (Archie, 1942):

$$T = - \frac{\log FF}{\log P} \quad (13)$$

The formation factor is the ratio of the electrical resistivity of a porous rock saturated with a brine to the electrical resistivity of the pure brine. For a given porosity, the more tortuous flow paths cause greater resistivities (and hence, higher formation factors) because it takes the conducting ions longer to migrate from one side of a sample to the other.

Only Winsauer et al. (1952) have attempted to measure pore tortuosity directly. They used a specially designed experimental apparatus where the conducting ions in a brine were forced to migrate a fixed distance between two electrodes having a constant voltage difference. The transit times were determined for the ions moving through a brine-saturated porous rock (t_r) and a pure brine (t_b). The pore tortuosity of the rock was computed from the following formula:

$$T = \sqrt{\frac{t_r}{t_b}} \quad (14)$$

6) Three Dimensional Pore Casts

In this technique porous rocks are impregnated under pressure with a fluid plastic or molten Wood's metal (a solder-like metal which melts at 65°C). After the plastic or metal hardens, the original rock components are dissolved with hydrofluoric or some other acid, leaving a three-dimensional pore cast (Wardlaw, 1976; Pittman, 1979; and Swanson, 1979). The pore cast geometry can then be qualitatively characterized when examined using a light petrographic or scanning electron microscope.

7) Pore Classifications

Classifications of the gross geometrical (and genetic) aspects of pore space in sandstone have been proposed by Schmidt et al. (1977), Schmidt and McDonald, 1979; and Pittman (1979). Although primarily designed for the characterization of secondary pore space (i.e., new pore space produced by diagenesis), these classifications, especially that of Schmidt and McDonald (1979, Table 1), are useful for the qualitative description of pore geometry in thin sections.

8) Optical Processing

In this seldom used technique, a high contrast black and white transparency (i.e., a film negative) is obtained for a plane or thin section of a porous rock. The pore space in the transparency is colorless and the solid part of the rock (i.e., grains, cement and matrix) is black. Laser light is then beamed through this transparency which

acts like a diffraction grating. The resulting diffraction pattern can be semi-quantitatively described and then interpreted in terms of the gross geometrical aspects of the pore space (Smith, 1968; Pincus, 1969; and Preston and Davis, 1976). None of the usual pore geometry parameters can be measured by this method. The diffraction pattern is said to be the optical analog of the double Fourier analysis of a digitized rock-pore pattern, a technique which will be described in considerable detail in a later section.

Stereological Approach

'Stereology' can be defined as the study of the statistical relationships that exist between quantities that are measured from two-dimensional planes and the features that these quantities represent in three-dimensional space: in other words, stereology involves the derivation of information about the whole volume of a sample from an areal examination of randomly-oriented plane sections through the sample. Most of the practitioners of stereology are material science and biomedical researchers. The bulk of the literature strongly reflects this disciplinary bias. Underwood (1970) and Weibel (1979/1980) are two excellent introductory texts which describe the theory and methodology of stereology from the largely material science and bio-medical viewpoints, respectively. Geologists have long been practitioners of stereology but their involvement in the application of this science

has been relatively minor. The estimation of porosity and volume percent of rock components from thin sections are the principal examples of applied stereology in geology (Chayes, 1956). It must be kept in mind, however, that stereological methods are strictly valid only for plane sections. As was pointed out in the section on 'measurement errors in the thin section analysis of grain packing', stereological determinations become increasingly less accurate for thin sections as the average grain size decreases.

There are two approaches to applied stereology. In the first, the 'statistical estimation approach', the properties of three-dimensional objects or structures are estimated from plane sections; and in the second, the 'descriptive approach', the plane sections are quantitatively described but no attempt is made to establish the statistical relationship between these descriptions and the three-dimensional sample properties. Both of these approaches will be briefly discussed below.

1) Statistical Estimation Approach

This approach employs methodologies which are derived from a consideration of the geometric probability associated with the random sectioning process. The derivations are based on the statistical proposition that the quantities calculated from random plane sections are distributionally related to the properties of the three-dimensional sample. The theoretical foundations for this approach are rigorously mathematical and typically involve integral geometry and random sets

theory. The statistical estimation approach to stereology is perhaps best exemplified by the so-called 'French school of stereology': la Centre de Morphologie Mathématique, Fontainebleau, France. Representative publications from this school include Matheron (1967 and 1971), Serra (1969), and Miles and Davy (1976).

Most of the effort in the development of the statistical estimation methodologies has been directed at those cases where it is necessary to characterize a population of discrete objects within a sample. The analyst is limited to determining the number of objects and their size distribution. For this to be possible it is required: first, that all objects have very similar shapes; and second, that the shape of the objects be both compact and convex. Such methodologies are clearly not suitable for porous media because pores are geometrically variable networks. Some analysts have attempted to circumvent this problem by processing a two-dimensional pore pattern prior to stereological analysis (Matheron, 1967; Serra, 1969; Pinault et al., 1971; and Rink and Schopper, 1978). The processing involves an image enhancement technique known as 'erosion'. Erosion results in the individualization and geometrical simplification of pores through the removal of the pore throats connecting the larger pore bodies, and the removal of the protuberances and irregularities on the pore body margins. Although the processing of pore patterns greatly improves the applicability of the statistical estimation methodologies, the results of the stereological analyses would seem to be of little value. In order to assess the

role of pore geometry in fluid transmissibility and entrapment, it should prove more useful to consider all of the pore space rather than just the simplified pore bodies.

There are some statistical estimation methodologies that do not require the recognition of discrete objects and thus are entirely suitable for pore patterns. Perez-Rosales (1967 and 1969), and ASTM (1977b) describe the stereological procedures for determining specific pore surface area and total porosity (or effective porosity if only the impregnated pore space is considered).

2) Descriptive Approach

In this stereological approach the objective is to describe quantitatively plane sections. The descriptive parameters measured do not have an established statistical relationship with the three-dimensional sample properties. Because there is no theoretical foundation, the methodologies are mathematically simple. The justification for this approach is that the descriptive parameters, if properly designed, will provide meaningful information about a sample. The physical significance of a parameter may be unclear but the parameter may still be useful in describing the variation in the morphometric or behavioral characteristics of a suite of samples.

The descriptive methodologies are probably most useful when applied to those cases where discrete objects are not recognized. Stereological procedures for the determination of pore tortuosity and average

pore dimension have been described by Preston and Davis (1976), and Perez-Rosales (1969), respectively. It is important to keep in mind that the names of these parameters are intended to reflect those sample properties that are thought to largely control the parameter values. The parameters are not necessarily estimates of the sample properties for which they are named.

In those cases where discrete objects within samples are recognized, a wide variety of stereological procedures are available for the determination of object size and shape distributions. Rink (1976) describes the application of these procedures to pore patterns.

Of the many approaches to the measurement of pore geometry described above, only the stereological approach was employed in the present study. More specifically, this study utilized the descriptive and statistical estimation methodologies for entire pore patterns, and the descriptive methodologies for individual pores. In addition to the stereological methodologies already mentioned, several new descriptive methodologies were developed and applied.

THE KOZENY EQUATION

The Kozeny equation describes the relationship between permeability and three of the four principal pore geometry parameters: effective porosity, specific pore surface area and pore tortuosity (Kozeny, 1927).

An explanation of the original derivation can be found in Chilingar (1957). Other derivations, each producing a somewhat different final equation, have been proposed (e.g., Carmen, 1937). The differences between the various forms of the 'Kozeny Equation' arise from differences in the underlying assumptions about the gross geometrical character of the pore space (i.e., different pore geometry models are assumed). The derivation which will be described below is similar to that of Chilingar (1957), and is based on the Darcy and Poiseuille Laws.

According to Darcy's Law, the fluid discharge through a porous granular aggregate like sand or sandstone can be computed from the following relation:

$$Q = \frac{K \cdot \Delta Pr \cdot A_c}{\mu \cdot D_1} \quad (15)$$

where,

Q = fluid flow rate or discharge (L^3T^{-1} ; volume per unit time)

ΔPr = pressure difference on opposite sides of a porous medium which drives the fluid ($ML^{-1}T^{-2}$; force per unit area)

A_c = cross-sectional area of the porous medium normal to the direction of fluid flow; assumed to remain constant in the direction of flow (L^2 ; area)

μ = absolute viscosity of the fluid ($ML^{-1}T^{-1}$; force applied through time per unit area)

D_1 = length of the porous medium in the direction parallel to fluid flow (L ; length)

K = permeability constant or coefficient (also simply called 'the permeability'); it is a proportionality constant with units of area (L^2)

Note that each of the above variables is characterized by its fundamental units: mass (M), length (L) and time (T). The reader should not confuse the 'T' used here for time with the same symbol used in other equations to represent tortuosity. The units of permeability may seem odd. In an attempt to put people at ease over permeability's L^2 dimension, Curtis (1971, p. 348) states that ". . . rationally it may be looked on as a sort of average pore area that determines the rate of fluid flow in a rock . . ." when all other parameters are held constant.

According to Poiseuille's Law, the fluid discharge through a bundle of equal-sized cylindrical tubes can be calculated from the following relation (all fluid is assumed to flow through the tubes):

$$Q = \frac{n \cdot \pi \cdot R^4 \cdot \Delta Pr}{8 \cdot \mu \cdot D_2} \quad (16)$$

where,

n = number of tubes

π = the universal dimensionless constant pi (3.14159 . . .)

R = radius of the tube interior (L, length)

D_2 = length of the tube; the tubes may be straight or sinuous (L, length)

Q , ΔPr and μ are as previously defined for equation 15.

If the right sides of equations 15 and 16 are equated, and then rearranged and simplified to solve for K we obtain,

$$K = \frac{n \cdot \pi \cdot R^4 \cdot D_1}{8 \cdot A \cdot D_2} \quad (17)$$

When solving for permeability as was done in equation 17, we are assuming that the pore channels in a porous granular aggregate are, to a good first approximation, analogous to a bundle of cylindrical tubes oriented parallel to the direction of fluid flow.

Equation 17 can be further simplified by substituting in terms for fractional porosity, specific pore surface area and tortuosity.

1) The Porosity Term

The fractional porosity (P) of a bundle of cylindrical tubes is equal to the ratio of the total tube volume ($n \cdot \pi \cdot R^2 \cdot D_2$) to the total bulk volume of the porous medium ($A \cdot D_1$). P is a dimensionless parameter. Substituting this term into equation 17 yields,

$$K = \frac{P \cdot R^2 \cdot D_1^2}{8 \cdot D_2} \quad (18)$$

2) The Tortuosity Term

The tortuosity (T) of a bundle of cylindrical tubes is equal to the length of the actual flow path (D_2) to the length of the porous medium in the direction of fluid flow (D_1). T is a dimensionless parameter. Substituting this term into equation 18 yields,

$$K = \frac{P \cdot R^2}{8 \cdot T^2} \quad (19)$$

3) The Specific Pore Surface Area Term

The specific pore surface area (S_s) is equal to the ratio of the internal surface area of the tubes ($n \cdot 2 \cdot \pi \cdot R \cdot D_2$) to the total bulk volume of the porous medium ($A \cdot D_1$ or, more conveniently, $p^{-1} \cdot n \cdot \pi \cdot R^2 \cdot D_2$). S_s has units of length to the minus one power. Substitution of this term into equation 19 yields the Kozeny Equation,

$$K = \frac{P^3}{2 \cdot T^2 \cdot S_s^2} \text{ or, more generally,} \quad (20)$$

$$K = c \cdot \frac{P}{T^2 \cdot S_s^2} \quad (21)$$

where c is a dimensionless proportionality constant which is often referred to as the 'Kozeny constant'. This formulation of the Kozeny equation is nearly identical to that derived by Wyllie and Spangler (1952) and Scheidegger (1972, p. 137-140) who used a very different derivation strategy.

The above derivation differs slightly from that of Kozeny (1927) and Chilingar (1957) because these two authors defined the specific pore surface area as the ratio of the internal surface area of the tubes to the volume of the tubes (rather than the volume of the medium). If this definition is used in the derivation, the Kozeny equation would be

$$K = c \cdot \frac{P}{T \cdot S_s^2} \quad (22)$$

The definition of S_s used in the derivation of equation 20 is preferred by this author because it is consistent with the stereological measure of S_s (Perez-Rosales, 1967) used in the present study. S_s based on bulk volume is a standardized measure of the 'absolute' internal surface area whereas S_s based on pore volume represents the internal surface area per unit volume of pore space and, as such, is little more than a measure of one aspect of pore shape (as S_s decreases and pore size remains constant, pores become more compact in form). Obviously, if one is interested in comparing the permeability characteristics of a suite of samples then an absolute measure of internal surface area is most appropriate. Both equations 21 and 22 are dimensionally correct: P and T are dimensionless, S_s has dimensions of L^{-1} , and thus K has dimensions of L^2 .

Equation 20 is valid only if the interconnected pores of a rock are analogous to a bundle of cylindrical tubes. Seldom, if ever, would this actually be the case. For real rocks the Kozeny constant would certainly differ from the value of $\frac{1}{2}$ in equation 20. The exponents for P and T in equations 21 and 22 would also probably differ. The S_s term would have to remain squared in order to assure that the equation is dimensionally correct. Thus we see that the details of the Kozeny equation are not important. What is important is the general relationship between permeability and the principal pore geometry parameters: all else being equal, permeability should increase as porosity increases, tortuosity decreases and surface area decreases. An interesting way

to look at the Kozeny equation is to consider the general effects of the numerator and denominator. Porosity determines the 'volume' of fluid flow, and the tortuosity and specific surface area determine the 'retardation' of the fluid flow. For a constant porosity, the surface area controls the extent of the surface tension forces between the pore walls and fluid, and the tortuosity controls the pore cross-sectional area normal to the direction of fluid flow (i.e., the more sinuous pores with a given volume have a smaller cross-sectional area). The greater the surface tension forces and the smaller the pore cross-sectional area are the greater the fluid retardation and, hence, the smaller the fluid discharge.

One of the intriguing things about the Kozeny equation is that it suggests the possibility of predicting the permeability of a rock from its pore geometry characteristics. A prediction equation could be derived through multiple regression analysis using a set of samples with known K , P , T and S_s . The optimal values for the Kozeny constant and the two exponents would be provided by the regression analysis. Such an equation, depending on the nature of the control samples, could have wide applicability. Of course if large sample specimens are available, permeability can be directly measured on cylindrical plugs. A prediction equation for permeability would be useful, however, for those frequent occasions when large sample specimens are not available. For example, cores from oil and gas wells are seldom taken because of their great expense but cuttings are always available. The cuttings consist of rock fragments up to a few tenths of an inch in diameter and are far

too small for the direct measurement of permeability. A thin section (or better, a plane section) prepared from the cuttings would permit the measurement of the pore geometry parameters and the consequent prediction of the permeability. Established stereological procedures exist for effective porosity and specific pore surface area, but not for pore tortuosity. This situation will be remedied in the present study when in a later section a modification of the Preston and Davis (1976) procedure for measuring tortuosity will be proposed.

There has been only one attempt in the past at predicting permeability from a thin section. Aschenbrenner and Chilingar (1960) describe Teodorovich's method for estimating permeabilities of carbonate rocks from pore space characteristics visible in a thin section. Permeability was calculated from the following formula:

$$K = C_1 \cdot C_2 \cdot C_3 \cdot C_4 \quad (23)$$

where K is permeability in millidarcys, and C_1 through C_4 are empirical coefficients based on percent effective porosity (C_1), maximum pore dimension in millimeters (C_2), and a qualitative characterization of 'pore space type' (C_3) and 'pore shape' (C_4). For the ten samples analyzed by Aschenbrenner and Chilingar the prediction equation proved to be surprisingly accurate: the computed permeabilities differed from those measured from plugs of the same samples by no more than ten percent. Equations like 23 would in practice be awkward to use because they rely on the qualitative (and hence, subjective) characterization of certain aspects of the pore geometry. The more direct and

quantitative approach to the estimation of permeability offered by the Kozeny equation should prove to be simpler, more objective and of wider applicability.

There is one fundamental problem which afflicts all measurement techniques for permeability and pore geometry. It was shown by Fatt and Davis (1952) that the pore geometry of a rock at depth may not be the same when that rock is brought to the earth's surface for analysis. The reason for this is that when a rock sample is removed from the subsurface, all the confining forces are also removed and thus the rock expands in all directions. The effect of this expansion on the pore geometry is unknown, but Fatt and Davis have reported increases of more than one hundred percent in permeability. It is widely believed, however, that carbonates and matrix-free sandstones probably experience only negligible changes in their pore geometries when brought to the surface.

DIGITIZATION OF PORE SPACE

In order to obtain a quantitative stereological description of the pore geometry for the 28 sand and sandstone samples analyzed in this study it was first necessary to 'digitize' the pore space visible in the plane sections. Digitization is the process whereby a two-dimensional image, like a plane section, is reduced to a matrix of equally-spaced sampling points. Each sampling point is numerically coded to reflect the character of the rock beneath it. In the present application, the sampling points are coded to reflect either pore space (-1) or

rock (+1). Conceptually the sampling points are located in the following way. Imagine a transparent square grid being laid on top of a plane section. This grid is said to be square because it consists of intersecting horizontal and vertical lines which form the sides of square compartments. The corners of these square compartments correspond to the grid intersections or 'nodes'. Each of the many grid nodes represents a sampling point. If a given grid node/sampling point is underlain by pore space it is given a value of -1, and if underlain by a grain, cement or matrix it is given a value of +1.

If only the determination of porosity, average pore dimension and specific pore surface area were desired there would be no need to digitize a plane section. These parameters can be readily measured using a petrographic microscope equipped with a mechanical stage. However, to measure pore geometry parameters like tortuosity and many others which will be described later it is necessary to submit the sampling point matrices to a computer for processing.

The digitization procedure employed in the present study is as follows.

Step 1 Standard petrographic thin sections were obtained for each sample.

Step 2 Using a Nikon Profile Projector, a thin section image was projected onto the back of a flat, circular (30 centimeter diameter) viewing screen. The thin section image could be viewed at any one of three magnifications: 20, 50 and 100 powers. Only the 50 and 100 power magnifications were used. The 20 power magnification was so low that

the pore and rock boundaries could not be accurately resolved. For the 50 and 100 power magnifications, respectively, the widths of the circular field of view were 6.00 and 3.00 millimeters, and the lengths of the side of the largest possible inscribing square were 4.24 and 2.12 millimeters. These dimensions are in terms of actual distances on the thin section. The 50 power magnification was used for all samples having a mean grain size coarser than 2.5 phi. All other samples were analyzed using the 100 power magnification.

Step 3 Translucent mylar drafting film (polished on one side and frosted on the other) was placed over the viewing screen with the frosted side towards the viewer.

Step 4 The pore outlines visible in the viewing screen were traced in pencil on the mylar film. The focus of the profile projector was set so that only the top of a thin section was visible. Thus the tracings represent plane section views of the pore geometry. The tracing was confined to a square area: 7.80 square inches on the mylar film, and on the thin section, 3.96 (50 power) or 1.98 (100 power) square millimeters. Figures 34 and 35 are examples of pore outline tracings for samples B2-16 and D5-16, respectively (the sampling area for both tracings is 3.96 square millimeters).

Step 5 The finished tracing was removed from the profile projector and placed on a light table where it was overlaid with a sheet of square grid graph paper (ten divisions per inch). The graph paper was aligned with the tracing so that the grid lines were coincident with the sides of the tracing square (i.e., the four corners of the tracing square were exactly overlain by grid nodes). Thus 79^2 or 6241 sampling points

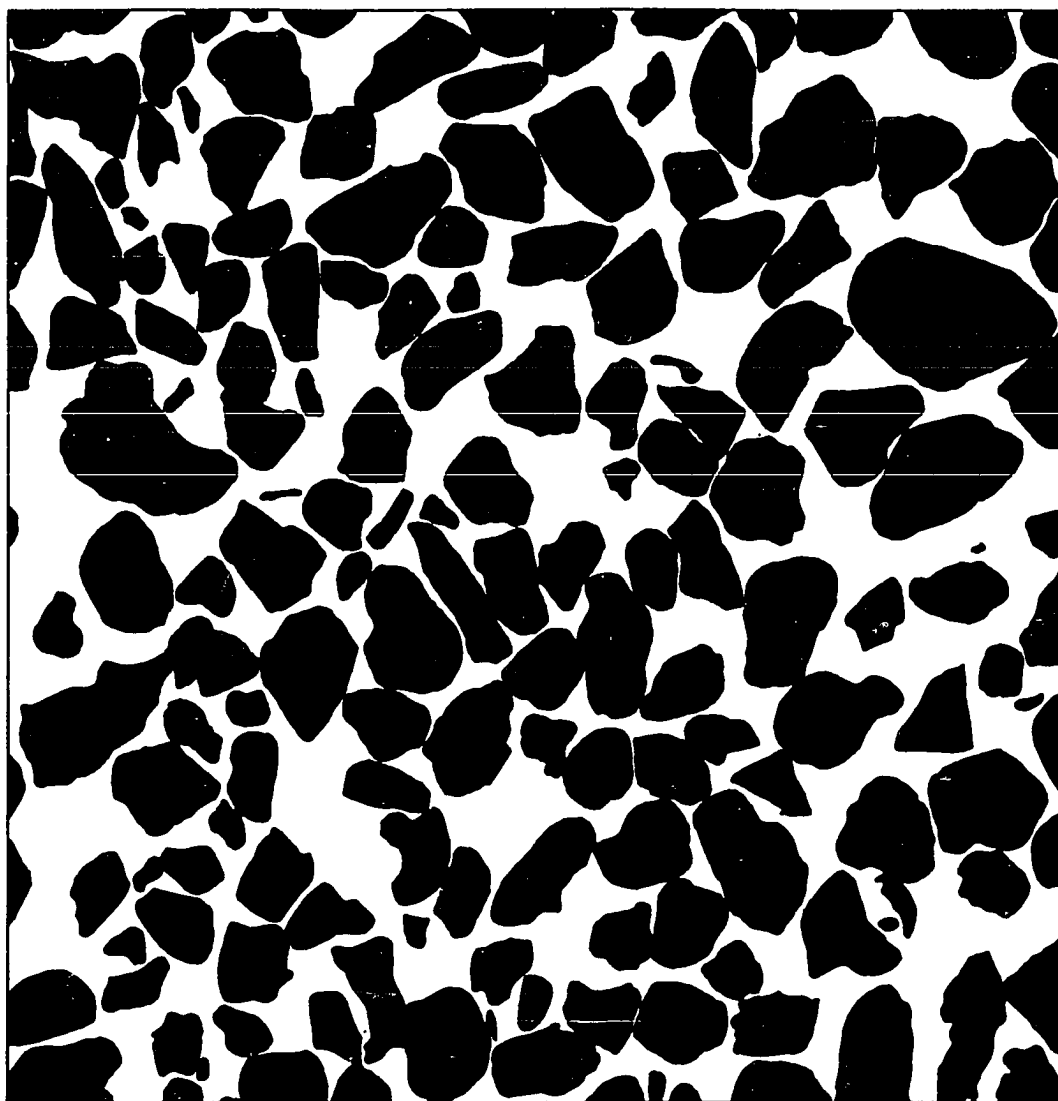


FIG. 34 – Pore outline tracing for sample B2-16.

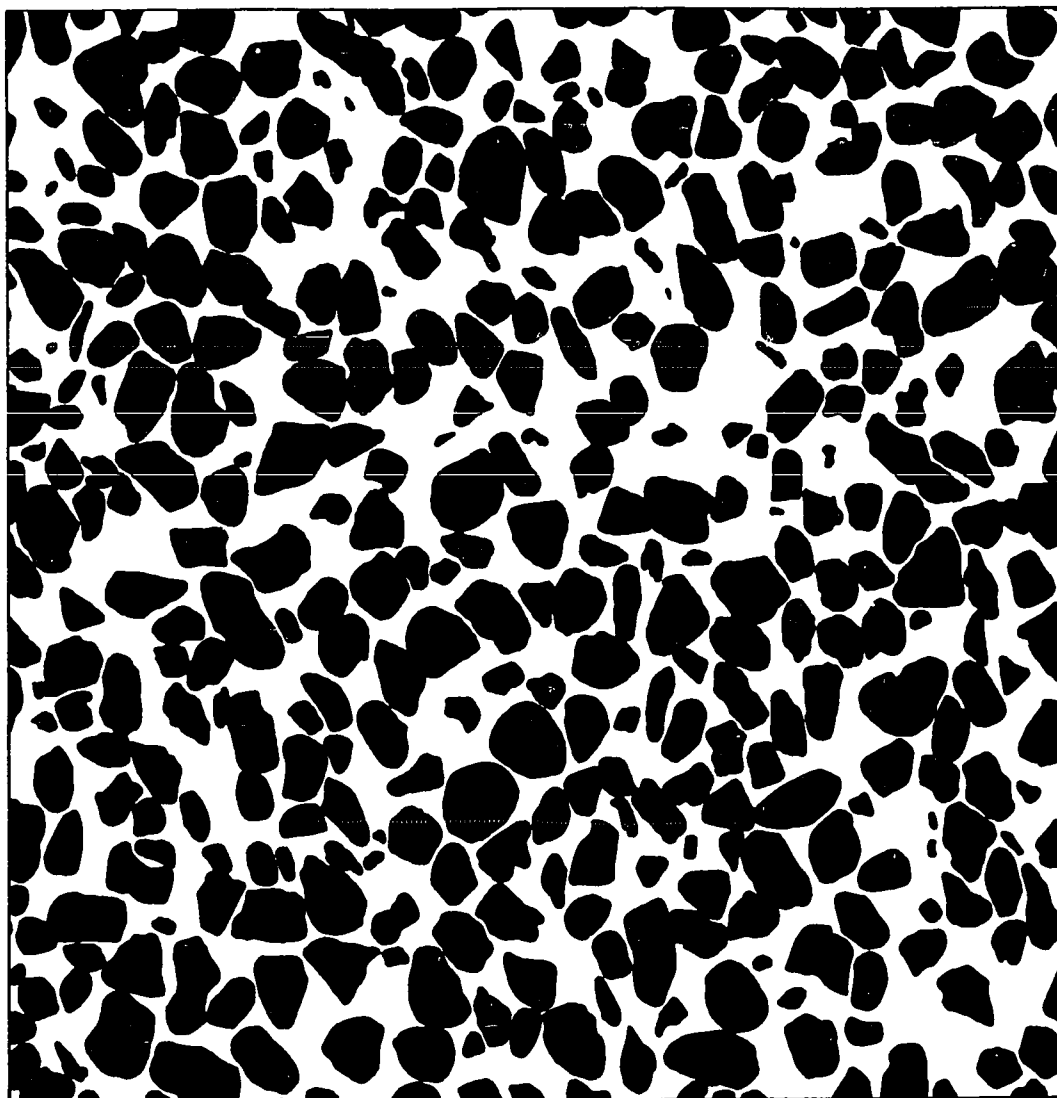


FIG. 35 – Pore outline tracing for sample D5-16.

(grid nodes) lay within the boundaries of the tracing square. In terms of thin section distances, the vertical and horizontal distance between adjacent sampling points equaled 0.0508 (50 power) or 0.0254 (100 power) millimeters.

Step 6 Each of the 6241 sampling points in a tracing was examined. If a sampling point lay within a pore, the corresponding grid node on the graph paper was marked with a black dot. All other grid nodes were left unmarked. This step constitutes the 'digitization' of a plane section.

Step 7 The digitized information on the graph paper was next punched onto 80 column computer cards: one card per horizontal grid line with each column on a card corresponding to a grid node (sampling point). Thus 79 computer cards were punched for each tracing. On each card, an 'X' was punched in every column corresponding to pore space (i.e., the marked grid nodes). All other columns represented rock and were left blank. In subsequent computer analyses, the 79 by 79 matrix of blanks and X's was converted to a 79 by 79 binary matrix of +1's (rock) and -1's (pore).

The rock-pore matrices generated by the above procedure are given in Part I of Appendix K. The digitization procedure employed in this study has three serious weaknesses:

- 1) The resolution is not high enough. With a spacing of 51 (50 power) or 25 (100 power) microns between adjacent sampling points the fine detail in the pore structure cannot be adequately resolved. This is especially unfortunate because it is the smallest pores that largely control the permeability characteristics of a rock. It would not be

practical, however, to 'hand digitize' at higher resolutions because of the extremely large number of sampling points involved.

2) The size of the area digitized on a thin section is too small. The probability is high that a 3.96 or 1.98 square millimeter area selected for digitization would not be representative of the thin section as a whole. Ideally a much larger area should have been digitized but because of equipment limitations this was not possible; even if it was possible, the loss of resolution would have largely invalidated the analysis. In this study great care was exercised in the selection of the sampling area on each thin section. The selection was guided by two considerations. First, the pore geometry in the sampling area should not differ markedly from the average overall character of the pore geometry in the thin section. Second, the sampling area should be free of flaws such as 'plucked' grains and improperly cured epoxy which obscured the rock-pore boundaries. Of the two considerations, the second of course had to take precedence.

3) The time and effort required for 'hand digitizing' is much too great. The digitization process, from tracing through card punching, required on the average about 5 hours for each 3.96 or 1.98 square millimeter sampling area. A total of about 175 hours was required for the 35 rock-pore patterns analyzed in this study.

The digitization procedure employed in this study is clearly both impractical and possibly error-prone. It was adopted for the simple reason that there was no viable alternative available at the University

of Cincinnati. These weaknesses in the approach, however, are not important because the focus of this study is on the quantitative description of pore geometry using a binary rock-pore matrix. It may be that the matrices analyzed in this study are not an accurate representation of the average pore geometry of the samples but this is immaterial because they are still very useful for the development, testing and comparison of the pore geometry parameters. What is important here is the measurement procedure and not the measurement result.

The technology and instrumentation for the accurate and efficient digitization of rock-pore patterns does exist. High contrast black and white photos of thin and plane sections can be obtained by any of a number of means: Winsauer et al., 1952; Zimmerle and Bonham, 1962; Winkel-molen et al., 1968; Minoura and Conley, 1971; Dullien and Dhawan, 1974; and Marshall and Walker, 1978. These photos can then be digitized by a computer-assisted scanning densitometer: Zimmerle and Bonham, 1962; Smith, 1968; and Dullien and Dhawan, 1974. The only pore geometry parameter measured to date by any of these techniques is porosity, but the data generated can be used to measure a whole host of other parameters. It is the purpose of this study to encourage the use of these techniques by developing a comprehensive set of stereological procedures for the measurement of pore geometry from digitized rock-pore patterns.

TEST PATTERNS

In addition to the 35 rock-pore patterns, 19 'test' patterns were

also analyzed in this study. These test patterns were used to aid in the development and the evaluation of the results of many of the pore geometry parameters, especially the double Fourier, autocorrelation and pore orientation analyses. With the exception of STRIPES, all the test patterns discussed below are displayed in Part II of Appendix K. All except the first two test patterns were generated by computer programs written by the author.

1) RAN-1

This pattern was obtained by digitizing a portion of Figure 21 in Norman et al. (1971). The figure is based on a computer-generated two-dimensional (i.e., one sphere deep) random packing of equal-sized spheres. The digitized pattern depicts the pore space between the spheres in a plane section which passes through the sphere centers.

2) RAN-2

This pattern was obtained by digitizing a portion of Figure 5 in Visscher and Bolsteri (1972). The figure is based on a computer-generated three dimensional random packing of approximately equal-sized spheres. The digitized pattern depicts the pore space between the spheres in a randomly oriented plane section. The plane section does not pass through the sphere centers.

3) RAN-3

This semi-random simulated rock-pore pattern was generated using the following computer algorithm. Beginning in the upper left corner of the 79 by 79 element matrix and then proceeding across the top row, then

across the second and succeeding rows, left to right, the matrix elements were semi-randomly assigned rock (+1) or pore (-1) values. For each matrix element a random number between 0 and 1 was generated. The proportion of the immediately adjacent elements to the left and above (both vertically and diagonally) the element in question which had pore values was determined. This proportion was free to take on any value within the range of 0.20 to 0.80. Values lower or higher than this range were reset to 0.20 and 0.80, respectively. The proportion was next compared to the random number. If it was larger, the matrix element in question was assigned the pore value, otherwise it was assigned the rock value.

4) CASE1-P

Graton and Fraser's (1935) 'case 1' or 'cubic' systematic packing arrangement for equal-sized spheres was simulated using a computer. The three-dimensional sphere packing was sliced parallel to one of the symmetry planes and through the sphere centers. The resulting plane section was digitized by the computer to produce this simulated rock-pore pattern.

5) CASE1-OB

The same cubic packing of spheres used for the CASE1-P pattern was sliced obliquely to the symmetry planes to obtain a plane section which was then digitized. The oblique slice was generated by the computer in the following manner. The computer first established a 'stationary' reference plane which cut through the center of the three-dimensional sphere pack parallel to the X and Y coordinate axes, and normal to the Z axis. The origin of the three coordinate axes was located at the

center of the sphere pack. The entire sphere pack was next rotated 7.45 degrees around the Z axis, then 37.24 degrees around the X axis, and finally 49.27 degrees around the Y axis. The rotation angles were obtained from a random number table. The circular cross-sectional traces of the spheres on the stationary reference plane were digitized by the computer to produce this simulated rock-pore pattern.

6) CASE2-P

Following a procedure similar to that for CASE1-P, a simulated rock-pore pattern was generated for Graton and Fraser's (1935) 'case 2' or 'orthorhombic' systematic packing arrangement for equal-sized spheres.

7) CASE2-OB

Following a procedure similar to that for CASE1-OB, a simulated rock-pore pattern was generated for the obliquely-sliced 'case 2' sphere pack.

8) CASE3-P

Following a procedure similar to that for CASE1-P, a simulated rock-pore pattern was generated for Graton and Fraser's (1935) 'case 3' or 'rhombohedral' systematic packing arrangement for equal-sized spheres.

9) CASE3-OB

Following a procedure similar to that for CASE1-OB, a simulated rock-pore pattern was generated for the obliquely-sliced 'case 3' sphere pack.

10) STRIPES

STRIPES is not one test pattern but actually a set of ten. Each pattern consists of broad parallel stripes with a constant orientation. The set of patterns exhibits a range of stripe orientations from 0 to 180 degrees with 18 degree increments. The test pattern for the 36 degree orientation (STRIPES-36) is shown in Part II of Appendix K.

THE PORESTAT ALGORITHMS

Introduction

The rock-pore matrices in Appendix K have been described in terms of a large number of pore geometry parameters. All of these pore geometry analyses were performed by a Fortran IV computer program called PORESTAT which was written by the author for this study. An annotated listing of this program and an example of the output (the results for sample D3-15) are provided in Appendix L. The pore geometry parameters and their corresponding computer algorithms will be described in this section. The term 'algorithm' refers to the sequence of calculations and logic operations followed by a computer in the process of arriving at a solution for a particular problem. With the exception of porosity, all of the algorithms described below represent either modifications of existing methodologies or methodologies newly developed for this study. The algorithms are of two basic types: those that generate descriptive parameters for the entire rock-pore pattern (individual

pores are not recognized), and those that generate descriptive parameters for individual pores. In the second case, the results are combined to produce summary statistics or frequency distributions.

The sample number and a map of the rock-pore matrix are given on pages A153 and A154 of the PORESTAT output in Appendix L.

Measures Based On The Entire Pore Pattern

Porosity

The percent porosity (P) is the percent of the total bulk rock volume occupied by pore space. If NP is the total number of pore points or elements in a rock-pore matrix and NPR is the total number of pore and rock points in a rock-pore matrix (in the 79 by 79 element matrices used in this study NPR always equals 6241) then the porosity can be computed as follows (Perez-Rosales, 1967 and 1969; and Perez-Rosales and Martinez, 1971):

$$P = \left(\frac{NP}{NPR} \right) \cdot 100 \quad (24)$$

If only the interconnected pore space is considered, then equation 24 represents the 'effective' porosity, but if the isolated pore space is included in NP, then the equation gives the 'total' porosity.

A new measure of porosity variability, the standard deviation of the quadrat porosity, is introduced here. This parameter is determined as follows. The rock-pore matrix is partitioned into nine approximately square, equal-sized subareas. These subareas can be referred

to as 'quadrats', a term borrowed from statistical map analysis (Davis, 1973, p. 301-302). The porosity is determined for each quadrat using equation 24. The moment standard deviation (part IA of Table 3) of the nine quadrat porosity values is then computed.

The porosity and standard deviation of the quadrat porosity are reported on pages A157 and A160, respectively, of the PORESTAT output in Appendix L.

Specific Pore Surface Area

The specific pore surface area (S_s) is the ratio of the surface area of the pore walls to the total rock (or pore) volume. Many stereological procedures for the estimation of S_s have been proposed (Rose and Wyllie, 1950; Kendall and Moran, 1963, p. 74 and 90; Perez-Rosales, 1967 and 1969; Perez-Rosales and Martinez, 1971 and ASTM, 1977b). The procedure developed by Perez-Rosales (1967) is the most widely used. The method used in the present study to determine the specific surface area is similar to that of Perez-Rosales (1967). The formula is as follows:

$$S_s = \frac{(NT \cdot RESO)}{(\sqrt{NPR} \cdot RESO)^2} = \frac{NT}{NPR \cdot RESO} \quad (25)$$

where NPR is as previously defined for equation 24; RESO is the resolution of the rock-pore matrix (i.e., the distance between adjacent sampling points); NT is the total number of rock-pore transitions (i.e., the number of times rock and pore points are found adjacent to one

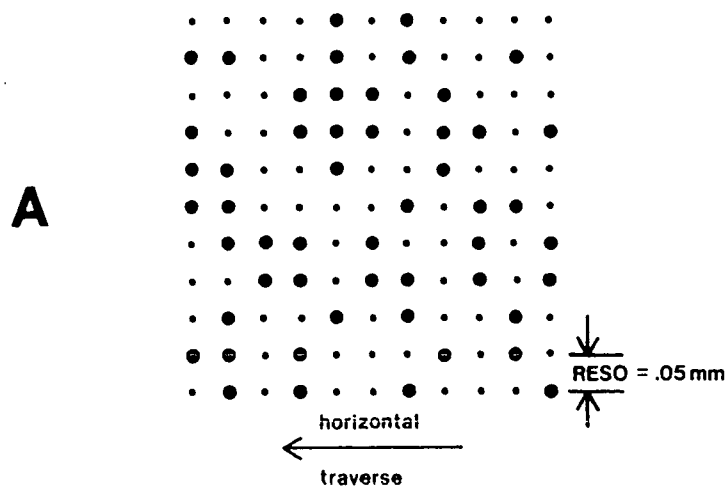
another) for all rows and columns of the rock-pore matrix; the product $NT \cdot RESO$ is the length of the perimeter of the pore space; and the quantity $(\sqrt{NPR} \cdot RESO)^2$ is the sampling area. Note that although S_s is defined in this equation as the ratio of the length of the pore perimeter to the sampling area, it still has units of L^{-1} . Thus equation 25 is a measure of the specific pore 'perimeter' but should be approximately equal to the specific pore surface area.

In the procedure advocated by Perez-Rosales (1967), the numerator in equation 25 was replaced by the number of rock-pore transitions for all rows (or columns) of the rock-pore matrix times 2. The assumption was that NT would be the same for both the rows and columns. This assumption, of course, is not necessarily correct. This point is well illustrated by Figure 36. In all fairness it should be pointed out that Perez-Rosales made his measurements by point-counting with a microscope equipped with a mechanical stage. It would have been too much trouble for him to determine the number of rock-pore transitions along both horizontal and vertical traverses. As a matter of practicality, he had to use a simplified (and hence, slightly less accurate) version of equation 25.

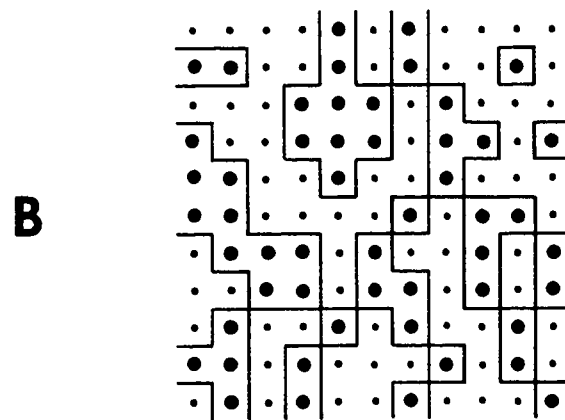
The specific pore surface area and the resolution ($RESO$) are reported on page A157 of the PORESTAT output in Appendix L.

Average Pore Dimension

The concept of 'pore size' is a difficult one to visualize because pores are usually not solitary, compact entities but rather are complex



$$S_s[\text{Perez-Rosales, 1967}] = 22.15 \text{ mm}^{-1}$$



$$S_s[\text{Equation 25}] = 19.34 \text{ mm}^{-1}$$

• Rock Point

● Pore Point

— Pore Perimeter

Total Number of Rock and Pore Points = 121

Number of Rock-Pore Transitions =

50 (vertically) and 67 (horizontally)

FIG. 36 — Illustration of the stereological procedure for determining the specific pore surface area.

anastomosing networks. Nevertheless, Perez-Rosales (1969) and Perez-Rosales and Martinez (1971) defined the 'average pore dimension' (D_p) in thin sections as the average length of a large number of equally-spaced lines spanning pores (i.e., pore segments). These lines are parallel to either the rows or columns of the rock-pore matrix. The stereological procedure used in the present study to determine D_p is similar to that proposed by these authors. The formula is as follows:

$$D_p = \frac{2 \cdot (NP \cdot RESO)}{NT/2} = \frac{NP \cdot RESO}{NT/4} \quad (26)$$

where NP, NT and RESO are as previously defined for equations 24 and 25. The numerator of this equation represents the sum of the lengths of the pore segments parallel to both the rows and columns of the rock-pore matrix (note: the total length parallel to either the rows or columns would be the same, $NP \cdot RESO$), and the denominator equals the total number of pore segments (note: there are two rock-pore transitions per pore segment).

In the procedure suggested by Perez-Rosales (1969) and Perez-Rosales and Martinez (1971), the pore segments are measured parallel to either the rows or columns of the rock-pore matrix but not both. D_p defined in this way would equal $(NP' \cdot RESO)/(NT'/2)$ where NP' and NT' are determined only for the rows or columns. Of the two approaches, clearly that expressed by equation 26 provides a better estimate of the true average pore dimension because it is largely independent of the orientation of the pore segments.

Following a line of reasoning similar to that used in the development of equation 26, the 'average rock dimension' (D_r) can be computed

from:

$$D_r = \frac{(NPR - NP) \cdot RESO}{NT/4} \quad (27)$$

where NPR is as previously defined for equation 24. Note that only in a sediment lacking cement and matrix will D_r be a measure of 'average grain size'.

The overall average pore and rock dimensions (equations 26 and 27), and the average pore and rock dimensions parallel to the matrix rows (normal to bedding) and columns (parallel to bedding) are reported on page A157 of the PORESTAT output in Appendix L.

It is important to recognize that the three pore geometry parameters discussed thus far are not mutually independent. If the equation for porosity (24) is rearranged and solved for NP, and this result is substituted for NP in equation 26; and if the equation for specific pore surface area (25) is rearranged and solved for NT, and this result is substituted for NT in equation 26, then the average pore dimension can be expressed as:

$$D_p = 0.04 \cdot (P/S_s) \quad (28)$$

From this result it is clear that it is sufficient to measure only two of the three parameters. Taken two at a time, the parameters are mutually independent but taken three at a time, they are mutually dependent. Because of their inclusion in the Kozeny equation, their greater conceptual convenience and their wider use, the only two pore geometry parameters which need and should be used are porosity and specific pore surface area.

Tortuosity

The tortuosity of a pore channel is the ratio of the actual length of the fluid flow path to the straight-line distance between the beginning and ending points of the flow path. Only one stereological procedure has been proposed for the measurement of tortuosity in plane sections (Preston and Davis, 1976). Unaccountably, this procedure has apparently never been used by these authors or any other students of pore geometry. The computer algorithm developed for the tortuosity determinations in the present study is similar in concept to the procedure of Preston and Davis but departs from it in two important respects: 1) the flow paths no longer have an element of randomness in their wanderings; and 2) the location of the terminus for the flow paths is subject to less error. The meaning and significance of these differences will become clearer later in this section.

Unlike the simple procedures based on NPR, NP, NT and RESO which were used to calculate the previous pore geometry parameters, the tortuosity determination involves a complex and lengthy series of 'logic operations' and because of this can only be performed using a computer. The basic steps in the tortuosity determination are as follows (see Figure 37).

Step 1 Three pore paths are to be 'tracked' across each rock-pore matrix. These paths will run in the same general direction as the matrix columns (i.e., bedding). Each path will begin in the first row of the matrix and end in the last row. If the matrix rows are N rock

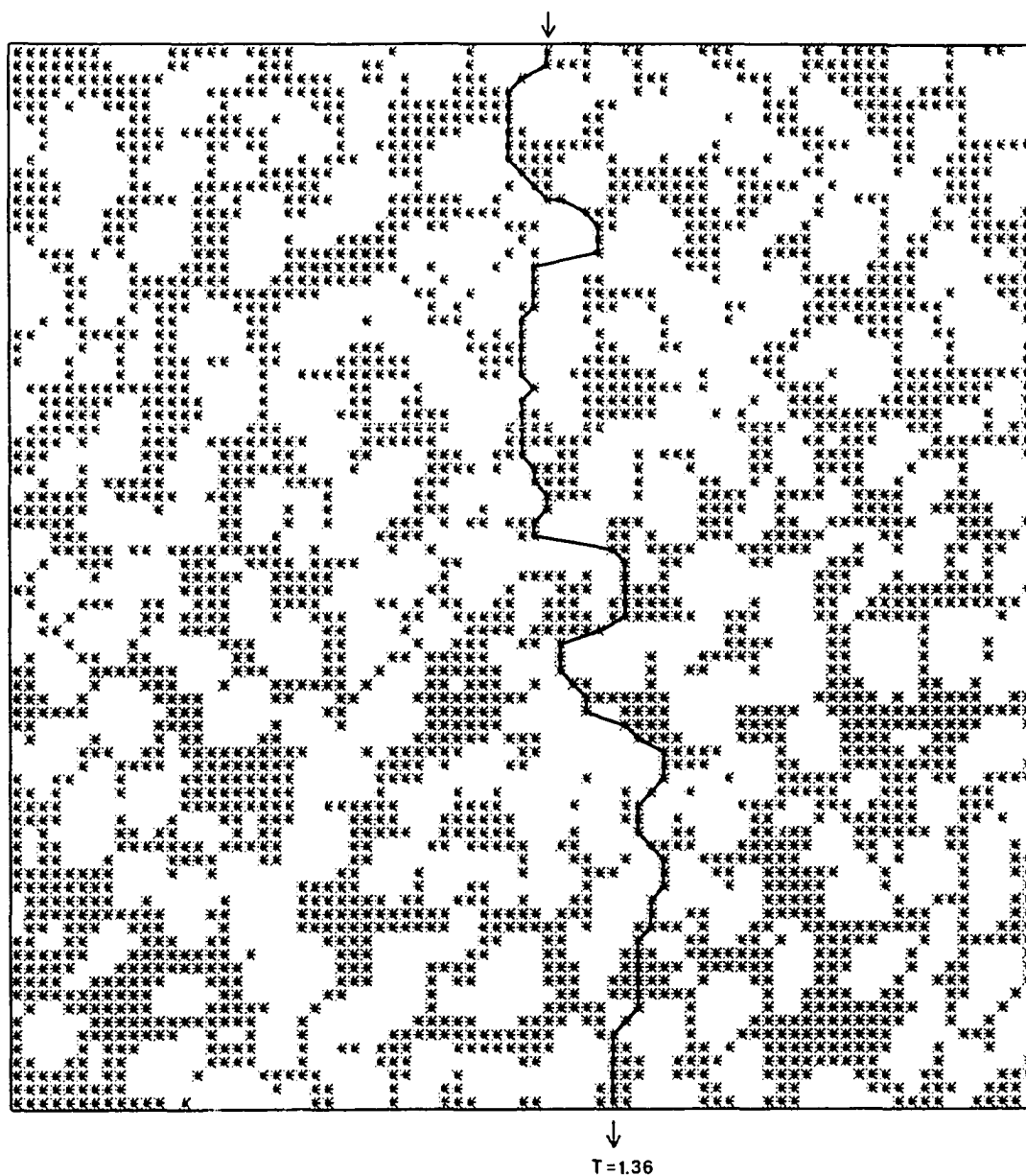


FIG. 37 – Illustration of the stereological procedure for determining the pore tortuosity (sample D3-15).

and pore points long ($N = 79$ in this study), then the starting points of the paths are located as close as possible to the $N/6$, $N/2$ and $5N/6$ elements of the first row. If no pore points exist at these locations then the closest pore point in row 1 is designated as the starting point. This spacing of the starting points will provide a reasonable separation between the three pore paths and at the same time will keep them an adequate distance from the left (column 1) and right (column 79) margins of the matrix.

Step 2 Each pore path is extended to the closest pore point in the second row of the matrix. Conceptually, this amounts to drawing a straight line from this point to the starting point. The pore point in row 2 need not be immediately adjacent to the starting point. If it happens that there are two pore points in the second row which are equally distant to the starting point, the first one encountered in the computer scan is added to the pore path (note: this always corresponds to the pore point to the right of the starting point).

Step 3 For each pore path, the computer scans the third row of the matrix and locates the pore point nearest to the pore point in the second row which lies on the pore path. The point so located is added to the lengthening pore path. This process is repeated in a recursive manner for each succeeding row of the matrix until the pore path reaches the last or 79th row. If it happens that there are two pore points in a given row which are equidistant from the pore path in the preceding row, then the pore point closest to the initial

starting point in row 1 is selected for inclusion in the pore path. If both pore points are equidistant from the starting point, the one on the right is selected. This selection process differs from that of Preston and Davis (1976) where the choice between the equidistant points is randomly made. The PORESTAT procedure has the advantage of maintaining the pore path in a direction roughly parallel to the starting column (i.e., bedding) whereas a random selection of one of the two points would allow the pore path to wander erratically. When searching for the next point to be added to the pore path it sometimes happens that the left or right margin of the matrix is closer to the pore path than the nearest pore point. In such cases the nearest pore point is selected but it is recognized that it is possible that a closer pore point may exist just beyond the margins of the matrix. In the unlikely event that no pore points are encountered in a given row the pore path will be routed through the rock point at the edge of the closer of the two matrix margins. The two pore path routing problems just discussed were not considered by Preston and Davis (1976).

Step 4 For each pore path, the end point or terminus is defined as the average column position (in row 79) of the last ten pore points on the path rather than the last pore point on the path, as was done by Preston and Davis (1976). The location of the end point is very important because in computing tortuosity the length of the pore path is divided by the straight-line distance between the starting and ending points. In the Preston and Davis approach, the end point could occur in any column of the last row, and thus the denominator of the

tortuosity equation is heavily dependent upon one pore point. This dangerous dependency is avoided in the PORESTAT procedure because the average column position of the last ten pore points provides a more stable estimate of the pore path terminus.

Step 5 The tortuosity of each pore path is computed. The length of the pore path is the sum of the straight-line distances between consecutive pore points on the path (note: in this calculation the end point of the pore path is taken to be the pore point selected in the computer scan of row 79 and not the average column position in row 79 of the last ten pore points on the path). To obtain the tortuosity, this length is divided by the straight-line distance between the starting and ending points where the end point is defined as described in step 4.

A map of the three resolved pore paths, the tortuosity of each path, and the average of the three tortuosities are given on pages A167 and A168 of the PORESTAT output in Appendix L.

In the procedure described above for the determination of tortuosity the pore paths were oriented roughly parallel to bedding. This was done in recognition of the fact that permeability is generally greatest parallel to bedding and least normal to bedding (Pryor, 1971; and Blatt et al., 1980). Ideally, several pore paths should be delineated for each rock-pore matrix. The average tortuosity of these paths would then provide an adequate characterization of the sample. In the present study only three pore paths were resolved because of the narrow width of the matrix. With a larger number of closely spaced pore paths

there would be a tendency for the paths to intersect and thereafter follow the same track. If this were to happen, the calculation of the average tortuosity would be biased in favor of the tracks where two or more pore paths had coalesced. It is apparent in Figure 37 and in the PORESTAT output in Appendix L that a given pore path is not confined to a single pore (i.e., an isolated area of contiguous pore points) but rather is free to wander from pore to pore. This sort of behavior is intuitively appealing because in most cases what appear to be isolated pores in a plane section are in reality interconnected in the third dimension.

In order to distinguish it from another measure of tortuosity introduced in a later section, the tortuosity measure described in this section will hereafter be referred to as the 'PD Tortuosity' in honor of its originators, Preston and Davis (1976).

Double Fourier Analysis

Introduction

Double Fourier analysis, like the more familiar 'trend surface' analysis, is widely used to study the areal variation in mappable parameters (James, 1966; Harbaugh and Merriam, 1968, p. 125-134; Harbaugh and Preston, 1968; Harbaugh and Sackin, 1968; Davis, 1973, p. 358-374). For both of these techniques, a typical application involves two 'independent' variables which represent the cartesian coordinates of sampling locations, and one 'dependent' variable which is some mappable parameter (e.g., elevation relative to some datum). The

areal variation in the dependent variable can be represented by a 'surface'.

Both double Fourier and trend surface analyses are forms of multiple regression with the only difference being that double Fourier analysis utilizes trigonometric (rather than simple algebraic) terms for the independent variables. Using double Fourier analysis any irregular surface can be exactly represented by the sum of a large number of sinusoidal surfaces, each resembling a sheet of corrugated metal (see Figure 38A) but differing from every other sinusoid in its wavelength, amplitude, orientation and/or phase angle. In the representation of surfaces, two sets of sinusoids are used. The orientation of each set is at right angles to that of the other, and the ridge axis of each set is parallel to one of the coordinate axes. The sinusoid wavelengths are preset but for each sinusoid of a given wavelength the amplitude and phase are determined by the least squares regression analysis. The higher the amplitude of a sinusoid, the greater its contribution to the representation of the surface. The wavelength of a high amplitude sinusoid indicates then the areal repetitions present in the surface morphology. One might reasonably anticipate that if periodic repetitions were present in a rock-pore pattern then they should be resolvable with double Fourier analysis.

Davis and Preston (1972) were the first and only investigators to 'suggest' applying double Fourier analysis to the pore pattern visible in a plane section. To my knowledge, double Fourier analysis has never actually been used to describe areal pore geometry. Ordinary or

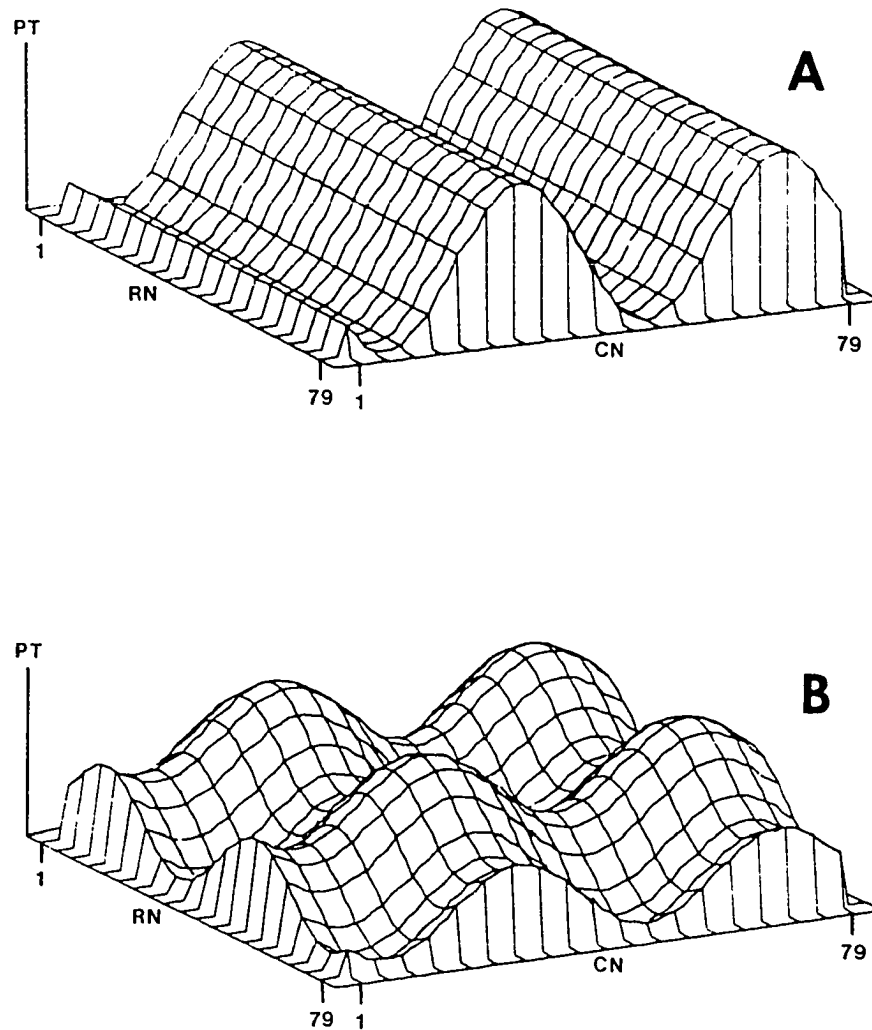


FIG. 38 – Examples of sinusoids fitted to rock-pore patterns in double Fourier analysis: A) a single sinusoid oriented parallel to the columns; B) a pair of sinusoids, each having wavelenths corresponding to the second harmonic (modified after Davis, 1973, Figure 6.24)

'single' Fourier analysis of the type commonly applied to 'time series' has, however, been used to study pore geometry in traverses across plane and thin sections (Fara and Scheidegger, 1961; Moran, 1962; Preston et al., 1966; and Davis and Preston, 1972). Obviously, the pore pattern manifested in a one-dimensional linear traverse provides an inadequate description of a three-dimensional rock property like pore geometry. A stereological procedure which characterizes an areal segment of a plane section should prove informative.

The rock-pore pattern visible in a plane section can be treated mathematically as an irregular surface where in double Fourier analysis the rows and columns of the rock-pore matrix would correspond to the two independent variables (i.e., the coordinate axes), and the identity of each sampling point (pore or rock) would correspond to the dependent variable. If the rock and pore points are assigned values of +1 and -1, respectively, then in a three-dimensional depiction of the rock-pore 'surface' the rock would appear as flat-topped plateaus and the pores would appear as flat-floored valleys with vertical cliffs between the two. If any periodic repetitions are present in this surface they would be identified by double Fourier analysis. These repetitions need not have any particular orientation to be resolved.

It is to be expected that, in general, double Fourier analysis will not be particularly informative. There are two reasons for this. First, the method is sensitive only to strictly- or quasi-periodic repetitions. Such regularity in a natural rock-pore pattern will seldom if ever occur. Second, the method is designed for a dependent

variable which takes on a continuous range of values. The use of binary (+1, -1) data will make the resolution of the periodicities in the rock-pore pattern very difficult. Even though these shortcomings of the technique are serious, still double Fourier analysis is an available descriptive tool which has the potential for revealing something meaningful about the pore geometry. It was with this possibility in mind that double Fourier analysis was applied in the present study.

Calculation procedure

The calculation procedure used in PORESTAT is based on the equations of Davis (1973, p. 366-367). The program operates directly on the rock-pore matrices. It is able to do this because each sampling point in the matrix has three values associated with it: a column number, CN (columns are numbered consecutively from 1 on the left to 79 on the right); a row number, RN (rows are numbered consecutively from 1 at the top to 79 at the bottom); and a point type, PT (+1 for rock and -1 for pore). The column and row numbers are treated in the regression calculations as the two independent variables, and the point type is treated as the dependent variable.

In double Fourier analysis, a pair of sinusoids with pre-specified wavelengths is 'fitted', via least squares regression, to a rock-pore matrix. These pre-specified wavelengths correspond to the so-called 'harmonics'. A harmonic is defined as the ratio of the width of the rock-pore matrix to the sinusoid wavelength (note: the wavelength of a sinusoid equals the distance between adjacent ridges or troughs). For

example, the seventh harmonic corresponds to a sinusoid with a wavelength equal to one-seventh the matrix width. For the low resolution matrices (RESO = 0.0508 millimeters) analyzed in this study, the seventh harmonic would be equal to a wavelength of $(78 \cdot 0.0508)/7 = 0.566$ millimeters or $79 \cdot 1/7 = 11.14$ column and row units. In this study the width of the matrix happens to be the same in the direction of both increasing column and row numbers. This, however, does not have to be true in order to perform double Fourier analyses. It should be kept in mind though that when the two matrix dimensions are different, the same harmonic for each direction will represent different wavelengths. The standard calculation formulas require that all sinusoids fitted to the data have wavelengths which are integer harmonics (i.e., 1, 2, 3, etc.). The inability to use fractional harmonics is one of the weaknesses of this methodology.

Figure 38A shows a single sinusoid with a wavelength equal to the second harmonic. Figure 38B shows a sinusoid pair with wavelengths equal to the second harmonic. Although not obvious in this figure, the surface represents the algebraic product of two sinusoids where one of the sinusoids has its ridges and troughs parallel to the columns, and the other sinusoid is oriented parallel to the rows. In general for multiplicative sinusoid pairs, the surface ridges are not of uniform height as shown in Figure 38B but rather rise and fall along their lengths in a regular manner. Further, the alignment of the ridges can be parallel to either the rows or columns but more often has some diagonal orientation.

In double Fourier analysis all possible multiplicative sinusoid pairs are fitted to the data. Each of these pairs represents a different combination of harmonics. In the present study, 20 harmonics were considered for each coordinate axis, and thus there was a total of 400 sinusoid pairs fitted. The sinusoid with the shortest period (harmonic 20) had a wavelength which was substantially less than the mean grain size of any sample analyzed. For rock-pore matrix widths of 3.96 and 1.98 millimeters, the minimum wavelengths were 0.198 and 0.099 millimeters, respectively. Thus any periodic repetitions occurring on the same scale as the intergranular or interpore distances should have been detected. Those sinusoid pairs that fit the data well will have the larger amplitudes or 'powers'. It is these sinusoid pairs that we are interested in because they identify the periodic repetitions present in the pore pattern. The power (PW) of a sinusoid pair with harmonics of n and m for the rows and columns, respectively, can be computed from the following equations (see Davis, 1973, p. 366-367):

$$a_{nm} = \frac{4}{L_r \cdot L_c} \cdot \sum_{i=1}^{L_r} \sum_{j=1}^{L_c} \left[P_{T_{ij}} \cdot \cos \frac{2 \cdot \pi \cdot n \cdot R_{N_j}}{L_r} \cdot \cos \frac{2 \cdot \pi \cdot m \cdot C_{N_j}}{L_c} \right]$$

$$b_{nm} = \frac{4}{L_r \cdot L_c} \cdot \sum_{i=1}^{L_r} \sum_{j=1}^{L_c} \left[P_{T_{ij}} \cdot \cos \frac{2 \cdot \pi \cdot n \cdot R_{N_j}}{L_r} \cdot \sin \frac{2 \cdot \pi \cdot m \cdot C_{N_j}}{L_c} \right]$$

$$c_{nm} = \frac{4}{L_r \cdot L_c} \cdot \sum_{i=1}^{L_r} \sum_{j=1}^{L_c} \left[PT_{ij} \cdot \sin \frac{2 \cdot \pi \cdot n \cdot RN_i}{L_r} \cdot \cos \frac{2 \cdot \pi \cdot m \cdot CN_j}{L_c} \right]$$

$$d_{nm} = \frac{4}{L_r \cdot L_c} \cdot \sum_{i=1}^{L_r} \sum_{j=1}^{L_c} \left[PT_{ij} \cdot \sin \frac{2 \cdot \pi \cdot n \cdot RN_i}{L_r} \cdot \sin \frac{2 \cdot \pi \cdot m \cdot CN_j}{L_c} \right]$$

$$PW_{nm} = (a_{nm}^2 + b_{nm}^2 + c_{nm}^2 + d_{nm}^2)/4 \quad (29)$$

where,

L_r is the length of the rows (= 79)

L_c is the length of the columns (= 79)

i is the row subscript ($i = 1, \dots, 79$)

j is the column subscript ($j = 1, \dots, 79$)

PT_{ij} is the value of the point type (+1 or -1) for the i^{th} row and the j^{th} column (i.e., it is the value of the i^{th} j^{th} sampling point)

π is the universal constant Pi (= 3.14159...)

RN_i is the number of the i^{th} row

CN_j is the number of the j^{th} column

sin and cos are the sine and cosine trigonometric functions

a_{nm} , b_{nm} , c_{nm} and d_{nm} are the amplitude coefficients for the n^{th} and m^{th} harmonics

PW_{nm} is the power of the sinusoid pair where the sinusoid with its ridge axis parallel to the columns corresponds to a harmonic of m and has a wavelength equal to $(L_r - 1) \cdot RES0/m$; and the sinusoid with its ridge axis parallel to the rows corresponds to a harmonic of n and has a wavelength equal to $(L_c - 1) \cdot RES0/n$ (note: $RES0$ is as previously defined for equations 25, 26 and 27).

These equations differ from those of Davis (1973) in one respect. In the calculation of 'power', Davis did not divide the sum of the squared amplitude coefficients by four. This was apparently an oversight because it is clear from the literature that this sum, be it for single or double Fourier analysis, should be divided by the number of amplitude coefficients (Jenkins and Watts, 1968, p. 7, equation 1.2.6.; Schickendanz and Bowen, 1977, equation 4).

The computational results for the double Fourier analysis are reported on pages A155 and A156 of the PORESTAT output in Appendix L. The powers of all possible combinations of harmonics are tabulated in the 'power spectrum'. The values in this table actually represent the relative rather than absolute powers. The relative powers were obtained by dividing each absolute power by the absolute maximum power (i.e., the largest of the 400 powers; given immediately below the table), and then multiplying this quotient by 100. The frequency distribution of the relative powers is given below the power spectrum. Immediately above the power spectrum in the output is the percentage of the total variance (of PT) accounted for by the 400 sinusoid pairs. If the maximum number of sinusoid pairs ($[L/2]^2$ or 1600 in the present study) were fitted to the data, the sum of their powers should equal the variance of PT (i.e., would account for 100 percent of the PT variance). A relatively small number of sinusoid pairs should ideally account for the bulk of the variance. Notice in the output for sample D3-15 that the 400 sinusoid pairs together account for about 60 percent of the variance. This is a disappointingly low value. From the output we can compute the percent of the variance explained by the single, most powerful sinusoid pair:

harmonics = 8 and 11, relative power = 100, absolute power = 0.0122, and percent of total variance = $(0.0122/0.9869) \cdot 100 = 1.24$ percent. Although this is the strongest periodic repetition recorded, it is still too subtle to be seen by visually examining the rock-pore pattern. If this werenot the case, however, we would expect to see some sort of repetitious pattern which has wavelengths of roughly $1.98/8 = 0.25$ millimeters parallel to bedding and $1.98/11 = 0.18$ millimeters normal to bedding.

When interpreting the results of double Fourier analyses allowances must be made for two factors. First, because only integer harmonics are considered, the harmonics in general do not match exactly the wavelengths of the repetitions actually present in the data. The potential for large mismatches increases as the harmonic number decreases. Second, many of the periodicities identified in the power spectrum are probably spurious (i.e., could have arisen from random variations in the data). The decision as to whether a given periodicity is real or spurious should be based as much on geological as statistical considerations. In a later section, the statistical significance of the observed periodicities will be evaluated using the results for some of the test patterns.

Autocorrelation Analysis

Autocorrelation (also known as Serial or Cross Correlation) is a statistical method which, like double Fourier analysis, attempts to identify periodic repetitions within a pattern. It does this by

comparing, through successive superimpositions, two copies of the same pattern. With each incremental change in superimposition, the offset between the two patterns increases and the overlapping portions of the two patterns decreases. For each superimposition, the similarity between the overlapping portions of the patterns is measured. The resulting sequence of similarity values is used to identify periodic repetitions within the pattern.

Autocorrelation is a method which has, with one exception, only been applied to one-dimensional patterns (i.e., time-series: a curve which describes the variation in a parameter at successive increments of time or distance; see Davis, 1973, p. 232-246). Conley and Preston (1976, abstract only) were the first and apparently only investigators to apply autocorrelation to two-dimensional patterns (i.e., surfaces). They used it to describe the 'spatial variation in petrographic characteristics' within a thin section. The pore geometry was not considered. In the present study, autocorrelation will be used for the first time to document the periodic repetitions in a plane section pore pattern.

The principle behind one- and two-dimensional autocorrelation analyses is the same. In the two-dimensional case, two identical copies of a rock-pore matrix are created. One is, so-to-speak, placed above the other so that the corresponding sampling points are superimposed. The degree of agreement or correlation between the superimposed sampling points is described using a 'similarity coefficient' which has a value of 1 when total agreement exists and 0 when total disagreement exists.

For the initial superimposition the value of the similarity coefficient will, of course, have a value of 1. If the two patterns are offset (or 'lagged' in the parlance of statisticians) by one row (or column) of the matrix and the similarity coefficient recomputed for the overlapping portions it will probably have a value of less than 1. If the two patterns are successively offset by unit increments (one row or column at a time) and the similarity coefficient computed for the overlapping portions, a series of similarity coefficient values will be obtained where each corresponds to a specific 'lag'. The curve which results from plotting this information has been referred to, for one-dimensional patterns, as a 'correlogram'. Any strictly- or quasi-periodic repetitions present in the rock-pore pattern will be represented by peaks in the correlogram curve.

Several similarity coefficients for one-dimensional patterns with binary data have been proposed (Cheetham and Hazel, 1969; and Mather, 1976, p. 311-316). All of these could be extended to two-dimensional patterns. Even so, none of these would be adequate for the rock-pore patterns analyzed in this study. In selecting a similarity coefficient for these patterns there are three relationships which must be considered: 1) the number of matching (superimposed) rock points, 2) the number of matching pore points, and 3) the number of mismatches between pore and rock points. The first two relationships should be given equal weight in the calculation of a similarity coefficient but this is not done in any of the published coefficients. It was necessary then to develop a new similarity coefficient for the present study. This coefficient has been named the 'areal mismatch coefficient' (AMC) and is

equal to:

$$1 - \frac{MMP}{MRP + MPP + MMP} \quad (30)$$

where,

MMP is the number of mismatched points

MRP is the number of matching rock points

MPP is the number of matching pore points.

AMC varies between 1 (perfect match) and 0 (complete mismatch).

The results of the autocorrelation analysis are reported on pages A158 and A159 of the PORESTAT output in Appendix L. In the first correlogram, the direction of successive lags was perpendicular to bedding or parallel to the rows of the rock-pore matrix (i.e., successive superimpositions were offset by one column increments). In the second correlogram, the lag movement was parallel to the bedding or parallel to the columns. In this study 40 lag positions were examined. In the autocorrelation of one-dimensional patterns it is recommended that the maximum lag be no more than one-tenth or, at most, one-fourth the number of points along the length of the pattern (Davis, 1973, p. 236). The reason for this is that for each successive lag the similarity coefficient is based on fewer total points. Eventually, the similarity coefficient will be based on so few overlapping points that the measure will become unreliable. It becomes possible at high lags for spuriously high correlations to occur. For the rock-pore patterns, the above recommendations correspond to maximum lags of 8 and 19. The correlograms in the output should therefore be interpreted with caution

at lags greater than the maximum recommended.

The correlograms in the PORESTAT output would be interpreted in the following way. In the first correlogram of the output for sample D3-15 there appears to be a repetition with a repeat interval of about 7 lags. Because each lag represents a shift equal to the distance between adjacent columns in the matrix (0.0254 millimeters), the pore pattern partially repeats itself about every 0.18 millimeters in a direction normal to bedding. In the first half of the second correlogram the pore pattern weakly repeats itself about every 10 lags or $10 \times 0.0254 = 0.25$ millimeters in a direction parallel to bedding. A comparison of the autocorrelation and double Fourier analysis results for sample D3-15 shows a remarkably good agreement between the two techniques. Even though detected by both techniques, the periodic repetitions in this sample are not apparent when the rock-pore pattern is visually examined. The repetitions in the first correlogram may be related to the mean grain size (0.14 millimeters) and microlaminations parallel to bedding.

It was stated at the beginning of this section that autocorrelation and double Fourier analyses have similar objectives: the identification of periodic repetitions in a pattern. It is generally true that both provide similar information. There are, however, advantages and disadvantages to each. The advantages of autocorrelation over double Fourier analysis are: 1) greater mathematical and conceptual simplicity, 2) easier visualization of results, and 3) greater resolution of periodicities. The last advantage is especially important. Whereas in double Fourier analysis the resolution is limited to the

integer harmonics, in autocorrelation analysis the repetitions of any wavelength or frequency can be accurately resolved provided the recommended maximum lag is not greatly exceeded. The disadvantages of autocorrelation are: 1) the resolution limit imposed by the maximum allowable lag (only repetitions with wavelengths less than the maximum lag can be accurately resolved), and 2) uninterpretable correlograms when two or more sets of periodic repetitions are present in a pattern. From these disadvantages it is clear that autocorrelation will be most effective when only a single set of periodic repetitions is present and the repeat interval for this set is less than about one-fourth the length of the pattern.

Pore Orientation

It is of interest to determine if there is any preferred directional orientation or elongation of the pore space within a rock-pore pattern. PORESTAT makes this determination by computing the average pore dimensions for variously oriented traverses across a rock-pore matrix. The approach taken here is similar in concept to that taken by Zimmerle and Bonham (1962) and Winkelmoen et al. (1968) in their studies of preferred grain orientation. These investigators made several sets of variously oriented parallel traverses across black (pore) and white (rock) photomicrographs of plane and thin sections of sandstones. The orientation for which the proportion of the total length of the traverses falling within grains was the greatest was said to correspond to the preferred orientation of the long axes of the sand

grains. In these studies, the photomicrographs were physically rotated to obtain the various traverse orientations. The actual traverses were made using an automated scanning densitometer. To obtain analogous information in the present study for the pore space using the average pore dimension measure, several rock-pore matrices (each having a different orientation) would have to be prepared for each sample. Clearly this would not be practical. And just as clearly it would not be possible to use a single rock-pore matrix and measure the average pore dimension along variously oriented traverses. This is true because the traverse lines must pass through contiguous rock and pore points. This happens only for orientations parallel to either the rows or columns, or at a 45 degree angle to the rows and columns. At all other orientations the traverse lines will not pass through contiguous rock and pore points.

The new PORESTAT algorithm developed in the present study provides a novel solution to the above problem. It generates from a single rock-pore matrix several matrices, each having its rows and columns oriented at a different angle to bedding (or some other stationary reference plane). Conceptually, the algorithm operates in the following way.

Step 1 A square grid is superimposed on top of a rock-pore matrix. The spacing between the grid intersections or nodes is exactly the same as the spacing between the rock and pore points in the matrix. The superimposition is such that the grid nodes are immediately above

the rock and pore points, and the center of the grid is positioned above the center of the rock-pore matrix. In outline the grid, like the matrix, is square but the length of its sides is only seven-tenths the length of the sides of the matrix. The reason for this difference will be explained in the next step.

Step 2 While the overlying grid remains stationary, the rock and pore points in the matrix below are rotated in a clockwise direction θ degrees about the common center of the grid and matrix. The mathematics for a rotational operation of this kind are discussed by Thomas (1968, p. 350-351). It is essential in this step that all of the grid nodes be underlain by some part of the matrix. If the grid was the same size as the matrix, then during rotation the corners of the grid would extend beyond the matrix boundaries. To prevent this from happening, the length of the sides for the grid was set equal to seven-tenths the length of the sides for the matrix. This practice does, however, have a drawback. Because of the relatively small size of the grid, the average pore dimension determinations are based on only about 50 percent of the rock-pore matrix.

Step 3 Each node in the overlying grid is assigned a value: -1 if the nearest point in the underlying matrix is a pore, and +1 when a rock point is closest. Note that in general the grid nodes will not directly overlie the rock and pore points in the matrix. The value assigned to the grid nodes must then be based on the identity of the nearest matrix point.

Step 4 At the conclusion of the preceding step, the overlying grid has been transformed into a rock-pore matrix. Using a modification of equation 26 the vertical (traverses parallel to the columns; orientation = θ) and horizontal (traverses parallel to the rows; orientation = $\theta + 90$) average pore dimensions (APD) are computed. Rather than using all the pore segments encountered during the traverses to compute the APD, the APD is instead computed using the square of the lengths of the pore segments longer than the 'overall' average pore dimension for the original rock-pore matrix. It was found through experimentation with the test patterns (especially STRIPES) that the inclusion in the calculations of the more numerous shorter-than-average pore segments tended to obscure the expression of preferred orientation in the longer pore segments. Attention was thus focused on the longer pore segments because the shorter ones seemed to have a greater element of randomness in their orientations. The length of the longer-than-average pore segments was squared in order to give greater weight to the longest and presumably most reliable pore segments.

Step 5 Steps 1 through 4 are repeated for different angles of rotation ($\theta = 0, 18, 36, 54$ and 72 degrees) to obtain average pore dimensions for ten different orientations (0 to 180 degrees with 18 degree increments).

The results of the pore orientation analysis are reported on page A169 of the PORESTAT output in Appendix L. The angles given in the left column assume that the bedding plane is oriented parallel to the

left and right margins of the page when the plane section analyzed is oriented normal to bedding. The first orientation, 90 degrees, is normal to bedding. The second through fifth orientations, 72 to 18 degrees, indicate a pore elongation dipping towards the top of the page. In the present study, the rock-pore patterns analyzed were always oriented with the dip of the bed (when inclined) towards the bottom of the page. Thus orientations 2 through 5 would indicate pore elongations which are inclined away from the direction of dip. Such happens to be the case for sample D3-15, an eolian foreset lamina. The sixth orientation, 0 degrees, is parallel to bedding; and the seventh through tenth orientations indicate pore elongations inclined in the same general direction as the bedding dip. Although the orientations expressed in the output are relative to the bedding plane, the results for, say, plane sections parallel to bedding, can be easily interpreted in terms of other datums like bedding strike and dip. The average pore dimensions in the right column of the output are standardized so that the minimum dimension has a value of 1. To the right of this column the average pore dimensions are graphically depicted in a histogram.

Measures Based On Individual Pores

Resolution of Individual Pores

A rock-pore pattern can be thought of as consisting of one or more individual pores. For example, the pattern for sample D3-15 in the

PORESTAT output (pages A153 and A154 in Appendix L) contains 49 discrete pores. Each of these pores consists of contiguous pore points which are completely surrounded (horizontally, vertically and diagonally) by rock points. Many of the pores visible in a rock-pore pattern are, of course, interconnected in the third dimension and thus are part of a single anastomosing pore. It may be useful, however, to resolve the individual pores visible in a plane section. The characteristics of these pores may provide important information on the pore geometry of a sample.

PORESTAT resolves the individual pores present in a rock-pore matrix in the following way.

Step 1 It begins by establishing a new matrix (hereafter referred to as the 'T matrix') which is exactly the same size as the original rock-pore matrix (hereafter referred to as the 'RP matrix'). All the points in the T matrix are initially given a +1 or rock value. The T designation for this matrix reflects its temporary nature. During the resolution process, an individual pore from the RP matrix will be transferred to the T matrix. After the pore has been resolved and characterized, the T matrix is so-to-speak erased and reset to its initial condition (i.e., all rock points).

Step 2 The resolution process begins with the computer scanning each row of the RP matrix until a pore point is encountered. Once encountered this pore point is 'deleted' from the RP matrix (i.e., the value of the RP matrix point is changed from -1 to +1) and 'resurrected'

at the same row and column position in the T matrix (i.e., the value of the T matrix point is changed from +1 to -1).

Step 3 The computer next scans the RP matrix points immediately adjacent (i.e., the next points over in the horizontal, vertical and diagonal directions) to the pore point just deleted. This scan conforms to what is called here a 'nearest-neighbor search configuration'. In Figure 39A this configuration is illustrated. Notice that in the scan of peripheral points, the first point examined is to the upper left of the last pore point deleted (i.e., the large dot in the center). The numbers indicate the sequence in which the other peripheral points are examined. Actually any search configuration will work equally well but the one in Figure 39A is the most efficient in terms of computer processing time.

Step 4 Any pore points encountered during the peripheral scan are considered to be part of the same pore as the pore point just deleted. These newly resolved pore points are removed from the RP matrix and added to the T matrix. The computer next scans the RP matrix points peripheral to the pore points just deleted. Any additional pore points resolved, like those which preceded them, are removed from the RP matrix and added to the T matrix. The RP matrix points immediately adjacent to the last pore points deleted are scanned in a search for more points belonging to the same pore. This resolution process is continued iteratively until all the pore points within a given pore are resolved.

Step 5 Once resolved, an individual pore is characterized in terms of its size and its tortuosity. The actual measurement

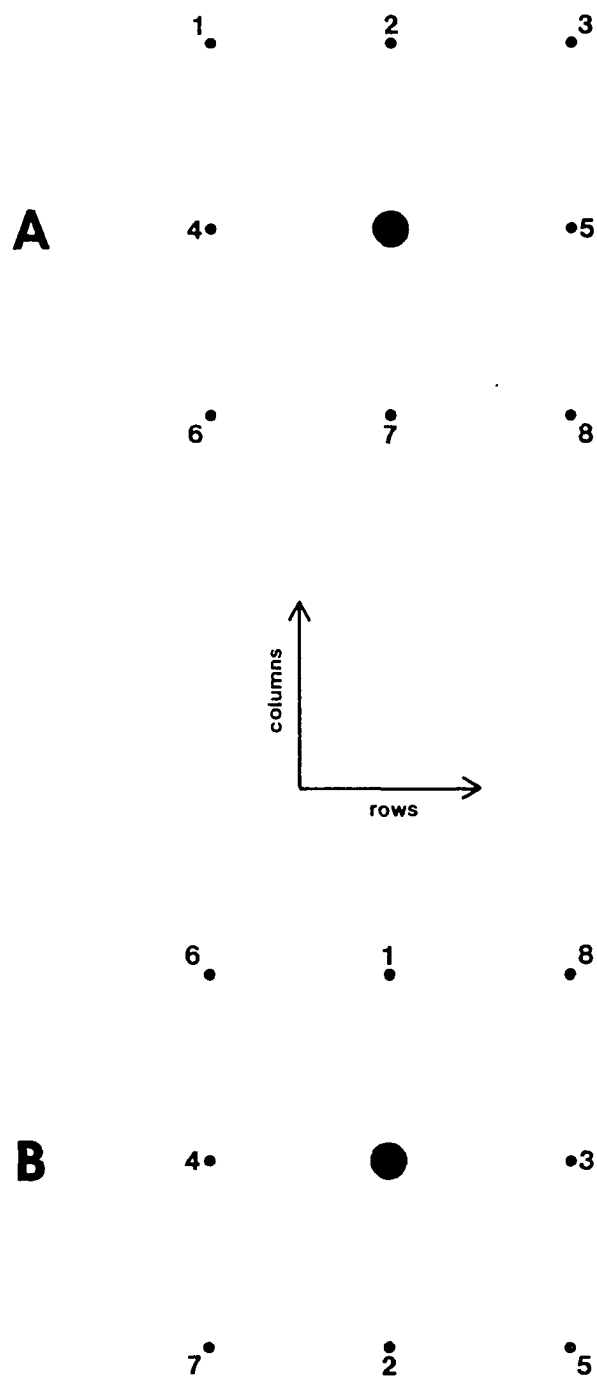


FIG. 39 – Nearest-neighbor search configurations for the resolution of individual pores (A), and the delineation of tortuous pore paths (B).

processes involved will be described in subsequent sections.

Step 6 The resolution process resumes by resetting the T matrix (i.e., all points are set equal to +1). The previously resolved pore is not returned to the RP matrix. The computer scans each row of the RP matrix until a pore point is encountered. Steps 2 through 5 are repeated. With the above procedure, all of the individual pores in the rock-pore matrix will eventually be resolved and described.

Apart from its ability to resolve individual pores, the algorithm described above is of further interest because it is able to simulate the flow of a fluid through a porous medium. Consider Figure 40. The point pattern depicted represents a single pore in the rock-pore matrix of sample B2-16. The adjacent large and small dots represent pore points resolved in successive iterations of the algorithm. The resolution process began with the small dot at the far right (to the left of F). During the next resolution cycle the large dots above, below and to the left were added. This resolution process went through 96 cycles in order to resolve the entire pore. The contiguous sets of large and small dots simulate the successive positions of an advancing fluid front.

The number of individual pores in a rock-pore matrix is reported on page A161 of the PORESTAT output in Appendix L.

Pore Size Distribution

When an individual pore is fully resolved as described in the preceding section, its size is measured in terms of the following four

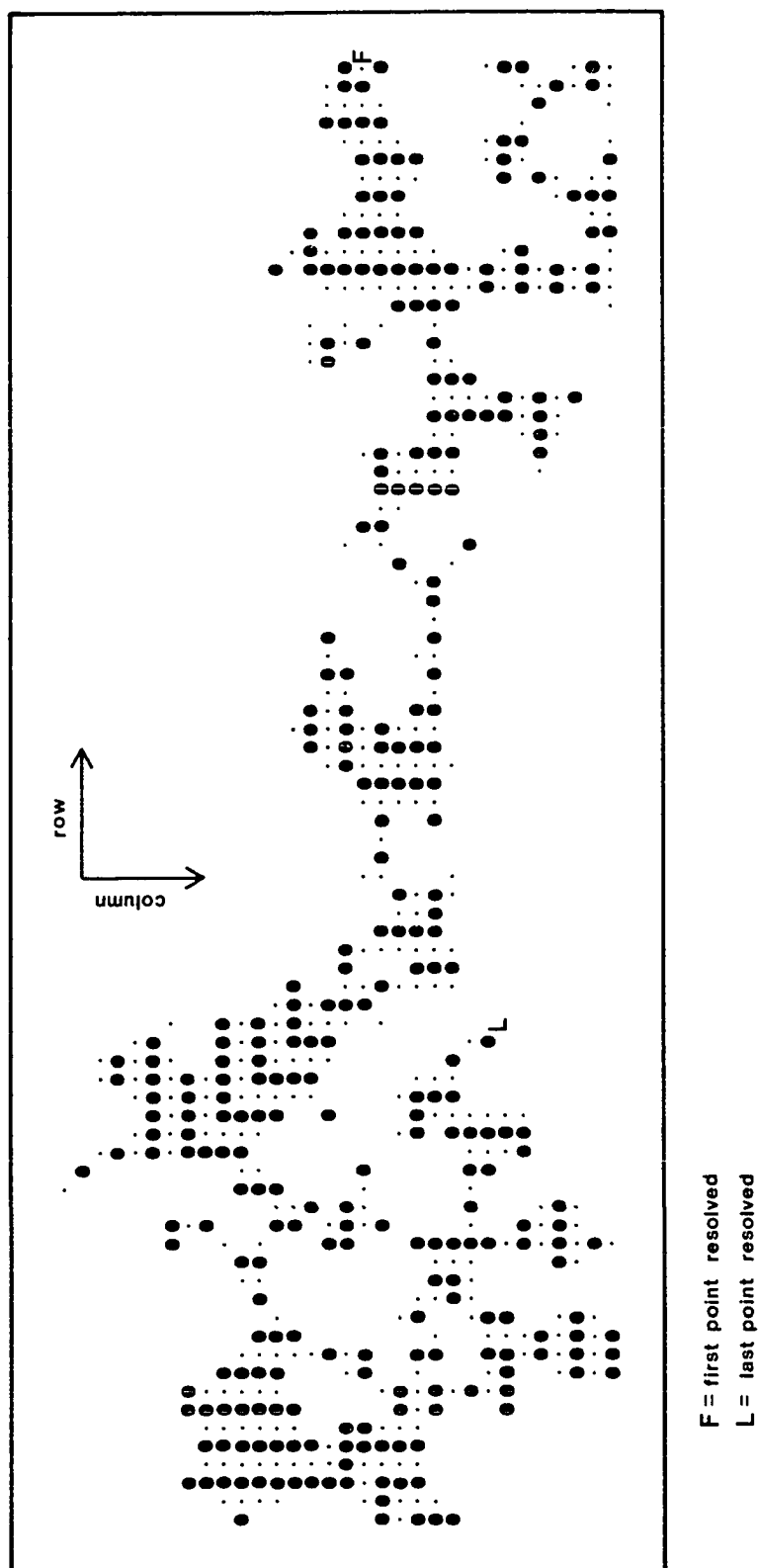


FIG. 40 – Illustration of the PORESTAT algorithm for resolving individual pores.

parameters:

- 1) area (i.e., the number of pore points within the pore)
- 2) maximum dimension of the pore parallel to bedding (i.e., parallel to the columns in the rock-pore matrix)
- 3) maximum dimension of the pore normal to bedding (i.e., parallel to the rows in the rock-pore matrix)
- 4) absolute maximum pore dimension (i.e., the distance between the two most widely separated pore points within the pore).

Histograms depicting the frequency distributions for these four measures of pore size are provided on pages A161, A162, A163 and A164, respectively, of the PORESTAT output in Appendix L. In each of these histograms the pore size corresponds to the vertical axis, and the frequency (the number of pores falling within a given size interval) corresponds to the horizontal axis. Note that for the pore area frequency distribution the size intervals are logarithmic. For all other histograms the size interval is uniform.

Two additional items of information are provided with each histogram: the percent of the total pore space represented by each size interval, and the moment mean (Part IB of Table 3) pore size. All of the pore size frequency distributions belong to the family of 'negative exponential' distributions. Such distributions tend to reach their maximum frequency when X (the parameter measured; e.g., pore size) approaches zero, and experience an exponential decline in frequency as X increases. An interesting characteristic of these distributions is that the moment mean and standard deviation are equal (Jenkins and Watts, 1968, p. 70).

Tortuosity

In this algorithm the tortuosity of an individual pore is defined as the ratio of the length of the shortest pore path joining the two most widely separated points within the pore to the straight-line distance between these two points (i.e., the absolute maximum pore dimension from the preceding section). This measure of tortuosity will hereafter be referred to as the 'IP (individual pore) Tortuosity' to distinguish it from the PD Tortuosity described earlier along with other measures based on the entire pore pattern.

PORESTAT delineates the pore path of an individual pore in a rock-pore matrix in the following way.

Step 1 The delineation process begins with the individual pore stored in the T matrix. A new matrix is established (hereafter referred to as the 'V matrix') which is exactly the same size as the T matrix. All points within the V matrix are initially given a +1 or rock value. The two most widely separated points (the 'extreme points') within the T matrix pore are located. Both of these points are deleted from the T matrix (i.e., the value of the T matrix point is changed from -1 to +1) and added to the V matrix at the same row and column position (i.e., the value of the V matrix point is changed from +1 to -1).

Step 2 Beginning at one of the two deleted extreme points, the pore in the T matrix is reresolved. The computer first scans the points peripheral to the extreme point. The 'nearest-neighbor search configuration' used (Figure 39B) differs from that employed in the original

resolution of the pore (Figure 39A). The reason for this difference will be explained later. Any pore points encountered in the peripheral scan are immediately removed from the T matrix and added to the V matrix.

Step 3 The pore points resolved in the previous step are each subjected, in the order in which they were resolved, to a peripheral scan. If it happens during the scan for a given pore point that no new pore points are encountered, then this pore point is deleted from the V matrix. Any additional pore points resolved, like those which preceded them, are removed from the T matrix and added to the V matrix. Each of these, in turn, is subjected to a peripheral scan and if found not to be bounded by other pore points is deleted from the V matrix. This resolution process is continued iteratively until the second extreme point is encountered in one of the peripheral scans.

Step 4 At the conclusion of Step 3, the V matrix contains only a portion of the original pore in the T matrix. Some points were deleted because no new pore points were encountered during their peripheral scans. Other pore points in the T matrix were never resolved (and thus never had a chance of being added to the V matrix) because the resolution process was terminated abruptly when the second extreme point was encountered. What remains in the V matrix is a set of contiguous pore points joining the two extreme points. The ultimate goal is to further reduce this set until the only pore points remaining are those which lie on the shortest or most direct path joining the two extreme points. To achieve this goal, the resolution process must be repeated. Accordingly, the following operations are carried out. First, the T matrix is re-initialized (i.e., all points are set equal to +1). Second, the contents

of the V matrix are transferred to the T matrix. Third, the V matrix is reinitialized (i.e., all points are set equal to +1).

Step 5 Steps 1 through 4 are repeated in a recursive manner until it is not possible to delete any more pore points from the V matrix. At the conclusion of this last resolution cycle, the pore points remaining in the V matrix will be those lying on the shortest pore path between the extreme points. The delineation process is illustrated in Figure 41. From the length of this pore path and the extreme point separation the tortuosity can be computed. Note that in the case of those pores containing only one or two points, the tortuosity was automatically set equal to 1.

The results of the tortuosity analysis are reported on pages A160, A165 and A166 of the PORESTAT output in Appendix L. On page A160 the following information is tabulated for each pore: the tortuosity squared, the number of resolution cycles required to delineate the shortest pore path, the original size of the pore (i.e., the number of points within the pore), and the row and column coordinates for the two extreme points. The square of the tortuosity was computed in order to enhance the typically small tortuosity differences among the pores, and to increase the absolute value of IP tortuosity so that it was closer in magnitude to the PD tortuosity values. On pages A165 and A166 a map of the individual pore paths is provided. In the output for sample D3-15, one pore accounted for about 90 percent of the total pore space. The shortest path between the extreme points for this pore can be seen snaking across the map from upper right to lower left. Below

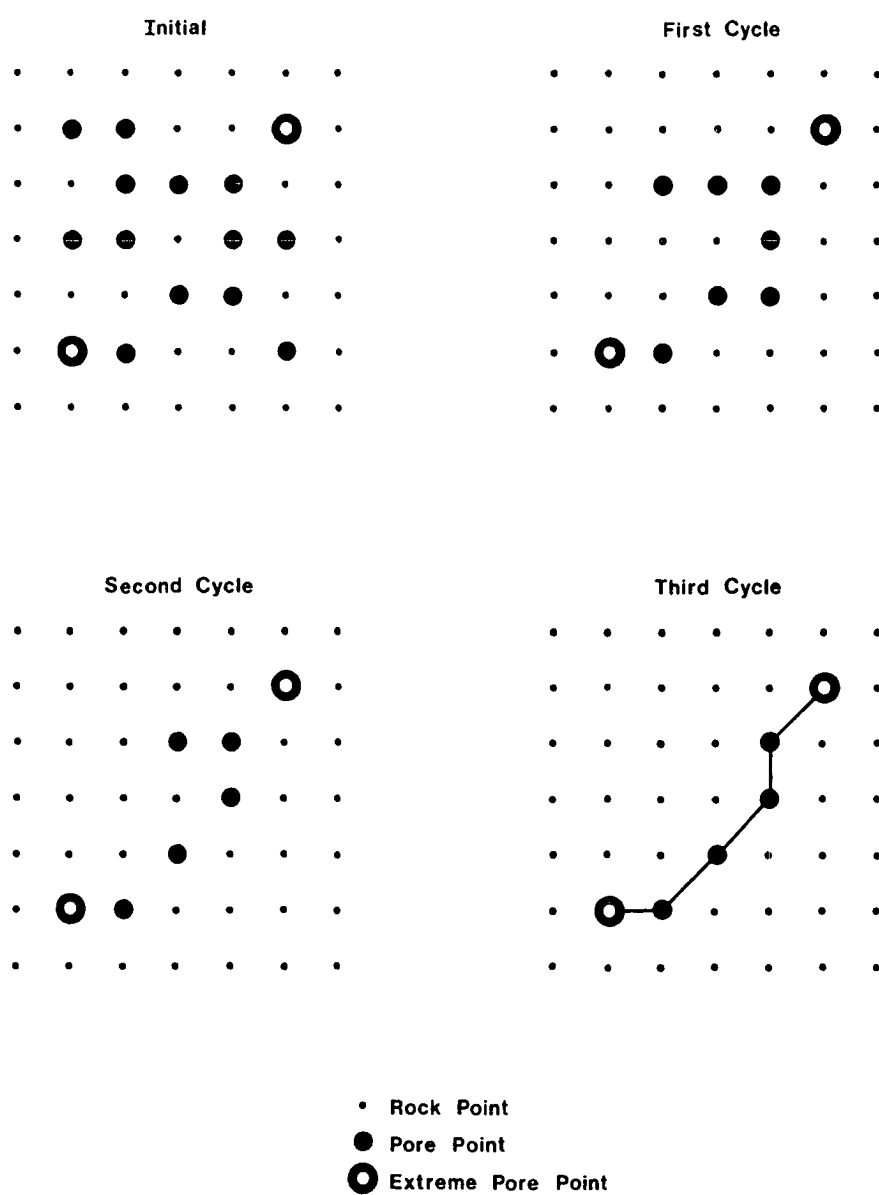


FIG. 41 — Illustration of the successive delineation of a pore path in the determination of tortuosity for an individual pore.

the map two weighted averages of the IP tortuosities are given. It would clearly be inappropriate simply to average the tortuosity values. Instead, the tortuosities should be weighted according to the size of the pores. Two measures of pore size were used for the weights: pore area (i.e., number of points in the pore) and absolute maximum pore dimension (i.e., straight-line distance between the extreme points).

The choice of the nearest-neighbor search configuration is of critical importance in the tortuosity analysis described above. In general, the pore paths delineated will be slightly different for each search configuration. The search configuration used by PORESTAT (Figure 39B) seems to be optimal for two reasons. First, it preferentially resolves pore points in the same row or column as the central pore point for which the peripheral scan is being conducted. These points are closer to the central point than those diagonally adjacent and so should be considered first. Second, no one side or corner of the configuration is given preference in the resolution of peripheral pore points. Consider, for example, Figure 39A. For this configuration the first three points examined are above the central point. This configuration has then a strong upward bias. No such obvious bias exists in the configuration of Figure 39B. There is, however, a slight directional bias in this configuration: the first two points examined are situated in the same column as the central point. This bias is actually advantageous because it would tend to direct the pore path parallel to the matrix columns and hence, the bedding. This is the most likely direction of fluid flow in a porous medium (Pryor, 1973).

Discussion Of Results

The results of the pore geometry analyses are tabulated in Appendix M. In the brief discussion which follows, no attempt will be made to interpret the results in terms of depositional environments and processes. Such interpretations would probably be a useless exercise because the measured parameters are based on a very small (4 or 2 squared millimeters) and possibly nonrepresentative portion of a plane section. The results are still of some interest, however, because they illustrate well what could be done in future research when a larger, more representative plane section area is digitized. A comprehensive summary of the statistical intercorrelations among the pore geometry, textural and packing parameters will be provided in a later section.

Porosity

For the modern sands the computed porosities range from 37 to 51 percent, and for the ancient sandstones the range is 17 to 30 percent. Not surprisingly, the linear correlation between the plane section (Appendix I) and PORESTAT 'digitization' porosities is a high +0.918. In general, the digitization porosities are slightly larger than the plane section porosities. Of the two sets of porosity values the latter is, of course, the more accurate because it is based on point counts of entire laminae. The standard deviation of the quadrat porosity generally ranged between 2 and 6 percent.

Specific Pore Surface Area

For the modern sands the computed specific pore surface areas range from 22 to 6 reciprocal millimeters, and for the ancient sandstones the range is 30 to 17 reciprocal millimeters.

Pore Size

With only one minor exception, the average pore dimension (based on the entire pore pattern) parallel to bedding was always larger than that normal to bedding. However, for the average maximum pore dimension (based on individual pores) no consistent relationship existed between pore size and orientation relative to bedding. The linear correlations between the overall average pore dimension (i.e., the mean of the row and column average pore dimensions), and both the absolute average maximum (individual) pore dimension and the average (individual) pore area are an expected high +0.929 and +0.873, respectively.

Tortuosity

For the modern sands the range of values for the modified Preston-Davis (PD) tortuosity, and the two weighted average individual pore tortuosities (IP-A, weighted by pore area; and IP-D, weighted by maximum pore dimension) are: 1.23 to 1.48, 1.31 to 2.43, and 1.30 to 2.13, respectively. For the ancient sandstones the range of values for the PD, IP-A and IP-D tortuosities are: 1.85 to 3.55, 1.14 to 1.37, and 1.17 to

1.37, respectively. It is apparent that the PD tortuosities are consistently larger for the sandstones whereas the IP-A and IP-D tortuosities are generally smaller for the sandstones. The results for the PD tortuosity are more appealing because they show a larger difference between the unconsolidated sands and indurated sandstones, and because the greater tortuosity of the sandstones is consistent with the findings of earlier investigations where the electrical resistivity measure of tortuosity was used. The PD tortuosity has a weak to moderate inverse curvilinear (quadratic) correlation with the IP-D and IP-A tortuosities: 0.728 and 0.753, respectively. Not unexpectedly, the IP-A and IP-D tortuosities have a very strong direct linear correlation of 0.977.

The PD tortuosity measure is easily the most significant result to come out of the pore geometry analyses. This is so because this methodology generates tortuosity values which are very similar to those obtained for sands and sandstones from the conventional electrical resistivity measure of tortuosity (i.e., Archie's Law, equation 13). For tortuosities estimated from Archie's Law, a range of tortuosities between 1.3 and 1.6 has been documented for unconsolidated sand (Archie, 1942; Wyllie and Gregory, 1955; Taylor-Smith, 1971; Barnes et al., 1972; Windle and Wroth, 1975; and Jackson et al., 1978), and a range of tortuosities between 1.5 and 2.3 has been documented for indurated sandstones (Archie, 1942; and calculations based on the raw data in Table 2 of Winsauer et al., 1952 and Tables 8, 9, 10 and 11 of Wyllie and Spangler, 1952). As described in an earlier section, Winsauer et al. (1952) are apparently the only investigators to have

actually measured three-dimensional tortuosity directly (equation 14). They report a tortuosity range of 1.5 to 3.3 for indurated sandstones, and a tortuosity value of 1.4 for the one unconsolidated sand analyzed.

Table 13 summarizes the tortuosity ranges for sands and sandstones reported by this and other studies. It is clear that the plane section PD tortuosity is highly consistent with the sample plug tortuosities determined by more conventional means. Thus it appears that tortuosity can be reliably estimated from plane sections.

Pore Orientation

The results of the pore orientation analyses are summarized in the PORESTAT output in a histogram which depicts the variation in the standardized average pore dimension with various directions in a plane section. The 'peaks' in the histogram can either be spurious (i.e., represent random noise in the data) or may correspond to 'real' directions of pore elongation. To interpret the histogram one must first determine how pronounced a peak must be in order to consider it significant rather than potentially spurious. This question can be at least partially answered by considering the results for the test patterns. For the three random patterns the standardized average pore dimensions (SAPD) for the two longest peaks are: 1.40, 1.08 (RAN-1); 1.19, 1.10 (RAN-2); and 1.39, 1.24 (RAN-3). For the six systematically packed sphere patterns, each of which has one or two well-developed preferred pore orientations, the largest two peaks have SAPD values of: 1.63, 1.63 (CASE1-P); 3.9, 2.00 (CASE1-OB); 10.6,

TABLE 13
TORTUOSITY RANGES FOR UNCONSOLIDATED SAND
AND INDURATED SANDSTONE

	Tortuosity Measured from Plane Sections in This Study ¹			Tortuosity Estimated from Archie's Law (Equation 13) ²	Tortuosity Measured Directly (Equation 14) ³
	IP-A	IP-D	PD		
Unconsolidated Sand	1.31- 2.43	1.30- 2.13	1.23- 1.48	1.3-1.6	1.4
Indurated Sandstone	1.14- 1.37	1.17- 1.37	1.85- 3.55	1.5-2.3	1.5-3.3

¹ PD=modified Preston-Davis Tortuosity
IP-A=weighted (by pore area) average individual pore tortuosity
IP-D=weighted (by maximum pore dimension) average individual pore
tortuosity
The ranges are based on 16 sands and 10 sandstones.

² Data sources: Archie (1942), Winsauer et al. (1952, tortuosities
computed from raw data in Table 2), Wyllie and Spangler (1952,
tortuosities computed from raw data in Tables 8, 9, 10 and 11),
Wyllie and Gregory (1955), Taylor-Smith (1971), Barnes et al. (1972),
Windle and Wroth (1975), and Jackson et al. (1978).
The ranges are based on a large but unknown number of sands and
sandstones.

³ Data source: Winsauer et al. (1952).
The ranges are based on 1 sand and 29 sandstones.

2.00 (CASE2-P); 2.57, 1.98 (CASE2-OB); 2.57, 1.98 (CASE2-OB); 31.9, 2.72 (CASE3-P); and 1.67, 1.32 (CASE3-OB). For the ten STRIPE patterns there is only one peak and it has a SAPD value which ranges between 65 and 154. From these results we can conclude that those peaks with SAPD values larger than about 1.5 are probably significant.

The maximum standardized average pore dimension for any plane section normal to bedding is 1.75 (samples AR1-15a and AR1-22c). Only three other samples have a maximum SAPD larger than 1.5 (B2-7, B2-9 and AB1-1d1). For all of these samples the maximum SAPD is parallel to bedding. For all other samples the maximum SAPD's cannot be considered significant.

When the results for the various lamina types are compared for the modern sands an interesting trend is revealed. If we consider only the principal pore orientation (i. e., the largest SAPD peak) for plane sections normal to bedding and to strike we see that all of the beach samples (B2-1, 16; and B1-15, 16) have pore orientations either normal to bedding or inclined away from the direction of bedding dip (see Part IV of Appendix M). In contrast, all river, washover fan and dune foreset samples (R5-21, 23, 25, 34; B2-20; D3-15, 19; and D5-10, 15, 16) have their pore orientations either parallel to bedding or inclined in the same direction as the bedding dip. Even though most of the principal pore orientations for these samples would not pass the significance test, the strength of the above trend argues against this result being wholly fortuitous. There are good geologic reasons why this result would be expected. In general, directions of preferred orientation for grains and pores should be coincident. It is well

known that grains on beaches are oriented by the wave backwash (Curry, 1956). Because of this they tend to be imbricated with their long axes inclined in an inland direction, away from the seaward bedding dip. The principal pore orientation for the beach samples may be a reflection of this tendency. For the foreset samples it seems reasonable to expect that grains will have their long axes oriented in the same general direction as the dip of the inclined surface on which they are deposited. Thus the principal pore orientation for the river, washover fan and dune foresets should be roughly parallel to the bedding dip.

Autocorrelation and Double Fourier Analyses

General statement

The results for the double Fourier and two-dimensional autocorrelation analyses should be considered together. One cannot easily be interpreted without reference to the other. Because of its greater conceptual simplicity and fewer mathematical limitations the autocorrelation results should always be considered first. Both the double Fourier and autocorrelation analyses are plagued by the same problem that afflicted the pore orientation analyses; namely, recognition of significant results. The question that needs to be answered is then, how large must the power of a sinusoid pair or the height of a correlogram peak be in order to be considered indicative of a real periodic repetition in the rock-pore pattern and not just an artifact of the random noise in the data? A partial answer to this question is provided by an analysis of the test

patterns. In the discussion which follows, the question of significance and other matters will be considered in some detail for each of the two methods.

Autocorrelation analysis

For the autocorrelation analyses a significant result is certainly suggested by the presence in the correlogram of a series of roughly equally-spaced peaks where the ratio of the maximum similarity coefficient for the peaks to the minimum similarity coefficient for the adjacent troughs is reasonably large. There are three reasons, however, why a well-developed series of peaks may not occur even when a real periodic repetition exists in the rock-pore pattern. First, if the repetition has a long wavelength it may be represented by only one or two peaks. Second, if two or more sets of repetitions exist (each with a different wavelength and phase), the correlogram may become hopelessly confounded. Third, at the intermediate and especially higher lags spurious peaks may begin to appear and thus distort the symmetry of a series of peaks generated at the lower lags. In general then we cannot always count on seeing a well-defined series of peaks and thus our principal tool for recognizing geologically meaningful peaks is the peak to trough similarity coefficient ratio. This approach is valid, however, only for the lower lags. For the correlograms presented in the PORESTAT output, the lower, statistically 'safe' lags, are 1 to 20, and the intermediate lags are 21 to 39. The results for the higher lags (40 to 79) were not printed out. The peaks generated during the intermediate

lags may still be real but they must be interpreted with caution. Periodic repetitions recorded in the lower lags would correspond to double Fourier sinusoids of harmonic 4 and above. The higher the harmonic number, the larger the number of correlogram peaks in lags 1 through 20. Sinusoids of harmonic 2 or 3 would require the first 39 lags in order to be represented in the correlogram.

For the three random patterns, the maximum peak to trough similarity coefficient ratios for the lower and intermediate lags in either one of the two correlograms were (the ratio for the lower lags is given first): 1.19, 1.08 (RAN-1); 1.13, 1.13 (RAN-2); and 1.06, 1.08 (RAN-3). For the six systematically packed sphere patterns, each of which has well-developed periodic repetitions and multiple equally-spaced correlogram peaks, the analogous ratios were: 1.52, 1.52 (CASE1-P); 2.19, 2.01 (CASE1-OB); 1.35, 1.35 (CASE2-P); 1.90, 1.83 (CASE2-OB); 2.98, 2.89 (CASE3-P); and 1.20, 1.19 (CASE3-OB). The results for the three random patterns and the one systematic pattern CASE3-OB indicate that a correlogram peak could not be considered significant unless its peak to trough similarity coefficient ratio exceeded about 1.20. The maximum value of this ratio for any of the samples in Appendix M is 1.11. Thus no periodic repetitions can be demonstrated for the rock-pore patterns on the basis of peak-to-trough ratios. A minority of the correlograms do display a weakly-developed series of approximately equally-spaced peaks. A typical example of one of these is the first correlogram for sample D3-15 in the PORESTAT output (page A158 of Appendix L). Although the maximum peak-to-trough ratio is only 1.10, the regularity of the peaks suggests that this result is not spurious. As pointed out in

an earlier section, the periodic repetition indicated by this correlogram has a wavelength similar to the mean grain size for the sample. It is generally true for all the other correlograms which exhibited a series of approximately equally-spaced peaks that the wavelength of the periodic repetition was of the same order of magnitude as the mean grain size.

The results of the autocorrelation analyses were disappointing. No useful information on pore geometry was generated. This is not really surprising because well-defined periodic patterns should only rarely be developed in natural porous media.

Double Fourier analysis

Both the autocorrelation and double Fourier techniques are sensitive only to periodic repetitions in the rock-pore patterns. The earlier discussions of the PORESTAT results for sample D3-15 clearly demonstrated that these two techniques do detect the same periodic repetitions. It is probably fair to say that if one of the techniques fails to recognize any repetitious patterns, the other will too. The inability of autocorrelation to reveal meaningful repetitions in the rock-pore patterns analyzed in this study suggests that double Fourier analysis will not be any more successful.

Evaluation of the 'significance' of the double Fourier results is very difficult because all one has to go on is the absolute power of the sinusoid pairs. The interpretation of the power magnitude is not, however, straightforward. There are two reasons for this. First, there

is a tendency for the threshold value of a statistically significant power to decrease with increasing harmonic number. Thus the power for the 20, 20 sinusoid pair would not need to be anywhere near as large as that for the 1,1 sinusoid pair in order to be considered significant. Second, the spectrum of power threshold values will be different for each pattern having a different proportion of rock and pore points. Significance tests which take these kinds of factors into account have been developed for single Fourier analysis (Bloomfield, 1976, p. 110-113) but not for double Fourier analysis.

In the present study, a very crude test of significance would be to compare the power of a sinusoid pair to the maximum observed power for the random test patterns (e.g., 0.025 for RAN-1). All of the systematically packed sphere patterns and only one of the 33 rock-pore patterns had a maximum power larger than 0.025. If we were to abide by these results then we would have to conclude that essentially all of the rock-pore patterns have power spectrums which are dominated by sinusoid pairs with spuriously high powers. From a statistical standpoint, double Fourier analysis was unable to demonstrate that geologically meaningful periodic repetitions exist within the sand and sandstone rock-pore patterns.

INTERCORRELATION AMONG TEXTURAL, PACKING AND PORE GEOMETRY PARAMETERS

INTRODUCTION

In this study data have been collected for a large number of textural, packing and pore geometry parameters. The question which comes immediately to mind is, "What is the nature of the interrelationships among the various parameters?" More specifically, one needs to know:

- 1) What is the 'strength' of the statistical correlation between a given pair of parameters? Do the parameters vary independently or are they mutually dependent upon one another? If the latter is the case, what is the extent of the interdependency?
- 2) Given a pair of interdependent (i.e., correlated) parameters, what is the nature of the relationship? Does one parameter vary directly or inversely with the other? Is the relationship a linear or curvilinear one?

In this section an attempt will be made to answer these questions for all possible pairs of parameters. The value of this section will lie not so much in the answers themselves, because the data set is

probably too small to establish geologically meaningful relationships, but rather in the method used to provide the answers. A novel system of analysis for bivariate correlations will be introduced. This system involves the use of two new methodologies: 1) a 'correlation matrix' which includes both linear and curvilinear correlation coefficients, the results of a statistical test of significance which will indicate the exact nature of the bivariate relationship, and a general description of the shape and orientation of the data trend for bivariate scatter plots; and 2) a verbal characterization of the strength of bivariate relationships based on the quadratic correlation. The correlation matrix is generated by CORMAT, a Fortran IV computer program written by the author. An annotated listing of this program is provided in Appendix N.

STATISTICAL PROCEDURES

The Correlation Matrix (CORMAT)

Bivariate Correlations

The first step in a correlation analysis of a large number of variables is to form the correlation matrix. This matrix contains correlation coefficients for all possible pairs of variables. Many 'canned' computer programs are available at university, industry and government computing centers which will compute the correlation matrices. As far as I am aware, all of these programs, without exception, utilize only the

'linear' Pearson product-moment correlation coefficient. This coefficient is a measure of the scatter about a least-squares straight line fitted to the sample data. The great flaw in this standard approach to bivariate correlation is that it does not consider the possibility that the relationship between two variables may be more accurately characterized with a curved rather than a straight line. If a straight line is fitted to a swarm of sample points having a curvilinear trend, the strength of the correlation between the two variables will be underestimated. The extent of underestimation will vary with the curvature and orientation of the curvilinear trend. It is easy to conceive of a situation where the linear correlation is zero while the true curvilinear correlation approaches one.

In the author's opinion most relationships between two interdependent variables are of the 'simple' curvilinear kind (i.e., the trend can be represented by a curve with one bend in it). It is not uncommon for variable pairs to have what seems to be a linear relationship. Many of these relationships, however, are perhaps more appropriately described as being broadly curvilinear. Equally unlikely as strictly linear relationships are 'complex' curvilinear relationships (i.e., the trend can be represented by a curve with two or more bends in it). Apart from those situations where parameters vary with time or distance, such complicated trends should be relatively rare in nature.

Clearly, in any correlation analysis curvilinear as well as linear relationships must be considered. This belief was the primary motive behind the development of the CORMAT computer program. This program computes for all possible pairs of variables the following three Pearson product-moment correlation coefficients:

- 1) Linear—describes the scatter of the observed Y values about the best-fit straight line; the fitted line corresponds to the first degree polynomial regression model: $\hat{Y} = a + (b \cdot X)$ where X is the set of observed values for the independent or predictor variable, $\hat{Y}$ is the set of predicted values for the dependent or response variable, and a and b are constants determined by the regression analysis.
- 2) Quadratic—describes the scatter of the observed Y values about the best-fit simple curve; the fitted curve is a parabola and corresponds to the second degree polynomial regression model: $\hat{Y} = a + (b \cdot X) + (c \cdot X^2)$ where $\hat{Y}$, X , a and b are as previously defined and c is another empirically determined constant.
- 3) Cubic—describes the scatter of the observed Y values about the best-fit complex (two bends) curve; the fitted curve is a double parabola and corresponds to the third degree polynomial regression model: $\hat{Y} = a + (b \cdot X) + (c \cdot X^2) + (d \cdot X^3)$ where $\hat{Y}$, X , a , b and c are as previously defined and d is another empirically determined constant.

The Pearson product-moment correlation coefficient (r) for all three types of bivariate relationships is computed using a single formula (Draper and Smith, 1981, p. 46):

$$r = \frac{\sum_{i=1}^n (\hat{Y}_i - \bar{Y})^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (30)$$

where $\bar{Y}$ is the mean of the n Y values, $\hat{Y}_i$ is the i^{th} predicted Y value and Y_i is the i^{th} observed Y value. The $\hat{Y}$ values will differ for each of the regression models. As the difference between the observed and corresponding predicted Y values decreases, the correlation increases with r approaching 1. The correlation and regression calculations performed by CORMAT are based on the equations and algorithms of Bevington (1969, p. 140-142) and Davis (1973, p. 192-221).

Two sets of calculation results are provided in the correlation matrix for each variable pair. In these sets each variable is alternately treated as the predictor (X) and response (Y) variable. The value of the linear correlation coefficient is the same regardless of which variable assumes the role of Y in the regression models, but the same is not true for the quadratic and cubic correlation coefficients. This is so because in the calculations the predictor and response variables are treated in fundamentally different ways. In regression analysis it is assumed that the values of the predictor variable are known without

error (i.e., they are true values and not estimates which are subject to random error: Crow et al., 1960, p. 149-150; and Draper and Smith, 1981, p. 3-4). In contrast, the values of the response variable are considered to contain some random error. It is because of these implicit assumptions about the data that the correlation coefficient is based only on the point scatter in the Y direction. For the linear correlation, the designation of predictor and response variables is immaterial because both of the best-fit straight lines, although different, still have the same symmetry relation with the point swarm. For the quadratic correlation, the corresponding best-fit parabolic curve always has its axis of symmetry parallel to the Y axis; and for the cubic correlation, the best-fit double parabola, which lacks a symmetry axis, always has a constant orientation relative to the Y axis. Because of this spatial constraint, it is virtually impossible for the two quadratic or cubic correlation coefficients to be equal. The assumptions of no error for the predictor variable is, of course, generally not true but the calculations can still be performed and meaningful information can still be extracted from the correlation coefficients.

It is important to keep in mind that the quadratic or second degree polynomial regression model is; in fact, the equation of a parabola. Strictly speaking then, the quadratic polynomials can be reliably fitted only to parabolic trends which have their axis of symmetry parallel to the Y axis. Although bivariate trends are generally curvilinear, it is seldom that they will actually be parabolic. Quadratic curves are remarkable, however, in that there usually exists a parabolic curve segment that closely approximates any of the large number of simple curve varieties. Thus the quadratic curves are ideally suited for regression

and correlation analyses. While it is true that a nonparabolic curvilinear trend will not be perfectly represented by a parabolic curve, still the trend will be closely approximated and the resulting quadratic correlation will be superior to the linear correlation as a measure of the strength of a bivariate relationship. Similar arguments can be made in support of the use of cubic or third degree polynomial curves for complex curvilinear relationships.

Significance Test

For each pair of variables the CORMAT program performs a series of 'F-tests' (i.e., an Analysis of Variance based on the F statistic). The purpose of these tests is to determine the most appropriate mathematical model for the bivariate relationship. In other words, the F-tests will tell us which of the following models best represents the relationship between Y (the response variable) and X (the predictor variable):

$$1) \quad \hat{Y} = a + (b_1 \cdot X) \quad (31)$$

$$2) \quad \hat{Y} = a + (b_2 \cdot X^2) \quad (32)$$

$$3) \quad \hat{Y} = a + (b_1 \cdot X) + (b_2 \cdot X^2) \quad (33)$$

$$4) \quad \hat{Y} = a + (b_3 \cdot X^3) \quad (34)$$

$$5) \quad \hat{Y} = a + (b_1 \cdot X) + (b_3 \cdot X^3) \quad (35)$$

$$6) \quad \hat{Y} = a + (b_2 \cdot X^2) + (b_3 \cdot X^3) \quad (36)$$

$$7) \quad \hat{Y} = a + (b_1 \cdot X) + (b_2 \cdot X^2) + (b_3 \cdot X^3) \quad (37)$$

The calculation procedure employed by CORMAT follows that of Davis (1973, p. 216). The procedural steps are as follows.

Step 1 First, second and third degree polynomials are fitted to the data.

Step 2 The contribution of each regression term ($b_1 \cdot X$, $b_2 \cdot X^2$ and $b_3 \cdot X^3$) to the 'explanation' of the variation in Y (i.e., reduction of the sample point scatter about the regression line) is determined. The 'sum of squares due to regression' ($SS_R = \sum_{i=1}^n (\hat{Y}_i - \bar{Y})^2$) is obtained for each of the regressions in Step 1: $SS_{R,1}$, $SS_{R,2}$ and $SS_{R,3}$. The contribution of the linear ($b_1 \cdot X$), quadratic ($b_2 \cdot X^2$) and cubic ($b_3 \cdot X^3$) terms is computed as follows: $SS_{R,L} = SS_{R,1}$; $SS_{R,Q} = SS_{R,2} - SS_{R,1}$; and $SS_{R,C} = SS_{R,3} - SS_{R,2}$.

Step 3 F statistics are computed for each of the three regression terms by dividing the respective SS_R 's by the 'mean sum of squares due to deviations' for the third degree polynomial ($MS_{D,3} = [\sum_{i=1}^n (\hat{Y}_i - Y_i)^2] / [n - 4]$): $F_L = SS_{R,L} / MS_{D,3}$; $F_Q = SS_{R,Q} / MS_{D,3}$; and $F_C = SS_{R,C} / MS_{D,3}$.

Step 4 In this last step the following question is asked: "does the addition of the k^{th} degree term ($b_k \cdot X^k$) significantly improve the fit of the regression line to the sample points beyond that obtained for some other model which lacks this term?" In answering this question we are testing the null hypothesis that $b_k = 0$ in the sampled population. Conventionally, one consults a F statistic probability table (found in the appendices of nearly all statistics books) and locates the 'critical' F value for a specified significance or confidence level, and 1 and $n-4$ degrees of freedom. For example, if it is found that

the observed or computed F value is larger than the critical F value for the 99 percent confidence level, then we say that the corresponding regression terms ($b_k \cdot X^k$) is significant at the 99 percent level because there is only a 1 percent chance that an observed F as large or larger than the critical F could occur in a sample when in fact b_k equals zero in the sampled population. CORMAT relieves the user of the need to consult F tables. Using an algorithm developed by Dorrer (1968) the program computes and prints out the significance level of each regression term.

In order to specify the statistical significance of a regression term there are five underlying assumptions to the F test which must first be met (Blalock, 1972, p. 464; and Davis, 1973, p. 220):

- 1) the samples were randomly selected from the population of all possible samples (i.e., the samples collected are unbiased);
- 2) for a given value of X, the variation in Y is normally distributed with a variance of S_Y^2 ;
- 3) the variance of Y, S_Y^2 , is the same for all values of X (i.e., the data exhibits homoscedasticity; $\sqrt{S_Y^2}$ is the 'standard error of the estimate of Y');
- 4) the X values are known without error and the Y values are subject to random error; and
- 5) the residuals or deviations from the regression line ($\hat{Y}_i - Y_i$) are free from 'autocorrelation' (i.e., the residuals for successive X values are mutually independent).

In geology these rather stringent assumptions are seldom, if ever, satisfied. We collect samples where it is convenient to get them and thus our sampling is likely to be biased. As regards the assumption of the normally distributed non-autocorrelated variation in Y which is constant for all values of X , in nearly all cases we simply do not know if this is true. There are statistical procedures which would allow us to determine the veracity of this assumption but they require a very large randomly selected set of samples. The general inability to satisfy the fourth assumption has already been alluded to in the discussion of the correlation coefficient. From the preceeding it clear that in most cases the data will not conform to the underlying assumptions for the F test. This means then that we cannot actually determine the absolute significance of regression terms. The stated significance level in the CORMAT output should be viewed as only a very rough estimate. The true absolute significance could be either higher or, more likely, lower depending on the nature of the assumption violations. Although the stated significance levels are not to be literally believed, the F test is still a valuable tool because it is an objective and reproducible means of evaluating the data. It represents essentially nothing more than a sample size correction: the smaller the sample size, the larger the F statistic must be in order for a regression term to be considered significant. This is so because the smaller the sample size, the more likely spurious relationships are to exist.

Shape and Orientation of Trends

As pointed out in an earlier section, the quadratic correlation coefficient is an adequate measure of the strength of both linear and simple curvilinear bivariate relationships. It follows then that the parabolic or second degree polynomial (quadratic) regression line provides an adequate representation of both near-linear and simple curvilinear trends. When evaluating bivariate relationships it is important to consider the shape and orientation of the trends as well as the correlation. It is often the case that two variables will have a high correlation and 'statistically significant' regression terms but geologically implausible trends.

CORMAT indicates for each pair of variables in the correlation matrix the general shape and orientation of the trend as defined by the quadratic regression line (equation 33). The code for one of the six 'quadratic curve types' in Table 14 is provided in the output. In this table quadratic curve types 5 and 6 are further subdivided. These subdivisions are not recognized by CORMAT because one of the criteria for their identification is based on a user specified level of significance. In the output, the curve designation will be either 5 or 6 and any further subdividing must be done by the user.

Program Output

An example of the CORMAT output is provided in Part II of Appendix N.

TABLE 14
CLASSIFICATION OF QUADRATIC CURVES

Numeric Code	Schematic Illustration ¹	Characteristics
1		Y increases monotonically with increasing X, and the rate of increase in Y increases with increasing X.
2		Y increases monotonically with increasing X, and the rate of increase in Y decreases with increasing X.
3		Y decreases monotonically with increasing X, and the rate of decrease in Y decreases with increasing X.
4		Y decreases monotonically with increasing X, and the rate of decrease in Y increases with increasing X.
5A,5B,5C		Y initially decreases and later increases with increasing X.
5A		Linear regression term is significant, and sign of linear correlation is positive

TABLE 14 (continued)

Numeric Code	Schematic Illustration ¹	Characteristics
5B		Linear regression term is significant, and sign of linear correlation is negative.
5C		Linear regression term is not significant, and sign of linear correlation is positive or negative.
6A,6B,6C		Y initially increases and later decreases with increasing X.
6A		Linear regression term is significant, and sign of linear correlation is positive.
6B		Linear regression term is significant, and sign of linear correlation is negative.
6C		Linear regression term is not significant, sign of linear correlation is positive or negative.

¹Y corresponds to the dependent or response variable, and X corresponds to the independent or predictor variable.



In the correlation matrix on page A197 the dependent or response variables are listed across the top of the page, and the independent or predictor variables are listed along the left margin of the page. Consider, for example, the results for the grain size mean and sorting (MEAN and SORT, respectively). When SORT is treated as the response variable we see that the linear, quadratic and cubic correlation coefficients are -0.322 , 0.352 and 0.370 , respectively; the significance levels for the linear, quadratic and cubic regression terms are 78, 42 and 34 percent, respectively; the quadratic curve type is 5 (probably 5C because of the low significance of the linear term); and the number of samples in the data set equals 18. When MEAN is treated as the dependent variable we see, as expected, that the correlation coefficients and significance levels are different.

Strength Of The Quadratic Correlation

The magnitude of the absolute value of the Pearson product-moment correlation cannot be used directly to indicate the significance or the strength of the relationship between two variables (Bevington, 1969, p. 122). This is true because as the sample size decreases, the likelihood of spuriously high correlations increases. Thus the smaller the sample size, the larger the correlation coefficient must be in order to assume the same level of significance as a smaller correlation coefficient in a data set containing a larger number of samples. This same reasoning was applied to the results of the F test.

There are two questions which should always be asked about an observed correlation coefficient. First, is the correlation statistically significant (i.e., does $r \neq 0$ in the sampled population)? The fact that a correlation is found to be significant at some specified level of certainty does not mean that the correlation between the two variables is 'strong', only that it is not zero. The second question is then, how strong is a statistically significant correlation?

Tests of the significance of correlation coefficients are applied almost exclusively in bivariate regression to the results of linear regression (i. e., only linear correlations are tested). It would probably be more useful to test the significance of the quadratic correlation. Such a test is readily performed by recognizing the equivalence between bivariate curvilinear and multiple linear regression. In the case of the former, the model is $\hat{Y} = a + (b_1 \cdot X) + (b_2 \cdot X^2)$. If the two X terms are redefined as $Z_1 = X$ and $Z_2 = X^2$ then we can describe the bivariate curvilinear relationship with a multiple linear regression model: $\hat{Y} = a + (b_1 \cdot Z_1) + (b_2 \cdot Z_2)$ where Z_1 and Z_2 are viewed as different predictor variables (Crow et al., 1960, p. 186). Variables Z_1 and Z_2 are certainly not statistically independent of one another but while such independence is desirable, it is not necessary in multiple regression. To evaluate the significance of a quadratic correlation coefficient we apply then a test designed for a correlation coefficient associated with a multiple linear regression model (Crow et al., 1960, p. 177-178). Our observed correlation will be compared with a 'critical' correlation value for some specified level of significance. The null

hypothesis tested is that the correlation is zero for the sampled population. If the observed correlation is larger we reject the null hypothesis and conclude that the correlation is significant. The critical correlation value (r_c) needed for the test can be obtained from 1) Table 7 of Crow et al. (1960, p. 241)—use $n-3$ degrees of freedom and the column for 3 variables; or 2) any F statistic probability table provided the following relation is used (Harris, 1975, p. 19):

$$F_c = \frac{n-3}{2} \cdot \frac{r_c^2}{(1-r_c^2)}$$

where F_c is the critical F value for a specified level of significance, and 2 and $n-3$ degrees of freedom. The underlying assumptions for the correlation test are the same as for the F test.

The comparison of observed (r_o) and critical (r_c) correlations is equivalent to a test of the statistical significance of the quadratic regression model (equation 33). If r_o exceeds r_c we conclude that X and X^2 explain a significant portion of the variation in Y (Crow et al., 1960, p. 177-178; and Bevington, 1969, p. 198).

Once the significance of the quadratic correlation coefficient has been established the next step is to characterize the strength of the correlation. No procedures for doing this have been devised to date. The following scale is therefore proposed.

<u>Interval</u>	<u>Strength of Correlation</u>
$r_c + 4 \cdot I$ to 1	very strong
$r_c + 3 \cdot I$ to $r_c + 4 \cdot I$	strong
$r_c + 2 \cdot I$ to $r_c + 3 \cdot I$	moderate
$r_c + I$ to $r_c + 2 \cdot I$	weak
r_c to $r_c + I$	very weak
less than r_c	no significant correlation

where $I = (1 - r_c)/5$. An observed correlation is characterized according to this verbal scale by noting the interval in which it falls.

DATA ANALYZED

Parameters Used

Not all of the variables considered in this study have been included in the correlation matrix analysis. No grain shape parameters (e.g., roundness and form) were included because they cannot at present be meaningfully quantified. For the grain size parameters only the moment statistics have been used because they provide a more reliable and complete description of a grain size distribution than do the graphical statistics. All of the packing parameters were included except for the average number of point, long and concavo-convex contacts per grain. For the samples analyzed nearly all of the intergranular contacts were of the 'point' variety. Thus the contact and floating indices, which were used, are largely a reflection of the number of point contacts. Most of the pore geometry parameters have been included. Conspicuously absent are the results for the double Fourier, autocorrelation and pore orientation analyses. The problem is that the results of these analyses cannot be meaningfully summarized by single-valued numerical descriptors. The only other deletions from the set of pore geometry parameters were the average pore and rock dimensions parallel to both the rows and columns of the rock-pore matrices. It was considered sufficient

to include instead just the averages of the two average pore and rock dimensions. The twenty variables used in the correlation matrix analysis are listed below (code names are given in parentheses):

1. Grain Size Parameters
 - a. moment mean (MEAN)
 - b. moment standard deviation (SORT)
 - c. moment skewness (SKEW)
 - d. moment kurtosis (KURT)
2. Packing Parameters
 - a. plane section porosity (PS-P)
 - b. contact index (CI)
 - c. floating index (FI)
 - d. minimum compactional porosity (MC-P)
 - e. packing efficiency (PKEF)
3. Pore Geometry Parameters
 - a. digitization porosity (DG-P)
 - b. standard deviation of the quadrat porosity (SDQP)
 - c. specific pore surface area (SSA)
 - d. average pore dimension (APD)
 - e. average rock dimension (ARD)
 - f. number of individual pores (PNUM)
 - g. average maximum dimension of individual pores (AMPD)
 - h. average area of individual pores (APA)
 - i. weighted (by area) average tortuosity of individual pores (T-AR)

- j. weighted (by maximum dimension) average tortuosity of individual pores (T-MD)
- k. Preston-Davis pore tortuosity (T-PD)

Data Sets Used

A total of 28 sand and sandstone samples were analyzed in this study. In assessing the intercorrelations for variable pairs it was not always possible or even desirable to use all 28 samples. For the correlation matrix analysis the samples were organized into four data sets. These are listed below along with the variable-pair categories they were used to evaluate:

1. all modern sands (AM)—18 samples
 - a. all grain size parameters versus PS-P and PKEF
 - b. all possible pairs for PS-P, MC-P and PKEF
2. nearly all modern sands (NAM)—16 samples (samples R5-27 and 29 were excluded)
 - a. all grain size parameters versus CI and FI
 - b. all grain size parameters versus all pore geometry parameters
 - c. CI versus FI
 - d. PS-P, MC-P and PKEF versus CI and FI
 - e. all pore geometry parameters versus CI and FI
3. all modern sands and ancient sandstones (AMA)—28 samples
 - a. all possible pairs for the grain size parameters
 - b. all grain size parameters versus MC-P

4. nearly all modern sands and ancient sandstones (NAMA)—26 samples (samples R5-27 and 29 were excluded)
 - a. PS-P versus DG-P
 - b. all possible pairs for the pore geometry parameters.

Two factors were considered in the selection of the data set for each variable-pair category. First, with the exception of plane section porosity, no thin section-derived packing and pore geometry data was available for samples R5-27 and 29. This was the unfortunate result of poor thin section quality for these two samples. Second, in the comparison of thin section-derived packing and pore geometry parameters with non-thin section packing and grain size parameters the ten sandstone samples were always excluded. This was necessary because the sandstones were diagenetically altered. Whereas for the sands the packing and pore geometry parameters reflect the influence of texture and depositional process, for the sandstones these parameters largely reflect burial compaction and quartz cementation.

Considerable care needs to be exercised in the formulation of data sets. This point is well illustrated by the following sobering example. For the correlation between plane section porosity and contact index the 16 available modern sands were used. The linear correlation coefficient was a remarkably low +0.011. If the data for the two quartz-cemented ancient sandstones (AD2-1e and 1f) are added to the data set, the linear correlation coefficient becomes -0.840. The two AD sample points are closely spaced outliers which are off trend and well separated from the main sample point cluster. Geologists need to keep in

mind that outliers can have a disproportionate and deleterious effect on the outcome of correlation analyses.

SUMMARY OF THE RESULTS FOR THE CORRELATION MATRIX ANALYSES

The results of the correlation matrix analysis are summarized in Appendix O. Rather than include the computations for the 190 different variable pairs (each of which has two sets of results), the computational results for 67 variable pairs were selected for inclusion on the basis of the following two considerations.

1) At least one of the first two regression terms (i.e., the linear and quadratic) must be significant at the 99 percent level. It would be more conventional perhaps to have used the 95 percent significance level. It is highly unlikely, however, that the more conservative significance level used in this study would cause an important bivariate relationship to go unrecognized. Results which are significant at the 95 percent level but not the 99 percent level are indicative of very weak relationships.

2) A choice had to be made between the two sets of results for each variable pair. For correlations between a grain size parameter on the one hand and a packing or pore geometry parameter on the other hand, the latter must always be potentially dependent on the former. The reverse could never be true. Thus the only results considered for inclusion in the appendix were where the grain size parameter was treated as the independent or predictor variable. For correlations between

two grain size parameters, two packing parameters, two pore geometry parameters, or a packing and a pore geometry parameter, with one exception, neither variable could be said to be dependent upon the other. In such cases, the one set of results selected for a variable pair was the one having the largest quadratic correlation. The one exception to this practice involves three of the packing parameters: packing efficiency, and plane section and minimum compactional porosities. Only the results where the packing efficiency was treated as the dependent variable were considered.

DISCUSSION OF THE RESULTS

In this section the correlation results for each division of Appendix 0 will be briefly discussed. It would be impractical to attempt to rationalize the correlations for all 67 variable pairs. For this reason most of the comments which follow will be directed at those variable pairs having a moderate to very strong quadratic correlation.

Comment 1 No important bivariate relationships exist for pairs of grain size parameters and for combinations of grain size and packing parameters. It was argued in an earlier section that the apparent relation between minimum compactional porosity and mean grain size (see Figure 33) was really a reflection of the controlling influence of grain roundness.

Comment 2 The grain size sorting and mean exhibit several high correlations with the pore geometry parameters. Most of the expected trends are observed: as grain size increases, the rock and pore

dimensions tend to increase and the specific surface area tends to decrease. Inexplicably, as the sorting becomes poorer, the specific surface area tends to decrease. These results are not surprising because in unconsolidated sands the pore geometry is a direct reflection of the sediment texture. In indurated sandstones the correlations between these parameters should be much lower because of the diagenetic 'remodeling' of the pore space.

Comment 3 Two of the three high correlations exhibited by the packing parameter pairs are expected: the contact and floating indices, and the plane section porosity and packing efficiency are mathematically related measures. The moderate relationship between the plane section and minimum compactional porosities suggests that depositional processes do generally achieve a tight packing configuration in sand deposits.

Comment 4 The single high correlation between the packing and pore geometry parameters (plane section versus digitization porosity) is not surprising because these two parameters are of course measures of the same sediment/rock property.

Comment 5 Numerous high correlations exist for the pore geometry parameter pairs. The observed trends are precisely what one would expect. Tortuosity tends to decrease with increasing porosity and pore size, and decreasing number of pores. The various pore size measures all vary directly with one another and with porosity. As the number of pores increases the pore size and porosity tend to decrease, and as the average rock dimension increases the porosity and specific surface area tend to decrease. The two tortuosity measures based on individual pores vary directly with one another, and both vary inversely with the Preston-Davis tortuosity.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. A detailed characterization of modern sandy depositional environments should be performed using samples of single laminae, and the joint I:S grain size and S/I grain form distributions. The results of such a study may lead to a procedure for identifying and interpreting the depositional environment of ancient sands on the basis of their texture.
2. Visual comparators need to be developed for modal grain size in thin sections, sorting in loose sediment (the existing comparators are inaccurate), and skewness in thin sections and loose sediment. Adequate visual comparators now exist for modal grain size in loose sediment, and sorting in thin sections. No comparators are needed for kurtosis because this textural parameter has no hydrodynamic significance.
3. More settling velocity experiments need to be conducted. The settling velocity prediction equation derived in this study is based on the experimental results for only 17 different rectangular parallelepiped (RP) forms. The equation could be improved if the experimental results for other RP forms are added to the calibration

data set. A second and more useful prediction equation, one that incorporates the effects of roundness as well as form, could be derived if settling experiments are conducted using RP's with varying degrees of roundness.

4. Pore geometry analyses should be performed on various sandstone, limestone and dolomite units. In place of the primitive procedure employed in this study, photomicrographs with high rock-pore contrasts and an automated scanning densitometer should be used. Experimental studies could be conducted to evaluate the functional relationship between pore geometry, and permeability and enhanced oil recovery. Other studies relating pore geometry to diagenetic history may also prove to be useful.

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APPENDICES

APPENDIX A

DESCRIPTION OF SAMPLES AND SAMPLING LOCALITIES

EXPLANATORY NOTES

The following information is provided for each sampling locality and sample.

Sampling Localities

- 1) location (names(s) of the immediate area and the deposit; county; state; latitude and longitude; name of the United States Geological Survey topographic quadrangle map; and, if available, the township, range and section, or Carter coordinates)
- 2) references describing the sedimentology of the sampled unit
- 3) general depositional environment

Samples

- 1) approximate composition of the light mineral fraction (after acid treatment)—relative volumetric proportions (percents) of grain varieties were visually estimated from a thin section.

Relative proportions of potash (K) and plagioclase (P) feldspar are indicated; the abbreviation 'QFM' refers to an igneous or metamorphic rock fragment consisting of quartz, feldspar and/or mica; the term 'Quartz' includes chert; and rock fragments are listed in decreasing order of abundance.

- 2) lamina type, and sedimentary structure and/or microenvironment sampled (see also Table 1).

- 3) maximum dip (in degrees) of lamina (for dip direction normal to the shoreline or bedform crest, i.e., normal to strike).
- 4) lamina thickness (in millimeters).
- 5) character of the bounding laminae immediately above and below.

B1 SAMPLES

Location: Matagorda Peninsula, Matagorda Co., Texas (lat. 28°38'30" N., long. 95°51'30" W.; Dressing Point, Texas 7½ minute topo. quad; no T. and R.)

References: McGowen and Brewton (1975), and Wilkinson and Basse (1978)

Environment: marine barrier island

Samples B1-15 and B1-16

- 1) Quartz = 98%
Feldspar (P>K) = 2%
- 2) foreshore (beach) laminae
- 3) dip = 3°
- 4) thickness = 7mm
- 5) heavy mineral layers (B1-15) and coarse shell hash layers (B1-16)

B2 SAMPLES

Location: Sheldon's Marsh Preserve (until recently privately owned and known as 'Sheldon's Folly'; now a wildlife preserve closed to the public and managed by the Ohio Department of Natural Resources), Cedar Point Spit on Lake Erie, Erie Co., Ohio (lat. 41°25'30" N., long. 82°36'30" W.; Huron, Ohio 7½ minute topo. quad; no T. and R.)

References: Pettijohn and Ridge (1932, 1933), Pettijohn and Lundahl (1943), Pincus et al. (1951), and Carter and Guy (1980)

Environment: lacustrine barrier island (spit)

Sample B2-1

- 1) Quartz = 88%
Feldspar (K=P) = 10%
Rock Fragments (siltstone, QFM, chloritic hornfels) = 2%
- 2) foreshore (beach) lamina on lake side of spit
- 3) dip = 7°
- 4) thickness = 8mm
- 5) heavy mineral layers

Sample B2-7

- 1) same as B2-1
- 2) topset lamina of washover fan on lagoon side of spit
- 3) dip = 0°
- 4) thickness = 6mm
- 5) heavy mineral layers

Sample B2-9

- 1) same as B2-1
- 2) topset lamina of washover fan on lagoon side of spit
- 3) dip = 0°
- 4) thickness = 6mm
- 5) heavy mineral layers

Sample B2-16

- 1) same as B2-1
- 2) foreshore (beach) lamina on lake side of spit
- 3) dip = 8°
- 4) thickness = 7mm
- 5) heavy mineral layers

Sample B2-20

- 1) Quartz = 78%
Feldspar (K>P) = 10%
Rock Fragments (sandstone, siltstone, QFM and chloritic
hornfels) = 12%
- 2) foreset lamina of washover fan on lagoon side of spit
- 3) dip = 29°
- 4) thickness = 7mm
- 5) coarser-grained, granule-rich sand

D3 SAMPLES

Location: Bird Island Basin, Padre Island National Seashore, North Padre Island, Kleberg Co., Texas (lat. 27°28'00" N., long. 97°18'30" W.; South Bird Island, Texas 7½ minute topo. quad; no T. and R.)

References: GCAGS (1972), and Hunter (1977)

Environment: eolian dune field situated along the lagoonal margin of a marine barrier island (i.e., back-island dunes)

Samples D3-15 and D3-19

- 1) Quartz = 99%
Feldspar (K=P) = 1%
- 2) foreset lamina from a transverse dune (dune height about 1 meter); samples taken just below the active slipface
- 3) dip = 30°
- 4) thickness = 9mm (D3-15) and 10mm (D3-19)
- 5) heavy mineral layers

D5 SAMPLES

Location: Mt. Baldy, Indiana Dunes National Lakeshore on Lake Michigan, Laporte Co., Indiana (lat. 41°42'36" N., long. 86°55'41" W.; Michigan City West, Indiana 7½ minute topo. quad; NW¼ of Sec 31, T38N, R4W)

References: Pettijohn (1931), and Gutschick and Gonsiewski (1976)

Environment: lakeshore eolian dune field

Samples D5-10, D5-15 and D5-16

- 1) Quartz = 94%
Feldspar (K>P) = 4%
Rock Fragments (QFM, siltstone) = 2%
- 2) foreset lamina from a transverse dune (dune height about 37 meters); samples taken from a deflation surface on the stoss side at an elevation about 10 meters below the crest
- 3) dip = 30° (D5-15) and 32° (D5-10 and 16)
- 4) thickness = 7mm (D5-10) and 8mm (D5-15 and 16)
- 5) heavy mineral layers

R5 SAMPLES

Location: Blasdel Point Bar on the Brazos River, just downstream from the city of Richmond, Fort Bend Co., Texas (lat. 29°35'00" N., long. 95°44'30" W.; Sugarland, Texas 7½ minute topo. quad; no T. and R.)

References: Bernard and Major (1963), and Bernard et al. (1970)

Environment: point bar on a meandering stream

Sample R5-21

- 1) Quartz = 99%
Feldspar (P>K) = 1%
Rock Fragments (shale/mud clasts) = trace
- 2) foreset lamina from a trough cross-bed set (40cm thick); the set was associated with the concave downstream portion of a sinuous-crested sandwave opposite a scour trough
- 3) dip = 29°
- 4) thickness = 6mm
- 5) finer-grained sand

Sample R5-23

- 1) same as R5-21
- 2) foreset lamina from a planar cross-bed set (15cm thick); the set was associated with a straight-crested sandwave
- 3) dip = 28°
- 4) thickness = 8mm
- 5) finer-grained sand

Sample R5-25

- 1) same as R5-21
- 2) foreset lamina from a planar cross-bed set (15cm thick); the set was associated with a straight-crested sandwave
- 3) dip = 28°
- 4) thickness = 5mm
- 5) finer-grained sand

Sample R5-27

- 1) same as R5-21
- 2) horizontal lamina from a thick sequence (at least 2 meters) of horizontally bedded sand; the sequence occurred near the top of the point bar deposit
- 3) dip = 4°
- 4) thickness = 5mm
- 5) finer-grained, micaceous sand

Sample R5-29

- 1) same as R5-21
- 2) horizontal lamina of the same type as R5-27
- 3) dip = 2°
- 4) thickness = 6mm
- 5) finer-grained, micaceous sand

Sample R5-34

- 1) same as R5-21
- 2) foreset lamina from a trough cross-bed set (35cm thick); the set was associated with the concave downstream portion of a sinuous-crested sandwave opposite a scour trough
- 3) dip = 27°
- 4) thickness = 8mm
- 5) finer-grained sand

AB1 SAMPLES

Location: Kenilworth Member of the Blackhawk Formation (Upper Cretaceous), Coal Creek Canyon, Book Cliffs, Carbon Co., Utah (lat. $39^{\circ}42'51''$ N., long. $110^{\circ}40'23''$ W.; Deadman Canyon, Utah $7\frac{1}{2}$ minute topo. quad; NW $\frac{1}{4}$ of Sec 10, T13S, R11E); samples collected from the gently inclined, finely

laminated sandstone exposed in the creek bed directly opposite of the abandoned Knight-Ideal Coal Mine--the 1000-1005 foot interval in J.D. Howard's Coal Creek Stratigraphic Section (from an unpublished manuscript)

References: Young (1957), and Howard (1972)

Environment: interpreted by Howard (1972) to be a foreshore beach deposit at the top of a regressive marginal marine sequence

Samples AB1-1d1 and AB1-1d2

1) Framework Grains:

Quartz = 100% (5% of the quartz is chert, the conspicuous black grains visible in hand specimens)

Cement:

Abundant quartz overgrowths as evidenced by the predominance of long intergranular contacts, and frequent 'dust rings' and crystal terminations

Matrix:

Scarce; appears to be squashed argillaceous rock fragments (removed during preparation of loose grain sample)

2) marine foreshore (beach) laminae

3) dip = 7° (may be tectonic in part)

4) thickness = 8-9mm

5) sand of identical aspect with the laminae boundaries marked by concentrations (one grain thick) of black chert grains

AD2 SAMPLES

Location: Navajo Sandstone (Lower Jurassic), Zion National Park, Washington County, Utah (lat. 37°13'10" N., long. 112°55' 5" W.; Springdale East, Utah 7½ minute topo. quad; T41S, R10W, no section)

References: Gregory (1950), Hamilton (1978), and McKee (1979)

Environment: widely interpreted to be an eolian dune field in a continental interior desert

Samples AD2-1e and AD2-1f

1) Framework Grains:

Quartz = 99% (4% of the grains are chert)

Feldspar (K>P) = 1%

Cement:

Minor quartz overgrowths as evidenced by the predominance of long intergranular contacts, and rare 'dust rings' and crystal terminations

Matrix:

- None, but abundant squashed chert, polycrystalline quartz and feldspar grains which often resemble matrix
- 2) foreset laminae from a planar cross-bed set (several meters thick)
 - 3) dip = 26°
 - 4) thickness = 8mm (AD2-1f) and 11mm (AD2-1e)
 - 5) slightly finer-grained sand

AR1 SAMPLES

Location: Kyrock Sandstone (Lower Pennsylvanian), Nolin Reservoir, Edmonton Co., Kentucky (lat. 37°16'39" N., long. 86°14'48" W.; Nolin Reservoir, Kentucky 7½ minute topo. quad; Carter coordinates, 25-J-40); samples AR1-4c and AR1-5c come from the Lower Kyrock Sandstone outcrops near the parking lot on the east side of the dam, and the other four samples come from the Upper Kyrock Sandstone outcrops in the spillway on the west side of the dam

References: Gildersleeve (1971), and Sedimentation Seminar (1978)

Environment: According to Sedimentation Seminar (1978, p. 15)
 "... the Kyrock Sandstone was deposited as the fluvial fill of a pre-existing subareally excavated river valley." The lower and upper parts of the Kyrock Sandstone are interpreted as braided and meandering stream deposits, respectively.

Sample AR1-4c**1) Framework Grains:**

Quartz = 99%

Feldspar (K) and Rock Fragments = trace

Cement:

Abundant quartz overgrowths as evidenced by the predominance of long intergranular contacts, frequent crystal terminations and rare 'dust rings'

Matrix:

Scarce hematite-stained authigenic kaolinite and squashed argillaceous rock fragments and chert grains (removed during preparation of loose grain sample)

Other Features:

Some primary intergranular porosity but mostly secondary porosity as evidenced by common elongate and over-sized pores

- 2) foreset lamina from a planar cross-bed set (95cm thick)
- 3) dip = 23°
- 4) thickness = 8mm
- 5) finer-grained sand

Sample AR1-5c

1) Framework Grains:

Quartz = 99%

Feldspar (K) and Muscovite = trace

Cement:

Abundant quartz overgrowths; same evidence as for AR1-4c

Matrix:

Abundant, occasionally hematitic, authigenic kaolinite plus
minor illite (removed during preparation of loose grain sample)

Other Features:

Essentially all porosity of secondary origin as evidenced by
elongate and over-sized pores

2) foreset lamina from a planar cross-bed set (90cm thick)

3) dip = 19°

4) thickness = 8mm

5) finer-grained sediment

Sample AR1-14

1) same as AR1-5c

2) foreset lamina from a trough cross-bed set (45cm maximum thickness)

3) axial dip of trough = 26°

4) thickness = 7mm

5) finer-grained sediment

Sample AR1-15a

1) same as AR1-5c

2) foreset lamina from a trough cross-bed set (65cm maximum thickness)

3) axial dip of trough = 19°

4) thickness = 8mm

5) finer-grained sediment

Sample AR1-18

1) same as AR1-5c

2) horizontal lamina from a thick sequence of horizontally bedded sand

3) dip = 12°

4) thickness = 5mm

5) finer-grained sediment

Sample AR1-22c

1) same as AR1-5c

2) horizontal lamina from a thick sequence of horizontally bedded sand

3) dip = 0°

4) thickness = 11mm

5) finer-grained sediment

APPENDIX B

RAW DATA FOR THE SIEVE ANALYSES

Sample	Percent of Total Sediment Weight (Light Mineral Fraction Only) ¹ in Each Quarter Phi Size Class													
	VC1 ²	VC2	VC3	VC4	C1	C2	C3	C4	M1	M2	M3	M4	F1	F2
B2-20	0.13	0.51	1.10	1.73	5.43	8.74	20.18	25.96	28.54	6.91	0.55	0.10	—	—
B2-7				0.03	0.19	0.26	1.10	3.08	35.42	39.69	10.19	6.06	1.81	1.25
B2-9					0.02	0.15	1.01	3.58	26.60	36.70	16.61	10.18	2.13	1.46
B2-1		0.12	0.16	0.18	0.42	0.68	1.97	4.64	24.92	36.92	17.90	7.71	1.42	0.96
B2-16				0.13	0.36	0.59	1.85	3.18	16.33	36.04	24.48	13.60	2.07	1.00
B1-15											0.11	3.06	8.19	24.00
B1-16									0.09	0.27	2.07	15.69	21.66	27.73
AB1-1d1										0.05	0.25	4.03	11.12	22.39
AB1-1d2										0.14	0.35	4.95	11.37	24.70
D5-10							0.09	0.13	0.11	0.51	1.87	14.52	21.12	29.94
D5-15							0.11	0.08	0.17	0.56	1.38	19.57	30.10	26.09
D5-16									0.02	0.21	0.40	16.67	18.67	26.92
D3-15														0.20
D3-19												0.01	0.16	2.51
AD2-1e								0.04	1.12	3.08	8.91	31.53	25.73	18.19
AD2-1f								0.03	0.49	10.06	30.60	36.75	10.93	6.50
R5-23								0.18	0.56	2.90	5.96	17.15	18.71	24.47
R5-25										0.35	1.41	12.19	19.32	31.81
R5-21								0.11	0.27	1.13	3.51	23.62	35.25	25.67
R5-34										0.01	0.10	2.78	11.80	31.18
R5-27											0.03	0.15	0.54	3.96
R5-29												0.01	0.20	1.59
AR1-4c							0.07	0.35	12.53	40.17	16.96	11.56	3.36	3.67
AR1-5c										0.18	0.27	1.17	3.99	15.57
AR1-14										0.12	0.49	3.46	7.06	12.79
AR1-15a										0.07	0.40	4.41	10.75	19.69
AR1-18										0.53	0.72	2.92	8.93	22.64
AR1-22c											0.35	1.78	5.85	21.64

¹Light and heavy mineral fractions were separated by floatation in bromoform (specific gravity = 2.89): light minerals <2.89< heavy minerals.

Sample	Percent of Total Sediment Weight (Light Mineral Fraction Only) ¹ in Each Quarter Phi Size Class							Weight of Light Mineral Fraction (grams)	Weight of Heavy Mineral Fraction (grams)
	F3	F4	VF1	VF2	VF3	VF4	PAN ³		
B2-20	—	—	—	—	—	—	0.12	24.533	0.775
B2-7	0.82	0.11	—	—	—	—	0.14	18.875	4.940
B2-9	1.13	0.18	0.04	—	—	—	0.20	17.135	9.161
B2-1	1.26	0.41	0.16	0.11	0.06	—	0.09	20.207	13.977
B2-16	0.32	0.01	—	—	—	—	0.03	20.242	10.212
B1-15	48.77	13.03	2.35	0.46	—	—	0.04	21.000	0.557
B1-16	27.29	4.40	0.68	—	—	—	0.12	19.445	0.096
AB1-1d1	43.73	10.45	2.58	1.48	1.36	1.02	1.41	17.538	0
AB1-1d2	41.25	10.04	2.44	1.37	1.12	0.84	1.42	19.305	0
D5-10	28.32	2.68	0.37	0.29	0.04	—	0.02	16.372	1.017
D5-15	19.84	1.71	0.21	0.10	0.04	—	0.05	12.934	0.237
D5-16	29.98	4.67	0.75	0.18	0.13	0.42	0.98	11.309	0.842
D3-15	25.14	54.29	16.16	3.85	0.30	—	0.06	16.349	0.119
D3-19	30.00	44.60	17.47	4.87	0.35	—	0.02	16.514	0.287
AD2-1e	8.71	0.90	1.22	0.20	0.17	—	0.18	24.431	0
AD2-1f	3.01	0.80	0.27	0.18	0.17	—	0.21	18.263	0
R5-23	23.71	2.33	1.14	1.27	0.83	0.38	0.40	15.736	0.006
R5-25	28.71	2.58	1.08	1.31	0.75	—	0.51	8.879	0.002
R5-21	9.45	0.30	0.09	0.17	0.14	—	0.29	15.971	0.001
R5-34	45.61	4.55	1.33	1.26	0.78	0.31	0.30	14.158	0.009
R5-27	31.09	27.97	14.90	10.67	6.46	2.38	1.84	14.760	0.013
R5-29	22.70	28.95	18.45	14.08	8.49	3.14	2.39	14.464	0.021
AR1-4c	5.28	3.07	1.29	0.78	0.49	0.26	0.13	18.833	0
AR1-5c	59.73	14.42	2.17	1.03	0.63	0.37	0.46	25.283	0
AR1-14	23.72	16.70	10.04	9.27	8.64	4.27	3.46	20.706	0
AR1-15a	30.69	13.33	5.97	5.35	4.62	2.39	2.33	16.554	0
AR1-18	37.78	13.06	4.75	3.04	2.23	1.30	2.10	15.974	0
AR1-22c	39.76	16.83	6.10	3.53	1.91	0.87	1.37	19.858	0

²See Table 2 for explanation of size class codes.³PAN is the finer than 4 phi size fraction.

APPENDIX C

GRAIN SIZE STATISTICS, POWERS ROUNDNESS AND
GRAIN SUBPOPULATIONS: RESULTS OF ANALYSES

Grain Size Distribution Statistics ¹									
Sample	GRAPHICAL ²				MOMENT ³				Powers
	M _G	S _{IG}	SK _{IG}	K _G	M	S	SK	K	Roundness ⁴
B2-20	0.83	0.35	-0.26	0.86	0.81	0.41	+0.04	11.41	VA-A-SA-SR
B2-7	1.34	0.26	+0.28	1.39	1.36	0.34	+1.96	15.31	A-SA-SR-R
B2-9	1.43	0.30	+0.25	1.09	1.43	0.37	+1.89	13.46	A-SA-SR-R
B2-1	1.38	0.32	+0.10	1.29	1.39	0.40	+0.80	10.21	A-SA-SR-R
B2-16	1.47	0.30	+0.04	1.09	1.45	0.34	-0.09	6.64	A-SA-SR-R
B1-15	2.54	0.24	-0.13	1.24	2.55	0.26	-0.17	5.06	A-SA-SR-R
B1-16	2.31	0.30	-0.13	0.83	2.32	0.32	+0.15	4.89	A-SA-SR-R
AB1-1d1	2.53	0.33	0.00	1.59	2.58	0.41	+1.80	9.53	VA-A-SA
AB1-1d2	2.52	0.32	-0.01	1.47	2.56	0.41	+1.74	9.66	VA-A-SA
D5-10	2.31	0.29	-0.19	0.87	2.32	0.32	-0.42	4.54	A-SA-SR-R
D5-15	2.24	0.28	+0.07	0.82	2.24	0.31	-0.02	5.32	A-SA-SR-R
D5-16	2.34	0.31	-0.09	0.87	2.37	0.39	+1.70	10.98	A-SA-SR-R
D3-15	2.87	0.17	+0.14	1.10	2.87	0.20	+0.92	6.05	A-SA-SR
D3-19	2.85	0.21	+0.13	1.02	2.86	0.23	+0.46	3.75	A-SA-SR
AD2-1e	2.09	0.33	+0.13	1.03	2.08	0.37	+0.77	6.65	SA-SR-R-WR
AD2-1f	1.83	0.30	+0.20	1.27	1.85	0.35	+1.82	11.30	SA-SR-R-WR
R5-23	2.26	0.38	-0.12	0.95	2.28	0.45	+0.63	5.84	A-SA-SR-R
R5-25	2.35	0.30	-0.09	1.02	2.38	0.36	+1.25	8.98	A-SA-SR-R
R5-21	2.16	0.26	+0.02	0.96	2.16	0.31	+1.20	12.46	A-SA-SR-R
R5-34	2.49	0.24	-0.12	1.26	2.51	0.30	+1.53	11.00	A-SA-SR-R
R5-27	2.96	0.37	+0.34	1.01	2.96	0.41	+1.20	5.09	VA-A-SA
R5-29	3.05	0.37	+0.30	0.92	3.06	0.42	+1.11	4.62	VA-A-SA
AR1-4c	1.64	0.47	+0.57	1.35	1.67	0.54	+1.61	5.60	A-SA
AR1-5c	2.62	0.20	-0.03	1.50	2.63	0.28	+1.51	14.13	A-SA
AR1-14	2.89	0.57	+0.22	1.01	2.89	0.59	+0.63	3.33	A-SA
AR1-15a	2.69	0.50	+0.25	1.34	2.71	0.53	+1.13	4.73	A-SA
AR1-18	2.61	0.39	+0.18	1.64	2.65	0.47	+1.43	7.13	VA-A-SA
AR1-22c	2.65	0.34	+0.18	1.46	2.68	0.41	+1.53	7.83	A-SA

Sample	Subpopulation Proportions ⁵ (weight percent)			Comments
	CT	IT	FT	
B2-20	3	61,26	1	Has 2 IT populations
B2-7	5	75	20	
B2-9	0	95	5	Population proportions uncertain
B2-1	8	87	5	
B2-16	6	90	4	Good linear segments
B1-15	0	100	0	Approx. lognormal; May have 2 IT populations
B1-16	0	100	0	Approx. lognormal; May have 2 IT populations; I:S joint distribution bimodal
AB1-1d1	0	92	8	Pan=1.41%; Grains faceted
AB1-1d2	0	93	7	Pan=1.42%; Grains faceted
D5-10	3	96	1	May have 2 IT populations; I:S joint distribution bimodal
D5-15	2	97	1	
D5-16	0	97	3	May have 2 IT populations; I:S joint distribution bimodal
D3-15	0	80,20	0	Approx. lognormal; Has 2 IT populations
D3-19	0	100	0	Approx. lognormal
AD2-1e	0	97	3	Grains frosted
AD2-1f	0	78,20	2	Grains frosted; Has 2 IT populations
R5-23	0	94	6	Good linear segments; May have 2 IT populations; I:S joint distribution bimodal
R5-25	0	94	6	Good linear segments
R5-21	5	94	1	Good linear segments
R5-34	0	92	8	Good linear segments
R5-27	1	63	36	Pan=1.84%; Population proportions uncertain
R5-29	2	50	48	Pan=2.39%; Population proportions uncertain
AR1-4c	0	54	46	Grains faceted; population proportions uncertain; I:S joint distribution bimodal
AR1-5c	5	90	5	Grains faceted
AR1-14	0	64	36	Pan=3.46%; Grains faceted; Approx. lognormal
AR1-15a	0	66	34	Pan=2.33%; Grains faceted
AR1-18	0	86	14	Pan=2.10%; Grains faceted
AR1-22c	0	86	14	Pan=1.37%; Grains faceted

¹Based on sieve data (I grain dimensions) with a $\frac{1}{4}$ phi interval.

²Graphical Size Statistics (see Table 3).

³Moment Size Statistics for Grouped Data (see Table 3).
Note: midpoint of pan fraction assumed to be 4.5 phi.

⁴Based on an examination of loose grains using a binocular microscope and the Powers (1953) visual comparator: VA=very angular, A=angular, SA=subangular, SR=subrounded, R=rounded, and WR=well rounded. Roundness range and mode (underlined) are shown.

⁵Estimate of grain subpopulation proportions based on the location of major slope breaks (i.e., boundaries of quasi-linear segments) on cumulative grain size curves: CT=coarse tail subpopulation, IT=intertail subpopulation and FT=fine tail subpopulation. Truncated lognormal subpopulations are assumed. The CT, IT and FT populations may correspond to the C, A and B populations, respectively, of Moss (1962 and 1963), Visher (1969) and Middleton (1976).

APPENDIX D

RAW DATA FOR THE COMBINED SIEVE AND ROLLER
MICROMETER ANALYSES

EXPLANATORY NOTES

- 1) All tabulated values are in units of weight percent.
- 2) Underlined values are the cumulative weight percent for all S fractions to the right of and including the one indicated.
- 3) See Table 2 for explanation of size class codes.
- 4) I is the intermediate grain dimension (measured with sieves) and S is the smallest grain dimension (measured with the roller micrometer).

Samples	I=VC1					
	S					
	VC1	VC2	VC3	VC4	C1	C2
B2-20	<u>0.13</u>					
B2-7	<u>0</u>					
B2-9	<u>0</u>					
B2-1	<u>0</u>					
B2-16	<u>0</u>					
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=VC2					
	S					
	VC2	VC3	VC4	C1	C2	C3
B2-20	0.04	0.18	0.22	0.02	<u>0.04</u>	
B2-7	<u>0</u>					
B2-9	<u>0</u>					
B2-1	<u>0.12</u>					
B2-16	<u>0</u>					
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I = VC3					
	S					
	VC3	VC4	C1	C2	C3	C4
B2-20	0.06	0.47	0.38	0.11	0.04	<u>0.03</u>
B2-7	<u>0</u>					
B2-9	<u>0</u>					
B2-1	<u>0.16</u>					
B2-16	<u>0</u>					
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=VC4					
	S					
	VC4	C1	C2	C3	C4	M1
B2-20	0.18	0.84	0.46	0.11	0.04	<u>0.03</u>
B2-7	<u>0.03</u>					
B2-9	<u>0</u>					
B2-1	<u>0.18</u>					
B2-16	<u>0.13</u>					
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=C1					
	S					
	C1	C2	C3	C4	M1	M2
B2-20	0.82	2.24	1.55	0.38	0.29	<u>0.06</u>
B2-7	<u>0.19</u>					
B2-9	<u>0.02</u>					
B2-1	<u>0.42</u>					
B2-16	<u>0.36</u>					
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=C2					
	S					
	C2	C3	C4	M1	M2	M3
B2-20	1.37	4.32	1.55	1.18	0.19	<u>0.08</u>
B2-7	<u>0.26</u>					
B2-9	<u>0.15</u>					
B2-1	0.03	0.32	0.16	<u>0.13</u>		
B2-16	0.04	0.32	0.11	<u>0.10</u>		
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0</u>					
D5-15	<u>0</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=C3					
	S					
	C3	C4	M1	M2	M3	M4
B2-20	4.28	7.14	6.50	1.71	0.39	<u>0.09</u>
B2-7	0.12	0.38	0.38	0.17	<u>0.01</u>	
B2-9	0.11	0.35	0.37	0.14	<u>0.02</u>	
B2-1	0.26	0.73	0.69	0.20	<u>0.04</u>	
B2-16	0.38	0.64	0.60	0.17	<u>0.01</u>	
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0.09</u>					
D5-15	<u>0.11</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0</u>					
AD2-1f	<u>0</u>					
R5-23	<u>0</u>					
R5-25	<u>0</u>					
R5-21	<u>0</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0.07</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=C4					
	S					
	C4	M1	M2	M3	M4	F1
B2-20	6.98	10.72	6.47	1.52	0.20	<u>0.04</u>
B2-7	0.56	1.14	1.20	0.11	<u>0.02</u>	
B2-9	0.72	1.42	1.14	0.23	<u>0.01</u>	
B2-1	0.93	1.73	1.50	0.40	0.05	<u>0.01</u>
B2-16	0.78	1.25	1.00	0.09	<u>0.02</u>	
B1-15	<u>0</u>					
B1-16	<u>0</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0.13</u>					
D5-15	<u>0.08</u>					
D5-16	<u>0</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	<u>0.04</u>					
AD2-1f	<u>0.03</u>					
R5-23	<u>0.18</u>					
R5-25	<u>0</u>					
R5-21	<u>0.11</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	<u>0.35</u>					
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=M1					
	S					
	M1	M2	M3	M4	F1	F2
B2-20	7.37	14.43	5.82	0.77	0.12	<u>0.02</u>
B2-7	2.92	24.71	6.10	1.51	0.13	<u>0.02</u>
B2-9	2.96	13.56	8.71	1.30	0.10	<u>0.01</u>
B2-1	2.65	12.08	8.61	1.44	0.14	<u>0.01</u>
B2-16	1.89	10.78	2.70	0.82	0.09	<u>0.01</u>
B1-15	<u>0</u>					
B1-16	<u>0.09</u>					
AB1-1d1	<u>0</u>					
AB1-1d2	<u>0</u>					
D5-10	<u>0.11</u>					
D5-15	<u>0.17</u>					
D5-16	<u>0.02</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	0.04	0.54	0.44	0.10	<u>0.02</u>	
AD2-1f	<u>0.49</u>					
R5-23	<u>0.56</u>					
R5-25	<u>0</u>					
R5-21	<u>0.27</u>					
R5-34	<u>0</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	0.88	6.36	4.65	0.58	<u>0.05</u>	
AR1-5c	<u>0</u>					
AR1-14	<u>0</u>					
AR1-15a	<u>0</u>					
AR1-18	<u>0</u>					
AR1-22c	<u>0</u>					

Samples	I=M2					
	S					
	M2	M3	M4	F1	F2	F3
B2-20	1.65	4.04	1.08	0.14	<u>0.03</u>	
B2-7	15.06	16.30	7.43	0.79	<u>0.05</u>	
B2-9	4.41	21.97	0.21	0.98	<u>0.06</u>	
B2-1	3.88	21.64	10.18	1.20	<u>0.05</u>	
B2-16	2.76	21.44	10.36	1.31	0.07	<u>0</u>
B1-15	<u>0</u>					
B1-16	<u>0.27</u>					
AB1-1d1	<u>0.05</u>					
AB1-1d2	<u>0.14</u>					
D5-10	<u>0.51</u>					
D5-15	<u>0.56</u>					
D5-16	<u>0.21</u>					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	0.17	1.76	1.03	0.14	<u>0.01</u>	
AD2-1f	0.33	5.15	3.76	0.78	<u>0.04</u>	
R5-23	0.25	1.59	0.88	0.18	<u>0.06</u>	
R5-25	<u>0.35</u>					
R5-21	0.04	0.60	0.40	<u>0.11</u>		
R5-34	<u>0.01</u>					
R5-27	<u>0</u>					
R5-29	<u>0</u>					
AR1-4c	4.58	25.14	9.36	0.99	<u>0.05</u>	
AR1-5c	<u>0.18</u>					
AR1-14	<u>0.12</u>					
AR1-15a	<u>0.07</u>					
AR1-18	<u>0.53</u>					
AR1-22c	<u>0</u>					

Samples	I=M3					
	S					
	M3	M4	F1	F2	F3	F4
B2-20	0.18	0.30	0.08	<u>0.01</u>		
B2-7	2.47	5.94	1.66	0.13	<u>0.02</u>	
B2-9	3.10	10.30	3.02	0.18	<u>0.02</u>	
B2-1	3.15	11.34	3.31	0.16	<u>0.01</u>	
B2-16	4.10	15.70	4.39	0.24	<u>0.02</u>	
B1-15	<u>0.11</u>					
B1-16	0.09	1.00	0.82	0.13	<u>0.06</u>	
AB1-1d1	<u>0.25</u>					
AB1-1d2	<u>0.35</u>					
D5-10	0.15	1.06	0.66	<u>0.04</u>		
D5-15	0.12	0.77	0.43	<u>0.08</u>		
D5-16	0.40					
D3-15	<u>0</u>					
D3-19	<u>0</u>					
AD2-1e	0.88	5.87	1.85	<u>0.32</u>		
AD2-1f	3.29	18.60	7.93	0.74	<u>0.06</u>	
R5-23	0.78	3.40	1.51	0.29	<u>0.10</u>	
R5-25	0.17	0.87	0.36	<u>0.07</u>		
R5-21	0.31	2.09	0.92	0.19	<u>0.06</u>	
R5-34	<u>0.10</u>					
R5-27	<u>0.03</u>					
R5-29	<u>0</u>					
AR1-4c	3.84	10.65	2.32	0.15	<u>0.02</u>	
AR1-5c	<u>0.27</u>					
AR1-14	0.04	0.31	0.13	<u>0.06</u>		
AR1-15a	<u>0.40</u>					
AR1-18	0.08	0.48	0.19	<u>0.02</u>		
AR1-22c	<u>0.35</u>					

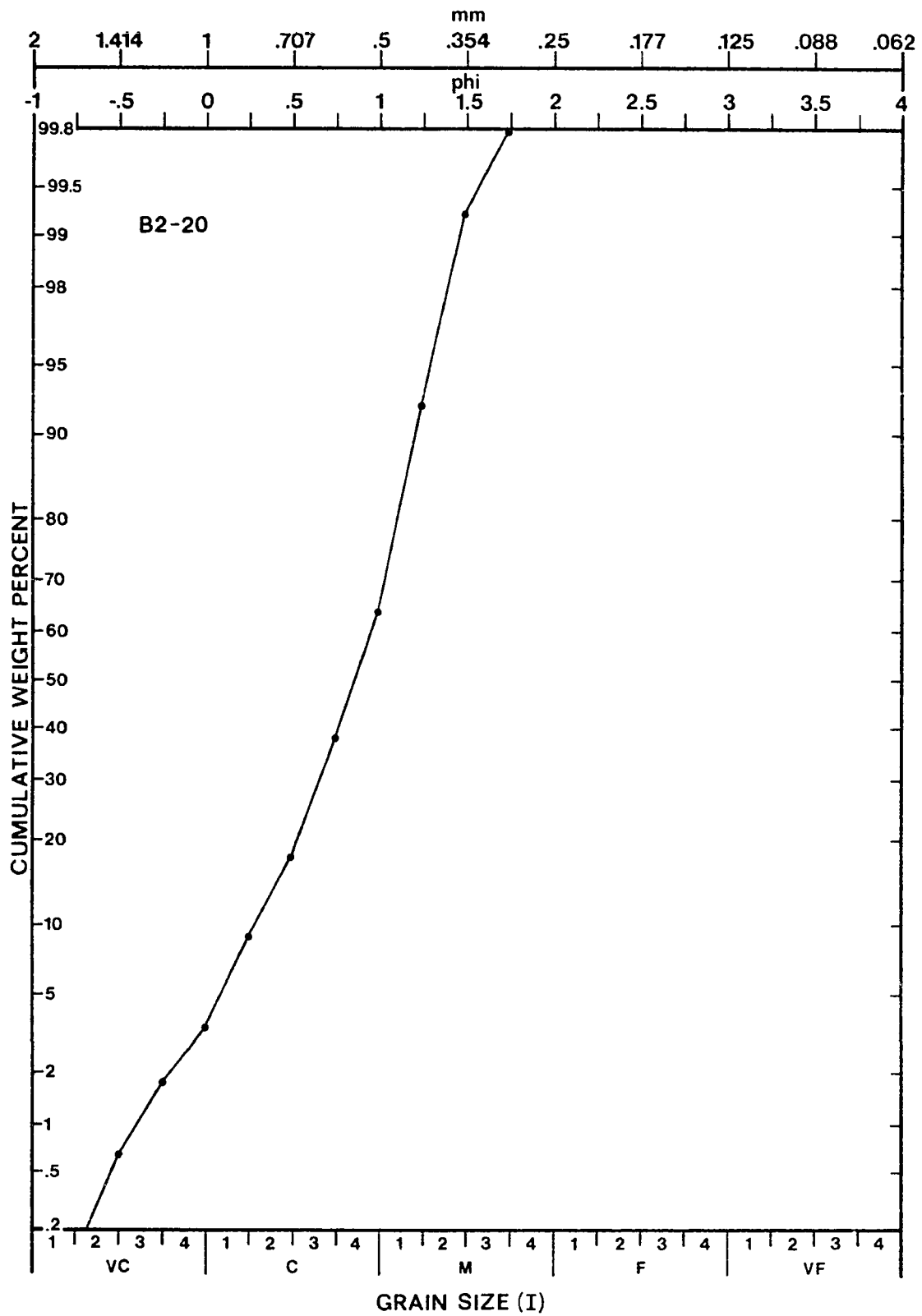
Samples	I=M4					
	S					
	M4	F1	F2	F3	F4	<F4
B2-20	<u>0.10</u>					
B2-7	1.65	3.63	0.69	<u>0.13</u>		
B2-9	2.98	6.05	1.00	<u>0.18</u>		
B2-1	2.53	4.58	0.55	<u>0.08</u>		
B2-16	5.20	7.32	1.02	<u>0.16</u>		
B1-15	0.10	1.47	1.00	0.43	<u>0.10</u>	
B1-16	1.57	9.52	3.26	1.21	<u>0.15</u>	
AB1-1d1	0.29	2.76	0.94	<u>0.10</u>		
AB1-1d2	0.40	3.43	1.06	<u>0.12</u>		
D5-10	1.69	9.90	2.25	0.64	<u>0.09</u>	
D5-15	1.76	11.18	5.06	1.30	<u>0.32</u>	
D5-16	0.73	11.22	3.44	1.13	<u>0.11</u>	
D3-15	<u>0</u>					
D3-19	<u>0.01</u>					
AD2-1e	7.67	17.24	5.68	0.86	<u>0.13</u>	
AD2-1f	8.72	22.72	4.74	<u>0.55</u>		
R5-23	2.93	9.98	3.44	0.61	<u>0.22</u>	
R5-25	2.38	7.14	2.40	<u>0.36</u>		
R5-21	2.93	14.53	4.56	1.36	<u>0.26</u>	
R5-34	0.25	1.52	0.82	<u>0.25</u>		
R5-27	<u>0.15</u>					
R5-29	<u>0.01</u>					
AR1-4c	5.19	5.19	1.02	<u>0.17</u>		
AR1-5c	0.28	0.67	0.19	<u>0.06</u>		
AR1-14	0.66	1.90	0.79	<u>0.16</u>		
AR1-15a	0.78	2.38	1.12	<u>0.19</u>		
AR1-18	0.46	1.77	0.59	<u>0.16</u>		
AR1-22c	0.14	1.00	0.50	<u>0.19</u>		

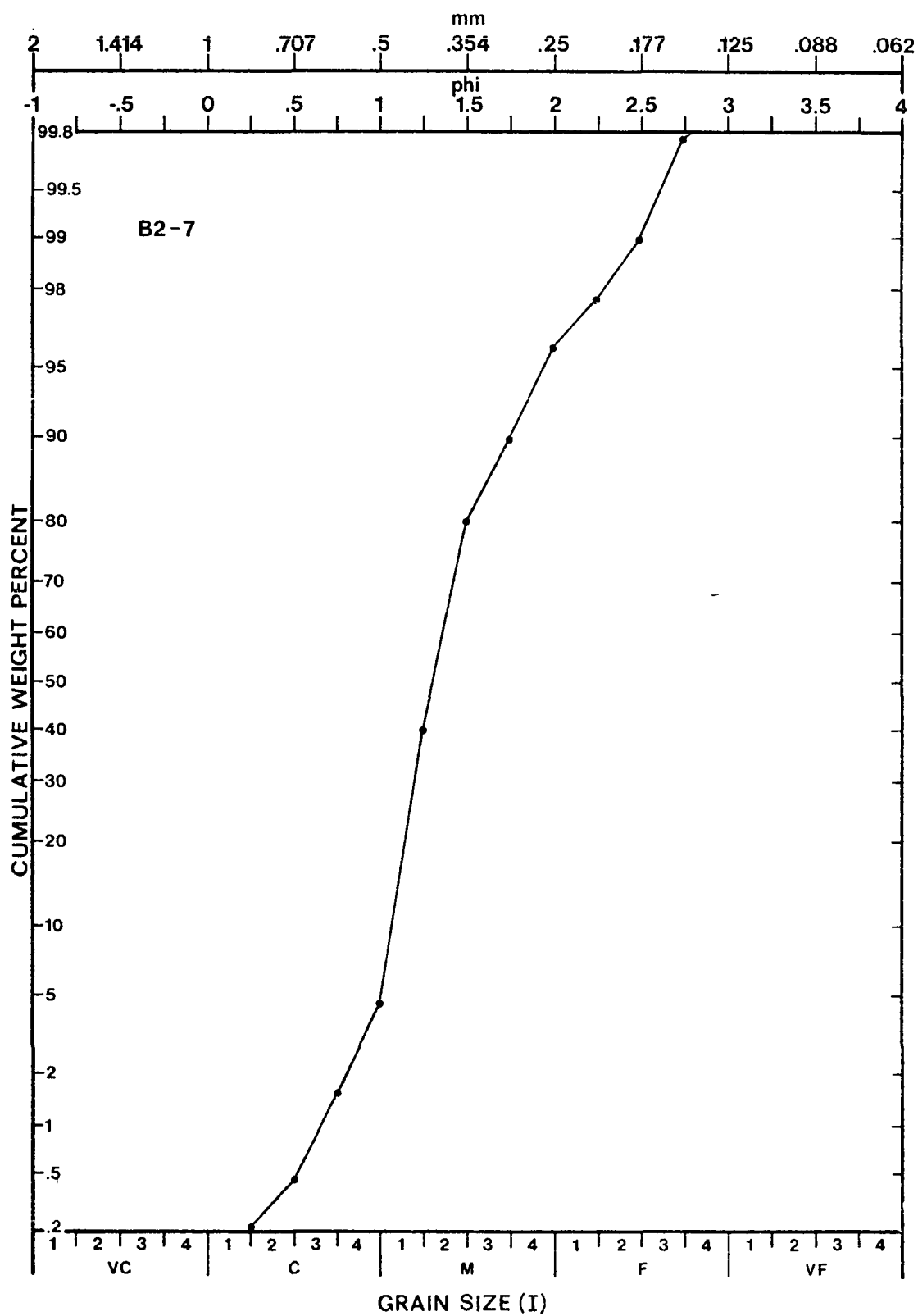
Samples	I=F1					I=F2			
	S					S			
	F1	F2	F3	F4	<F4	F2	F3	F4	<F4
B2-20	<u>0</u>					<u>0</u>			
B2-7	0.91	0.74	<u>0.21</u>			0.89	<u>0.40</u>		
B2-9	1.12	0.81	<u>0.23</u>			1.02	<u>0.49</u>		
B2-1	0.78	0.52	<u>0.15</u>			0.63	<u>0.36</u>		
B2-16	1.24	0.72	<u>0.14</u>			0.78	<u>0.25</u>		
B1-15	2.12	3.89	1.88	<u>0.30</u>		11.59	9.99	2.29	<u>0.10</u>
B1-16	8.68	8.36	3.94	0.55	<u>0.04</u>	16.12	9.70	1.77	<u>0.13</u>
AB1-1d1	4.23	5.93	0.93	<u>0.09</u>		15.73	6.04	<u>0.62</u>	
AB1-1d2	4.02	6.33	0.97	<u>0.08</u>		17.03	6.82	<u>0.84</u>	
D5-10	9.88	7.53	3.33	<u>0.37</u>		16.09	12.09	1.61	<u>0.11</u>
D5-15	10.45	13.07	5.02	1.47	<u>0.07</u>	14.03	9.60	2.32	<u>0.14</u>
D5-16	7.44	7.70	3.14	<u>0.32</u>		15.02	10.39	1.31	<u>0.11</u>
D3-15	<u>0</u>					0.06	<u>0.14</u>		
D3-19	<u>0.16</u>					0.80	1.25	0.42	<u>0.09</u>
AD2-1e	10.95	12.09	2.22	0.47		12.25	4.78	<u>1.17</u>	
AD2-1f	5.69	4.14	0.97	<u>0.15</u>		4.48	1.66	<u>0.43</u>	
R5-23	8.32	7.87	1.78	0.56	<u>0.01</u>	17.32	5.40	1.73	<u>0.03</u>
R5-25	8.10	8.80	1.84	<u>0.53</u>		22.62	6.92	<u>2.24</u>	
R5-21	13.66	17.43	3.13	0.97	<u>0.03</u>	19.28	5.05	1.31	<u>0.06</u>
R5-34	3.57	6.12	1.56	<u>0.57</u>		19.87	8.20	<u>3.06</u>	
R5-27	<u>0.54</u>					1.24	1.14	<u>1.60</u>	
R5-29	<u>0.20</u>					0.44	0.59	<u>0.59</u>	
AR1-4c	1.87	1.15	<u>0.34</u>			2.55	0.78	<u>0.37</u>	
AR1-5c	1.75	1.67	0.45	<u>0.17</u>		8.69	4.45	<u>2.44</u>	
AR1-14	2.68	3.40	0.85	<u>0.15</u>		8.62	3.31	<u>0.85</u>	
AR1-15a	3.73	5.73	1.15	<u>0.18</u>		13.22	5.55	<u>0.92</u>	
AR1-18	2.77	4.83	1.12	<u>0.24</u>		14.65	6.47	<u>1.49</u>	
AR1-22c	1.66	2.65	1.35	<u>0.25</u>		11.89	7.81	<u>1.92</u>	

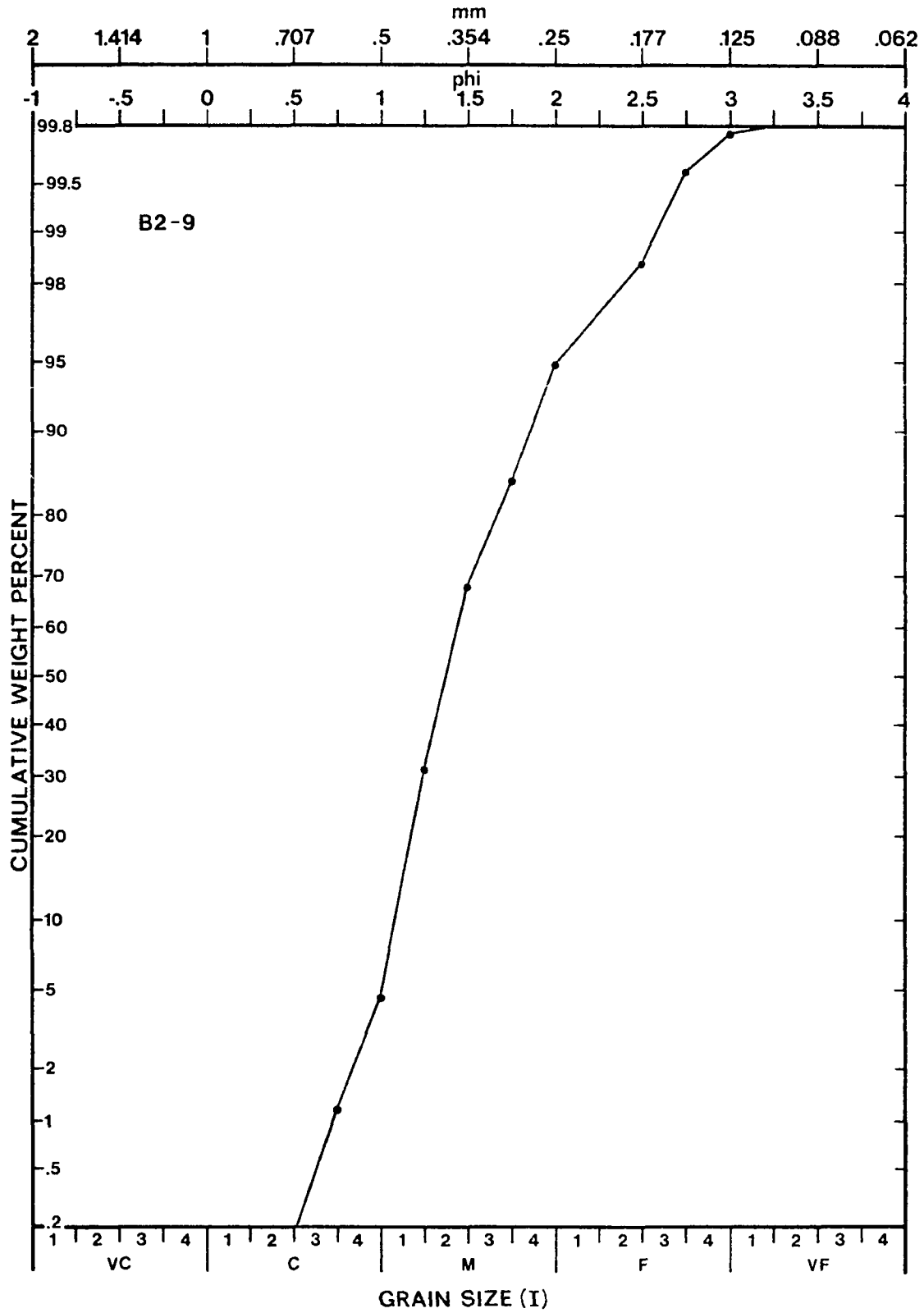
Samples	I=F3			I=F4		I<F4
	S			S		
	F3	F4	<F4	F4	<F4	
B2-20	<u>0</u>			<u>0</u>		0.12
B2-7	<u>0.82</u>			<u>0.11</u>		0.14
B2-9	<u>1.13</u>			<u>0.18</u>		0.24
B2-1	0.85	<u>0.41</u>		<u>0.41</u>		0.42
B2-16	<u>0.32</u>			<u>0.01</u>		0.03
B1-15	31.66	16.00	<u>1.05</u>	11.14	<u>1.89</u>	2.85
B1-16	19.61	7.17	<u>0.50</u>	3.84	<u>0.56</u>	0.81
AB1-1d1	35.44	<u>8.30</u>		<u>10.45</u>		7.86
AB1-1d2	34.42	<u>8.79</u>		<u>10.04</u>		7.20
D5-10	22.29	5.38	<u>0.62</u>	2.26	<u>0.42</u>	0.71
D5-15	14.62	4.86	<u>0.36</u>	1.52	<u>0.19</u>	0.40
D5-16	23.55	5.61	<u>0.82</u>	4.01	<u>0.66</u>	2.48
D3-15	9.13	14.59	<u>1.50</u>	47.63	<u>6.68</u>	20.37
D3-19	12.93	14.86	<u>2.25</u>	34.21	<u>10.41</u>	22.71
AD2-1e	6.71	<u>2.00</u>		<u>0.90</u>		1.77
AD2-1f	2.06	<u>0.96</u>		<u>0.80</u>		0.82
R5-23	9.88	3.59	<u>0.04</u>	2.21	<u>0.13</u>	4.02
R5-25	22.86	<u>5.87</u>		2.58		3.65
R5-21	8.27	1.16	<u>0.05</u>	<u>0.30</u>		0.69
R5-34	31.74	<u>13.89</u>		<u>4.55</u>		3.98
R5-27	13.61	<u>17.42</u>		<u>27.97</u>		36.25
R5-29	11.17	<u>11.51</u>		<u>28.95</u>		46.54
AR1-4c	3.11	<u>2.19</u>		<u>3.07</u>		2.96
AR1-5c	34.68	<u>24.93</u>		<u>14.42</u>		4.66
AR1-14	16.52	<u>7.16</u>		<u>16.70</u>		35.68
AR1-15a	23.08	<u>7.61</u>		<u>13.33</u>		20.65
AR1-18	27.69	<u>10.02</u>		<u>13.06</u>		13.41
AR1-22c	26.47	13.23		16.83		13.78

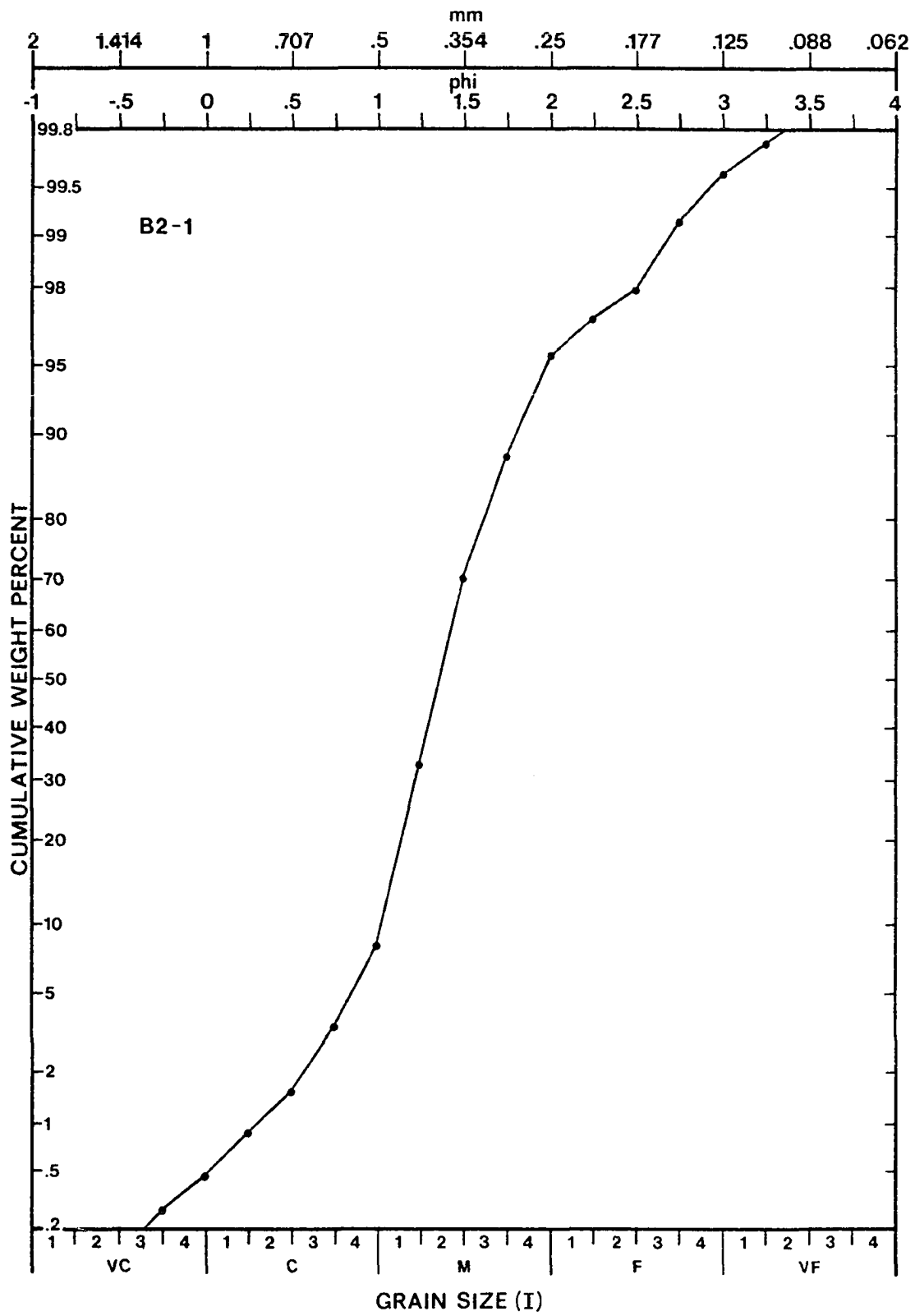
APPENDIX E

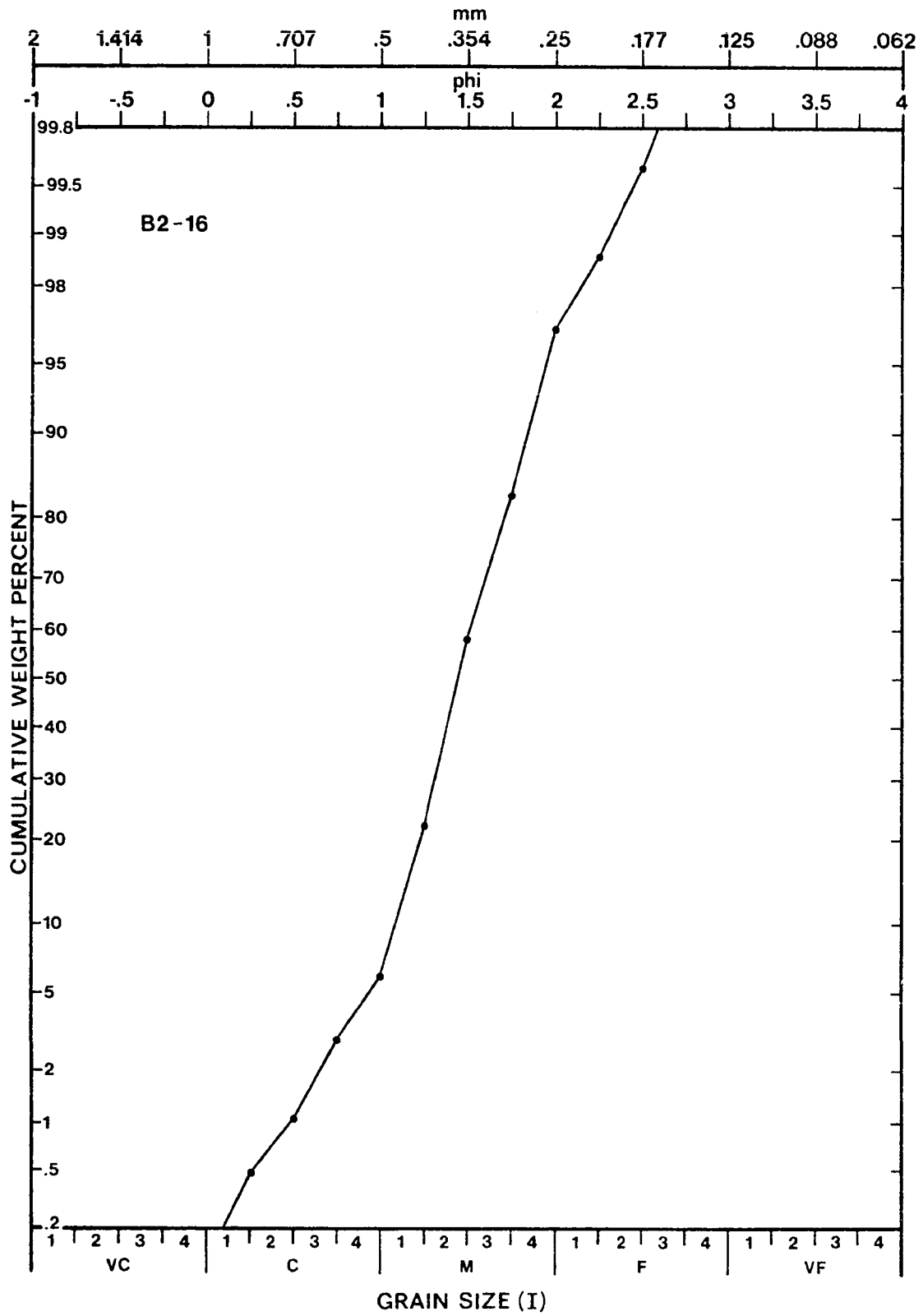
CUMULATIVE GRAIN SIZE CURVES

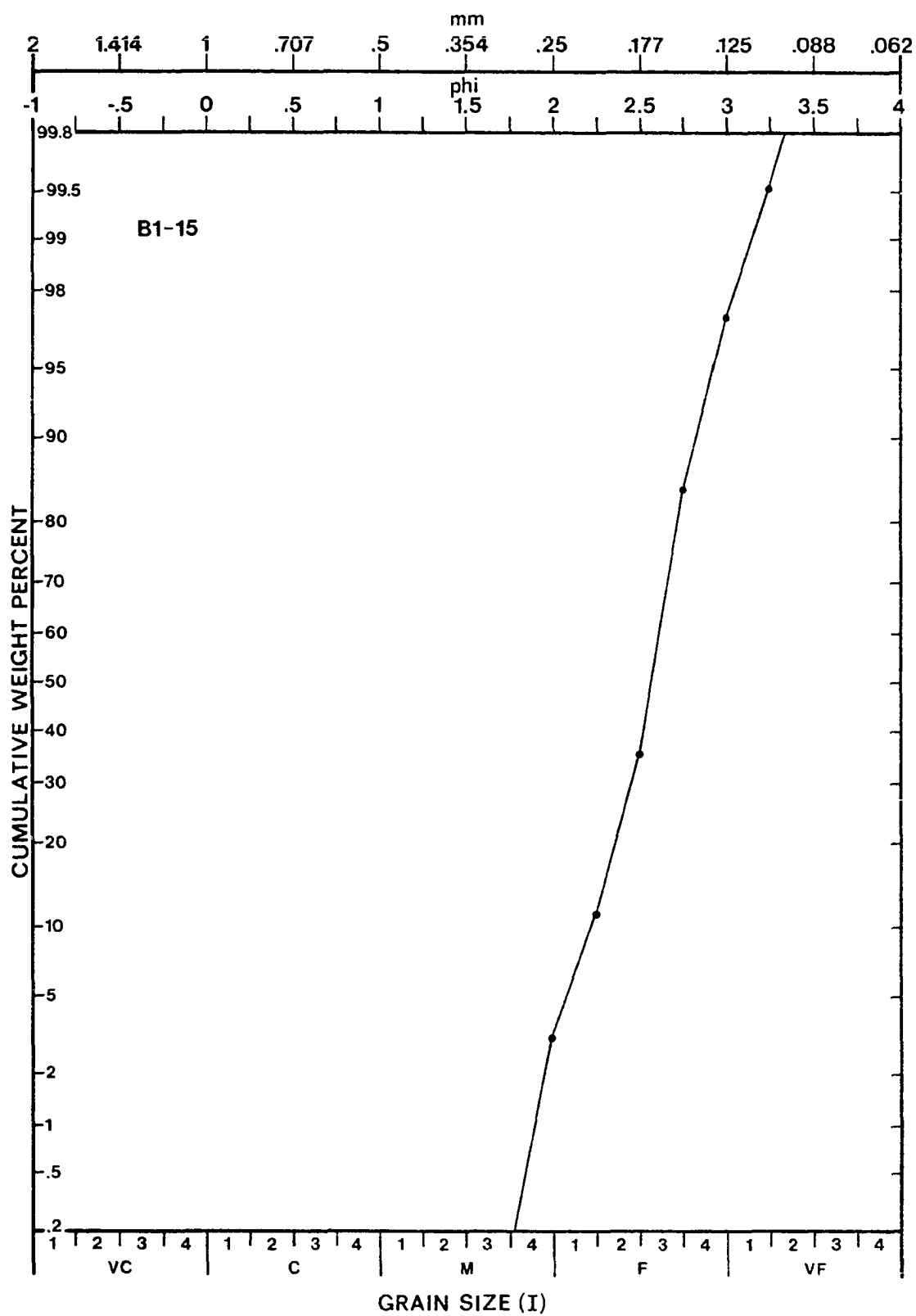


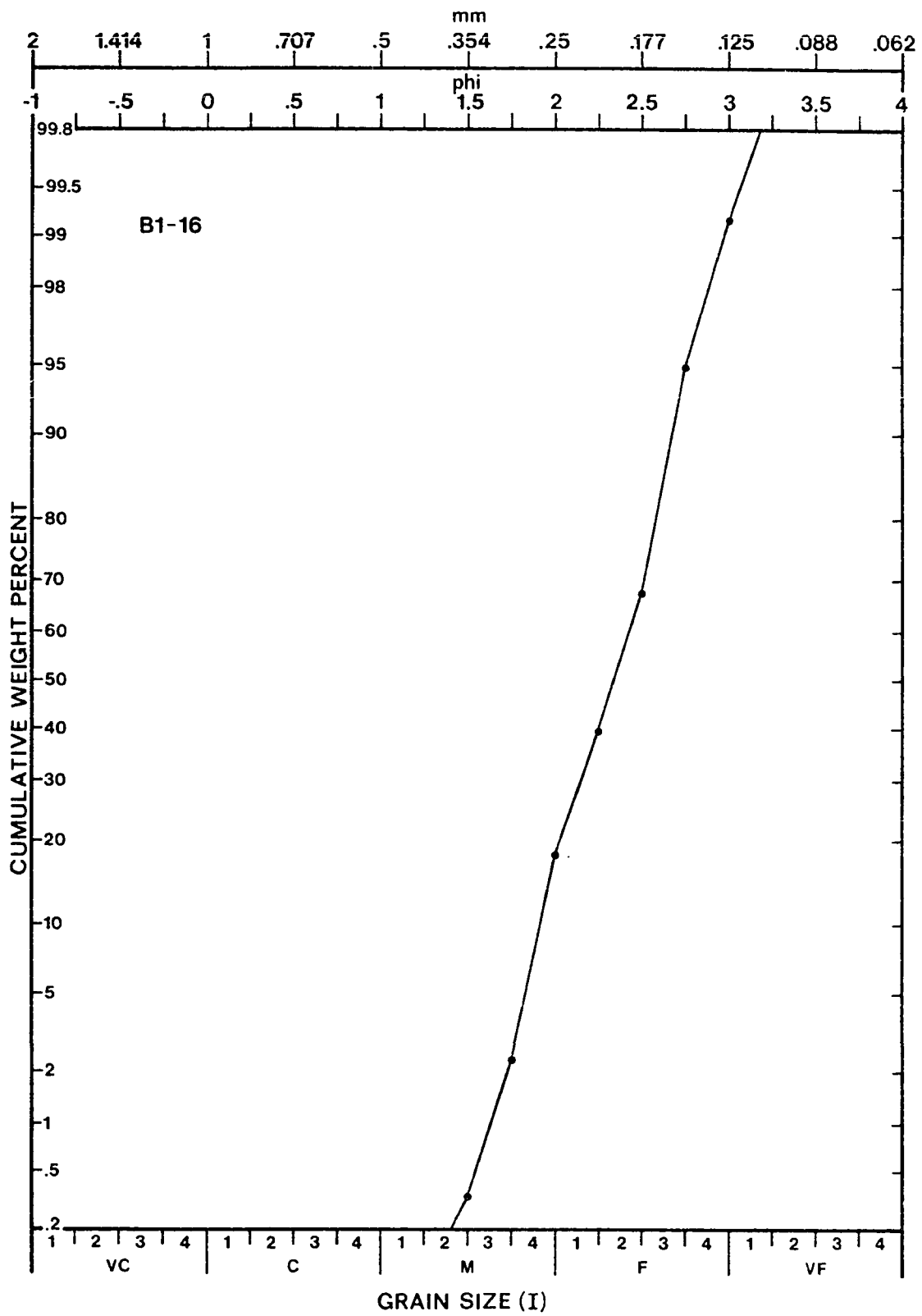


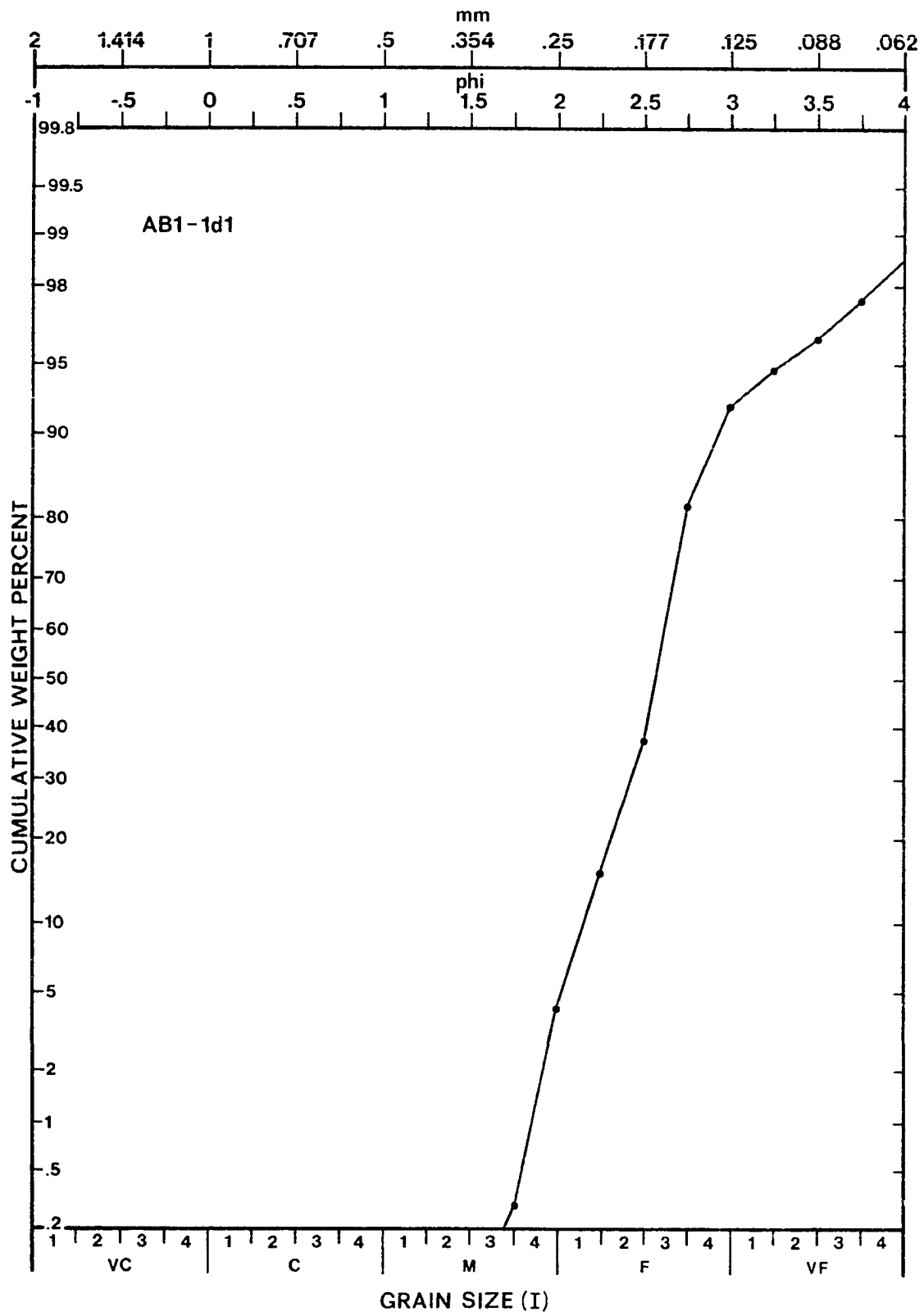


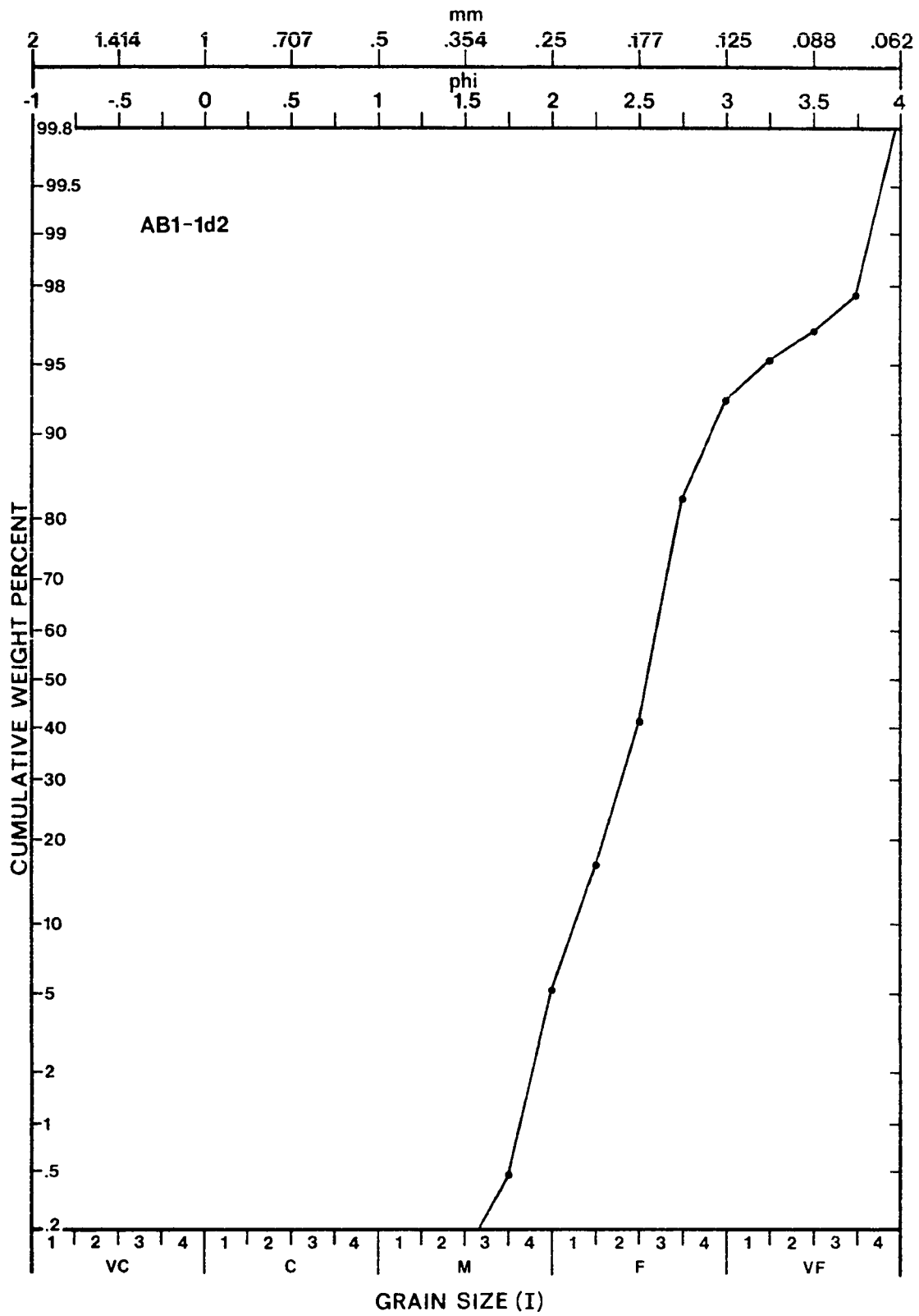


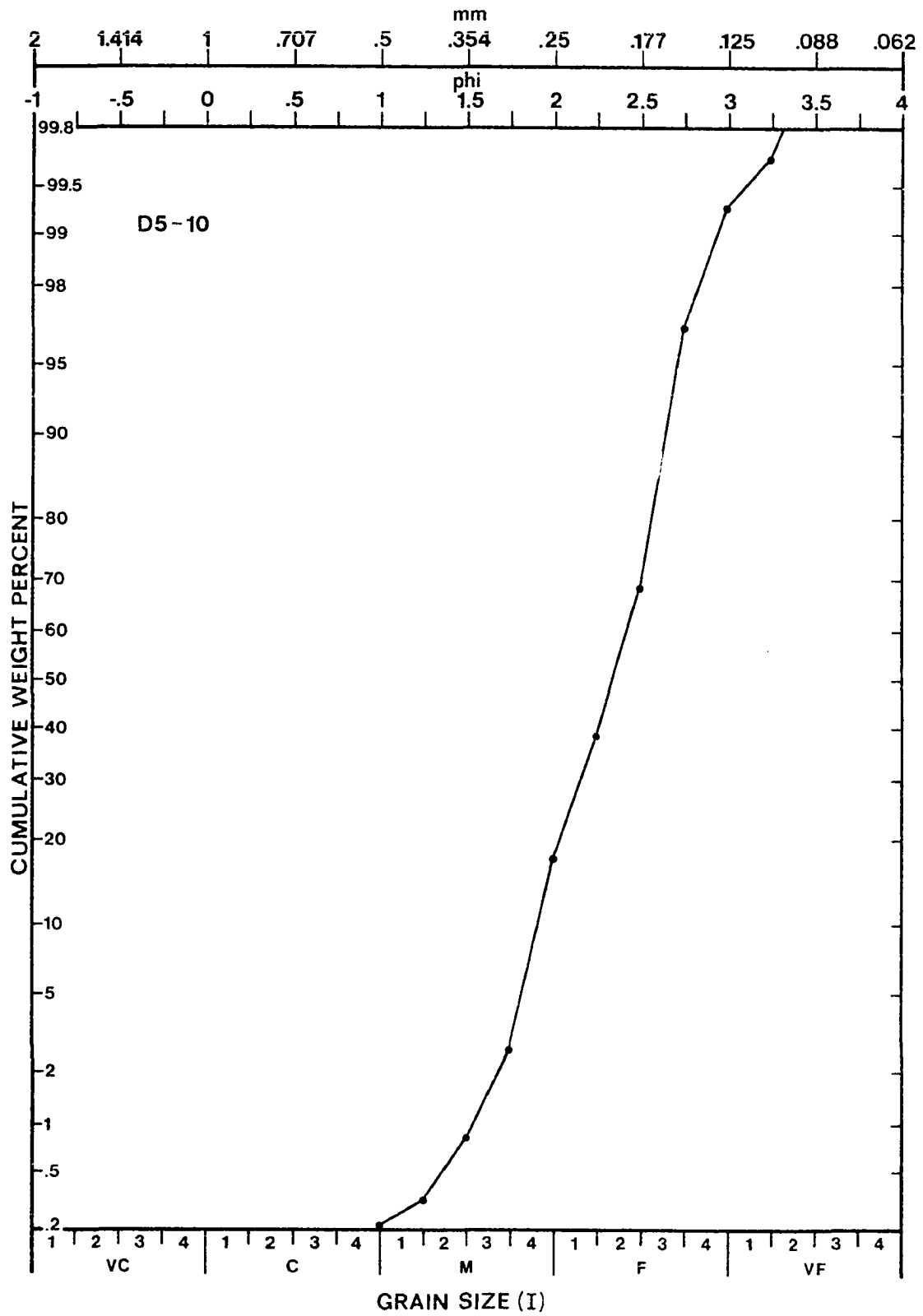


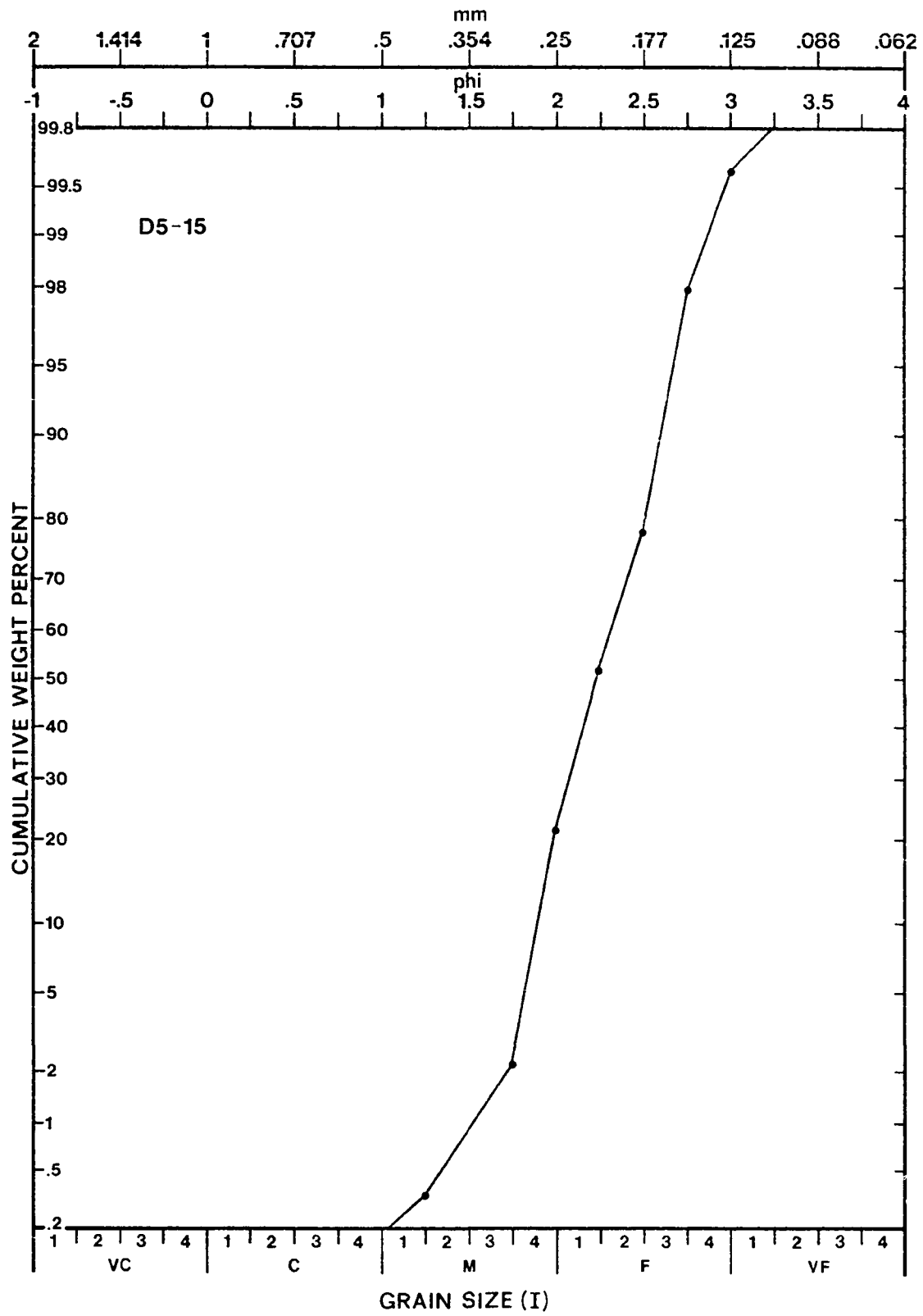


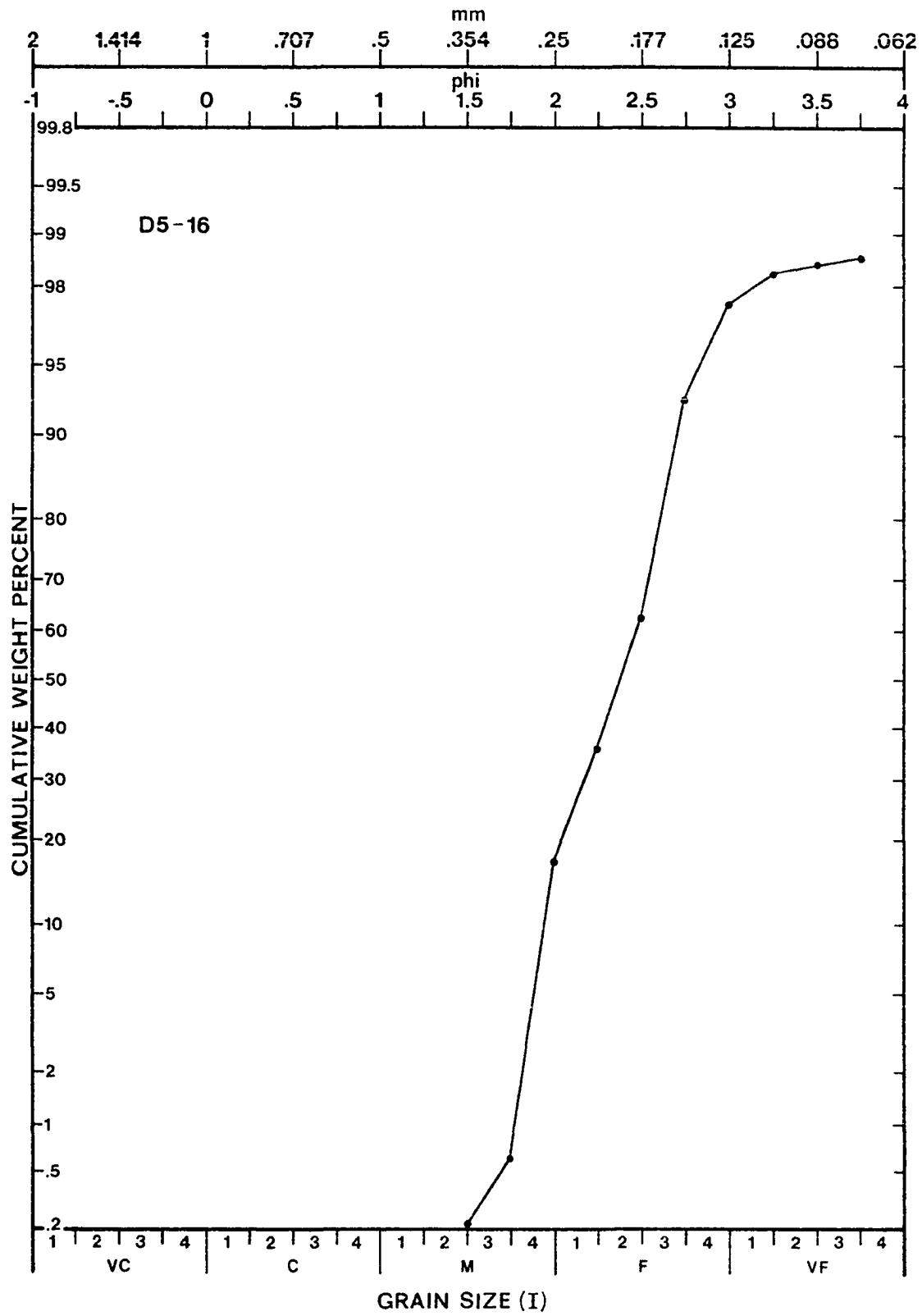


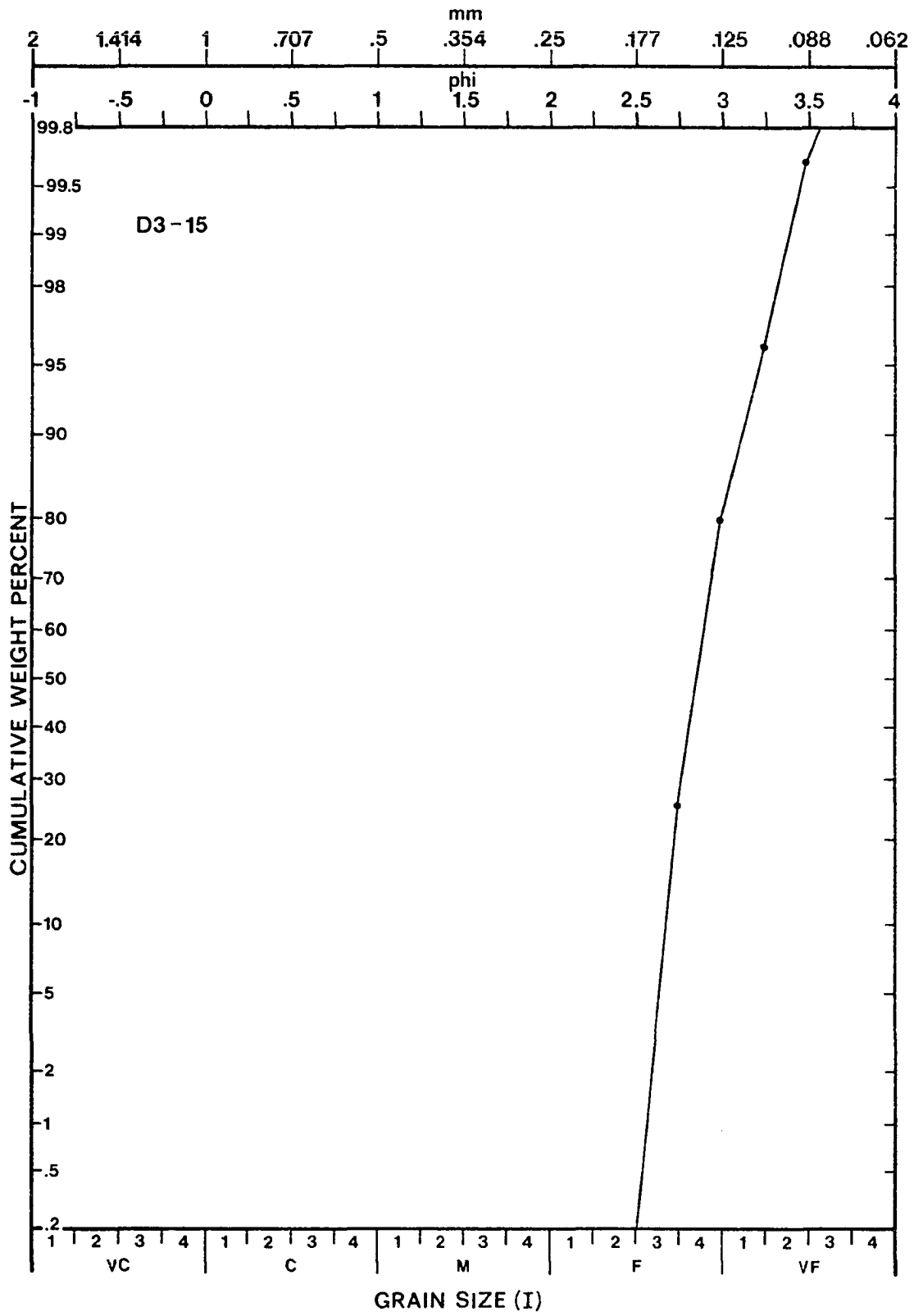


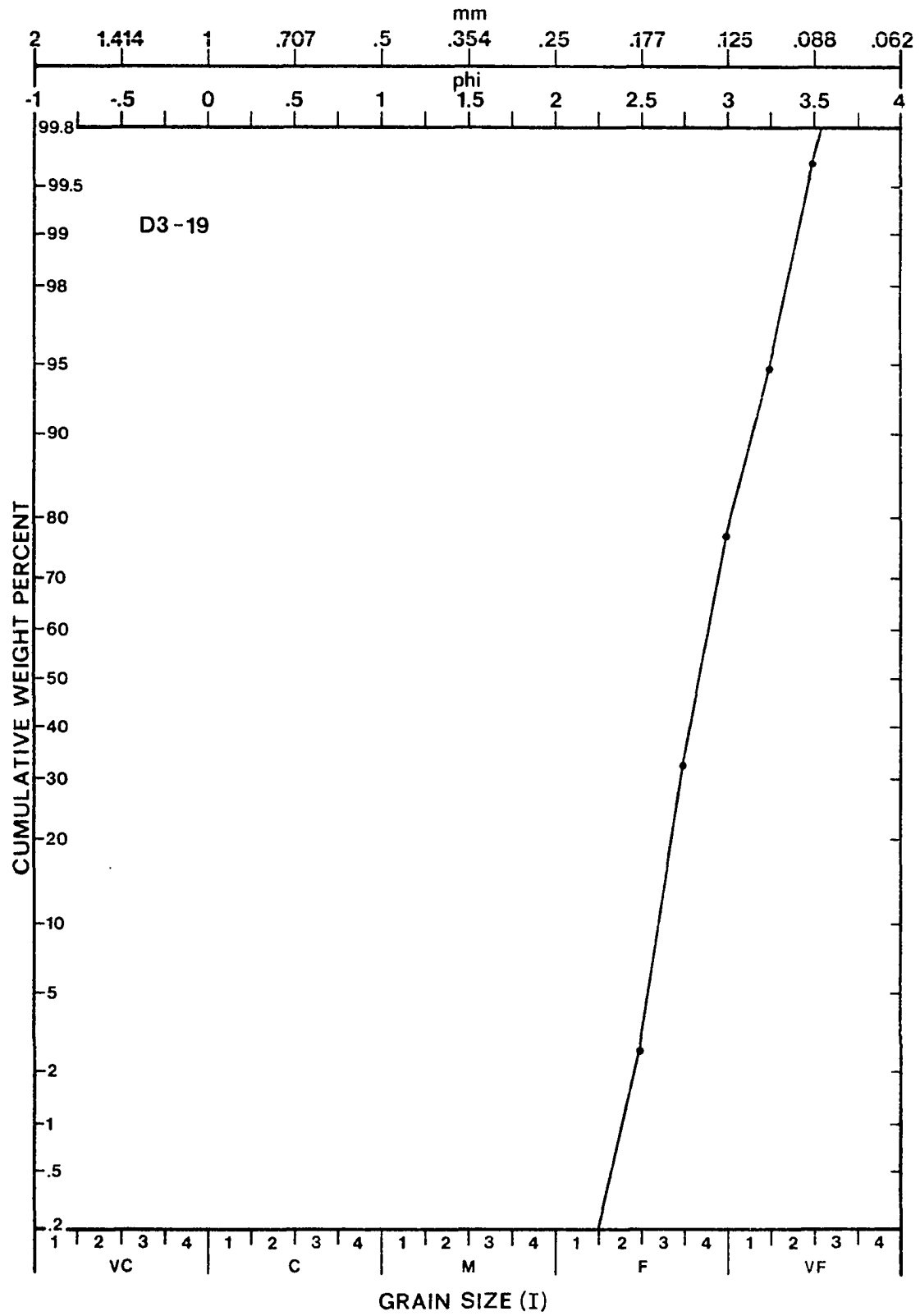


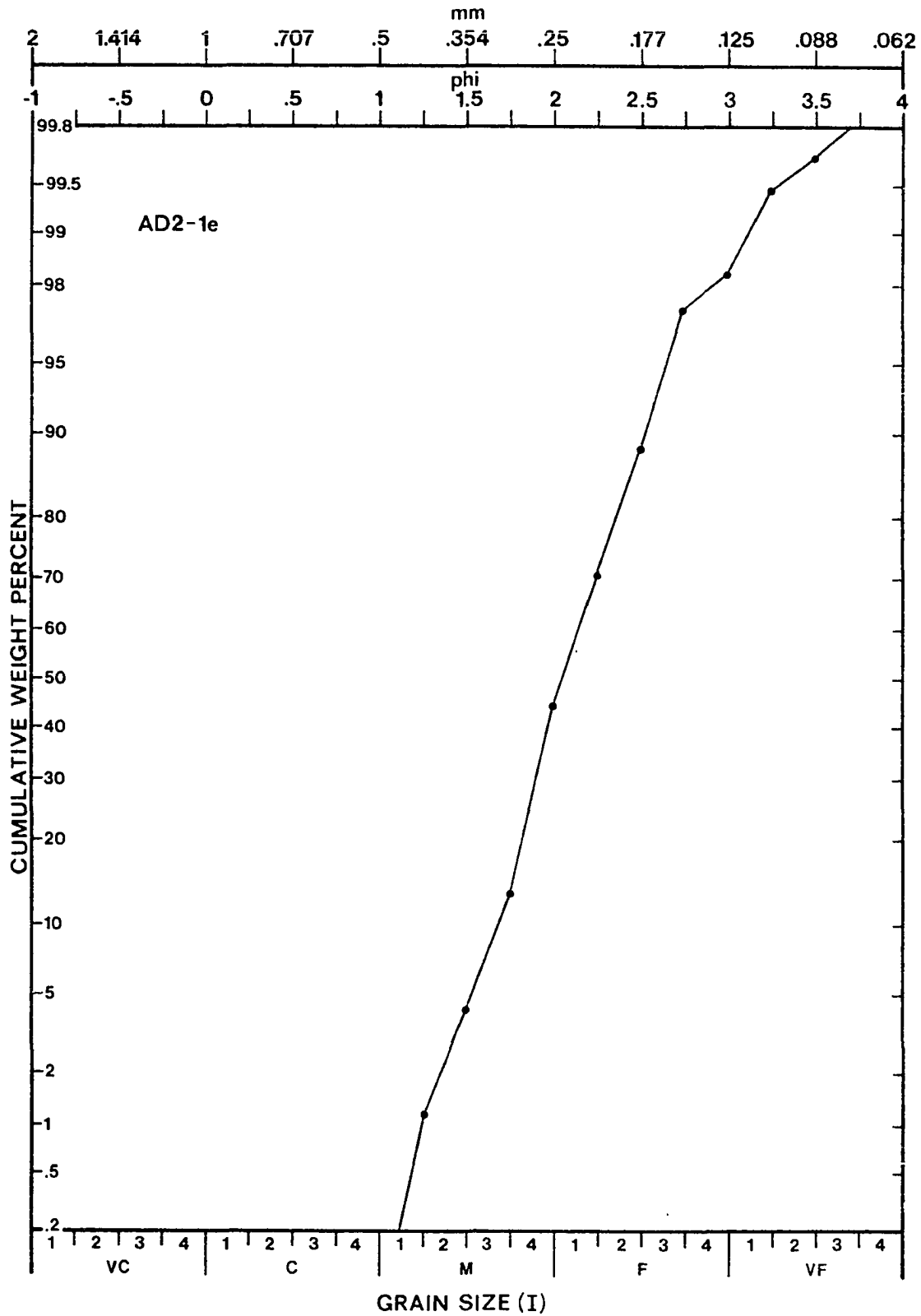


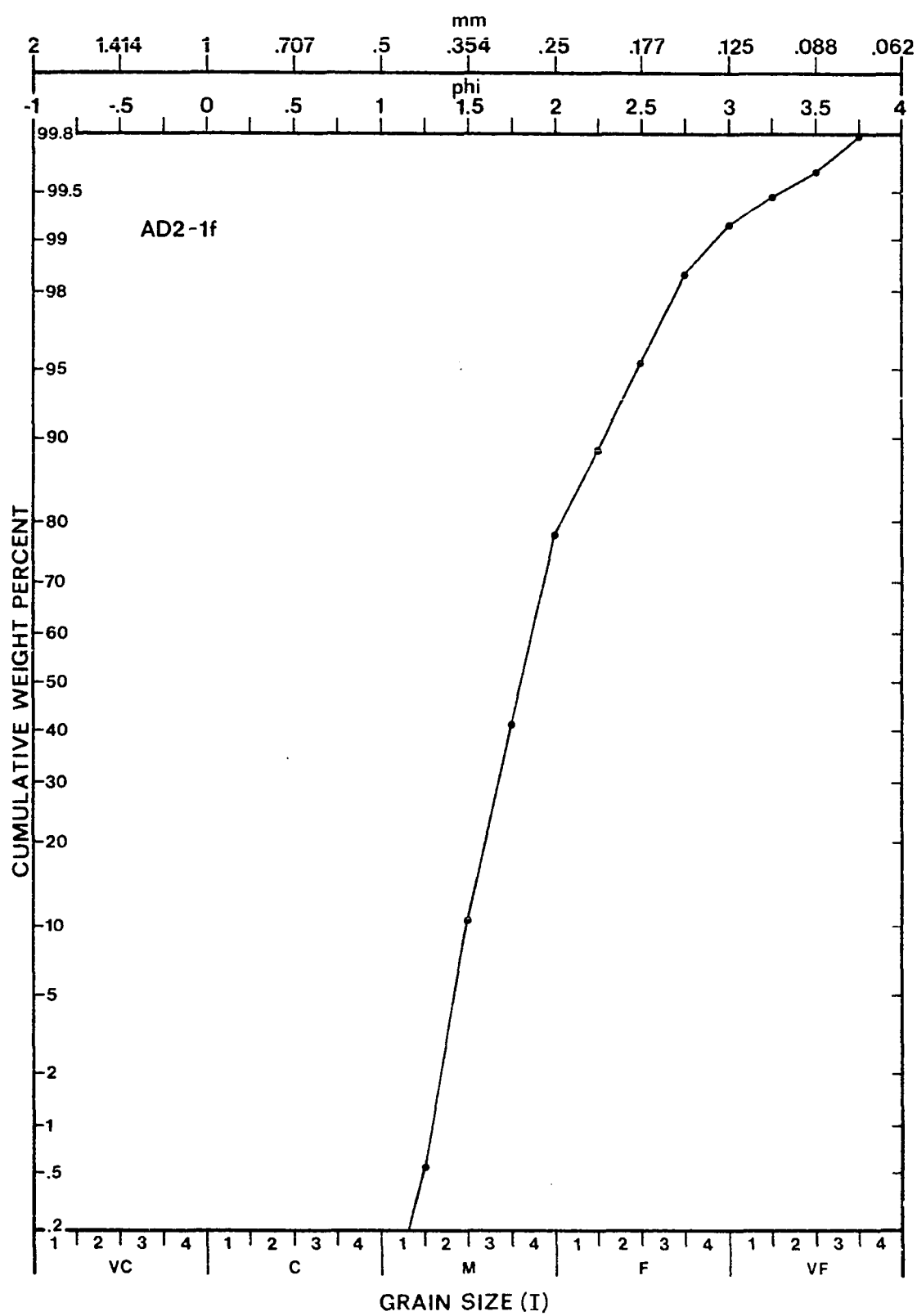


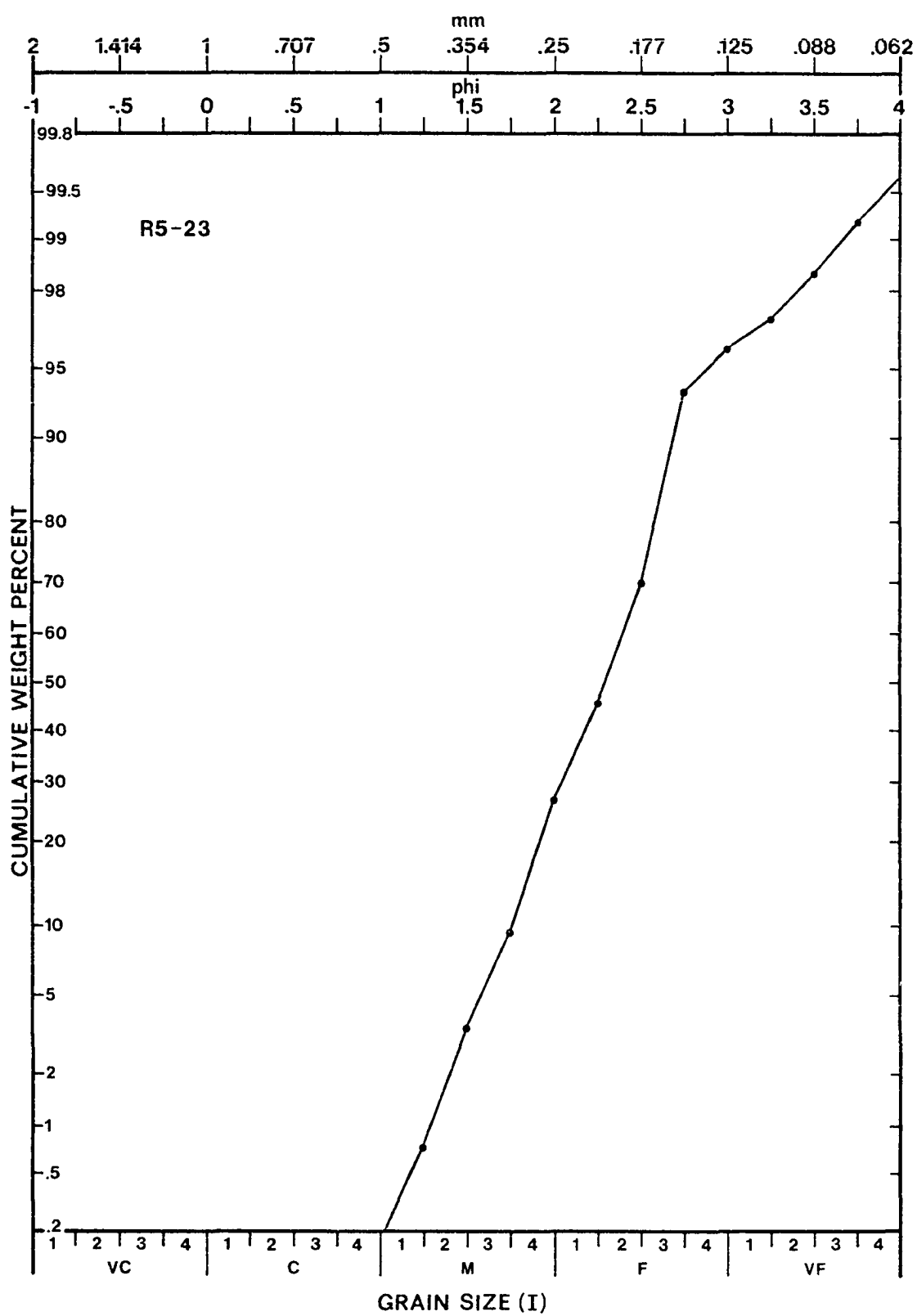


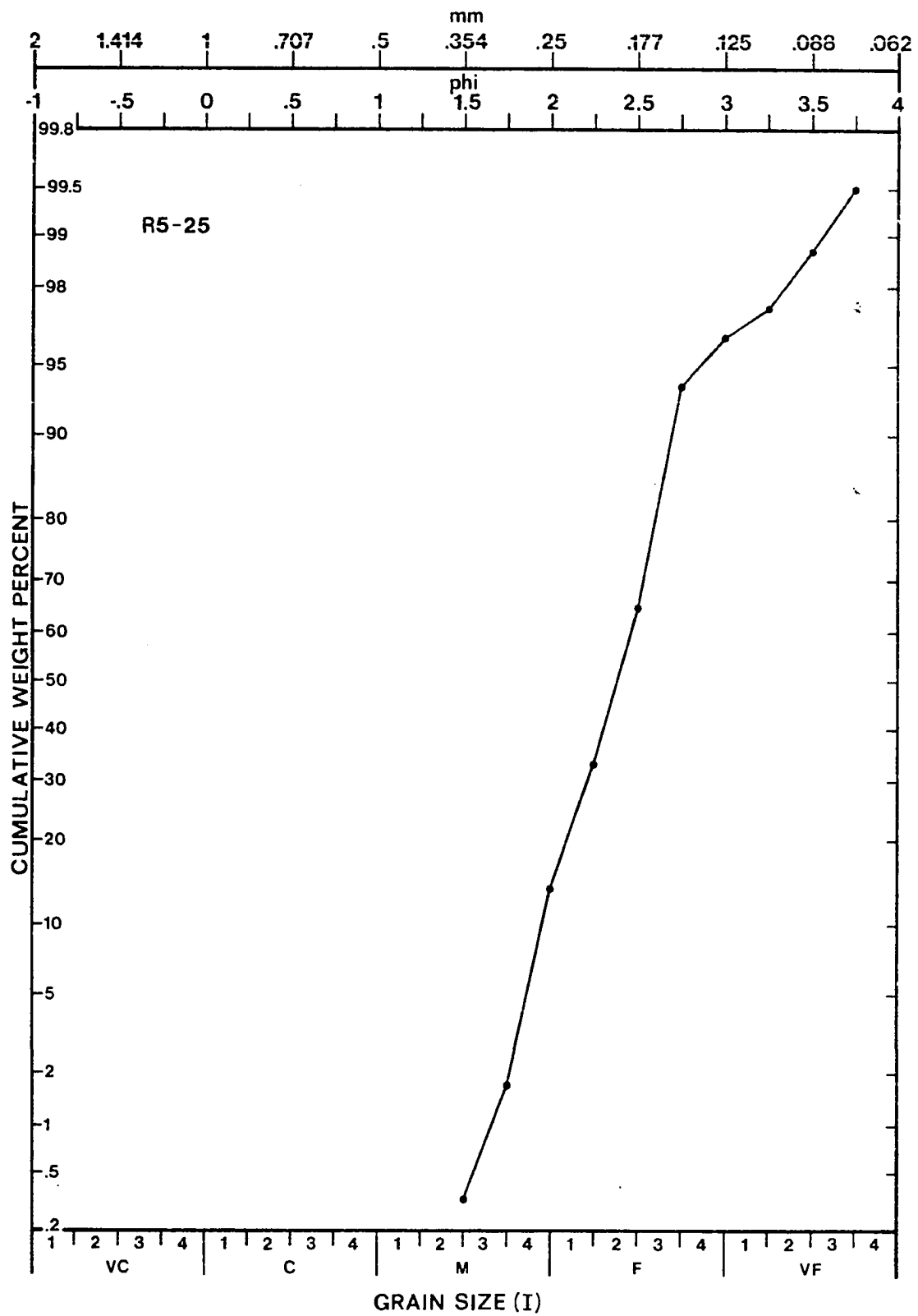


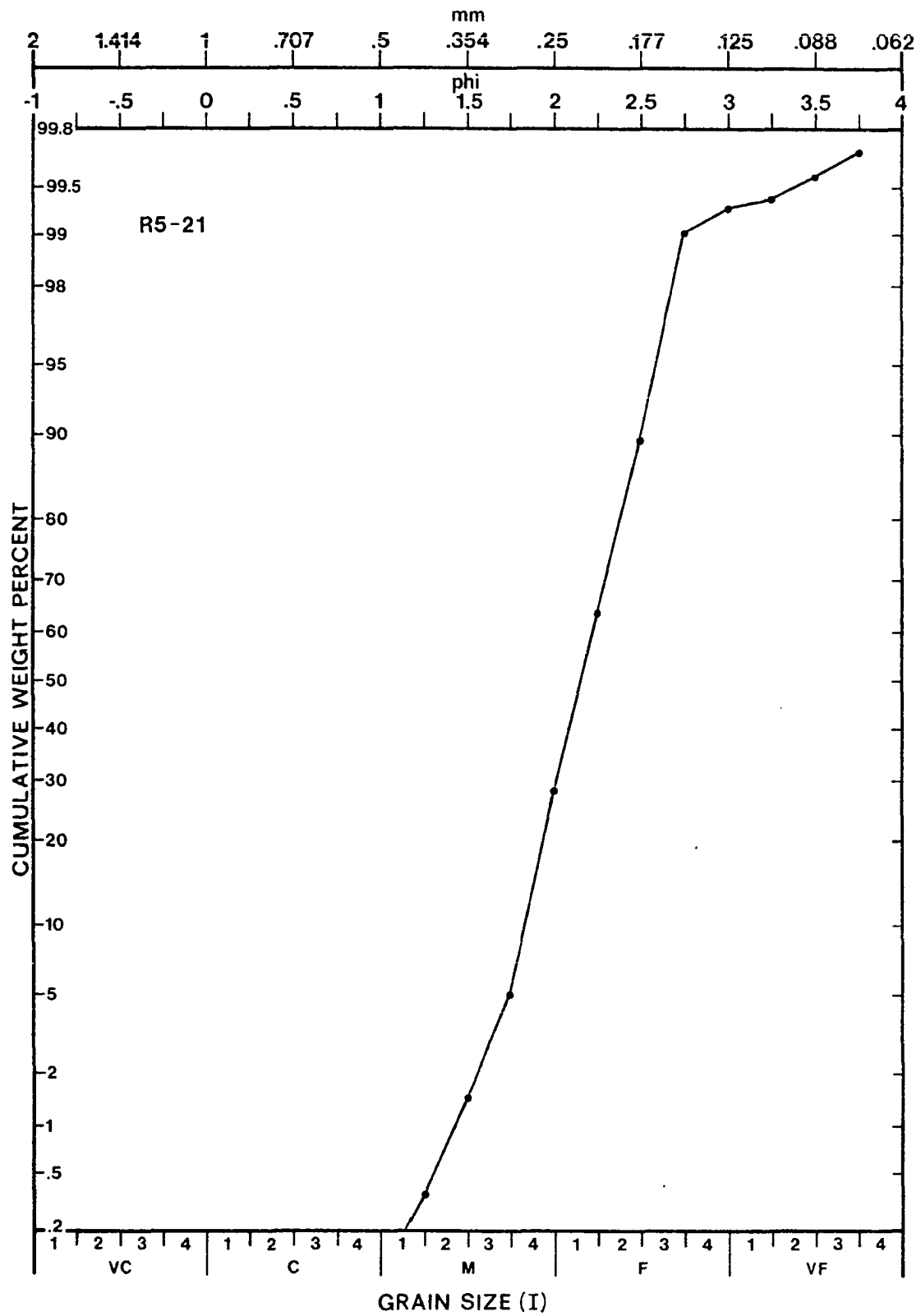


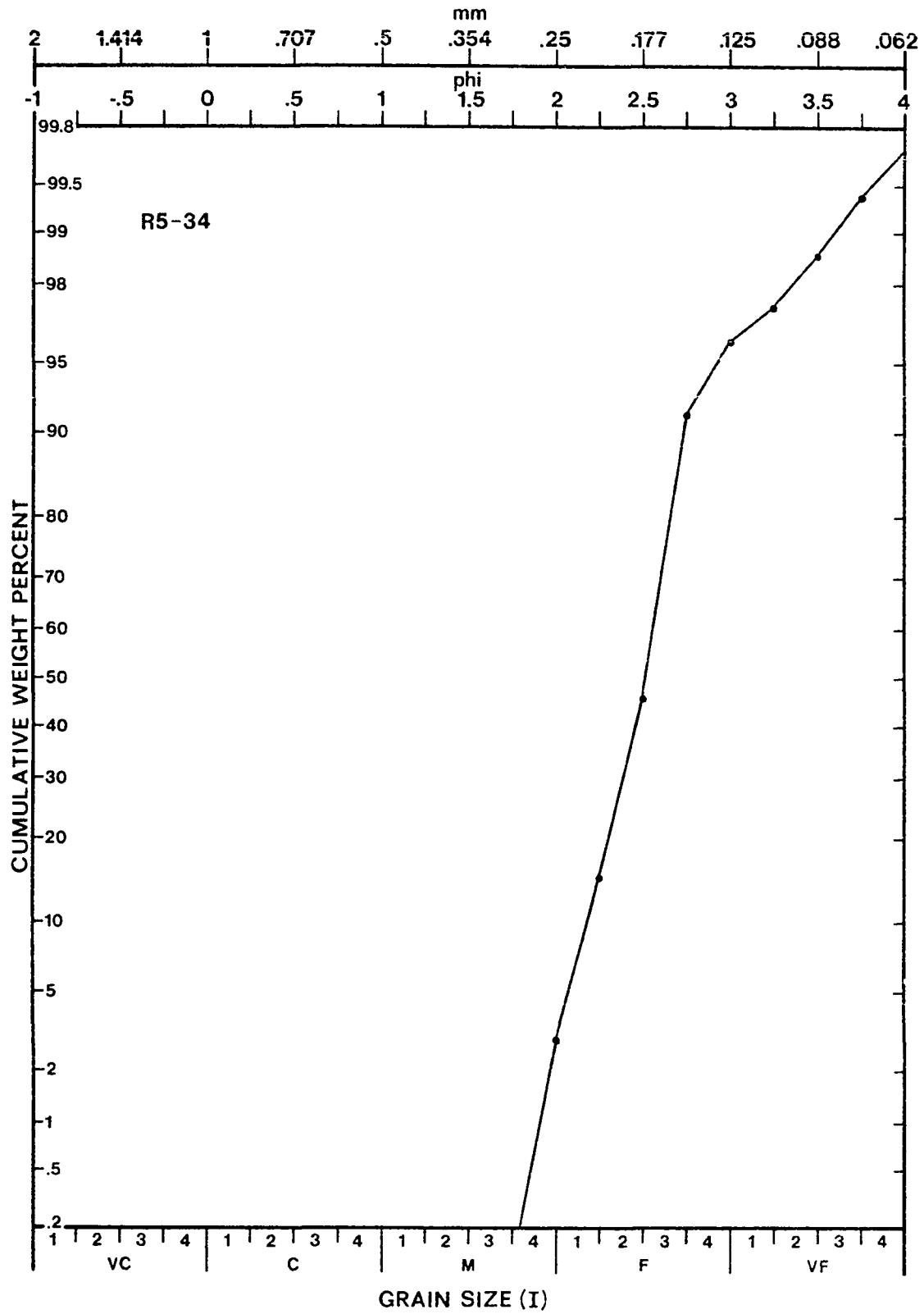


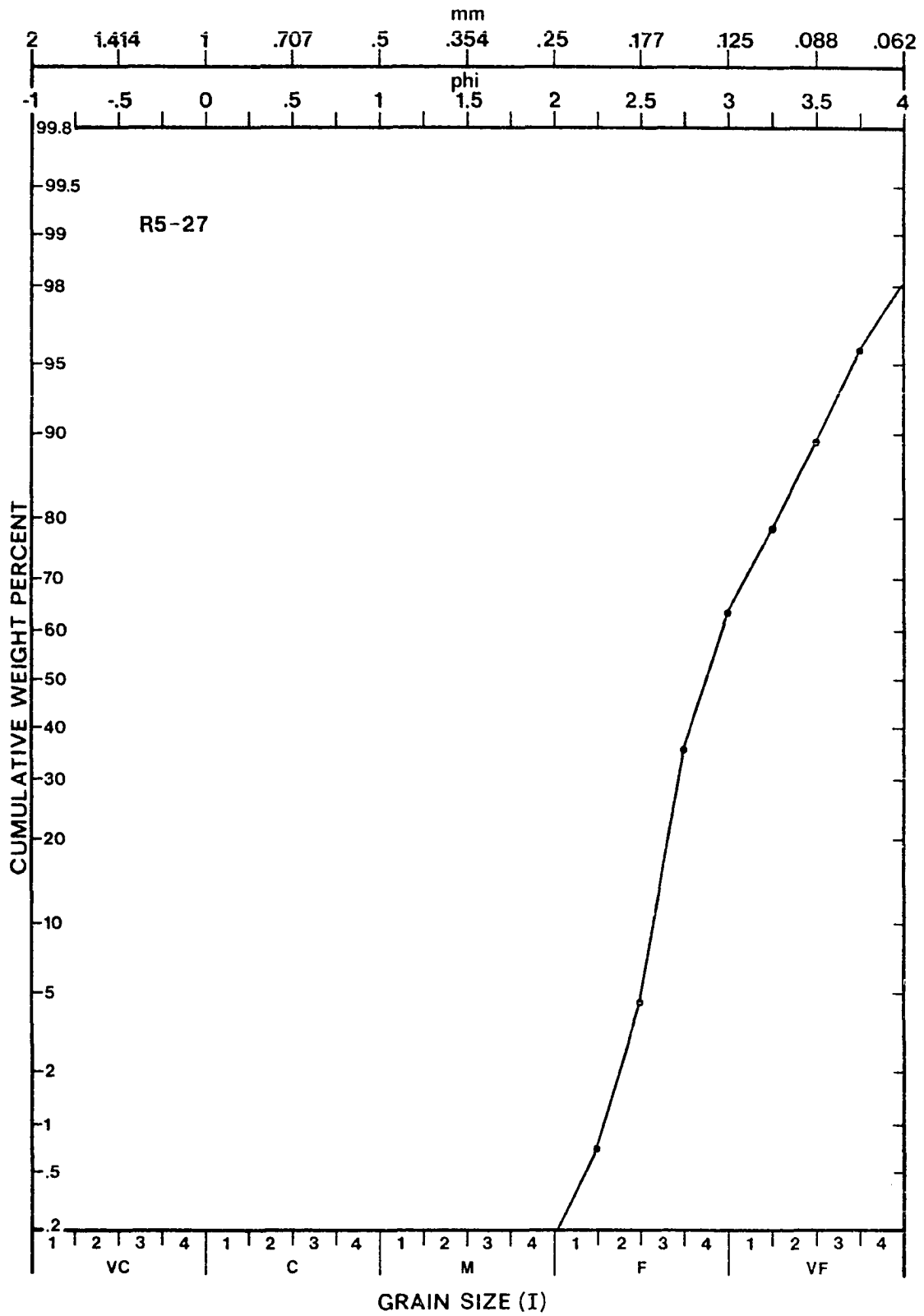


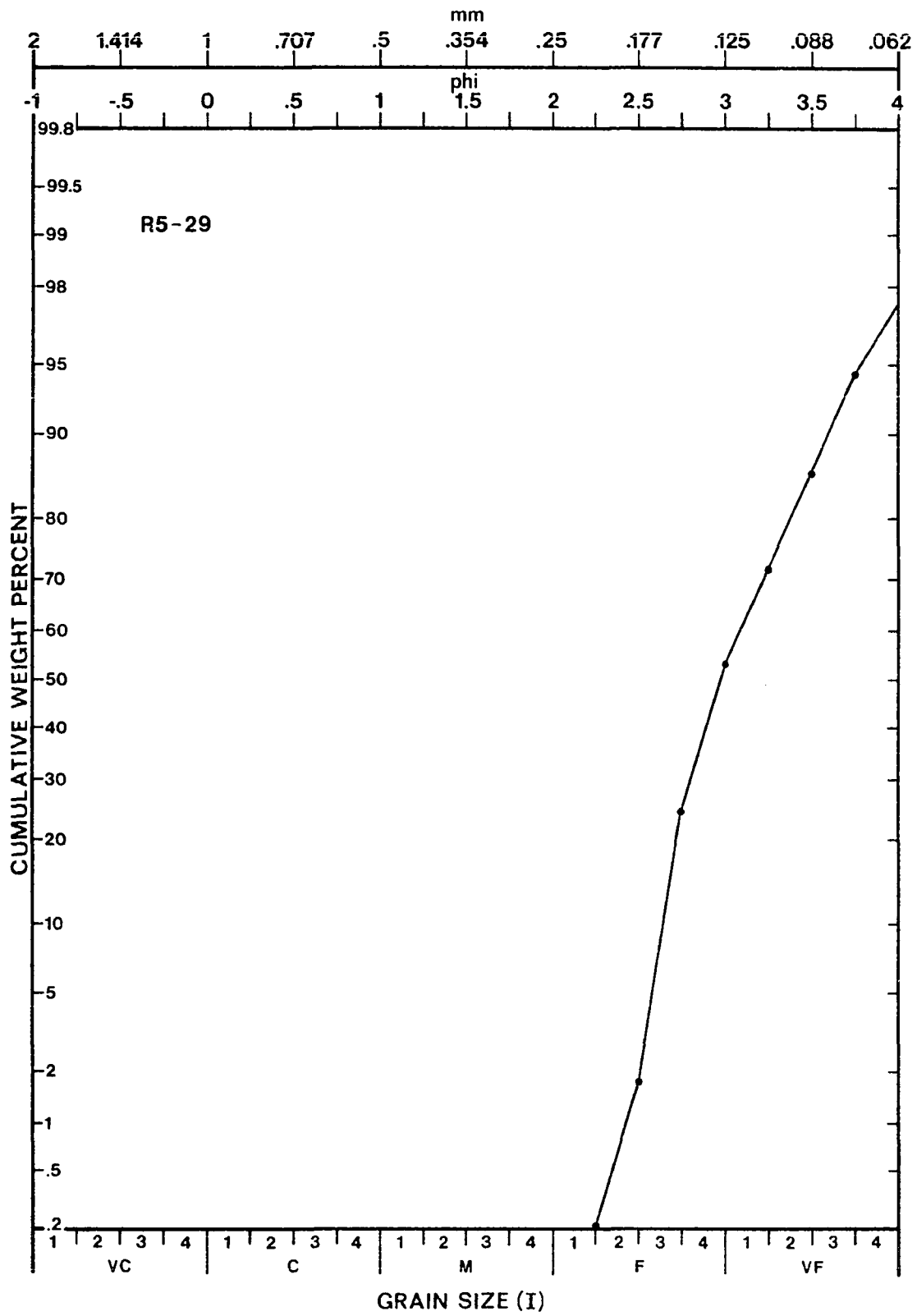


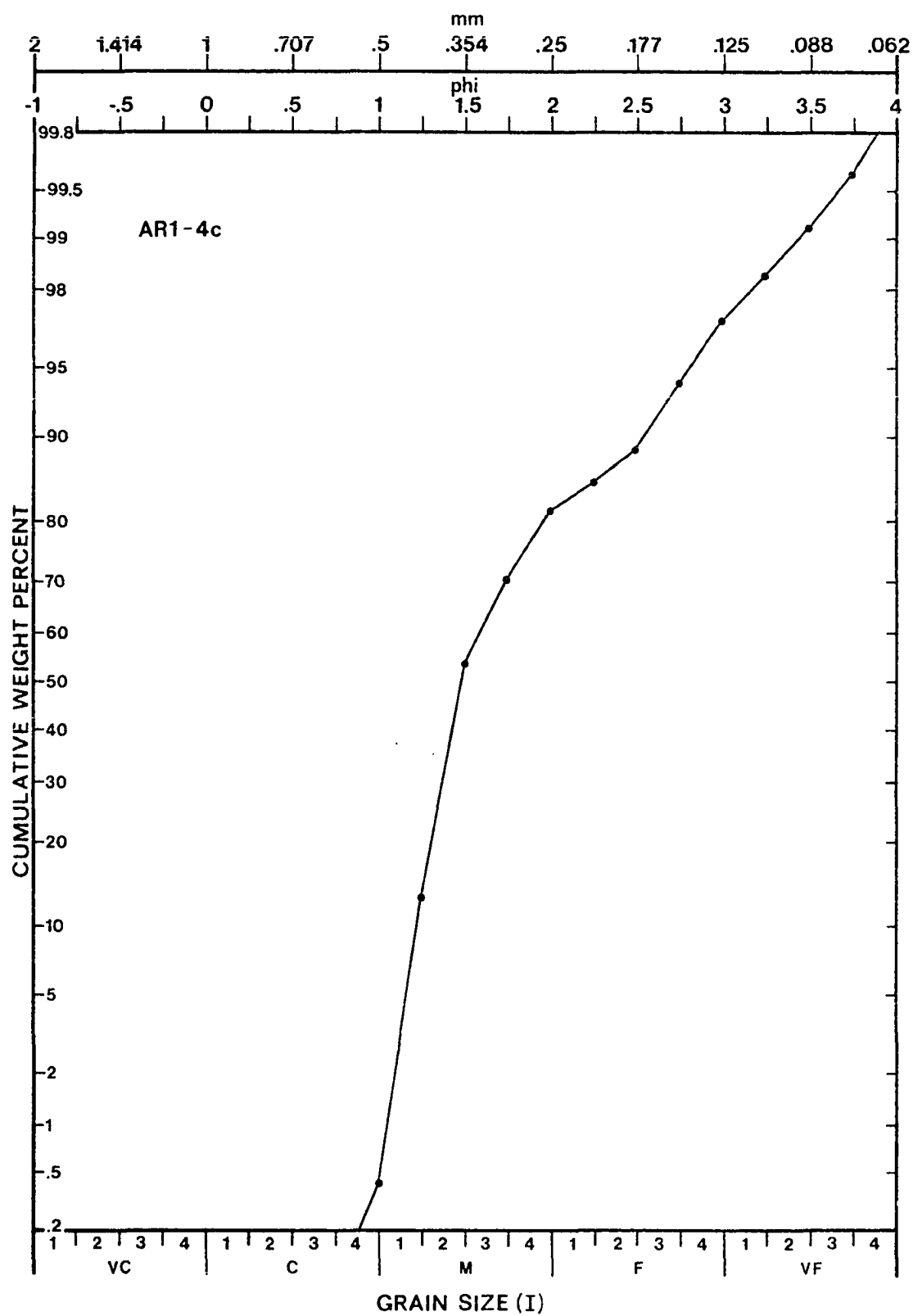


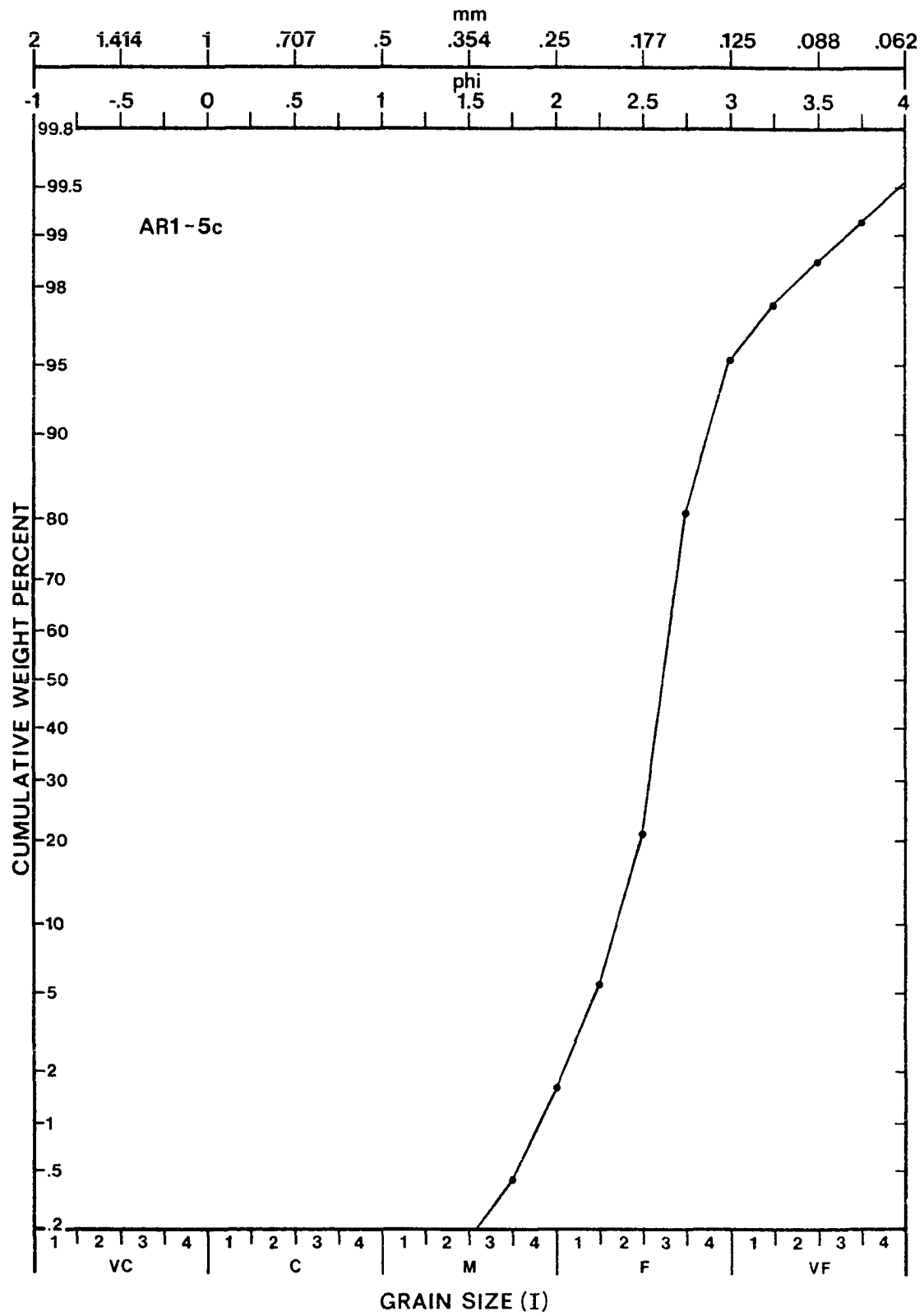


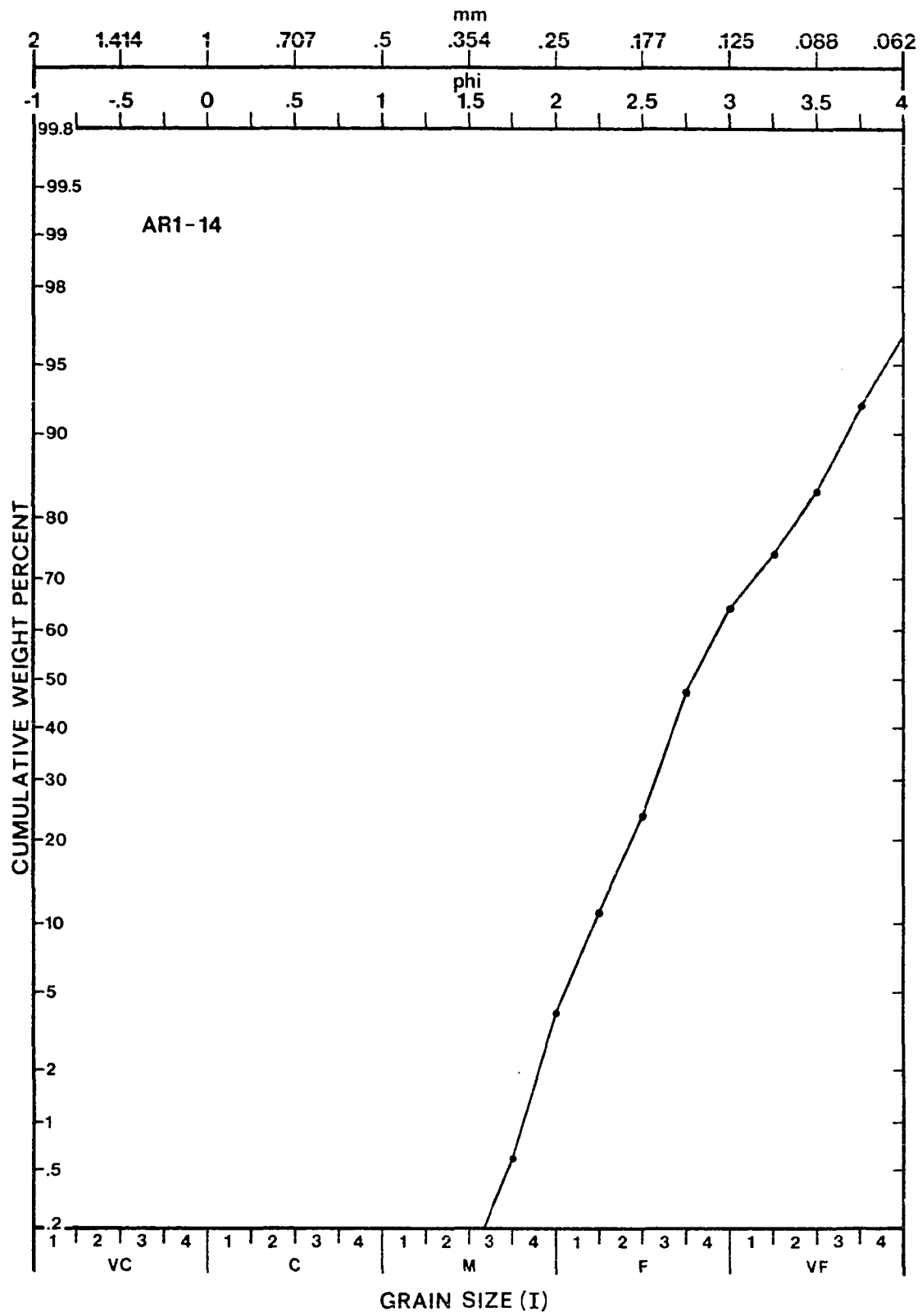


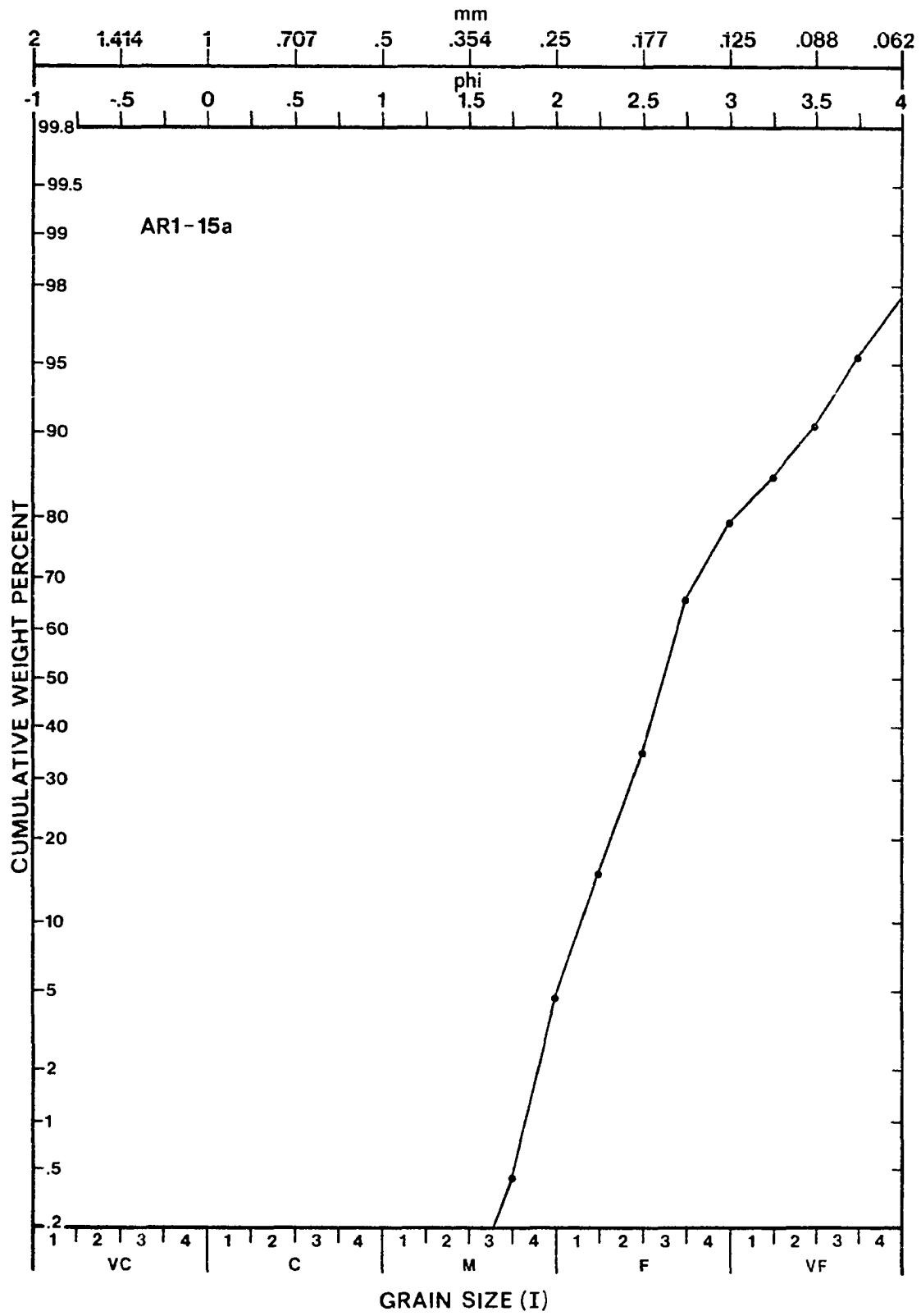


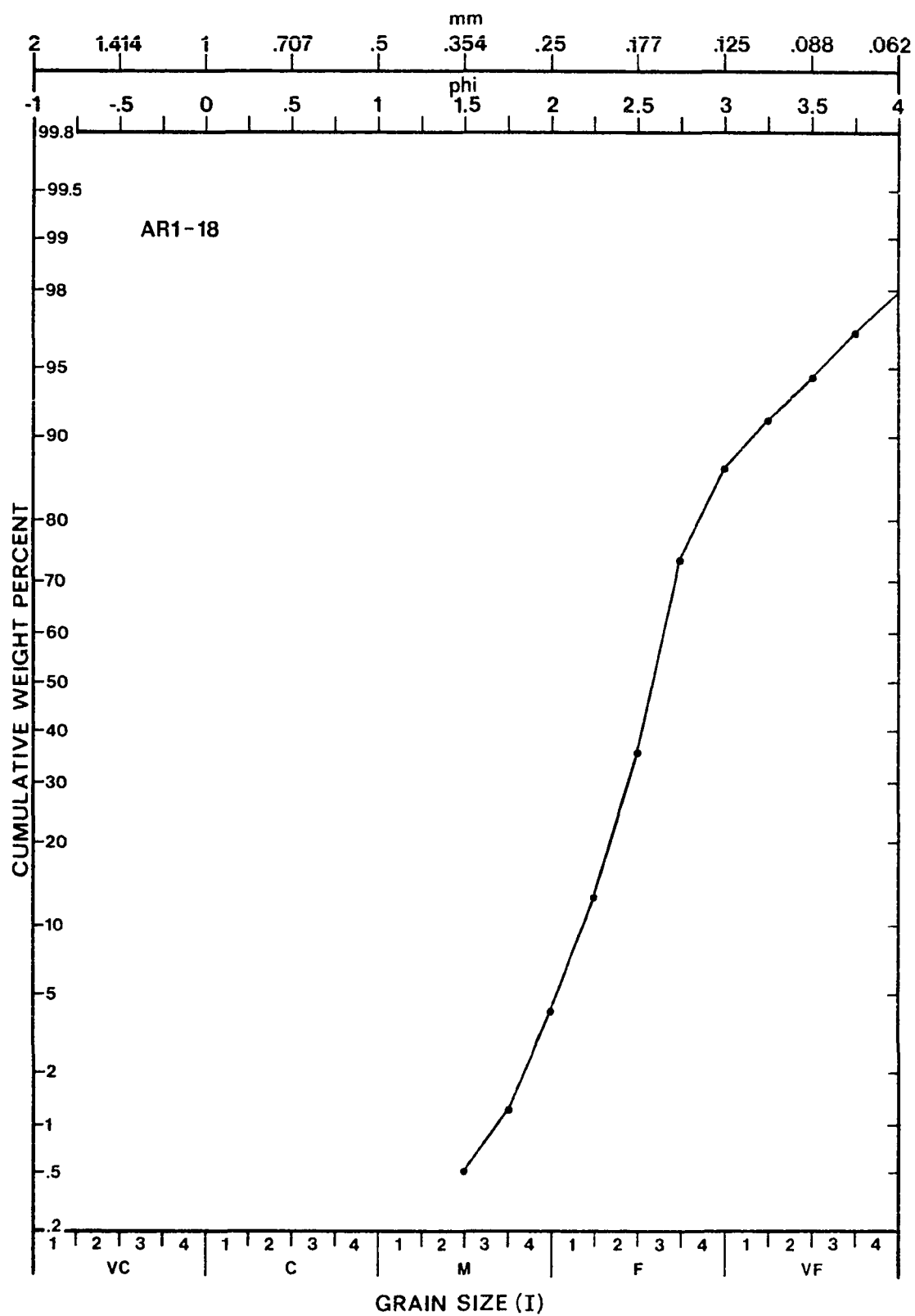


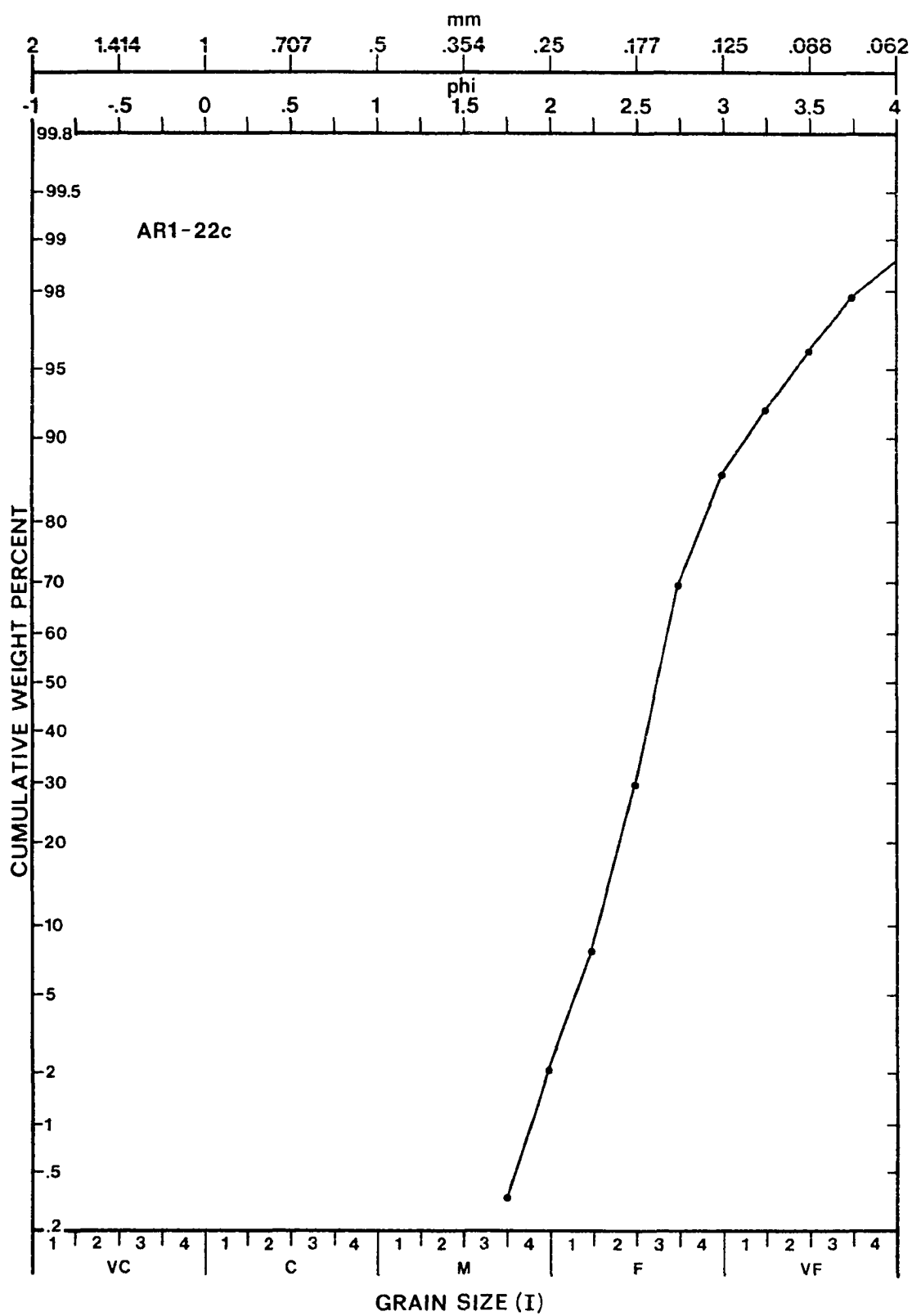












APPENDIX F

RAW DATA FOR THE SETTLING VELOCITY EXPERIMENTS:
RECTANGULAR PARALLELEPIPEDS

Test Particle	Reynolds Number	$\frac{V_n^1}{V_s}$	Particle Volume (cm ³)	Particle Density (gm/cm ³)	Kinematic Viscosity ² (cm ² /sec)	Fluid Density (gm/cm ³)	Particle Settling Velocity (cm/sec)	Zingg Ratios I/L	S/I
PRAMANIK (1950)									
SRP811	0.75	0.644	0.0266	7.825	4.115	0.850	8.32	0.12	0.99
SRP821	0.91	0.661	0.0320	7.825	4.115	0.850	9.45	0.25	0.50
SRP841	0.92	0.655	0.0329	7.825	4.115	0.850	9.51	0.50	0.25
SRP421	0.89	0.767	0.0266	7.825	4.115	0.850	9.91	0.51	0.48
SRP811	0.79	0.630	0.0266	7.825	3.935	0.850	8.43	0.12	0.99
LRP811	3.6	0.621	0.1660	7.825	3.935	0.850	21.03	0.12	0.99
LRP821	6.6	0.646	0.1850	7.825	2.911	0.847	27.37	0.25	0.50
LRP841	6.4	0.637	0.1780	7.825	2.911	0.847	26.55	0.50	0.25
LRP421	7.5	0.771	0.1720	7.825	2.911	0.847	31.64	0.51	0.49
SRP811	4.5	0.602	0.0266	7.825	1.359	0.840	16.58	0.12	0.99
SRP821	5.5	0.633	0.0320	7.825	1.359	0.840	18.93	0.25	0.50
SRP841	5.5	0.625	0.0329	7.825	1.359	0.840	18.93	0.50	0.25
SRP421	5.6	0.748	0.0266	7.825	1.359	0.840	20.60	0.51	0.48
LRP821	19	0.590	0.1850	7.825	1.359	0.840	36.52	0.25	0.50
LRP811	17	0.581	0.1660	7.825	1.359	0.840	34.53	0.12	0.99
LRP811	37	0.579	0.1660	7.825	0.786	0.836	43.07	0.12	0.99
LRP821	40	0.576	0.1850	7.825	0.786	0.836	44.47	0.25	0.50
LRP841	17	0.571	0.1780	7.825	1.359	0.840	34.81	0.50	0.25
LRP841	36	0.541	0.1780	7.825	0.786	0.835	41.27	0.50	0.25
LRP841	37	0.552	0.1780	7.825	0.796	0.835	41.94	0.50	0.25
LRP421	21	0.709	0.1720	7.825	1.359	0.840	42.67	0.51	0.49
LRP421	45	0.684	0.1720	7.825	0.781	0.836	51.66	0.51	0.49
SRP811	10	0.592	0.0266	7.825	0.781	0.836	22.01	0.12	0.99
SRP811	71	0.560	0.0266	7.825	0.187	0.862	35.81	0.12	0.99
SRP821	15	0.605	0.0320	7.825	0.676	0.834	25.97	0.25	0.50
SRP821	78	0.526	0.0320	7.825	0.187	0.820	37.00	0.25	0.50
SRP841	12	0.601	0.0329	7.825	0.781	0.836	24.35	0.50	0.25
SRP841	12	0.597	0.0329	7.825	0.796	0.835	23.99	0.50	0.25
SRP841	74	0.505	0.0329	7.825	0.187	0.862	34.50	0.50	0.25

Test Particle	Reynolds Number	Vn^1 V_s	Particle Volume (cm ³)	Particle Density (gm/cm ³)	Kinematic ² Viscosity (cm ² /sec)	Fluid Density (gm/cm ³)	Particle Settling Velocity (cm/sec)	Zingg Ratios I/L	S/I
PRAMANIK (1950) continued									
SRP421	12	0.734	0.0266	7.825	0.781	0.836	27.25	0.51	0.48
SRP421	82	0.651	0.0266	7.825	0.187	0.862	41.60	0.51	0.48
LRP811	202	0.504	0.1660	7.825	0.187	0.862	55.29	0.12	0.99
LRP821	203	0.473	0.1850	7.825	0.187	0.862	53.49	0.25	0.50
LRP841	174	0.416	0.1780	7.825	0.187	0.862	46.51	0.50	0.25
LRP421	225	0.549	0.1720	7.825	0.187	0.862	60.84	0.51	0.49
SRP811	397	0.424	0.0266	7.825	0.037	0.836	39.62	0.12	0.99
SRP821	442	0.425	0.0320	7.825	0.037	0.836	41.45	0.25	0.50
SRP841	380	0.360	0.0329	7.825	0.037	0.836	35.36	0.50	0.25
SRP421	455	0.486	0.0266	7.825	0.037	0.836	45.42	0.51	0.48
JANKE (1963)									
CF	80	0.611	0.0245	2.74	0.0765	1.07	17.10	0.99	0.30
BF	91	0.698	0.0240	2.74	0.0765	1.07	19.40	0.95	0.42
DF	111	0.859	0.0238	2.74	0.0765	1.07	23.80	0.97	0.75
D1	122	0.936	0.0240	2.74	0.0765	1.07	26.00	1.00	1.00
D2	115	0.879	0.0242	2.74	0.0765	1.07	24.50	0.71	0.95
D3	100	0.772	0.0238	2.74	0.0765	1.07	21.40	0.42	0.99
B1	86	0.658	0.0241	2.74	0.0765	1.07	18.30	0.20	0.96
DA	111	0.859	0.0238	2.74	0.0765	1.07	23.80	0.75	0.79
BA	92	0.710	0.0239	2.74	0.0765	1.07	19.70	0.58	0.58
CA	75	0.578	0.0237	2.74	0.0765	1.07	16.00	0.44	0.43
CF	0.79	0.622	0.0245	2.74	1.43	1.24	3.15	0.99	0.30
BF	0.86	0.677	0.0240	2.74	1.43	1.24	3.43	0.95	0.42
DF	0.94	0.745	0.0238	2.74	1.43	1.24	3.77	0.97	0.75
D1	0.97	0.766	0.0240	2.74	1.43	1.24	3.88	1.00	1.00
D2	0.94	0.741	0.0242	2.74	1.43	1.24	3.75	0.71	0.95

Test Particle	Reynolds Number	$\frac{V_n}{V_s}$	Particle Volume (cm ³)	Particle Density (gm/cm ³)	Kinematic Viscosity (cm ² /sec)	Fluid Density (gm/cm ³)	Particle Settling Velocity (cm/sec)	Zingg Ratios I/L	S/I
JANKE (1963) continued									
D3	0.88	0.697	0.0238	2.74	1.43	1.24	3.53	0.42	0.99
B1	0.74	0.585	0.0241	2.74	1.43	1.24	2.96	0.20	0.96
DA	0.92	0.729	0.0238	2.74	1.43	1.24	3.69	0.75	0.79
BA	0.84	0.667	0.0239	2.74	1.43	1.24	3.38	0.58	0.58
CA	0.75	0.590	0.0237	2.74	1.43	1.24	2.99	0.44	0.43
MALAIKA (1949)									
P4A	0.13	0.710	0.1786	7.882	28.980	0.859	5.24	0.25	1.00
P4B	0.59	0.739	0.0226	7.882	4.710	0.847	7.92	0.25	1.00
P1B	0.89	0.926	0.0233	7.882	4.710	0.847	10.09	1.00	1.00
P14B	0.51	0.711	0.0215	7.882	4.877	0.847	7.19	1.00	0.25
P4A	3.5	0.754	0.1786	7.882	4.710	0.847	23.90	0.25	1.00
P1A	1.4	0.928	0.0448	7.882	4.710	0.847	14.54	1.00	1.00
P14A	1.2	0.709	0.0553	7.882	4.877	0.847	12.13	1.00	0.25
P4A	51	0.685	0.1786	7.882	0.739	0.832	53.95	0.25	1.00
P4B	12	0.702	0.0226	7.882	0.739	0.832	25.30	0.25	1.00
P4B	76	0.698	0.0226	7.882	0.194	0.861	42.09	0.25	1.00
P1A	25	0.899	0.0448	7.882	0.739	0.832	42.67	1.00	1.00
P1B	16	0.910	0.0233	7.882	0.739	0.832	33.22	1.00	1.00
P1B	81	0.899	0.0233	7.882	0.228	0.863	51.82	1.00	1.00
P14A	23	0.646	0.0553	7.882	0.743	0.832	33.16	1.00	0.25
P14A	93	0.584	0.0553	7.882	0.228	0.863	44.50	1.00	0.25
P14B	11	0.668	0.0215	7.882	0.743	0.832	23.53	1.00	0.25
P14B	64	0.604	0.0215	7.882	0.194	0.861	35.84	1.00	0.25
P4A	101	0.649	0.1786	7.882	0.194	0.861	72.54	0.25	1.00
P1A	101	0.897	0.0448	7.882	0.228	0.863	64.01	1.00	1.00

Test Particle	Reynolds Number	$\frac{V_n}{V_s}$ ¹	Particle Volume (cm ³)	Particle Density (gm/cm ³)	Kinematic ² Viscosity (cm ² /sec)	Fluid Density (gm/cm ³)	Particle Settling Velocity (cm/sec)	Zingg I/L	Ratios S/I
PETTYJOHN AND CHRISTIANSEN (1948)									
C1	0.11	0.921	0.030655	2.8521	5.3515	1.3456	1.554	1.00	1.00
C2	9.6	0.927	0.25503	2.7925	1.2639	1.3055	15.44	1.00	1.00
C3	57	0.927	0.10808	2.7936	0.2547	1.2446	24.38	1.00	1.00
C2	101	0.928	0.25503	2.7925	0.2547	1.2446	32.69	1.00	1.00
C4	158	0.932	0.50268	2.7939	0.2547	1.2446	40.75	1.00	1.00
C5	222	0.935	1.1805	2.7924	0.2547	1.2446	48.00	1.00	1.00
C6	285	0.957	0.0022015	1.8629	0.008986	0.9971	15.86	1.00	1.00

¹V_n=the settling velocity of the nonspherical test particle and V_s=settling velocity of the equivalent sphere (calculated from Equation 3).

²Kinematic Viscosity=Dynamic Viscosity/Fluid Density.

APPENDIX G

RAW DATA FOR THE SETTLING VELOCITY EXPERIMENTS:
MAGNETITE GRAINS

Grain	Nominal ¹ Diameter (cm)	Grain Settling Velocity (cm/sec)	Zingg Ratios		Roundness ²
			I/L	S/I	
9	0.0352	7.1	0.76	0.66	0.2
24	0.0218	4.2	0.53	0.70	0.2
134	0.0408	9.5	0.63	0.79	0.5
135	0.0386	8.3	0.50	0.91	0.3
136	0.0387	8.3	0.57	0.69	0.4
137	0.0287	6.0	0.80	0.57	0.3
138	0.0301	6.4	0.49	0.71	0.3
139	0.0252	5.4	0.72	0.59	0.4
140	0.0308	5.1	0.64	0.36	0.2
141	0.0260	4.5	0.45	0.51	0.4
142	0.0151	3.0	0.83	0.68	0.5
143	0.0196	3.6	0.93	0.44	0.5
145	0.0187	3.6	0.84	0.42	0.4
147	0.0421	9.0	0.74	0.64	0.3
148	0.0358	8.1	0.63	0.70	0.3
149	0.0444	8.3	0.47	0.55	0.2
150	0.0263	6.5	0.91	0.92	0.5
151	0.0246	4.5	0.73	0.32	0.4
152	0.0207	3.7	0.83	0.52	0.3
153	0.0366	6.0	0.55	0.44	0.4

Grain Density = 5.07 gm/cm³

Fluid Density = 0.998 gm/cm³

Kinematic Viscosity = 0.01007 cm²/sec

¹Nominal diameter calculated using the Reynolds number equation (Equation 3) and data in Table 3 of Briggs et al. (1962): R and V_s , where V_s is the settling velocity of the grain and not its equivalent sphere, V_n (the notation is the opposite of that used in the present study). Note that the Reynolds number was calculated using the grain settling velocity rather than the more conventional sphere settling velocity. The fluid density and kinematic viscosity were taken to be those of pure water at 20°C.

²Based on the roundness comparator of Krumbein, 1941 (smaller values indicate greater angularity).

APPENDIX H

RAW DATA FOR THE PLANE SECTION PACKING ANALYSES

Sample ¹	Number of Grains With a Given Number of Contacts					Porosity Point Counts			Number of Contacts of a Given Type			Total Number of Contacts		
	0	1	2	3	4	Total No. of Grains	No. of Pore Points	No. of Rock Points	Total Points	Point	Long		Concavo -Convex	
B2-20	205	94	18	0	0	317	272	327	599	125	5	0	130	
B2-7	206	119	32	2	0	359	226	364	590	178	11	0	189	
B2-9	202	130	42	2	2	378	228	397	625	206	21	1	228	
B2-1	182	154	46	7	1	390	256	394	650	240	28	3	271	
B2-16A ²	212	116	21	1	0	350	259	354	613	142	17	2	161	
B2-16B ²	221	103	40	1	0	365	239	369	608	172	10	3	185	
B2-16//S ³	227	88	27	2	0	344	236	355	591	146	2	0	148	
B2-16//B ⁴	199	95	20	0	0	314	224	318	542	126	9	0	135	
B1-15	173	116	33	5	0	327	231	327	558	187	10	0	197	
B1-16	165	112	24	5	1	306	198	308	506	156	23	0	179	
AB1-1d1	—	—	—	—	—	—	167	629	796	—	—	—	—	
AB1-1d2	—	—	—	—	—	—	172	561	733	—	—	—	—	
D5-10	162	113	25	6	0	306	219	306	525	175	5	1	181	
D5-15	145	105	46	10	0	306	225	307	532	215	12	0	227	
D5-16A ²	166	119	47	5	1	338	279	339	618	215	13	1	229	
D5-16B ²	154	102	42	7	0	305	259	304	563	188	18	0	206	
D5-16//S ³	162	114	28	6	0	310	242	314	556	179	9	0	188	
D5-16//B ⁴ ,5	171	116	25	3	0	316	234	318	552	165	15	0	180	
D3-15	154	122	43	2	2	323	254	323	577	208	13	1	222	
D3-19 ⁶	174	142	45	3	0	361	264	362	626	226	15	0	241	
AD2-1e ⁷	2	27	59	113	87	330	126	331	457	262	656	129	1047	
AD2-1f ⁷	7	25	53	98	82	305	129	315	444	156	665	133	955	
R5-23	181	104	33	4	0	322	223	323	546	178	4	0	182	
R5-25	177	94	29	4	0	304	258	305	563	161	3	0	164	
R5-21	178	91	38	8	0	315	275	314	589	183	8	0	191	
R5-34	158	115	37	4	0	314	261	312	573	194	7	0	201	
R5-27	—	—	—	—	—	—	289	353	642	—	—	—	—	
R5-29	—	—	—	—	—	—	303	323	626	—	—	—	—	

Sample ¹	Number of Grains With a Given Number of Contacts					Total No. of Grains	Porosity Point Counts			Number of Contacts of a Given Type			Total Number of Contacts
	0	1	2	3	4		No. of Pore Points	No. of Rock Points	Total Points	Point	Long	Concavo -Convex	
AR1-4c	—	—	—	—	—	—	160	500	660	—	—	—	—
AR1-5c	—	—	—	—	—	—	180	464	644	—	—	—	—
AR1-14	—	—	—	—	—	—	125	394	519	—	—	—	—
AR1-15a	—	—	—	—	—	—	133	381	514	—	—	—	—
AR1-18	—	—	—	—	—	—	127	392	519	—	—	—	—
AR1-22c	—	—	—	—	—	—	116	428	544	—	—	—	—

¹Unless stated otherwise, all thin sections are oriented normal to both bedding and strike.

²Analyses for two different thin sections of the same sample.

³Thin section is oriented normal to bedding and parallel to strike.

⁴Thin section is oriented parallel to bedding.

⁵D5-16//B. also has 1 grain with 5 intergranular contacts.

⁶AD2-1e also has 37 grains with 5 intergranular contacts and 5 grains with 6 intergranular contacts.

⁷AD2-1f also has 34 grains with 5 intergranular contacts, 6 grains with 6 intergranular contacts, and 1 sutured intergranular contact.

APPENDIX I

COMPUTATIONAL RESULTS FOR THE PLANE SECTION PACKING ANALYSES

Sample ⁵	Floating Index ¹	Contact Index ²	Average Number of Contacts per Grain ³			Porosity ⁴
			Point	Long	Concavo-Convex	
B2-20	64.7	0.41	0.39	0.02	0	45.4
B2-7	57.4	0.53	0.50	0.03	0	38.3
B2-9	53.4	0.60	0.54	0.06	0	36.5
B2-1	46.7	0.69	0.62	0.07	0.01	39.4
B2-16A ⁶	60.6	0.46	0.41	0.05	0.01	42.3
B2-16B ⁶	60.5	0.51	0.47	0.03	0.01	39.3
B2-16//S ⁷	66.0	0.43	0.42	0.01	0	39.9
B2-16//B ⁸	63.4	0.43	0.40	0.03	0	41.3
B1-15	52.9	0.60	0.57	0.03	0	41.4
B1-16	53.9	0.58	0.51	0.08	0	39.1
AB1-1d1	—	—	—	—	—	21.0
AB1-1d2	—	—	—	—	—	23.5
D5-10	52.9	0.59	0.57	0.02	0	41.7
D5-15	47.4	0.74	0.70	0.04	0	42.3
D5-16A ⁶	49.1	0.69	0.64	0.04	0	45.1
D5-16B ⁶	50.5	0.68	0.62	0.06	0	46.0
D5-16//S ⁷	52.3	0.61	0.58	0.03	0	43.5
D5-16//B ⁸	54.1	0.57	0.52	0.05	0	42.4
D3-15	47.7	0.69	0.64	0.04	0	44.0
D3-19	48.2	0.68	0.63	0.04	0	42.2
AD2-1e	.6	3.17	0.79	1.99	0.39	27.6
AD2-1f	2.3	3.14	0.51	2.18	0.44	29.1
R5-23	56.2	0.57	0.55	0.01	0	40.8
R5-25	58.2	0.54	0.53	0.01	0	45.8
R5-21	56.5	0.61	0.58	0.03	0	46.7
R5-34	50.3	0.64	0.62	0.02	0	45.5
R5-27	—	—	—	—	—	45.0
R5-29	—	—	—	—	—	48.4
AR1-4c	—	—	—	—	—	24.2
AR1-5c	—	—	—	—	—	28.0
AR1-14	—	—	—	—	—	24.1
AR1-15a	—	—	—	—	—	25.9
AR1-18	—	—	—	—	—	24.5
AR1-22c	—	—	—	—	—	21.3

¹Floating Index=percent of all grains which have no intergranular contacts; using the data in Appendix H, it is the ratio of the 'number of grains with no intergranular contacts' to 'the total number of grains counted' times one hundred.

- ²Contact Index=average number of intergranular contacts per grain; using the data in Appendix H, it is the ratio of 'the total number of intergranular contacts' to 'the total number of grains counted'. The sum of the average number of point, long, concavo-convex and sutured contacts per grain equals the contact index.
- ³Average number of intergranular contacts of a given type per grain; using the data in Appendix H, it is the ratio of 'the total number of intergranular contacts of a given type' to 'the total number of grains counted'.
- ⁴Porosity; using the data in Appendix H, it is the ratio of 'the number of pore points' to 'the total number of points counted' times one hundred.
- ⁵Unless stated otherwise, all thin sections are oriented normal to both bedding and strike.
- ⁶Analyses for two different thin sections of the same sample.
- ⁷Thin section is oriented normal to bedding and parallel to strike.
- ⁸Thin section is oriented parallel to bedding.

APPENDIX J

RAW DATA AND COMPUTATIONAL RESULTS FOR THE COMPACTION ANALYSES

PART I: DATA¹

Sample	Initial Bulk Volume ²	Final Bulk Volume After: ³		Sample Weight ⁴	Grain Volume ⁵	Min. Porosity ⁶	Max. Porosity ⁷	Packing Efficiency ⁸
		15 Min. Ultrasonic	Plus 2 Min. Tamping					
B2-20	16.40	14.80	14.78	14.5248	9.25	37.4	43.6	0.83
B2-7	12.25	11.20	11.15	18.8914	7.13	36.1	41.8	0.94
B2-9	11.15	10.25	10.15	17.1464	6.47	36.2	42.0	0.99
B2-1	13.15	11.90	11.85	20.1991	7.62	35.7	42.0	0.91
B2-16	13.05	11.90	11.80	19.97	7.54	36.1	42.2	—
B2-16	12.95	11.95	11.85	"	"	36.4	41.8	— ⁹
B2-16	13.10	11.80	11.75	"	"	35.8	42.4	0.89 ⁹
B2-16	13.10	11.85	11.85	"	"	36.4	42.4	—
B2-16	13.10	11.80	11.75	"	"	35.8	42.4	—
B1-15	14.00	12.50	12.45	20.9900	7.92	36.4	43.4	0.88
B1-16	12.60	11.59	11.55	19.4141	7.33	36.6	41.8	0.93
AB1-1d1	12.00	10.95	10.75	17.5282	6.61	38.5	44.9	1.82
AB1-1d2	13.20	12.06	11.99	19.3219	7.29	39.2	44.8	1.67
D5-10	10.80	9.95	9.87	16.3823	6.18	37.4	42.8	0.90
D5-15	8.80	7.90	7.90	12.9331	4.88	38.2	44.5	0.90
D5-16	7.40	6.75	7.75	11.20	4.23	37.3	42.8	—
D5-16	7.45	6.80	6.76	"	"	37.4	43.2	— ¹⁰
D5-16	7.60	6.75	6.74	"	"	37.2	44.3	0.83 ¹⁰
D5-16	7.40	6.80	6.77	"	"	37.5	42.8	—
D5-16	7.40	6.75	6.75	"	"	37.3	42.8	—
D3-15	10.75	9.90	9.80	16.3569	6.17	37.0	42.6	0.84
D3-19	11.00	9.90	9.89	16.5230	6.24	37.0	43.3	0.88
AD2-1e	16.50	14.70	14.60	24.2187	9.14	37.4	44.6	1.35
AD2-1f	12.25	11.00	10.90	18.24	6.88	36.9	43.8	—
AD2-1f	12.25	11.15	11.00	"	"	37.4	43.8	— ¹¹
AD2-1f	12.26	11.10	11.02	"	"	37.6	43.9	1.28 ¹¹

PART I: DATA¹ (continued)

Sample	Initial Bulk Volume ²	Final Bulk Volume After: ³		Sample Weight ⁴	Grain ⁵ Volume	Min. Porosity ⁶	Max. Porosity ⁷	Packing Efficiency ⁸
		15 Min. Ultrasonic	Plus 2 Min. Tamping					
AD2-1f	12.25	11.10	11.00	18.24	6.88	37.4	43.8	—
AD2-1f	12.20	11.00	10.95	"	"	37.1	43.5	—
R5-23	10.35	9.32	9.30	15.7157	5.93	36.2	42.7	0.88
R5-25	6.00	5.50	5.45	8.8745	3.35	38.6	44.2	—
R5-25	5.85	5.50	5.41	"	"	38.1	42.7	0.84 ¹²
R5-21	10.60	9.75	9.71	15.9440	6.02	38.0	43.2	0.81
R5-34	9.20	8.60	8.55	14.1690	5.35	37.5	41.8	0.83
R5-27	10.25	9.60	9.35	14.7644	5.57	40.4	45.6	—
R5-27	10.00	9.45	9.34	14.7221	5.56	40.5	44.4	0.90 ¹²
R5-29	10.00	8.90	8.86	14.4644	5.46	38.4	45.4	0.79
AR1-4c	12.65	11.41	11.30	18.8463	7.11	37.1	43.8	1.54
AR1-5c	17.40	16.15	15.91	25.3032	9.55	40.0	45.1	1.43
AR1-14	14.10	12.98	12.74	20.6902	7.81	38.7	44.6	1.61
AR1-15a	11.39	10.40	10.20	16.5552	6.25	38.8	45.1	1.49
AR1-18	11.10	10.38	9.99	15.9813	6.03	39.6	45.7	1.61
AR1-22c	14.00	12.81	12.70	19.8397	7.49	41.0	46.5	1.92

¹Bulk and grain volumes are in cubic centimeters, and sample weight is in grams.

²Sediment volume prior to compaction.

³Sediment volume after compaction.

PART I: DATA¹ (continued)

⁴Dry weight of sediment sample.

⁵Grain volume=sample weight divided by the assumed average density of the grains (2.65 grams per cubic centimeter for quartz).

⁶Minimum sediment porosity = $[1 - (\text{grain volume}/\text{final bulk volume})] \cdot 100$.

⁷Maximum sediment porosity = $[1 - (\text{grain volume}/\text{initial bulk volume})] \cdot 100$.

⁸Packing Efficiency = plane section porosity (from Appendix I) divided by the minimum porosity.

⁹Computed using the average plane section porosity for B2-16A and 16B, and the average of the five minimum porosities.

¹⁰Computed using the average plane section porosity for D5-16A and 16B, and the average of the five minimum porosities.

¹¹Computed using the average of the five minimum porosities.

¹²Computed using the average of the two minimum porosities.

PART II: REPRODUCIBILITY¹

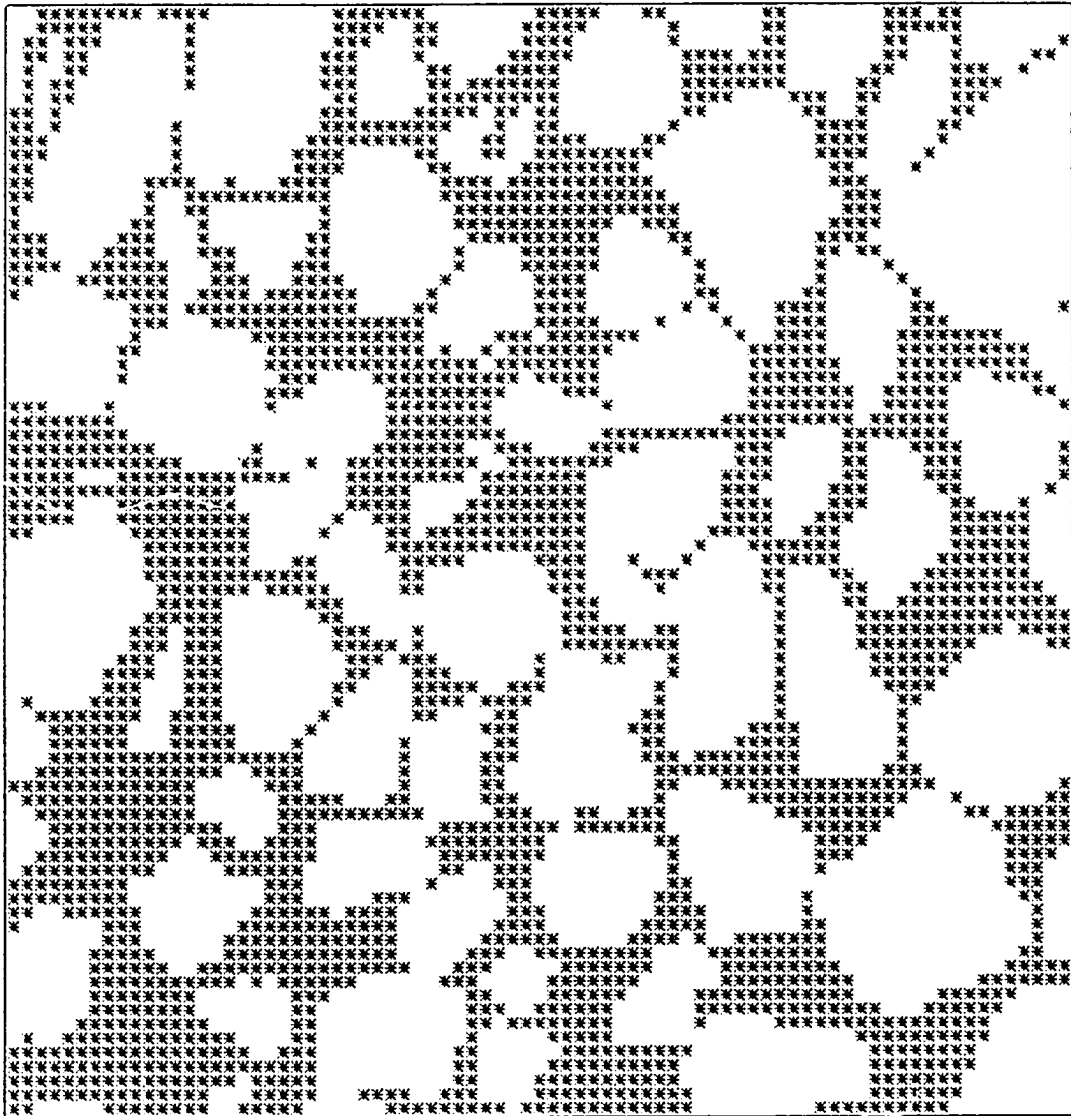
Sample	Minimum Porosity		Maximum Porosity	
	Mean	Standard Deviation	Mean	Standard Deviation
B2-16	36.10	0.30	42.24	0.26
D5-16	37.34	0.11	43.18	0.65
AD2-1f	37.28	0.28	43.76	0.15

¹All statistics are based on five observations for each sample (data in Part I of this appendix).

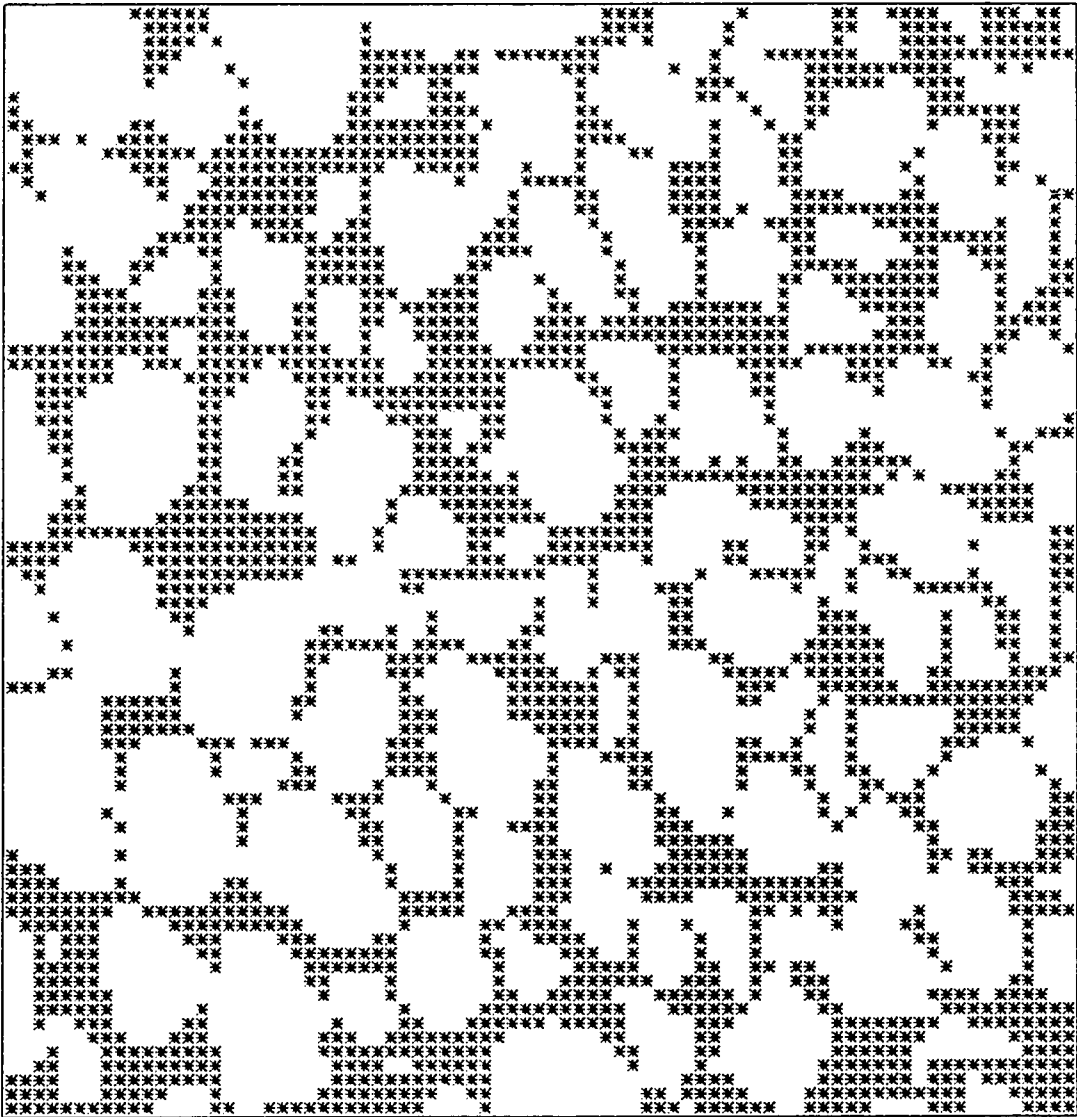
APPENDIX K

ROCK-PORE MATRICES

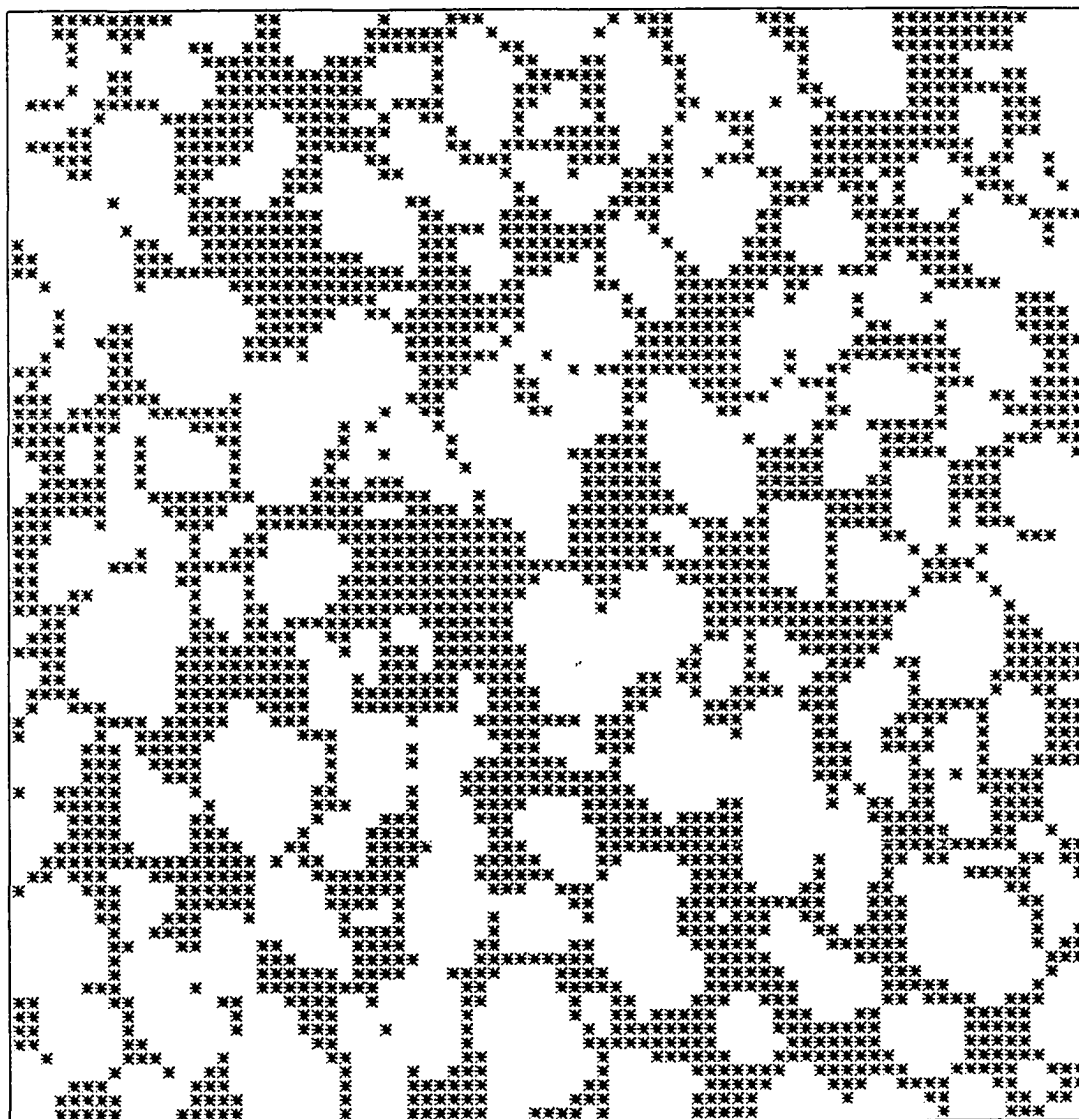
Part I: Rock-Pore Patterns



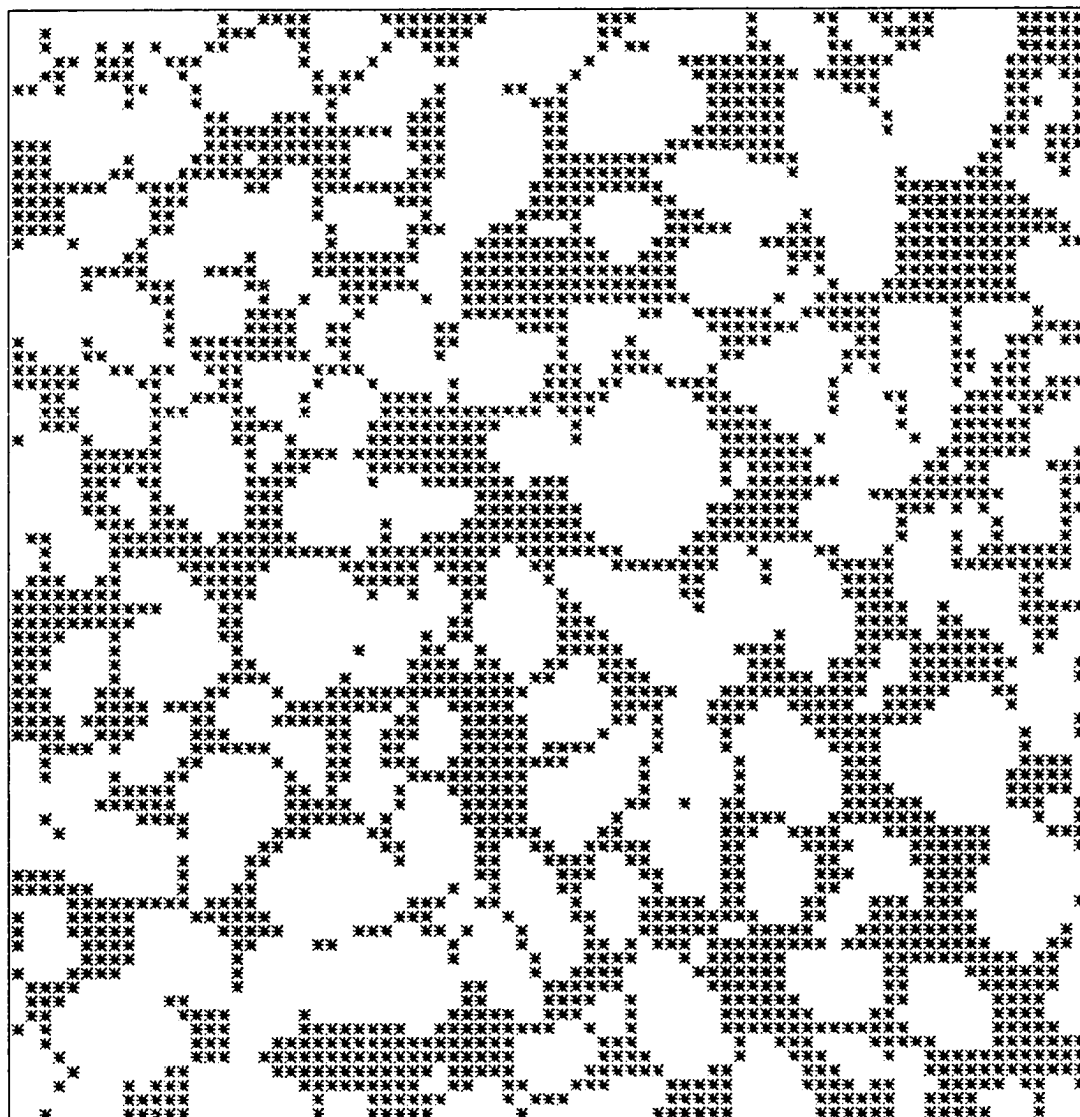
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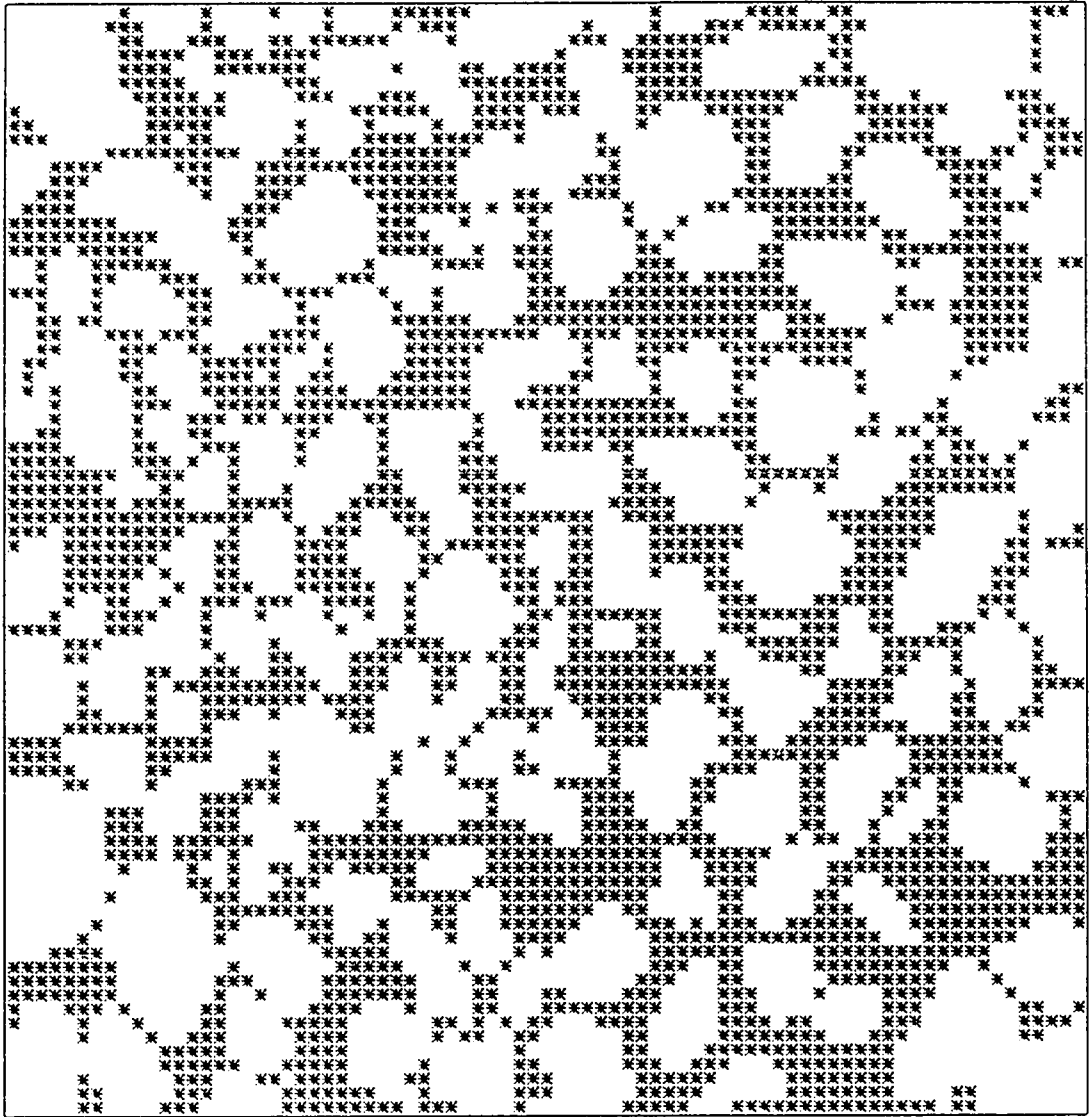
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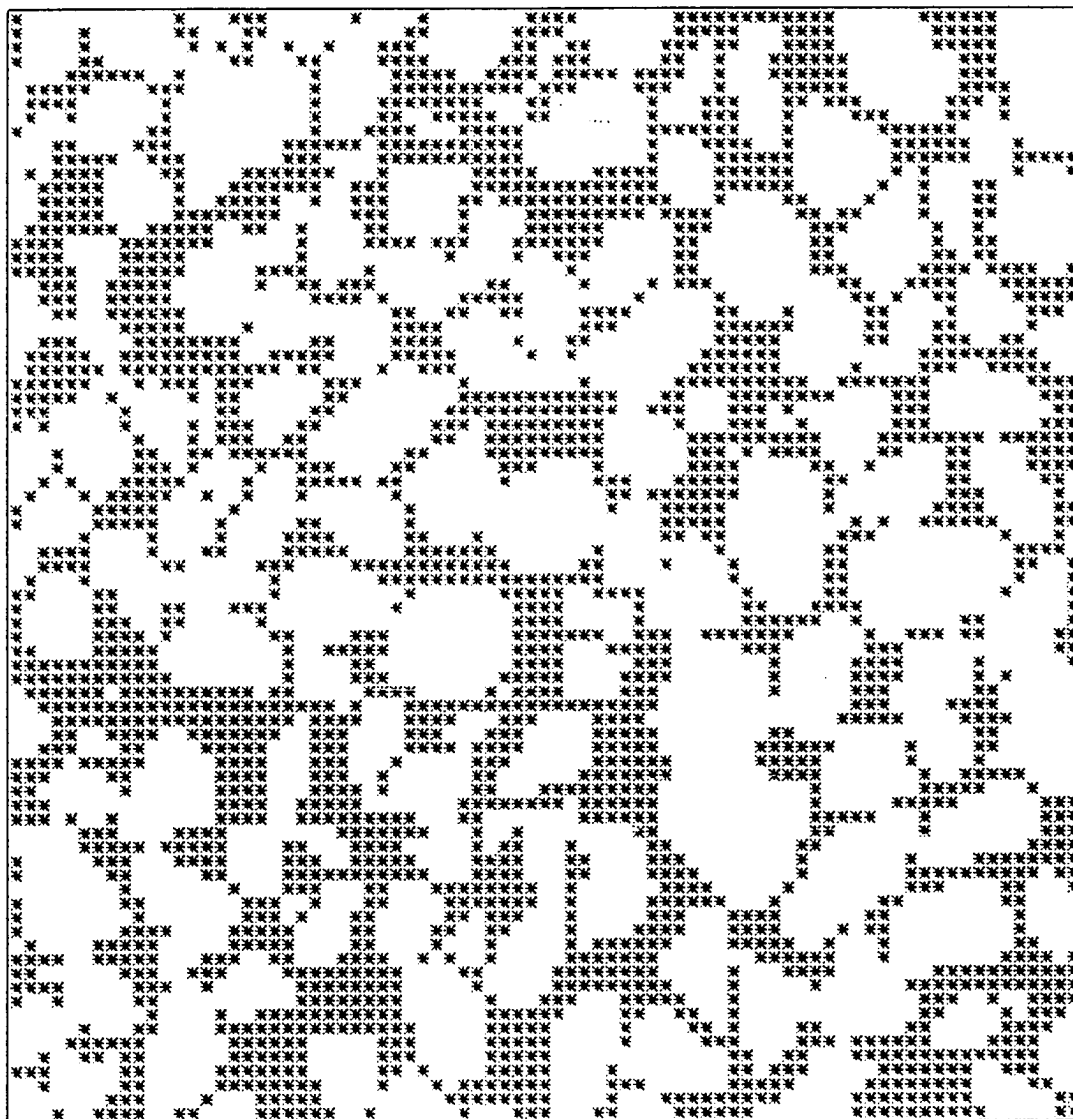
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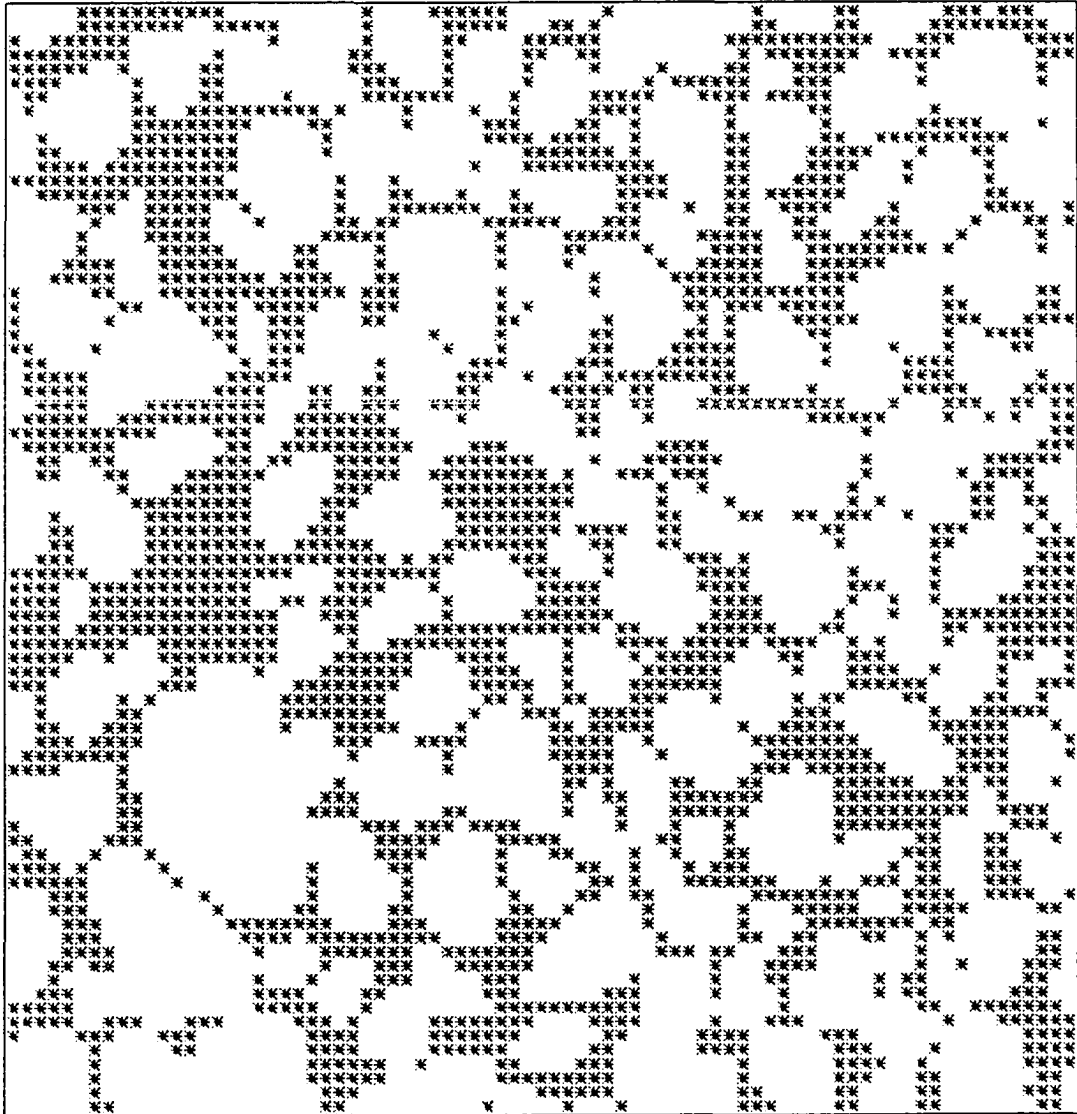
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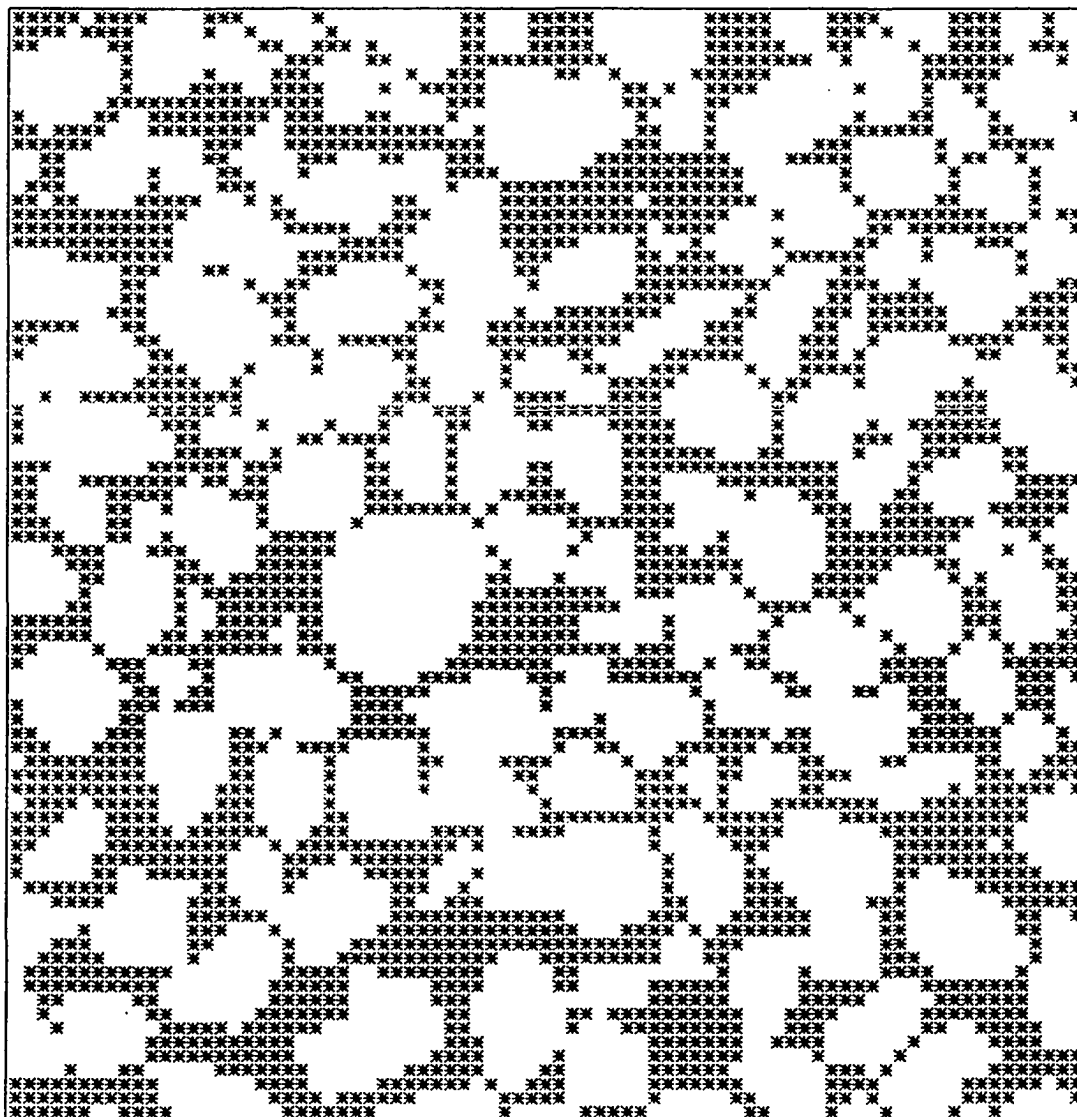
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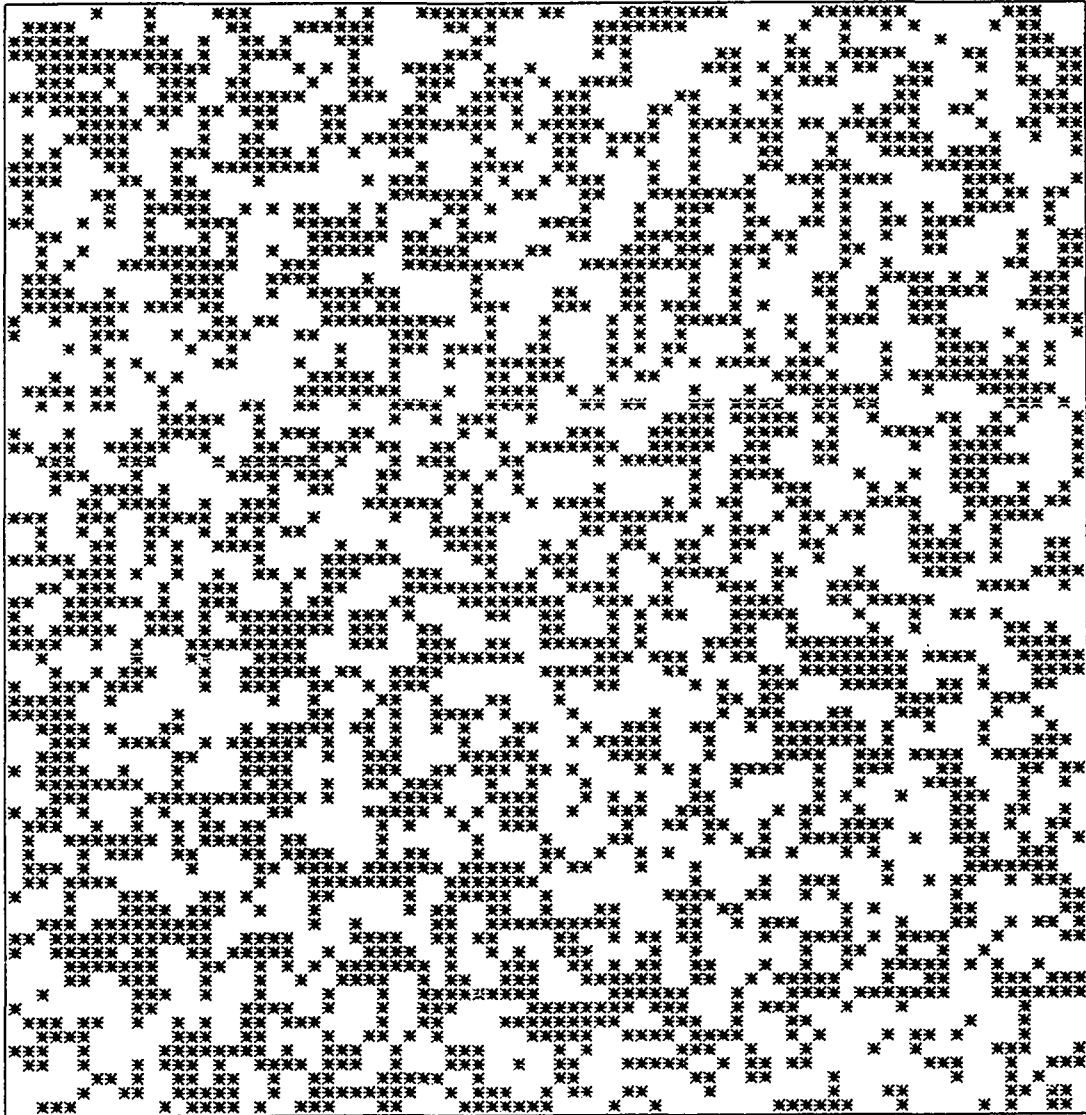
B2 - 16B



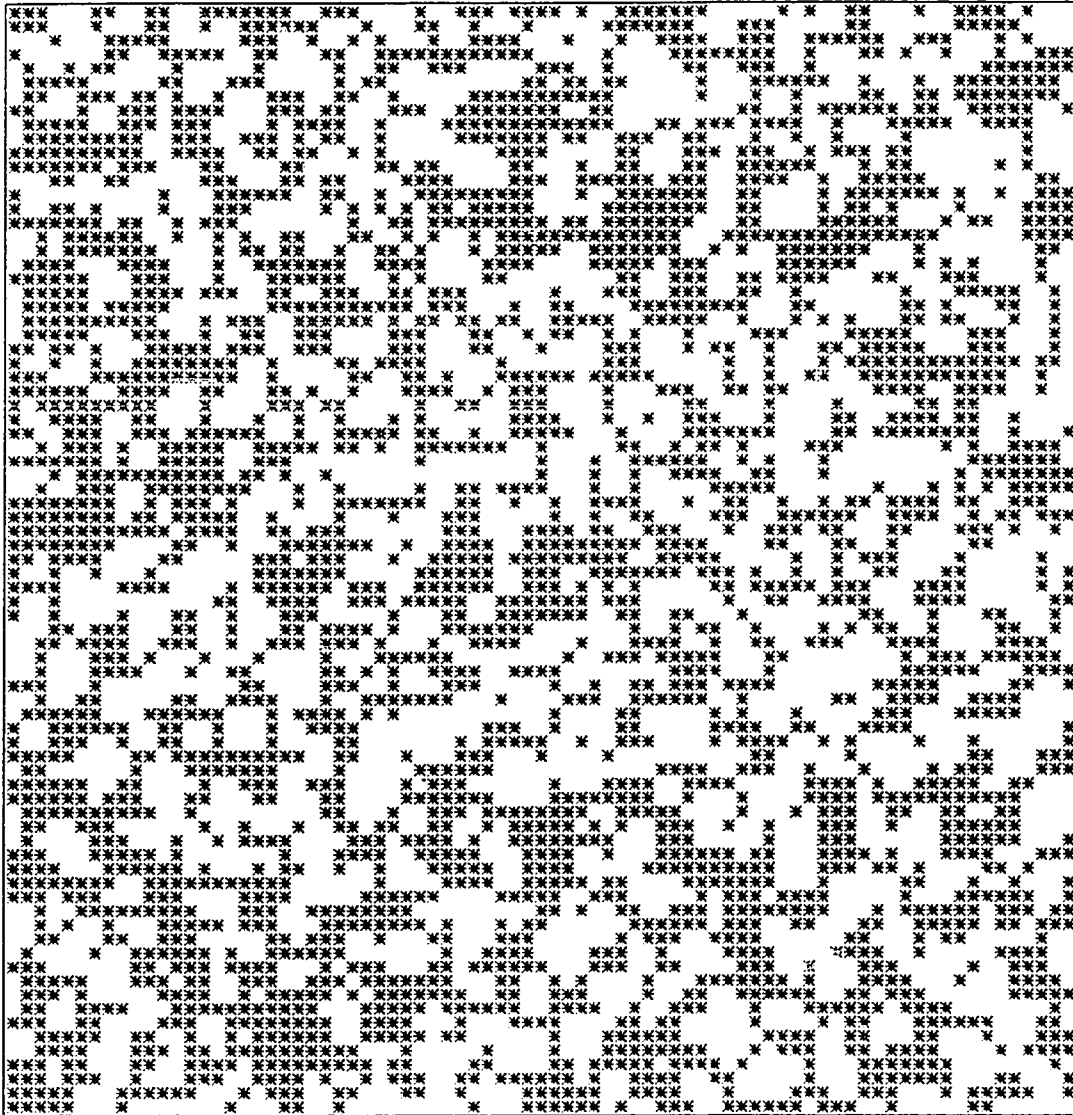
B2-16//S.



B2-16//B.



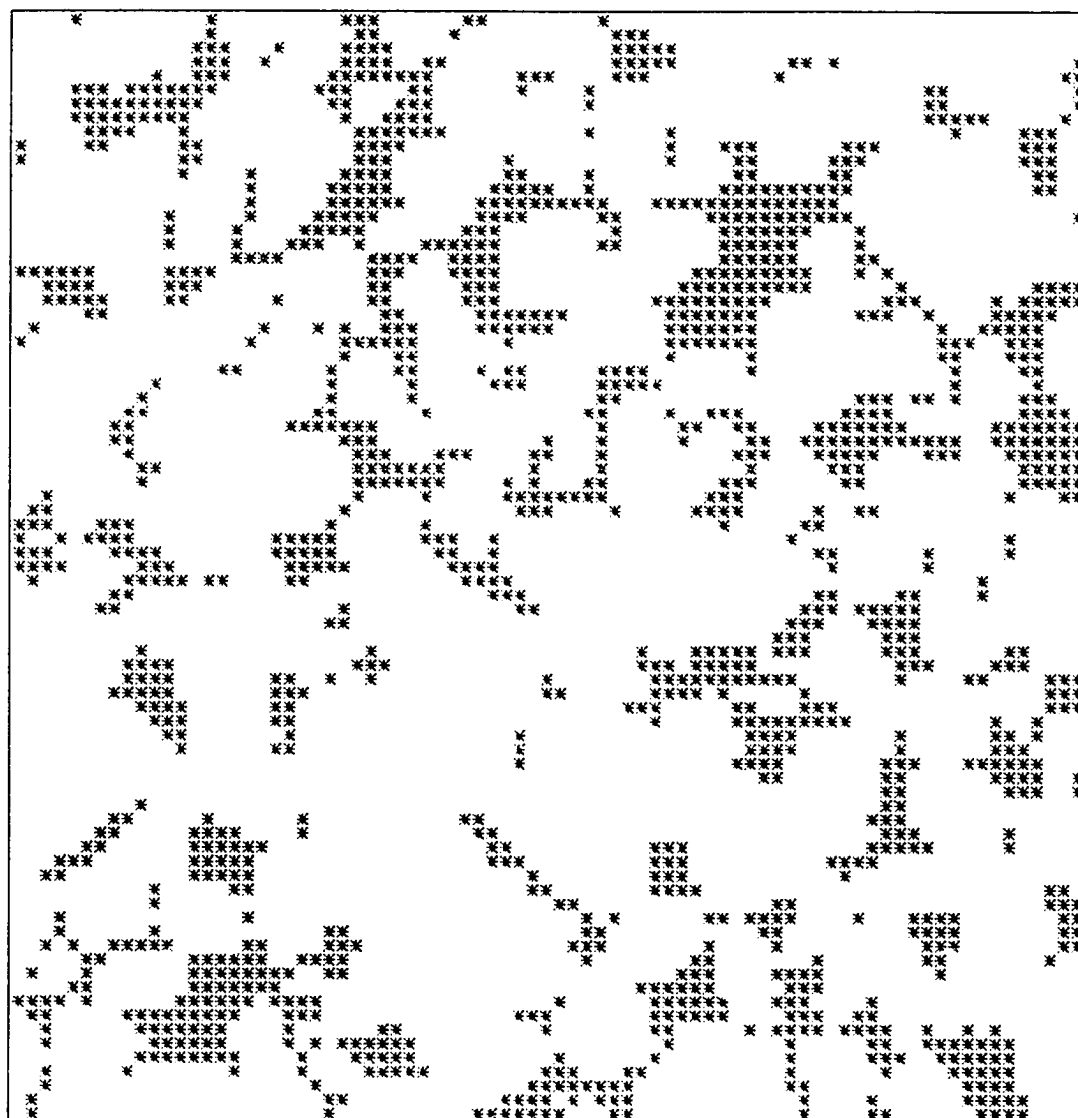
B1-15



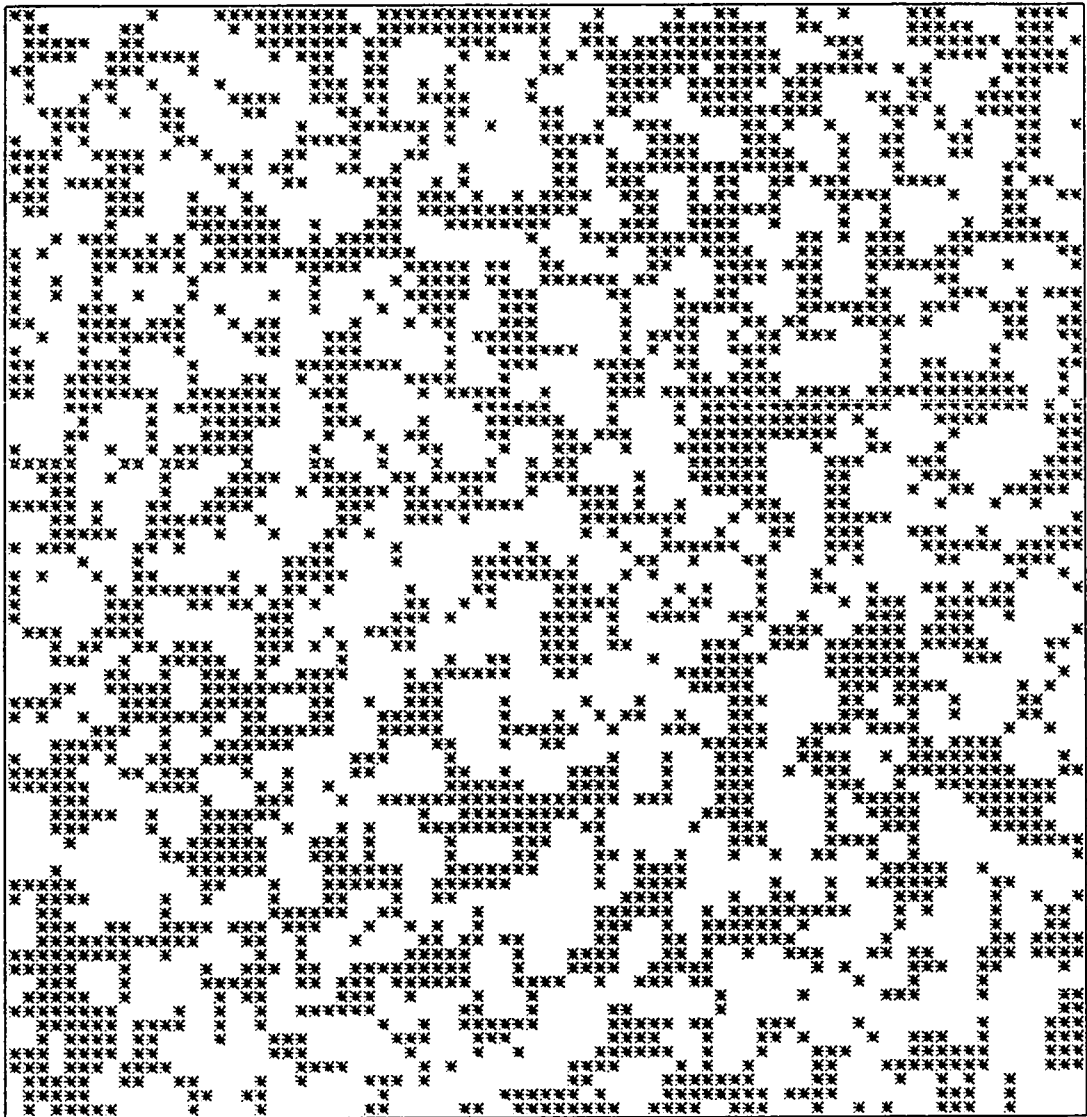
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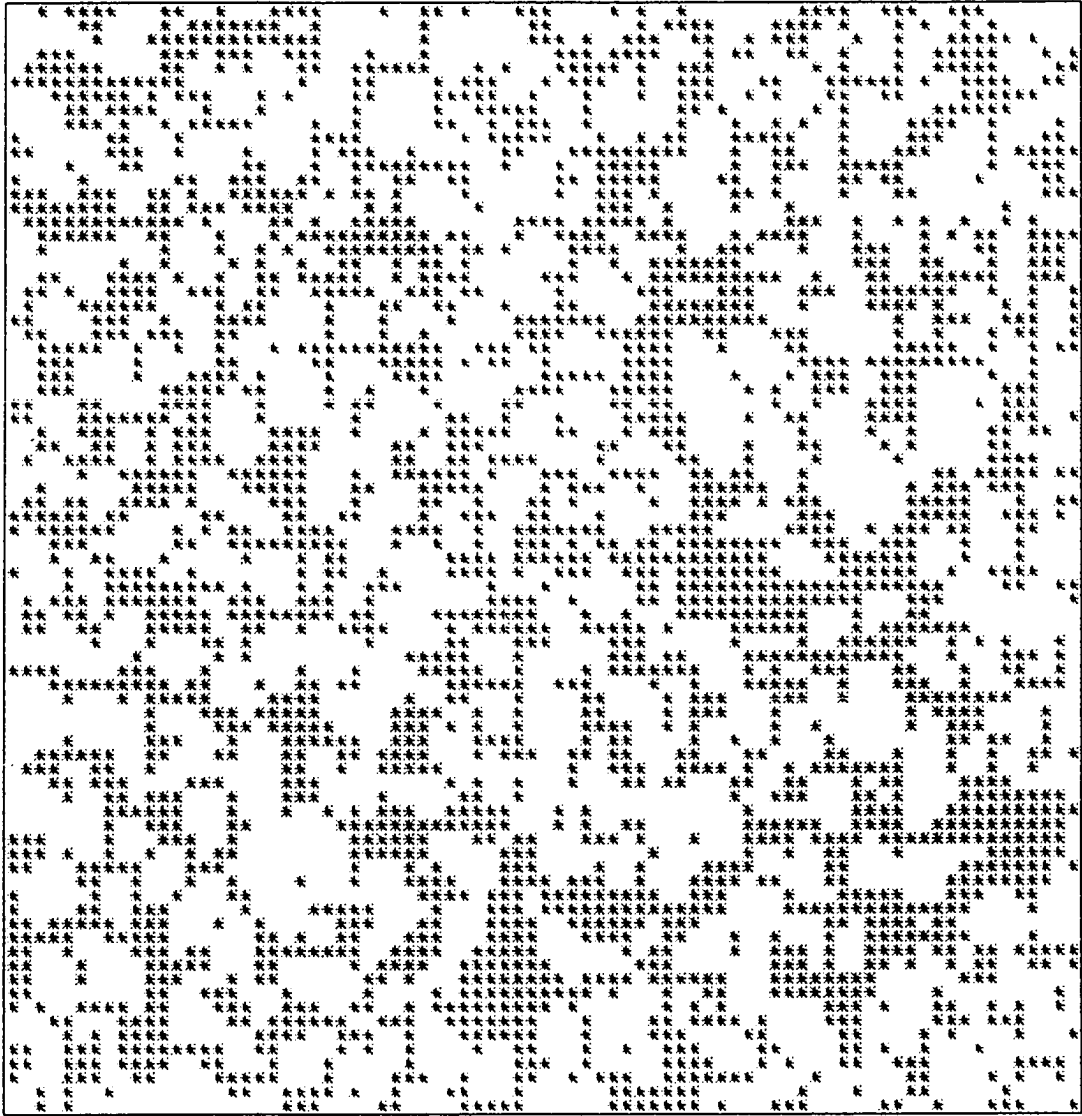
AB1-1d1



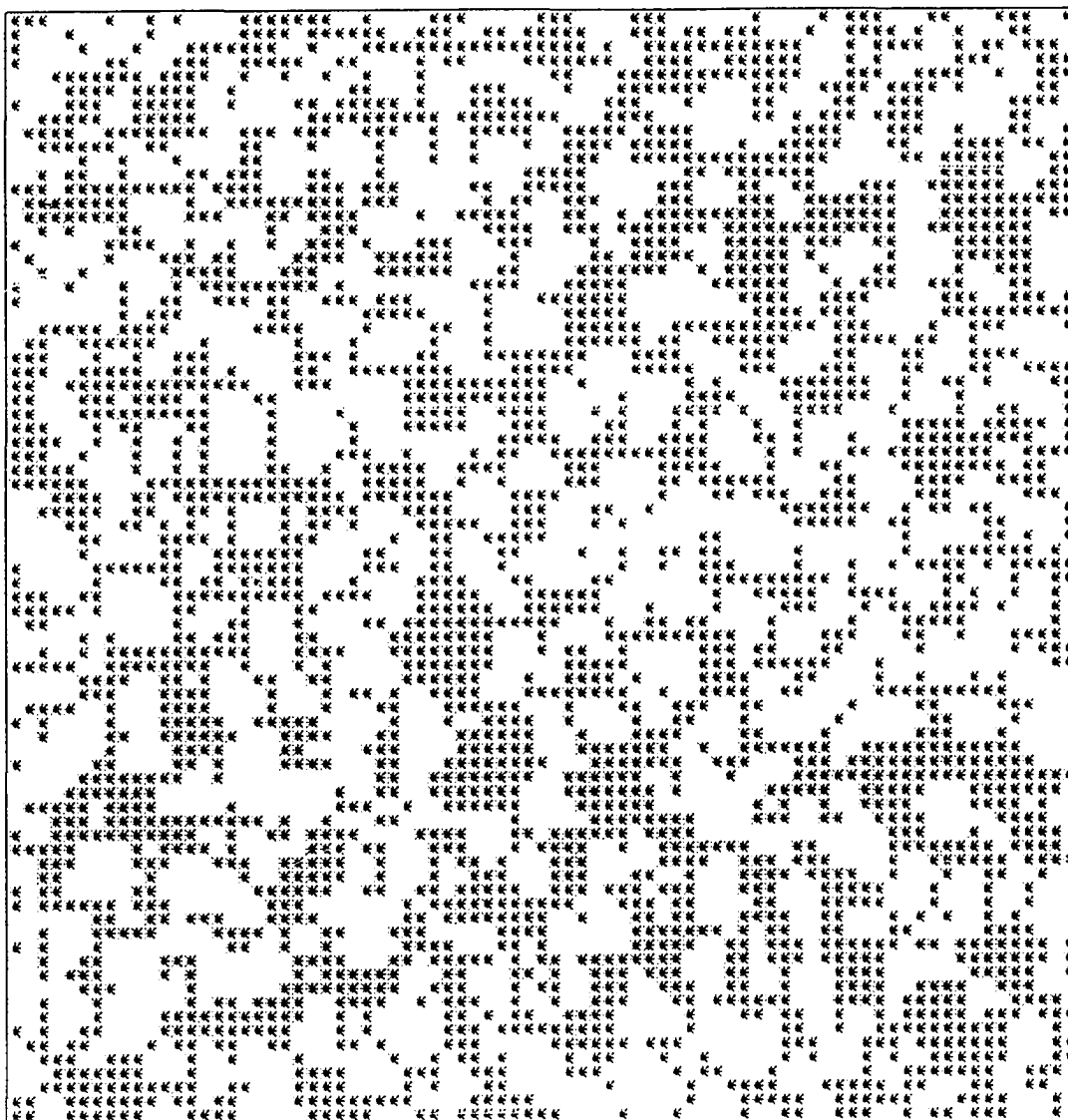
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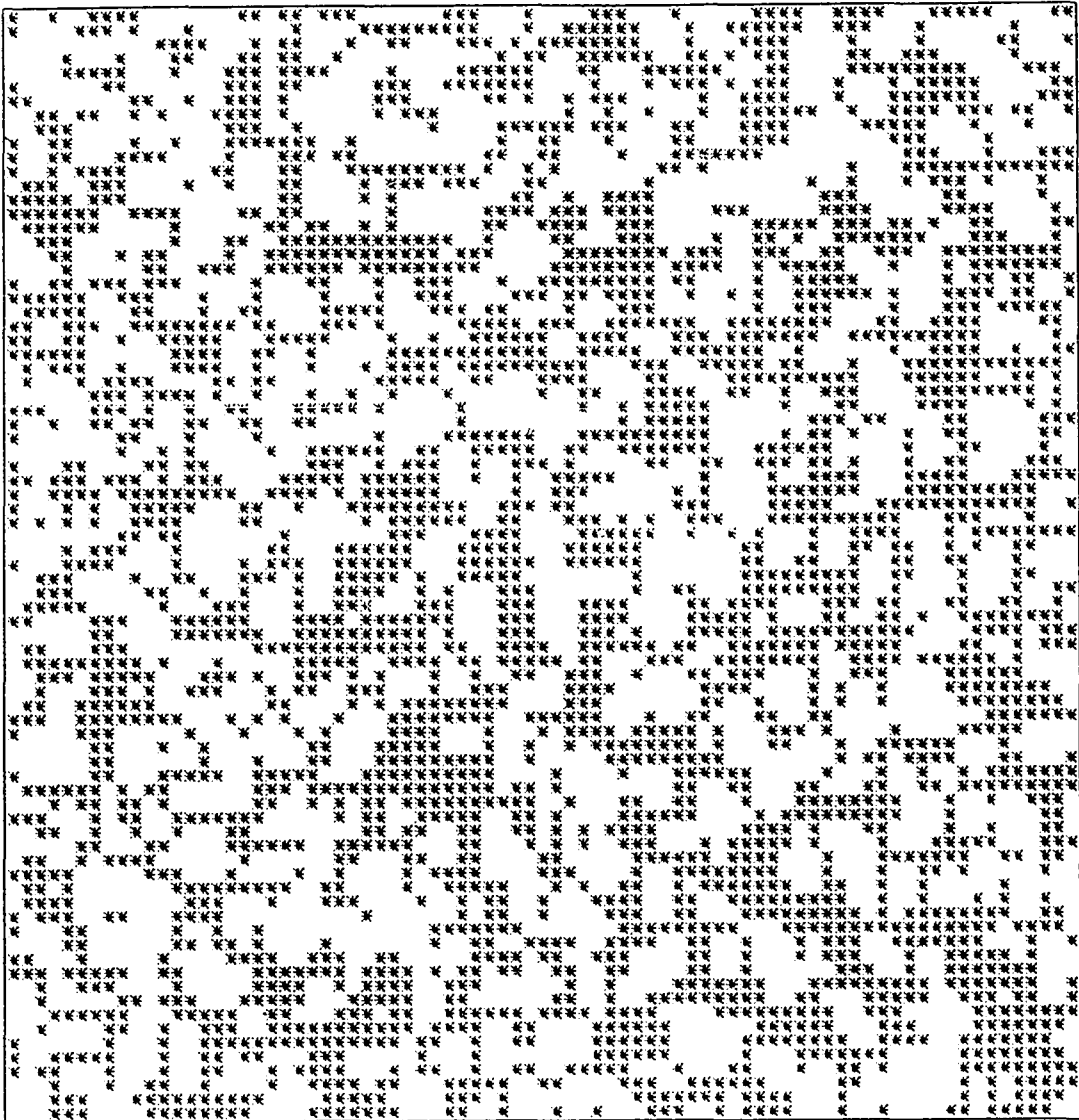
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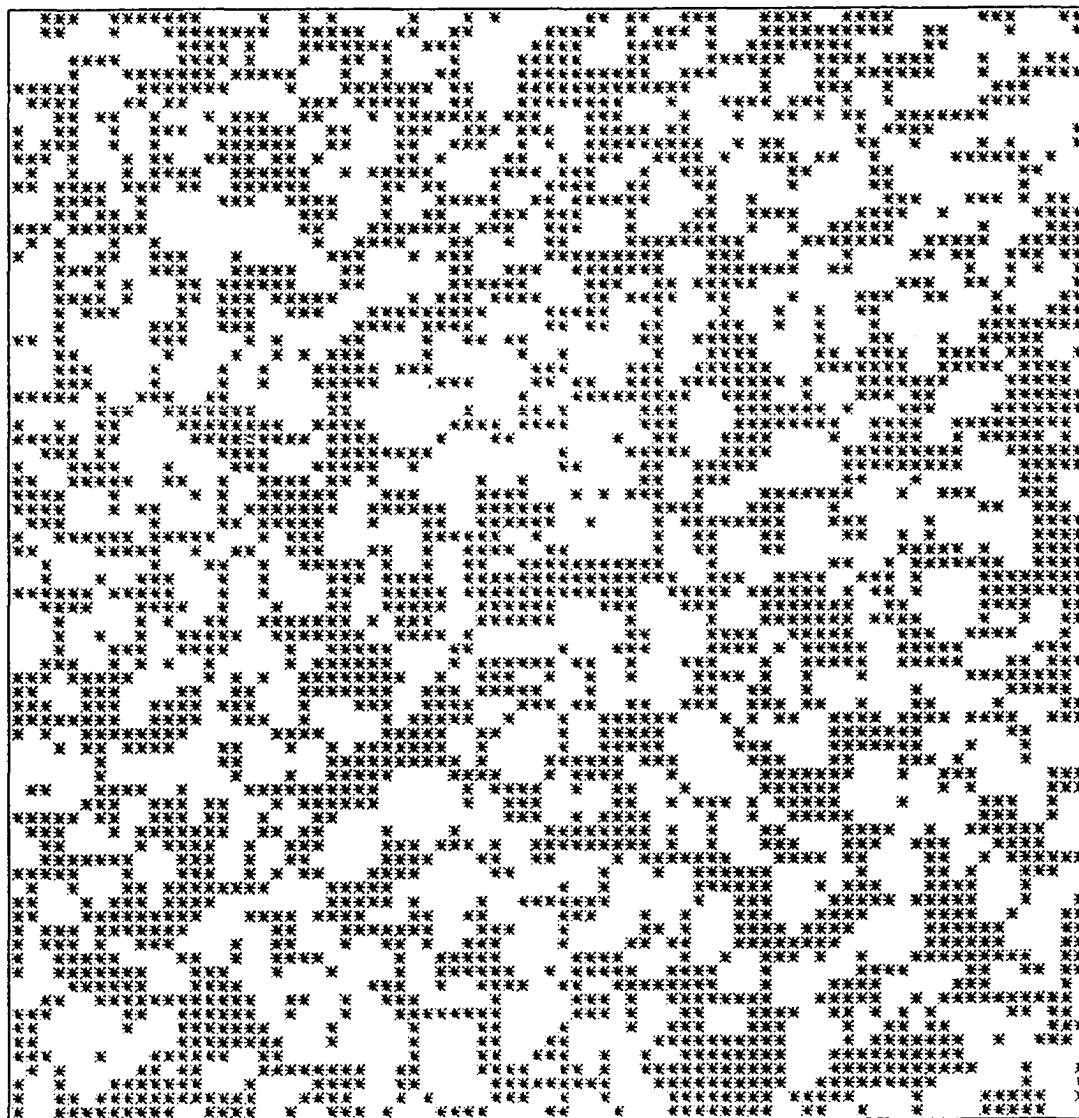
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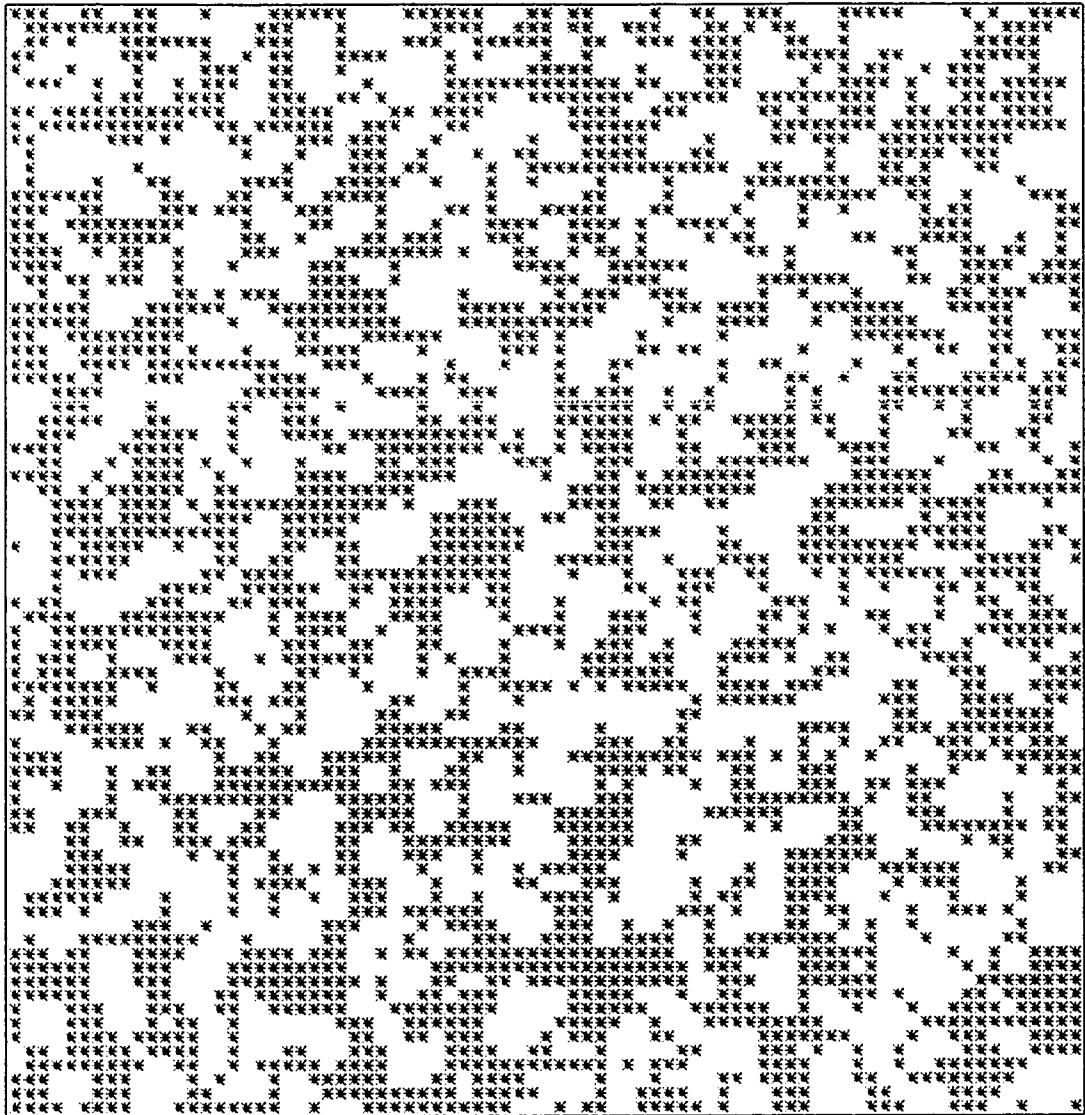
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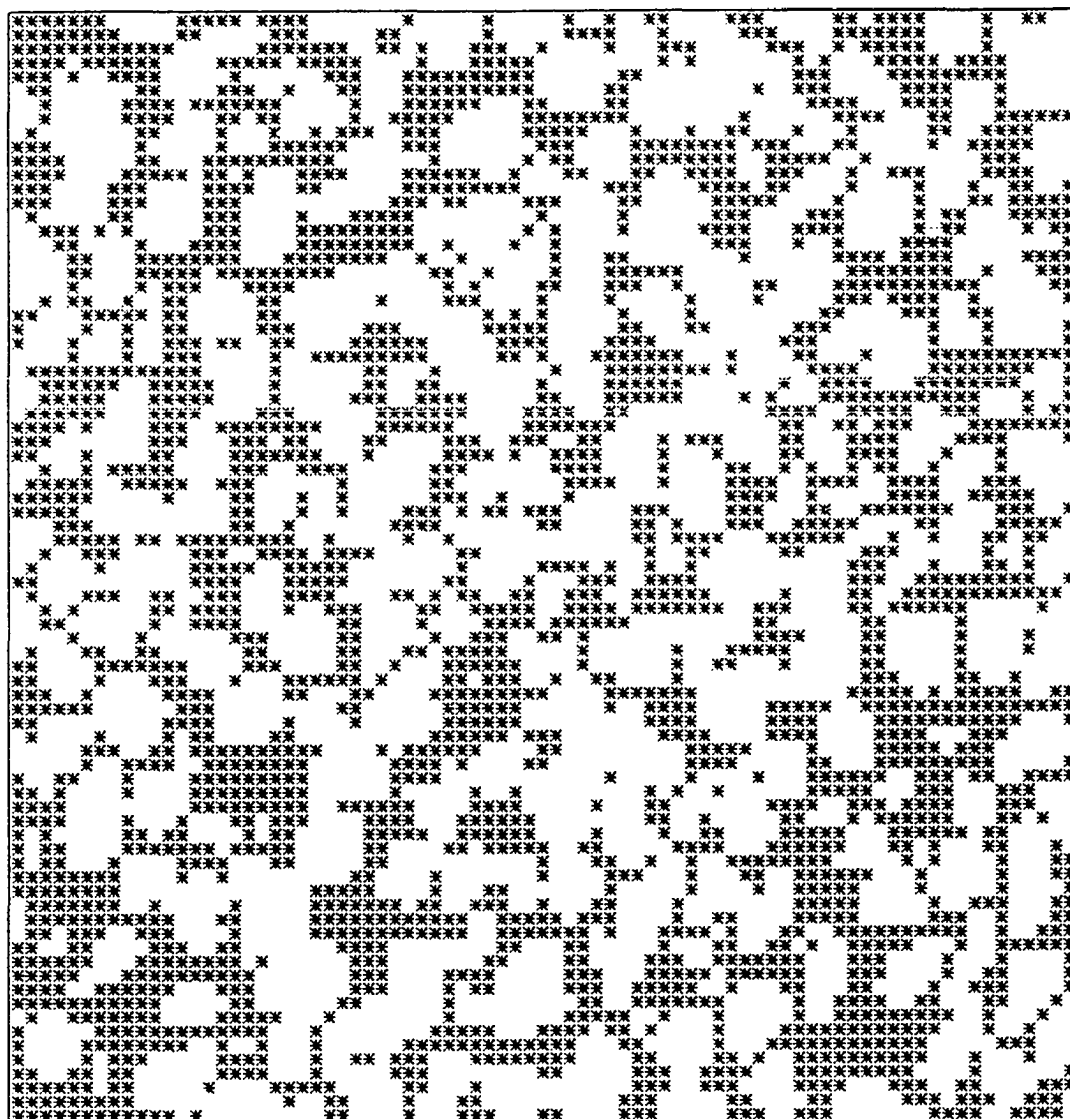
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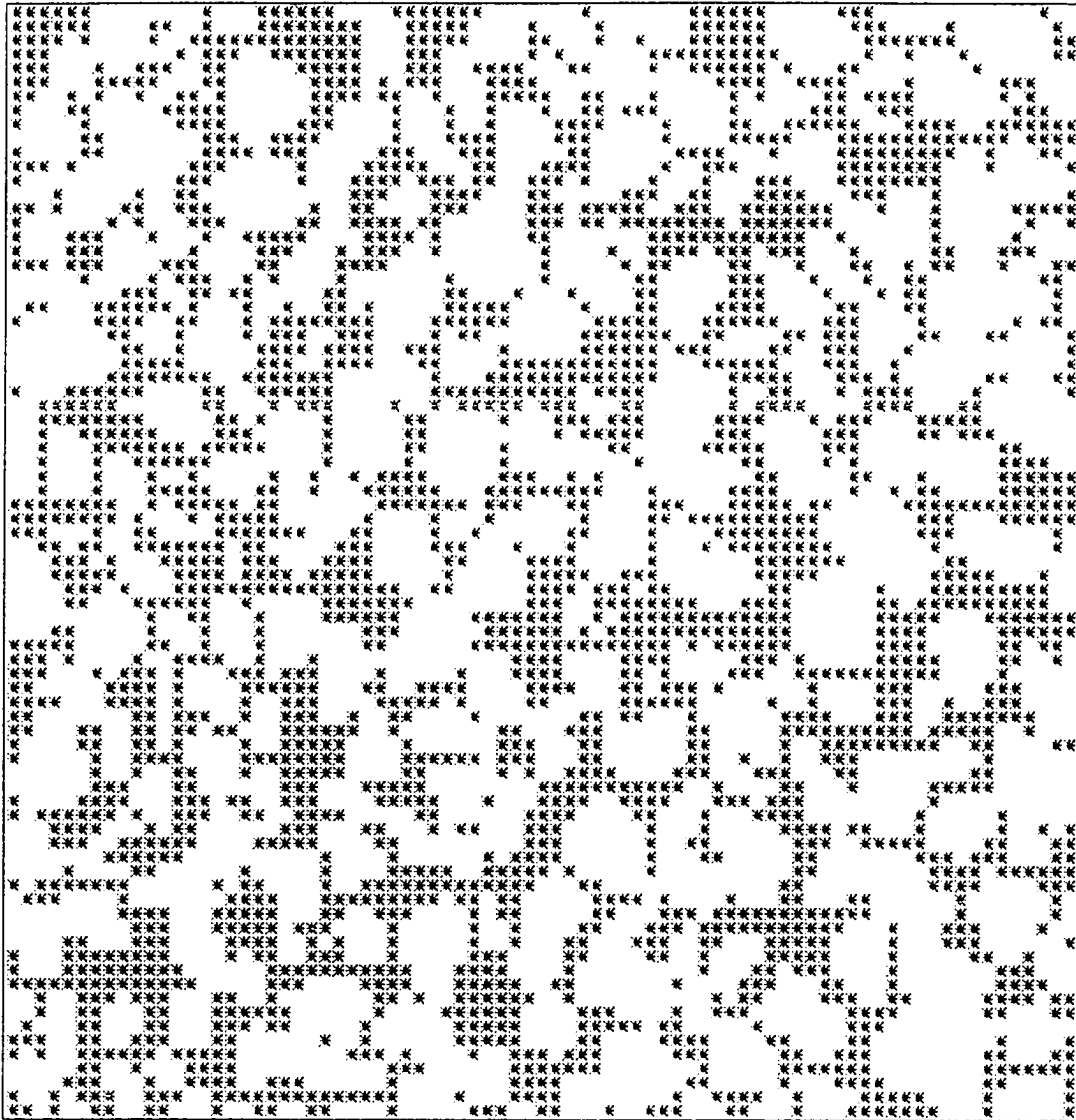
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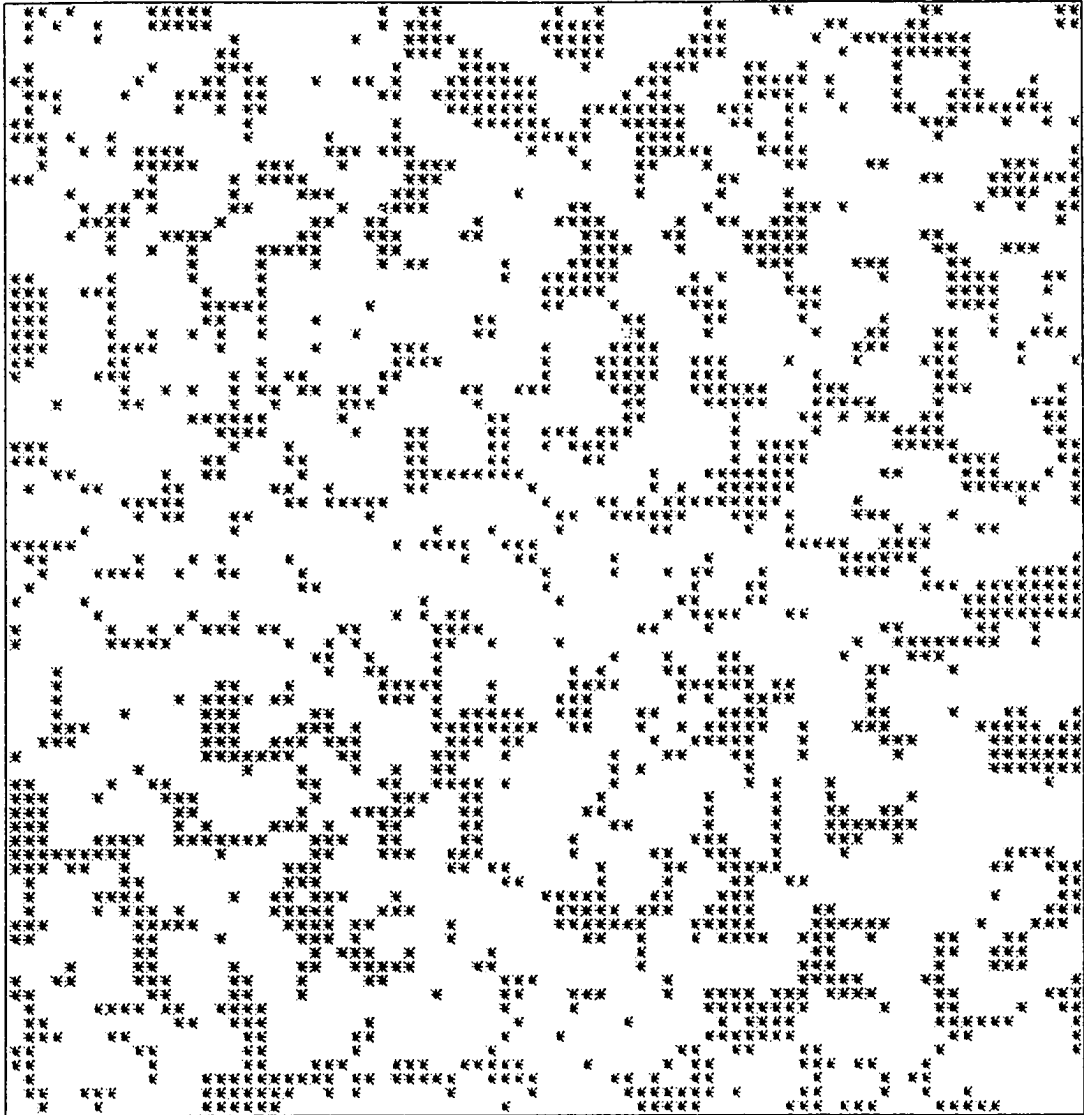
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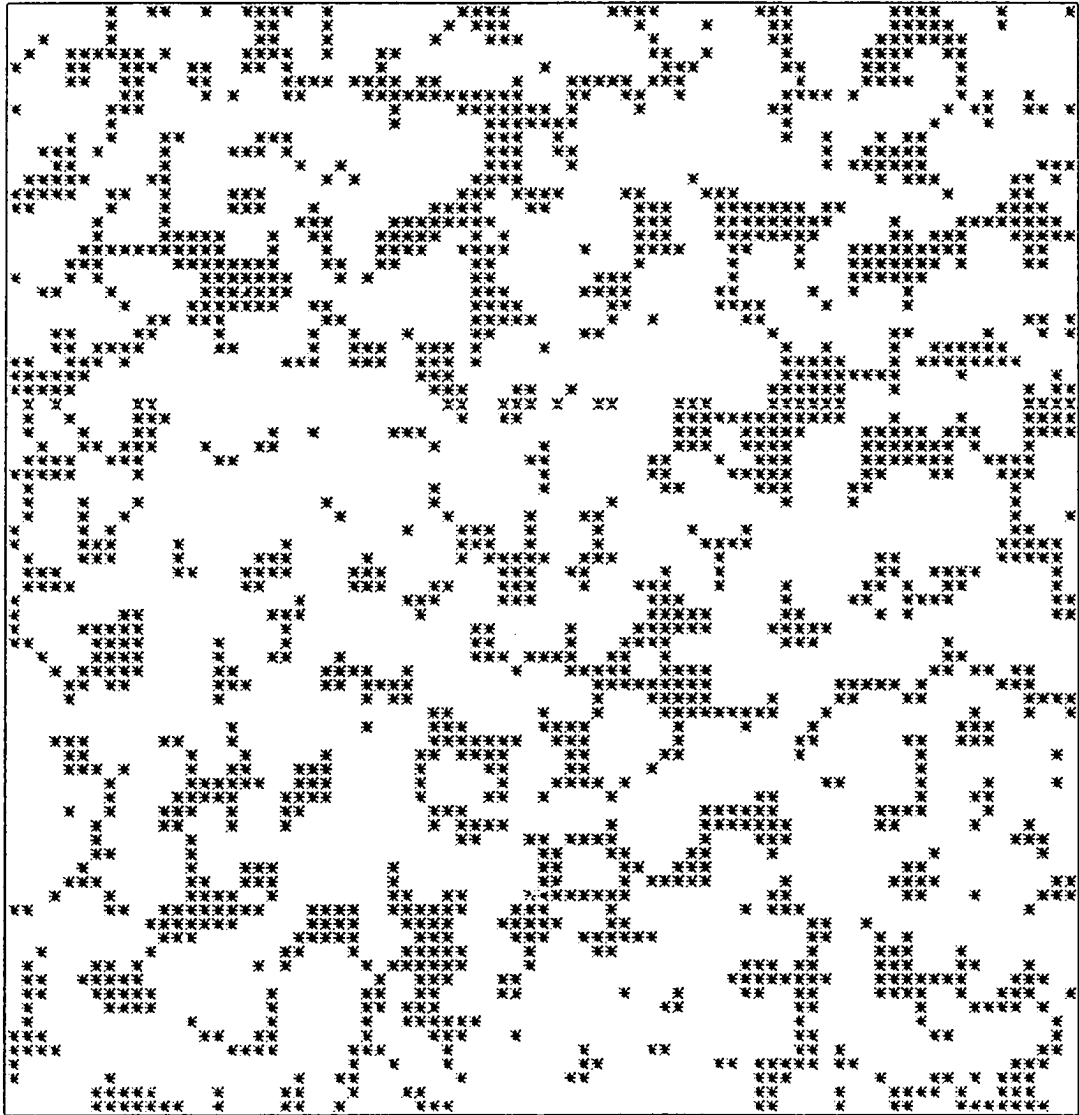
D3-15



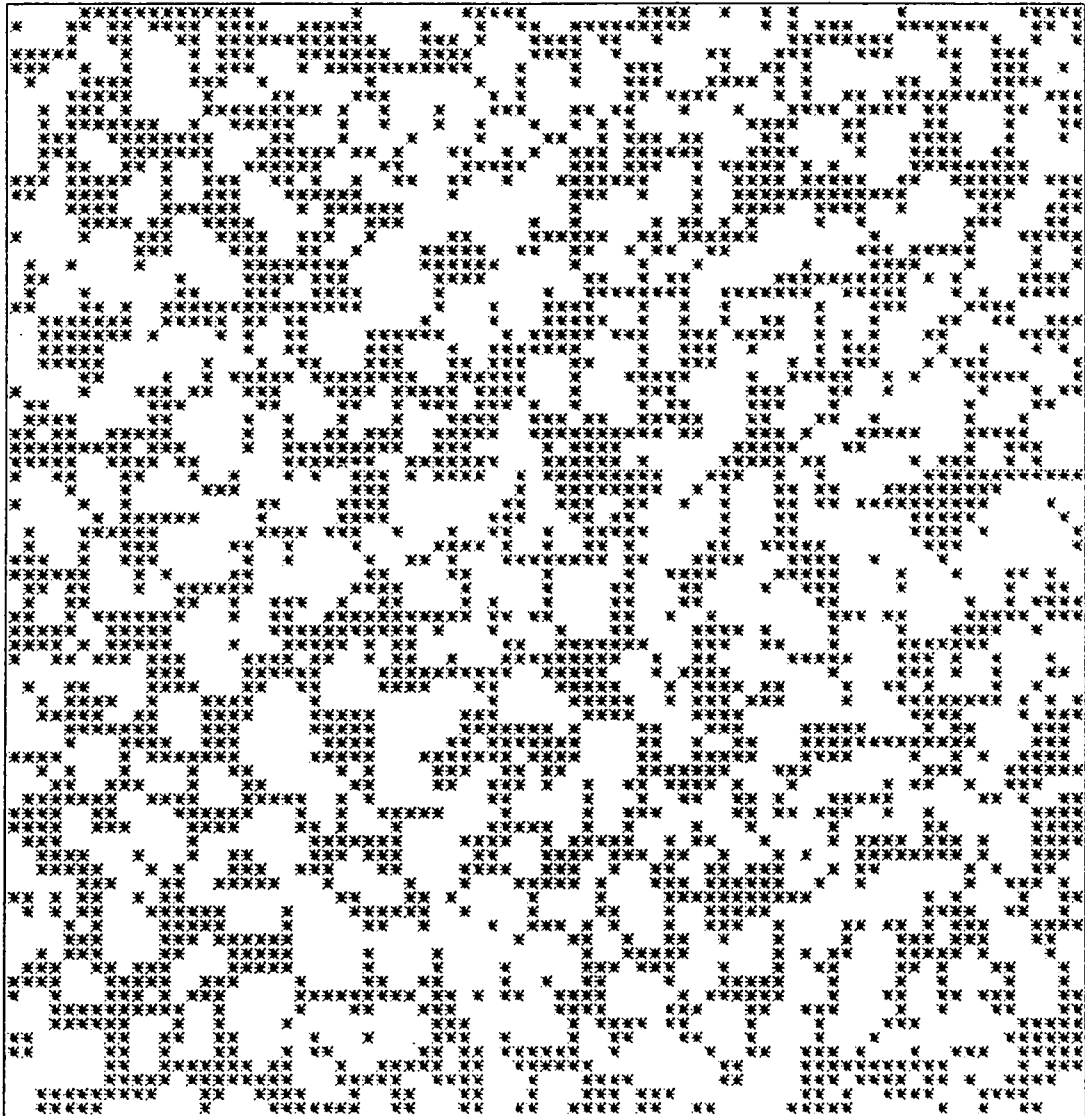
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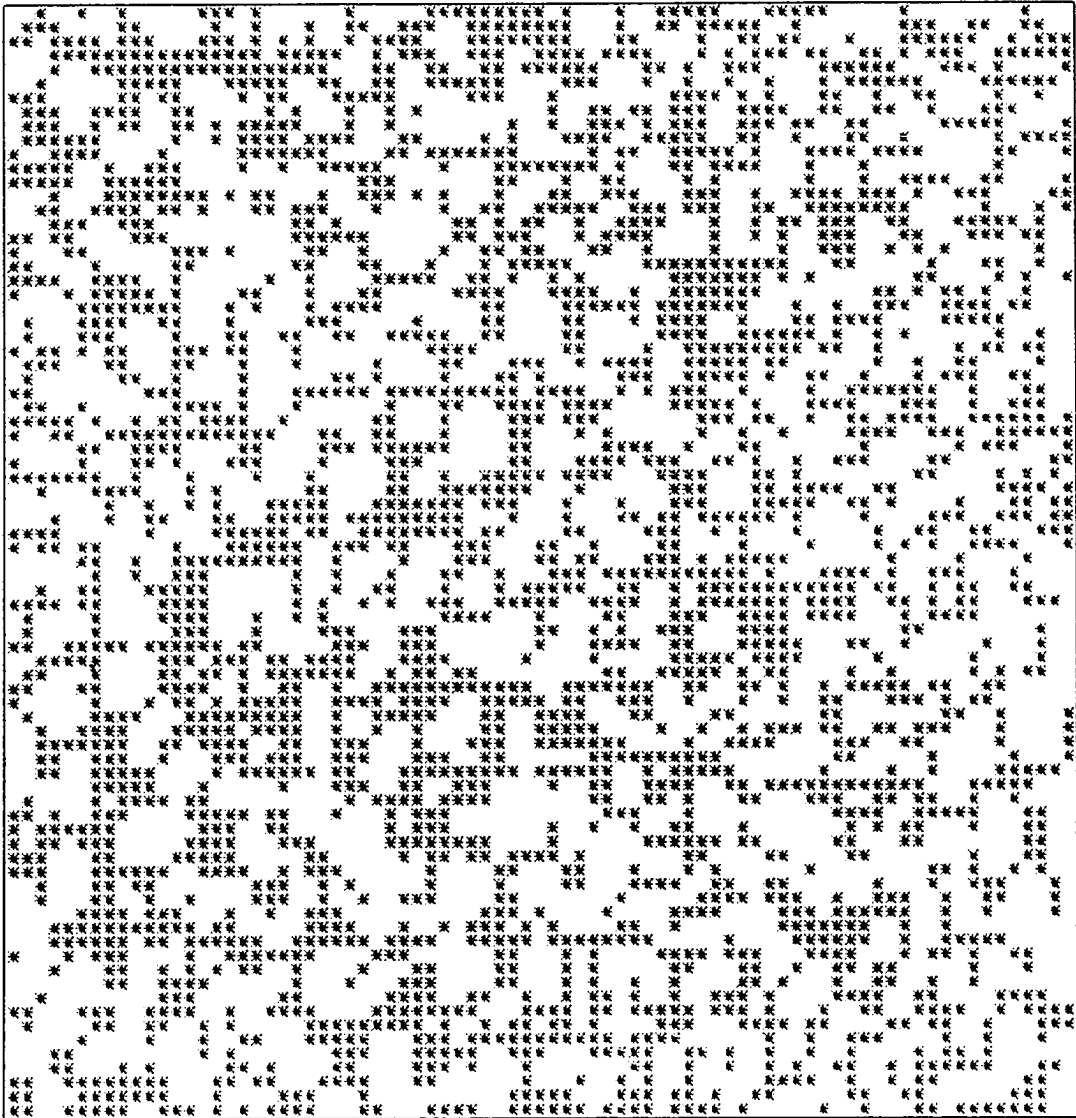
AD2-1e



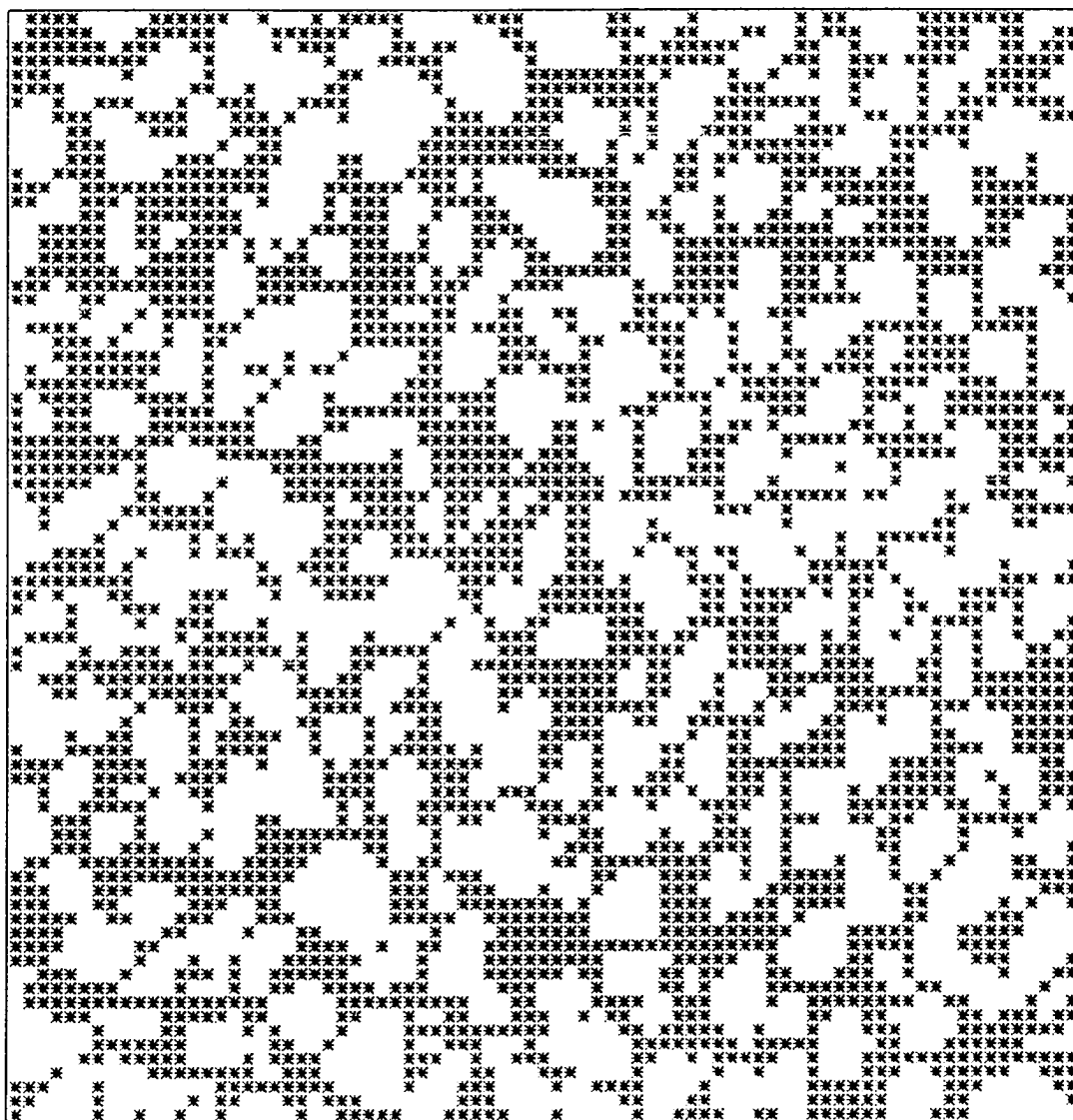
AD2-1f



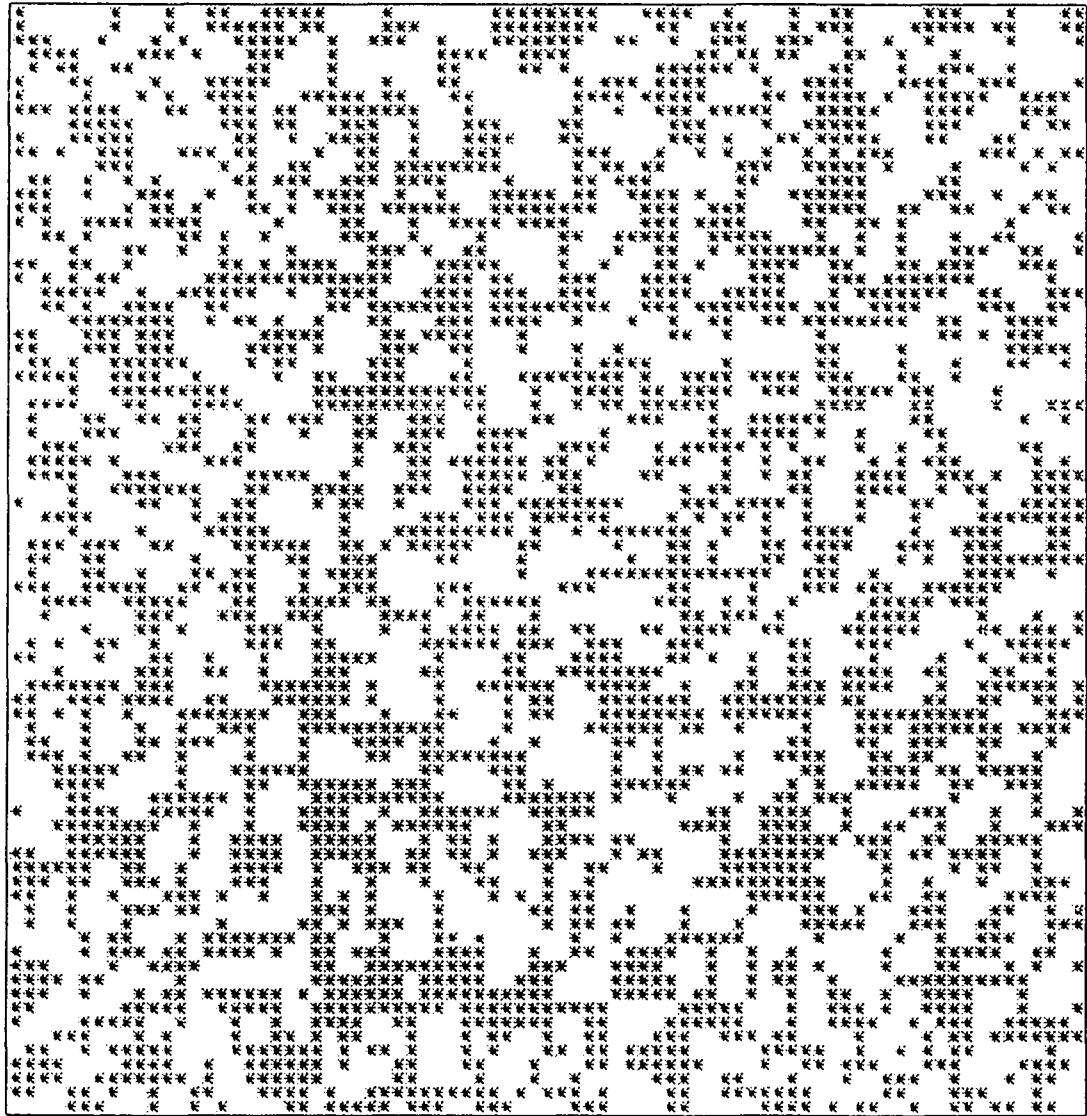
R5-23



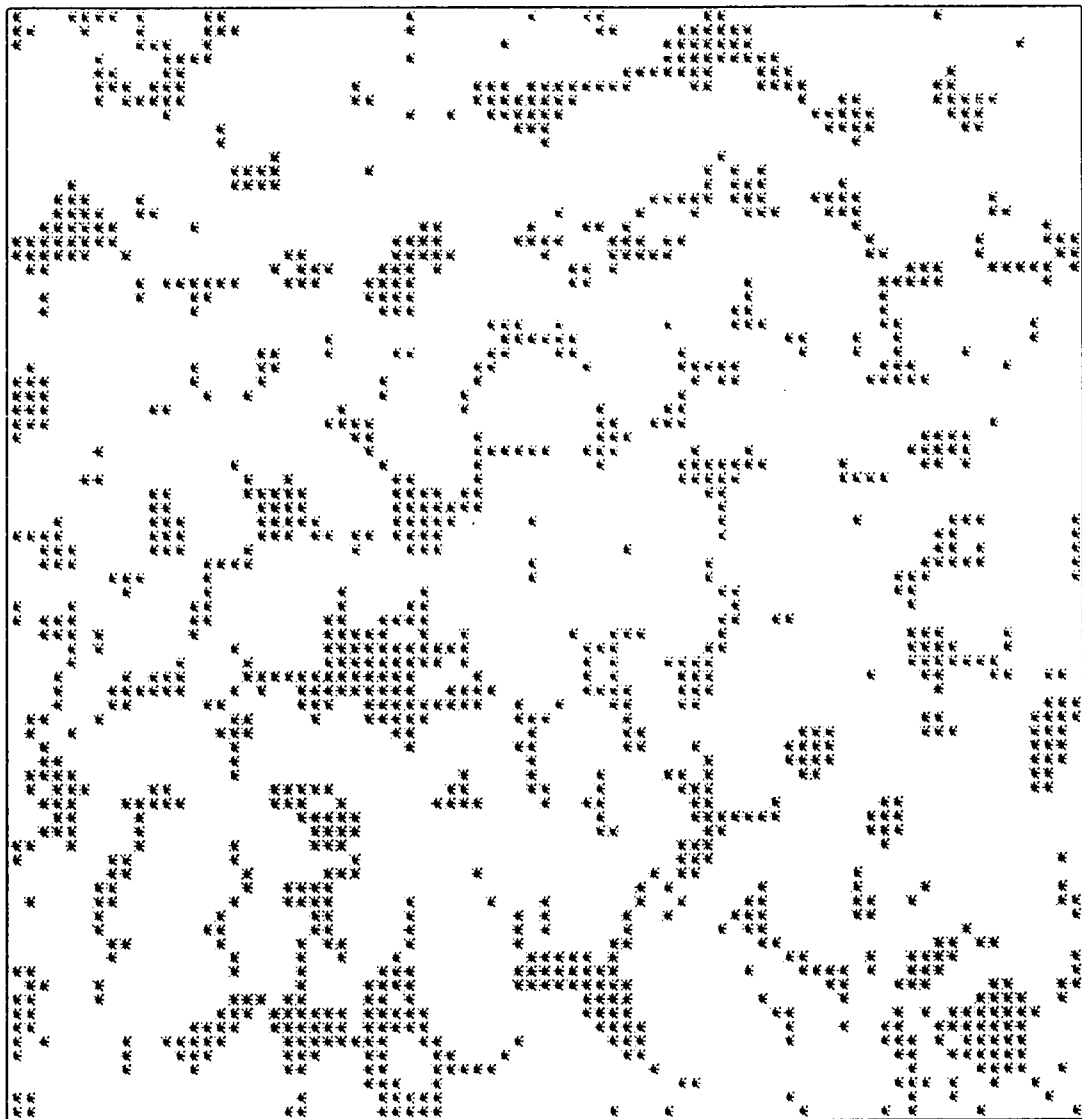
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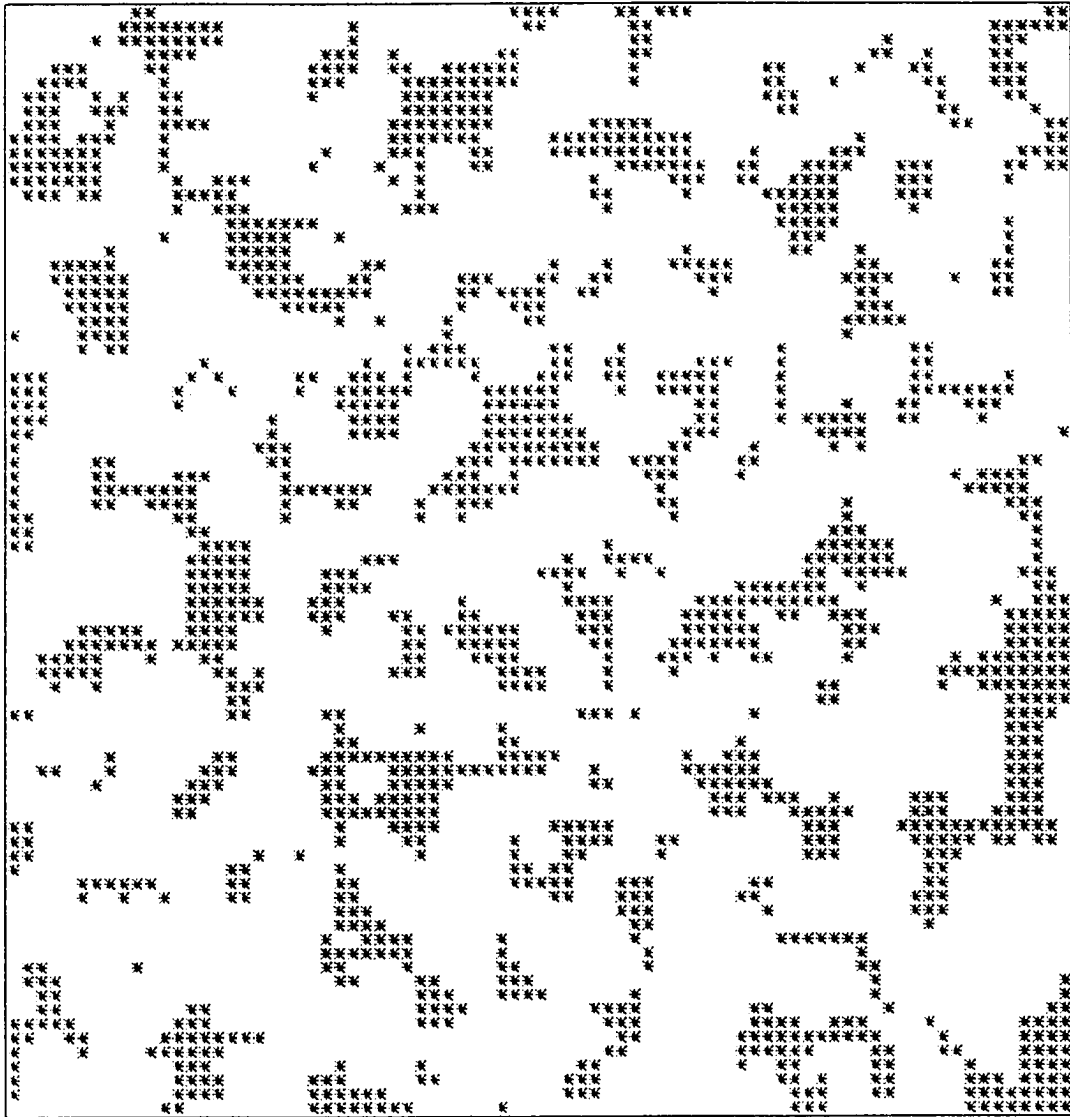
R5-21



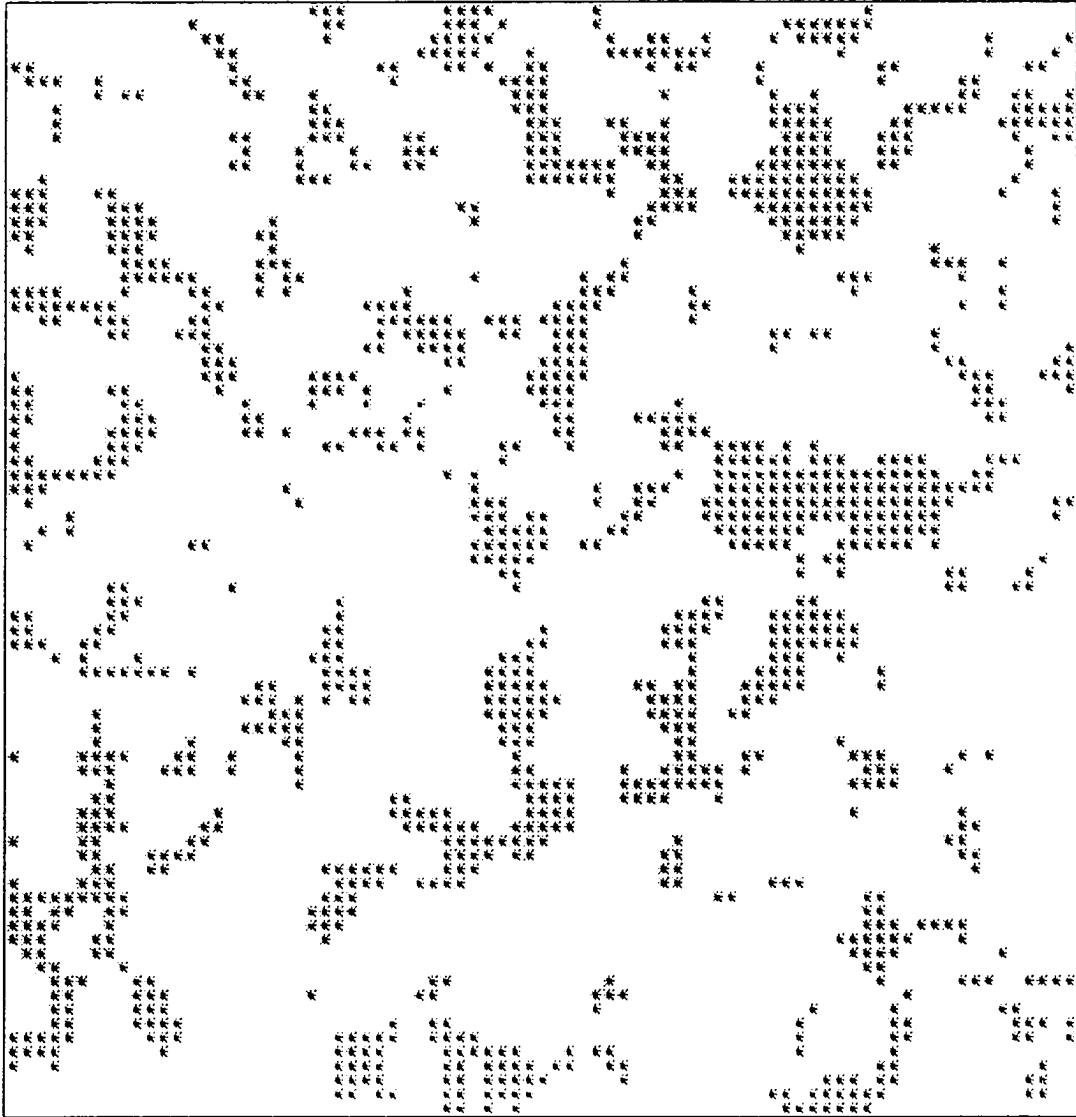
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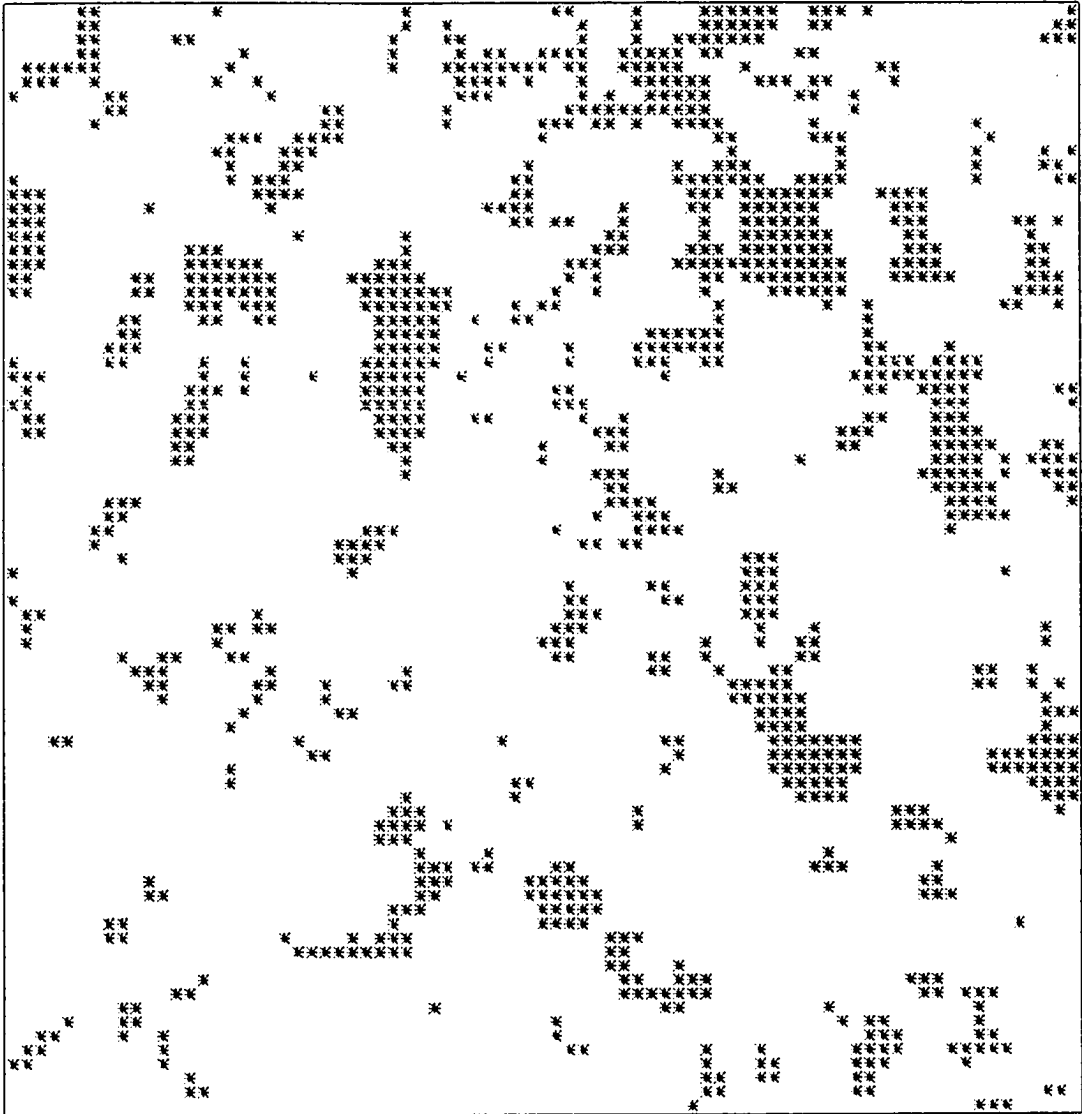
AR1-4c



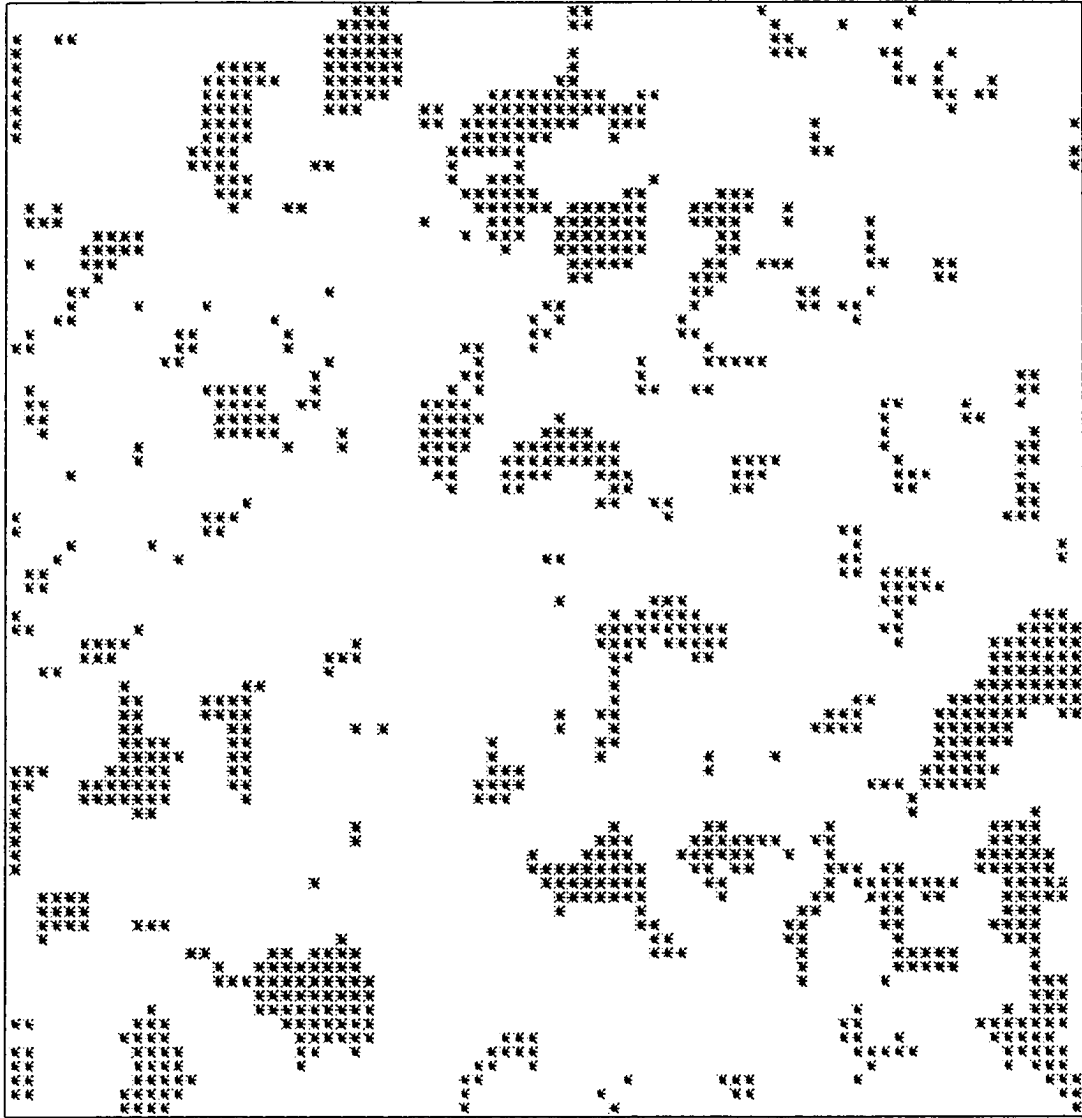
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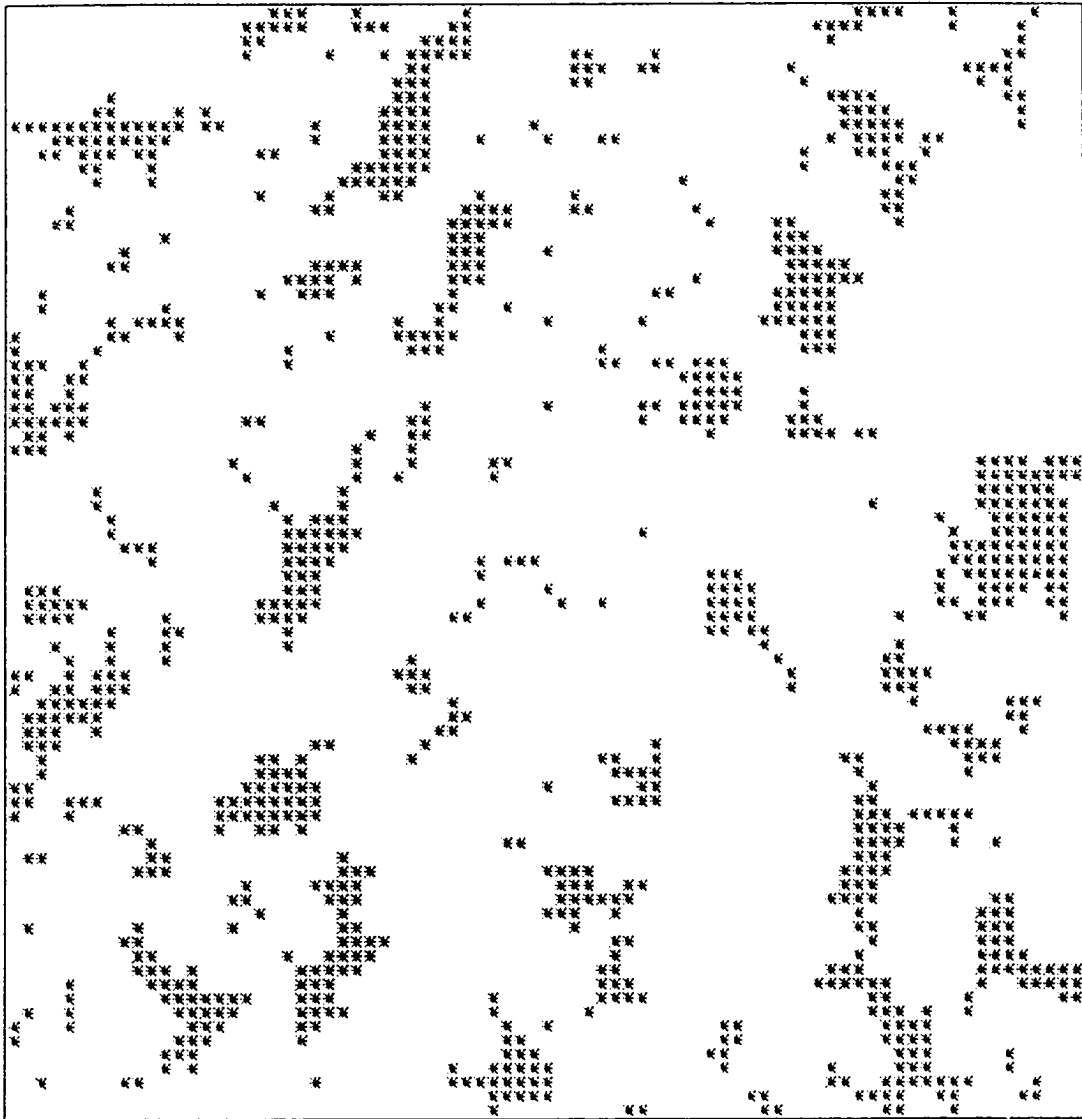
AR1-14



AR1-15a

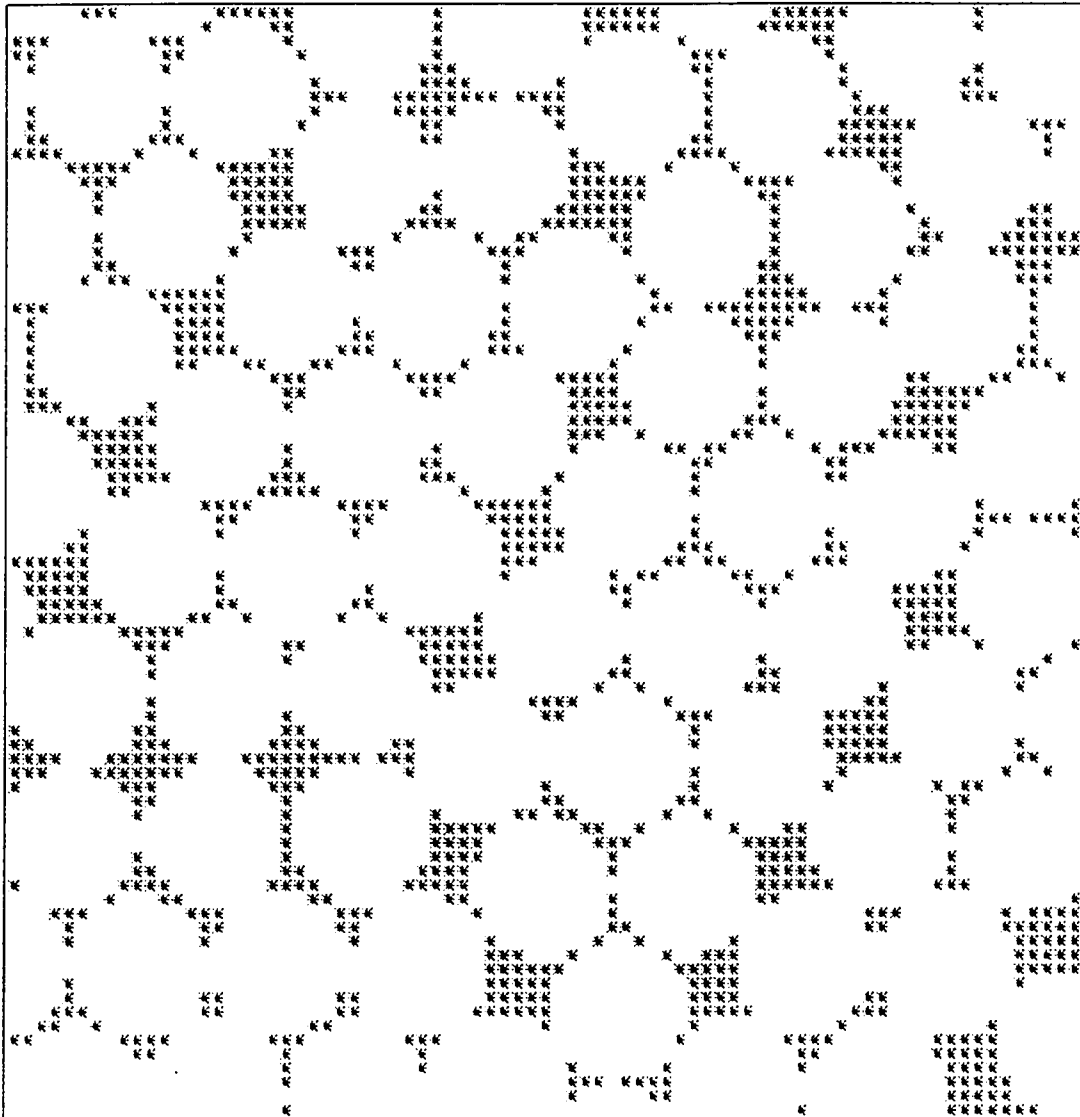


AR1-18

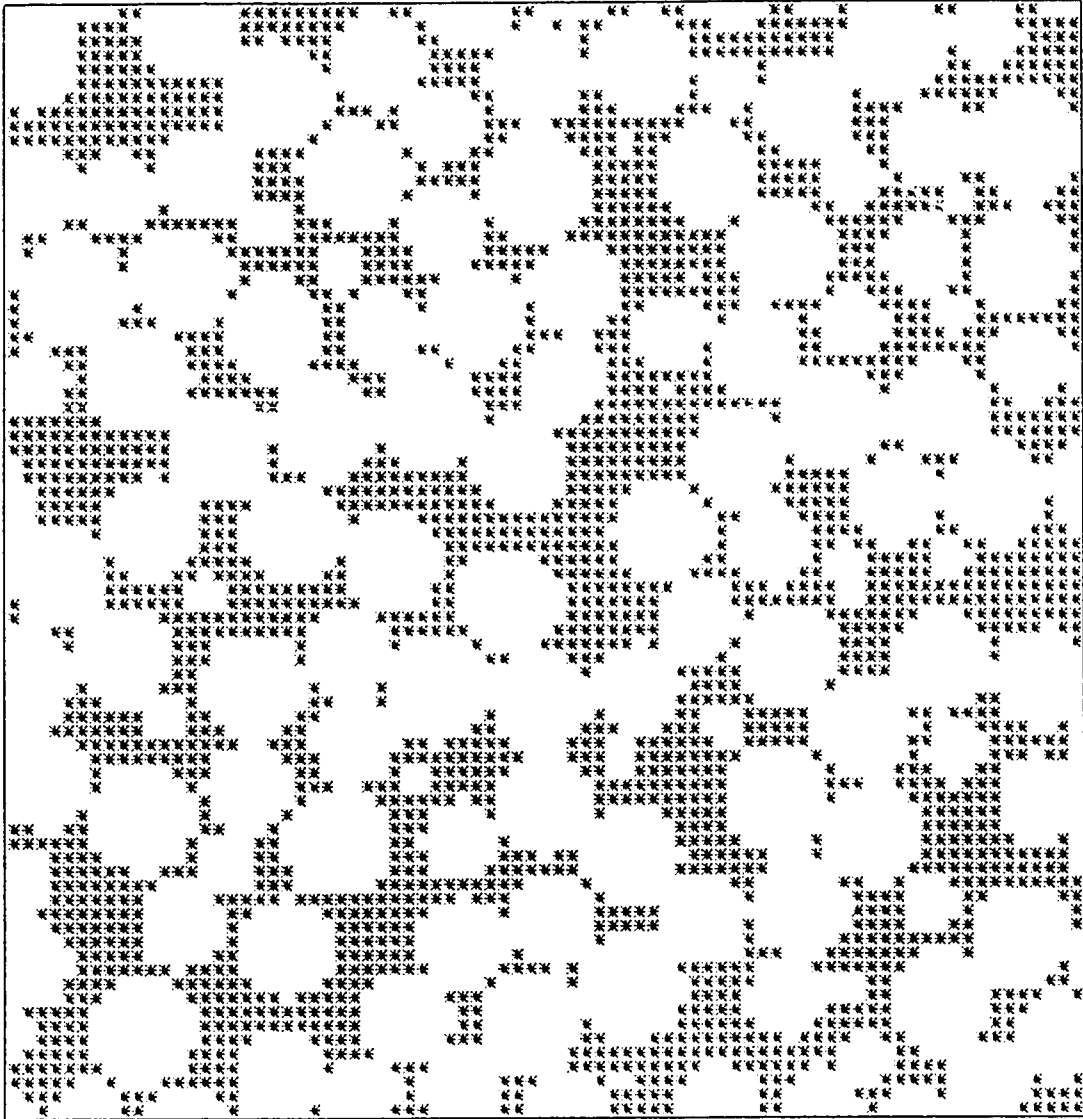


AR1-22c

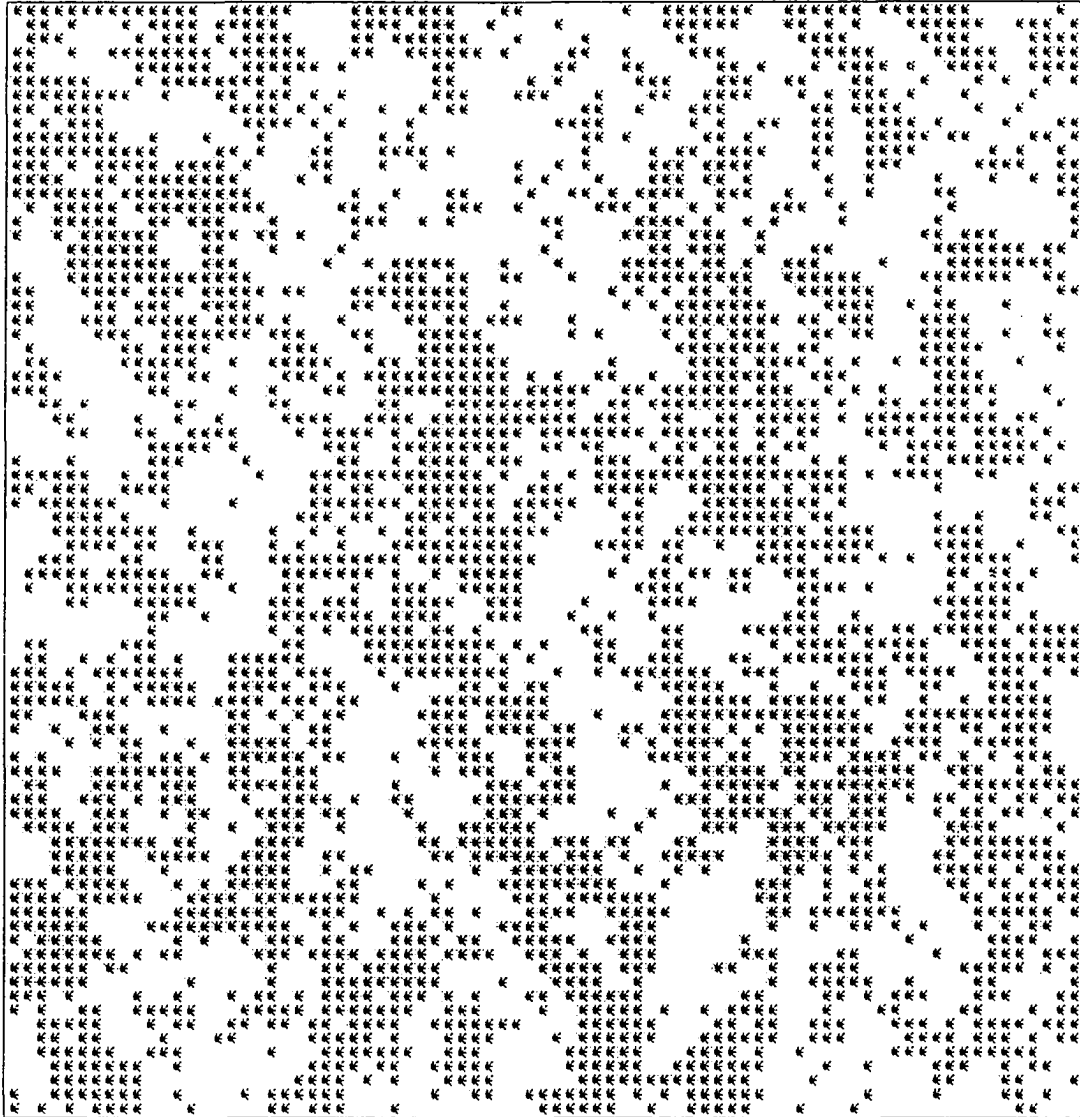
Part II: Test Patterns



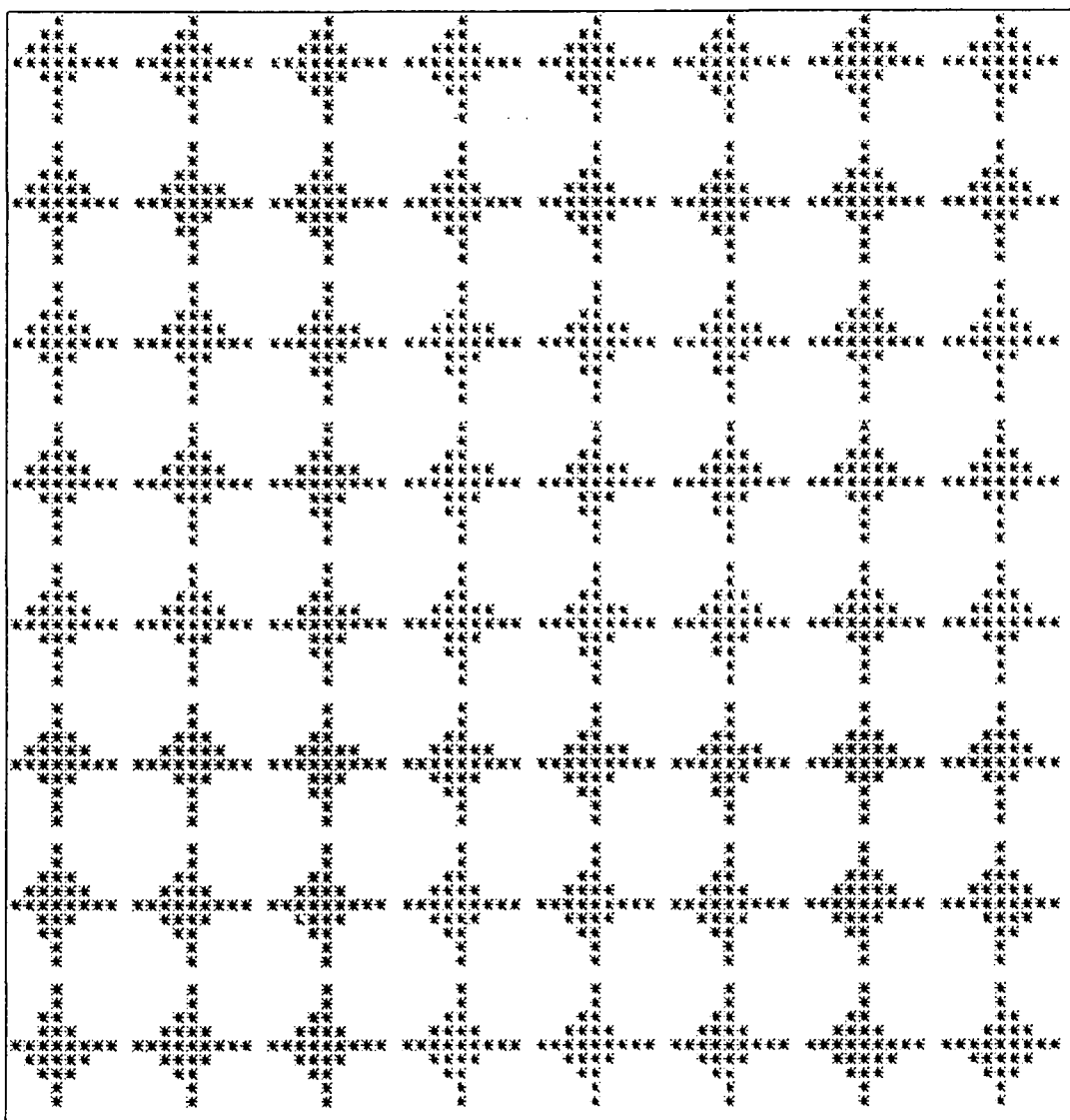
RAN-1



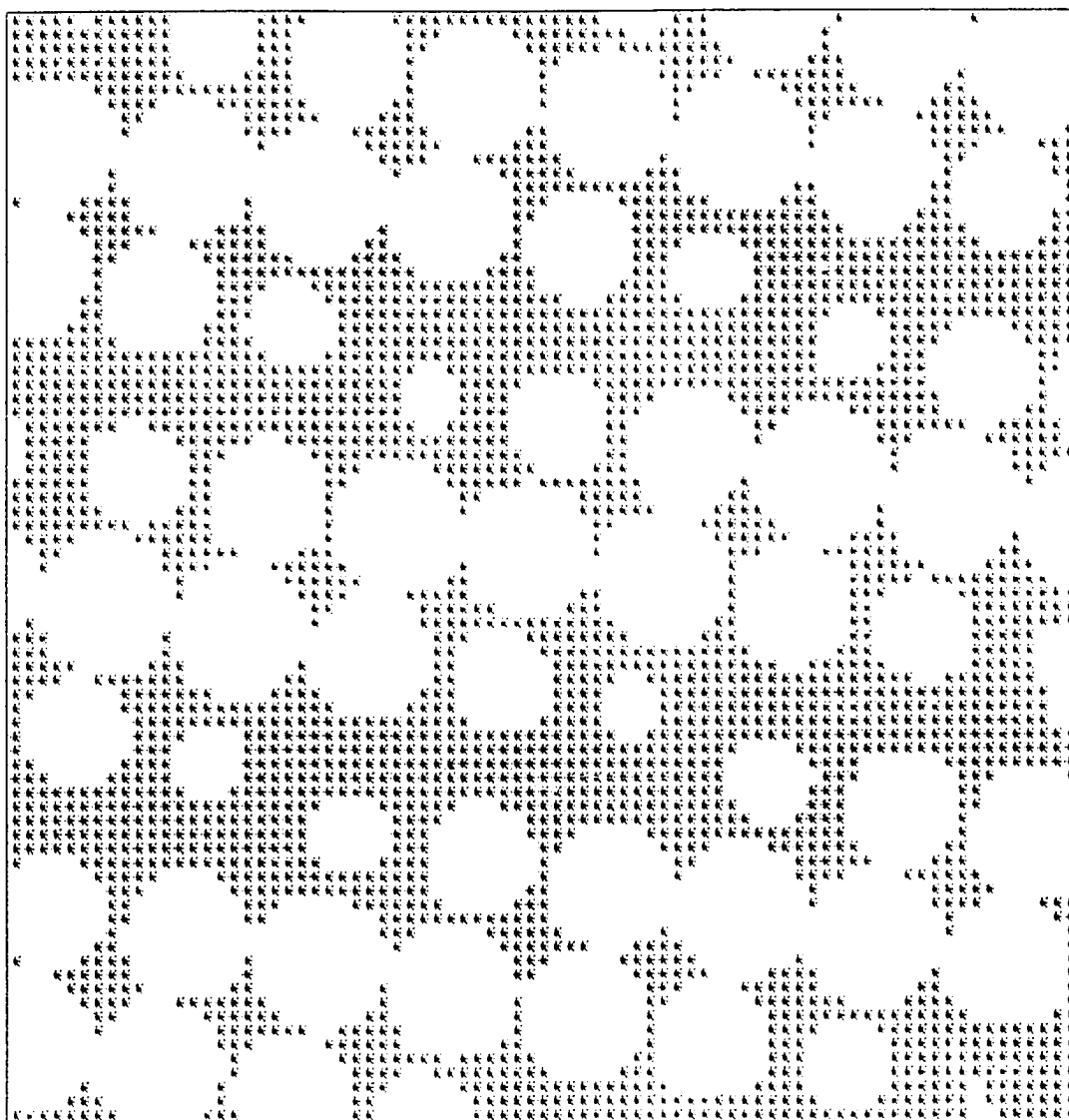
RAN-2



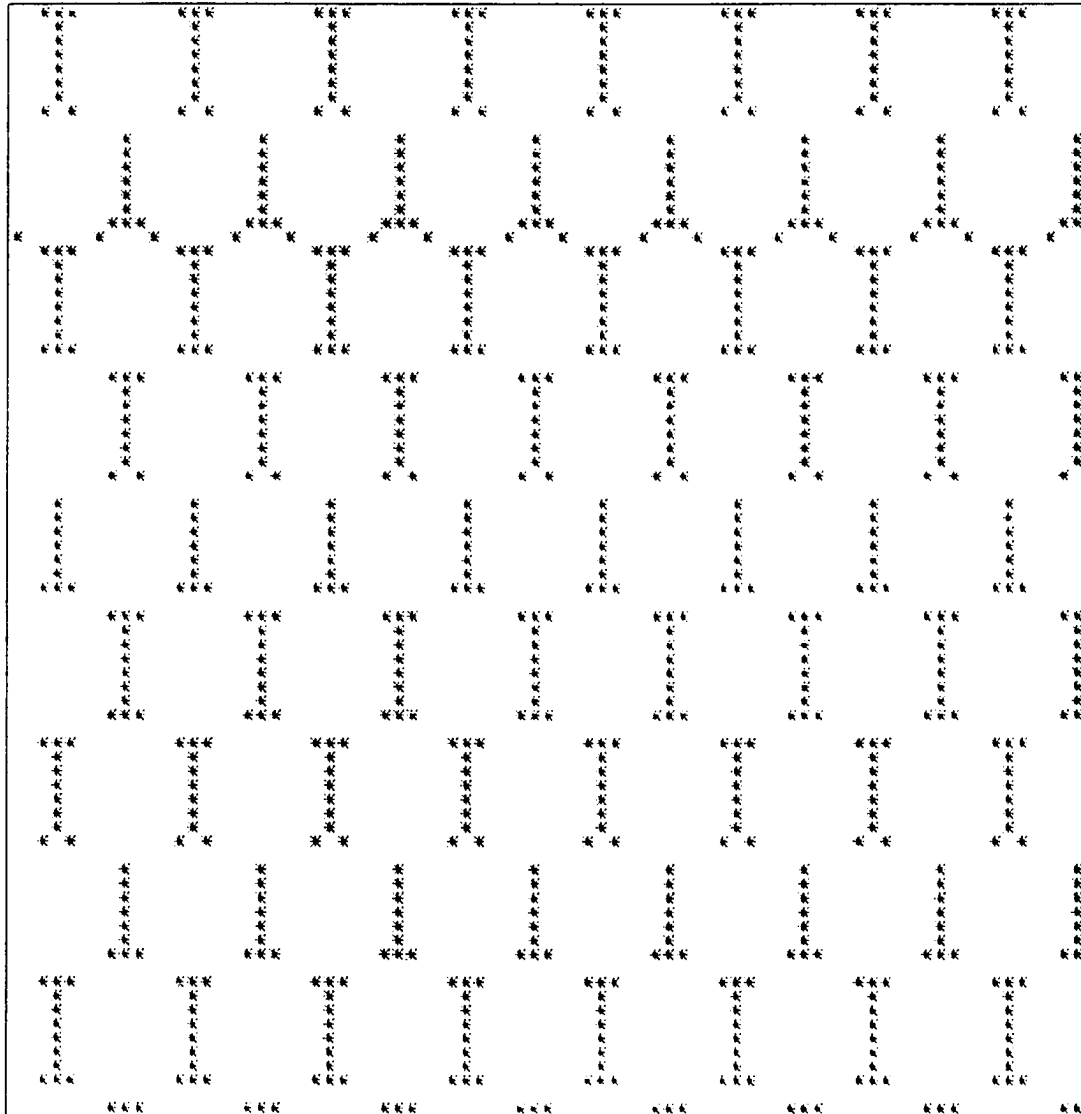
RAN-3



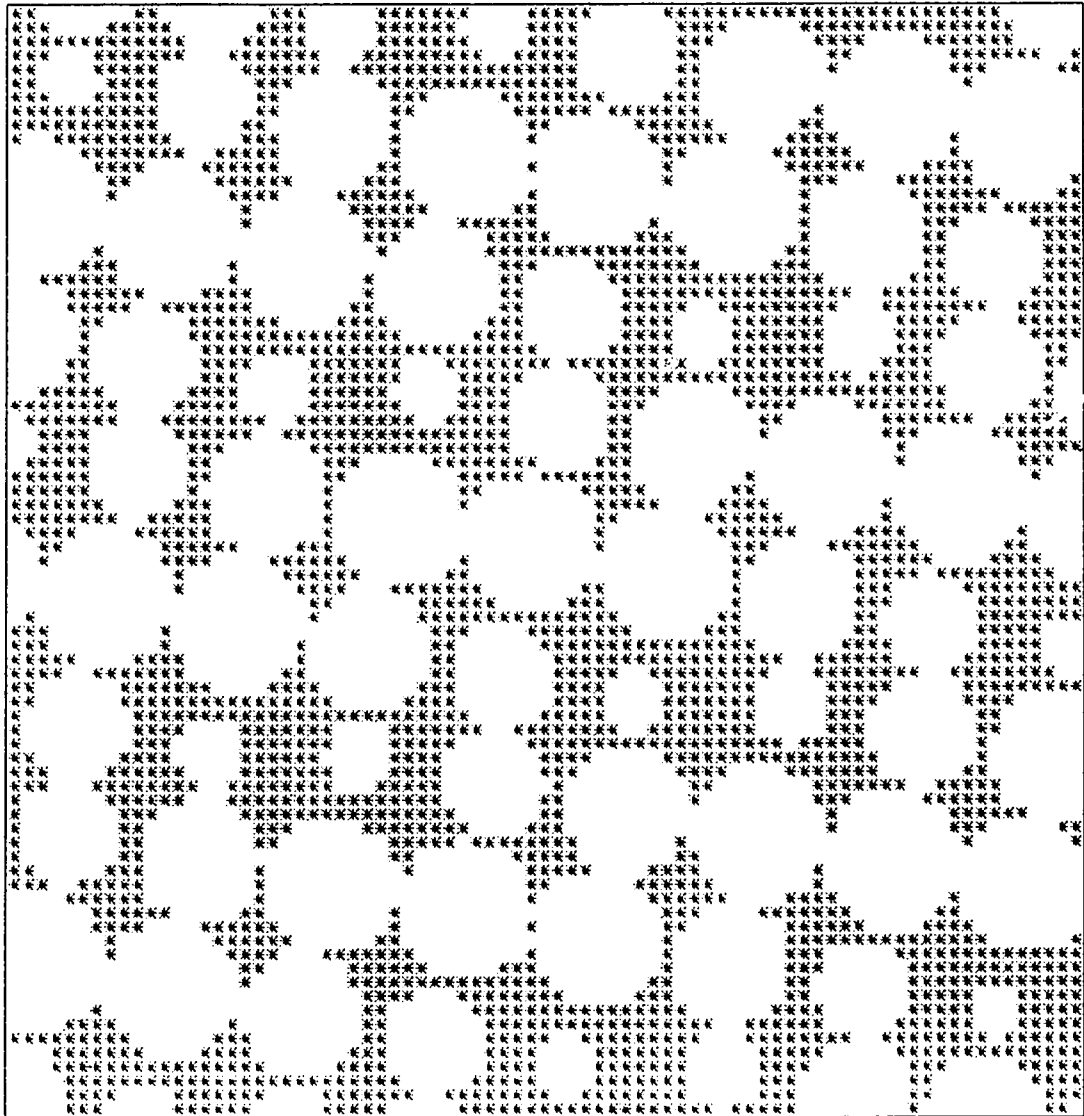
CASE1-P



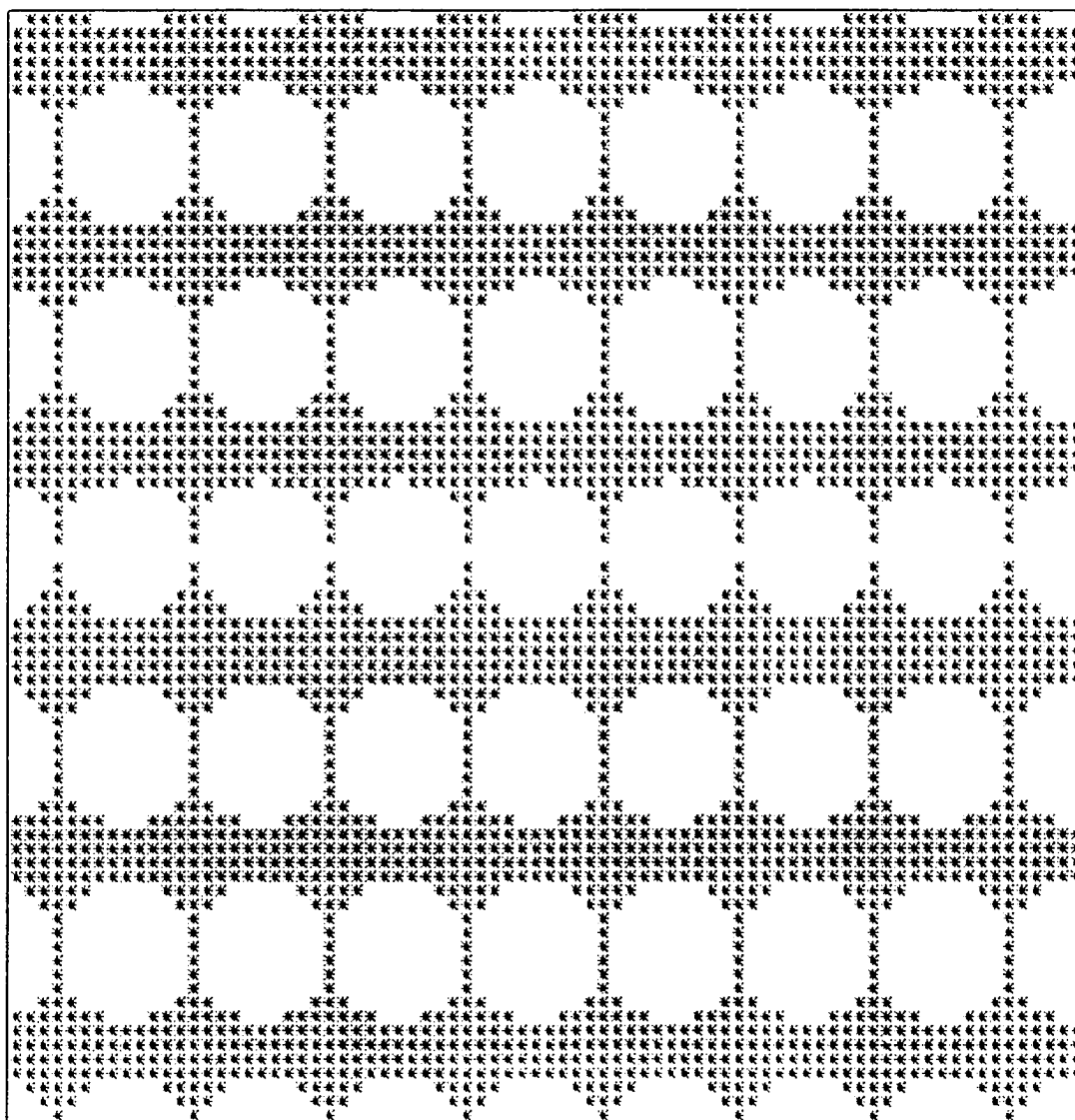
CASE1-OB



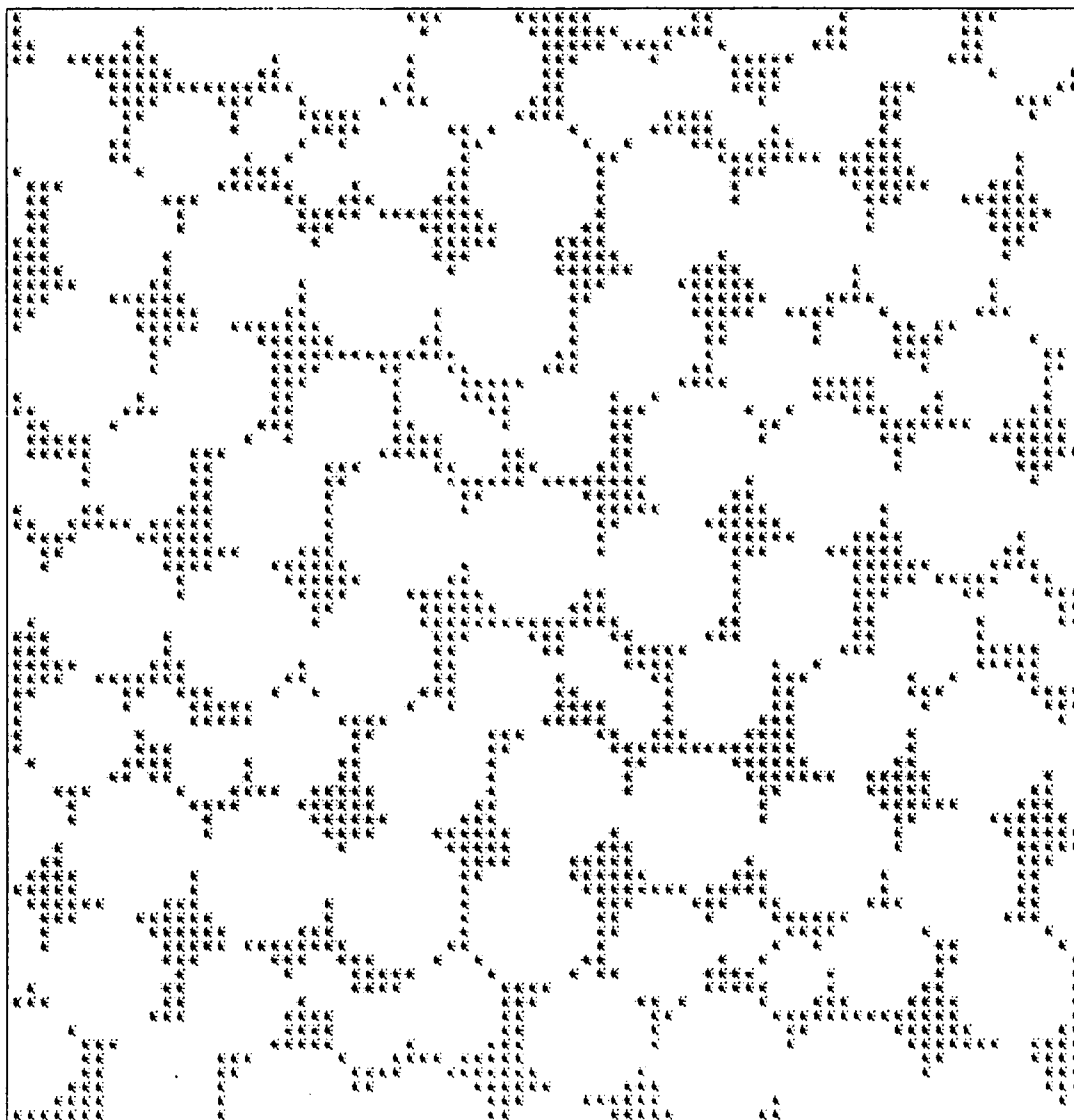
CASE2-P



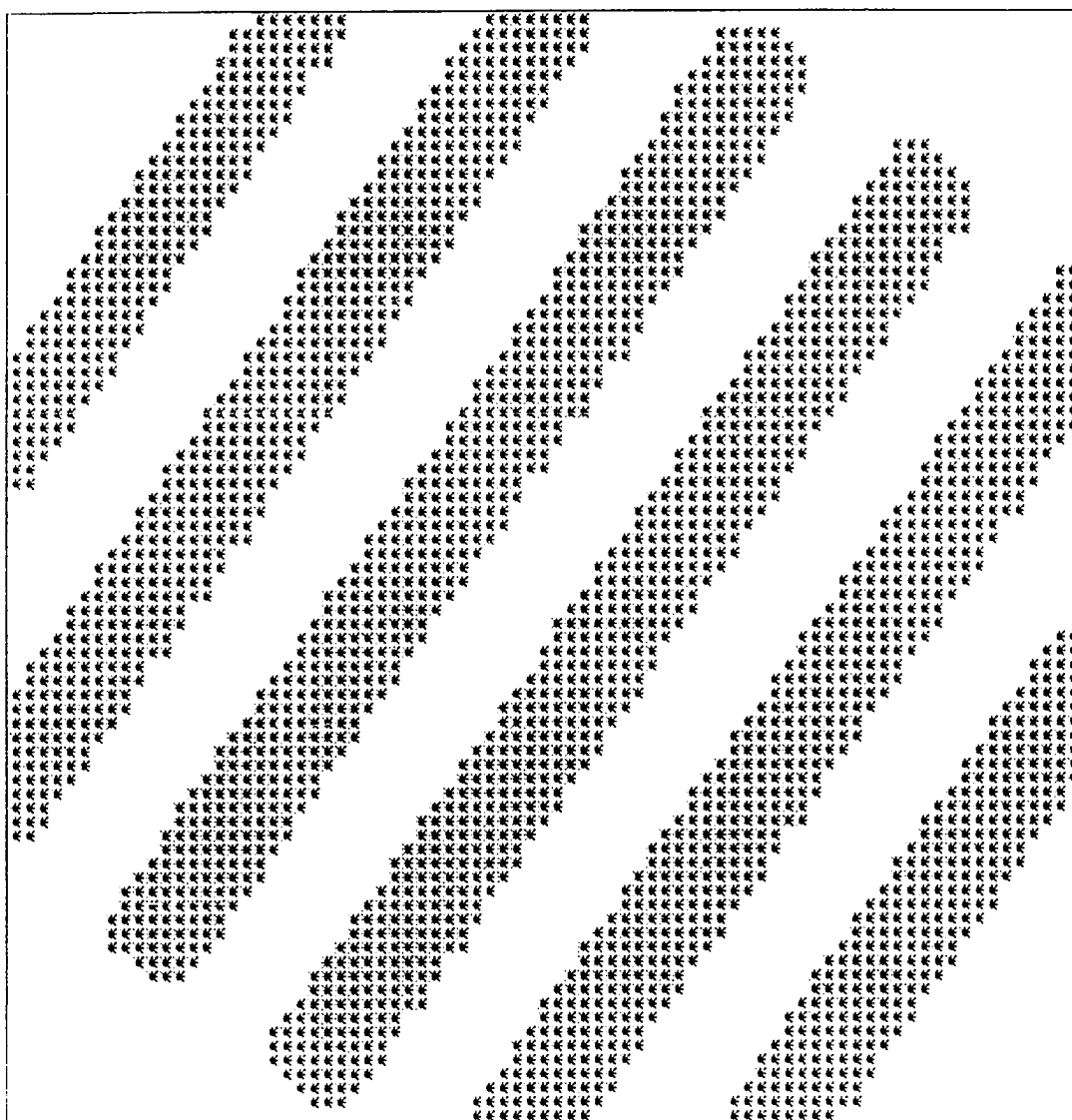
CASE2-OB



CASE3-P



CASE3-OB



STRIPES-36

APPENDIX L

ANNOTATED LISTING AND OUTPUT EXAMPLE FOR
THE FORTRAN IV COMPUTER PROGRAM 'PORESTAT'

Part I: Program

```

C *****
C *      *
C * PORESTAT *
C *      *
C *****
C
C
C THE PORESTAT PROGRAM COMPUTES PORE GEOMETRY STATISTICS (IT PROVIDES
C QUANTITATIVE DESCRIPTORS OF NUMEROUS GEOMETRICAL ASPECTS OF A PORE
C NETWORK).
C THE DATA SET REPRESENTS A DIGITIZED TWO-DIMENSIONAL PORE NETWORK.
C DIGITIZATION WAS ACHIEVED BY SUPERIMPOSING A NRC BY NRC SQUARE GRID
C ON A PICTURE OF THE PORE NETWORK. AT EACH GRID INTERSECTION THE
C PRESENCE OF PORE SPACE OR ROCK (I.E., GRAINS, CEMENT OR MATRIX)
C WAS NOTED. IN THIS WAY THE PICTURE WAS REDUCED TO A NRC BY NRC ARRAY
C OF 1'S (ROCK) AND -1'S (PORE).
C
C ***** CONTROL AND DATA CARDS *****
C
C ***** CONTROL CARD 1 *****
C NDFA (COL 1) = DOUBLE FOURIER ANALYSIS (BLANK/1 -- N/Y)
C NH (COLS 4-5) = NUMBER OF HARMONICS FOR DFA (MUST BE MULTIPLES
C                OF 10)
C NPOR (COL 8) = ANALYSIS OF POROSITY, SPECIFIC PORE PERIMETER, AND
C                AVERAGE PORE AND ROCK DIMENSIONS (BLANK/1 -- N/Y)
C RESO (COLS 11-15) = HORIZONTAL AND VERTICAL DISTANCE (IN MM)
C                BETWEEN ADJACENT ROCK/PORE POINTS
C NACA (COL 18) = AUTOCORRELATION ANALYSIS (BLANK/1 -- N/Y)
C NQUAD (COL 21) = QUADRAT POROSITY ANALYSIS (BLANK/1 -- N/Y)
C NFREQ (COL 24) = ANALYSIS OF PORE SIZE DISTRIBUTION (BLANK/1 -- N/Y)
C NORN (COL 27) = ANALYSIS OF PREFERRED DIRECTION OF PORE ELONGATION
C                (BLANK/1 -- N/Y)
C NTORT (COL 30) = PORE TORTUOSITY ANALYSIS (BLANK/1 -- N/Y)
C NPRNT (COL 33) = PRINT THE PORE NETWORK (BLANK/1 -- N/Y)
C NROCK (COL 36) = ANALYZE THE ROCK (NOT PORE) PATTERN (BLANK/1 - N/Y)
C
C ***** CONTROL CARD 2 *****
C COLS 1-12 = DATA SET NAME
C
C ***** DATA CARDS *****
C
C
C DIMENSION DC(80,80), MAT(80,80), PW(51,51), CARG(80),SARG(80),
C $ MHA(10),COM(99),IOUT(256),QP(10),MI(4000),MJ(4000),XE(500),
C $ YE(500), NE(500),NESUM(40),NEE(40),LAL(20)
C DIMENSION MROT(80,80),XIX(3600),YJY(3600),AXDD(10),AYDD(10),
C $ ANGS(10),NTPAV(3)
C DIMENSION MSAT(80,80), DE(500),MIS(500),MJS(500),NTP(3)
C DIMENSION MTOR(80,80),TE(500),NSI(9),NSJ(9),NTPS(3),TPTH(3)
C REAL*8 SUMCC,SUMCS,SUMSC,SUMSS,SUM,PSUM,SUMQP,SUMQP2,TORSUM

```

```

DATA ROCK/' '/
DATA ISTAR,IBLNK/'*', '/'
READ 902,NDFA,NH,NPOR,RESO,NACA,NQUAD,NFREQ,NORN,NTORT,NPRNT,NROCK
902 FORMAT(I1,2X,I2,2X,I1,2X,F5.0,2X,I1,2X,I1,2X,I1,2X,I1,2X,I1,
$2X,I1)
C ASSIGN VALUES TO THE VARIOUS CONSTANTS
NRC=79
IF(NTORT.EQ.1) NFREQ=1
IF(NORN.EQ.1) NPOR=1
LAGMAX=NRC/2.
MAG=50
NPASS=0
MSUM=0
DO 901 I=1,NH
901 MHA(I)=I
C READ THE DATA SET NAME
READ 904, TAG1,TAG2,TAG3
904 FORMAT(3A4)
C READ THE INFORMATION ON THE DATA CARDS INTO THE ARRAY DC (BLANK
C COLUMN = PORE, AND COLUMNS WITH NONBLANK CHARACTERS = ROCK)
DO 910 I=1,NRC
READ 905, (DC(I,J),J=1,NRC)
905 FORMAT(79A1)
910 CONTINUE
C TRANSFORM THE DATA IN ARRAY DC SO THAT PORE SPACE HAS A NUMERICAL
C VALUE OF -1 AND ROCK HAS A NUMERICAL VALUE OF 1. TRANSFER THIS QUAN-
C TITIZED ROCK/PORE INFORMATION INTO THE ARRAY MAT.
DO 920 I=1,NRC
DO 920 J=1,NRC
IF(DC(I,J).EQ.ROCK) GO TO 912
GO TO 915
912 MAT(I,J)=1
IF(NROCK.EQ.1) MAT(I,J)=-1
GO TO 918
915 MAT(I,J)=-1
IF(NROCK.EQ.1) MAT(I,J)=1
C MSUM = THE SUM OF ALL NRC * NRC ELEMENTS IN MAT
918 MSUM=MSUM + MAT(I,J)
MSAT(I,J)=MAT(I,J)
920 CONTINUE
C PRINT THE DATA SET NAME
PRINT 930, TAG1,TAG2,TAG3
930 FORMAT('1',20('*')/1X,'*',18X,'*/1X,'*',1X,16('*'),1X,'*/1X,'* *
$',14X,'* */1X,'* * ',3A4,' * */1X,'* *',14X,'* */1X,'*',1X,16(
$*'),1X,'*/1X,'*',18X,'*/1X,20('*')////////)
IF(NROCK.EQ.1) GO TO 1681
GO TO 1683
1681 PRINT 1682
1682 FORMAT(1X,'ONLY THE ROCK PATTERN WILL BE ANALYZED'///)
1683 CONTINUE

```

```

C   PRINT THE CONTENTS OF ARRAY DC (ROCK = BLANKS, PORE SPACE = SYMBOL)
      IF(NPRNT.EQ.0) GO TO 5341
      PRINT 931
931  FORMAT(37X,' ROCK(BLANK)/PORE(X) MAP'////)
      DO 940 I=1,NRC
      PRINT 935,(DC(I,J),J=1,NRC)
935  FORMAT(10X,79A1)
940  CONTINUE
      PRINT 942
942  FORMAT(///1X,'|| C'/1X,'|| O'/1X,'|| L'/1X,'|| U'/1X,'|| M',
      $/1X,'|| N'/1X,'|| S')
5341 CONTINUE
      IF(NDFA.EQ.0) GO TO 156
C   *****
C
C   DOUBLE FOURIER ANALYSIS
C
C   *****
      PIL=(2.*3.141593)/NRC
      CONST=4./(NRC*NRC)
      DO 80 N=1,NH
      DO 80 M=1,NH
      SUMCC=0.
      SUMCS=0.
      SUMSC=0.
      SUMSS=0.
      DO 40 I=1,NRC
      ARG=PIL * N * I
      COSIN=COS(ARG)
      SININ=SIN(ARG)
      DO 30 J=1,NRC
      ARG= PIL * M * J
      CARG(J)=COS(ARG)
      SARG(J)=SIN(ARG)
30  CONTINUE
      DO 40 J=1,NRC
      SUMCC=SUMCC + MAT(I,J)*COSIN*CARG(J)
      SUMCS=SUMCS + MAT(I,J)*COSIN*SARG(J)
      SUMSC=SUMSC + MAT(I,J)*SININ*CARG(J)
40  SUMSS=SUMSS + MAT(I,J)*SININ*SARG(J)
C   A, B, C AND D ARE THE FOURIER COEFFICIENTS
      A=CONST*SUMCC
      B=CONST*SUMCS
      C=CONST*SUMSC
      D=CONST*SUMSS
C   PW = POWER OF THE N TH AND M TH HARMONICS
      PW(N,M)=(A*A + B*B + C*C + D*D)/4.
80  CONTINUE
      SUM=0.

```

```

C   AMAT = THE AVERAGE VALUE OF NRC * NRC ELEMENTS IN THE ARRAY MAT
      AMAT=MSUM/(NRC*NRC*1.)
      DO 90 I=1,NRC
      DO 90 J=1,NRC
90   SUM=SUM + (MAT(I,J)-AMAT)**2
C   VMAT = THE VARIANCE OF THE NRC * NRC ELEMENTS IN THE ARRAY MAT
      VMAT=SUM/(NRC*NRC*1.-1.)
      PSUM=0.
      PWMAX=0.
      DO 100 N=1,NH
      DO 100 M=1,NH
      PSUM=PSUM + PW(N,M)
      IF(PW(N,M).GT.PWMAX) PWMAX=PW(N,M)
100  CONTINUE
      DO 7768 N=1,NH
      DO 7768 M=1,NH
      MROT(N,M)=((PW(N,M)/PWMAX) + .00001) * 100.
7768 CONTINUE
C   PSUM = THE PERCENTAGE OF THE TOTAL VARIANCE EXPLAINED BY THE NH * NH
C   HARMONICS
      PSUM=(PSUM/VMAT)*100.
C PRINT THE RESULTS OF DOUBLE FOURIER ANALYSIS
      PRINT 932
932  FORMAT('1',4X,'***'/5X,'***'/5X,'***'/3X,'*****'/4X,'*****'/5X,'
$***'/6X,'*')
101  FORMAT(1H1)
      PRINT 110,NH,NH
110  FORMAT(1X,'DOUBLE FOURIER POWER SPECTRUM',10X,I2,' X ',I2,' HARMON
$ICS'////)
      PRINT 120, AMAT,VMAT,NH,PSUM
120  FORMAT(1X,'ROCK/PORE MATRIX ELEMENTS: MEAN =' ,F7.4, ' AND VARIA
$NCE =' ,F8.4//1X,'THE PERCENTAGE OF THE TOTAL VARIANCE EXPLAINED BY
$ THE ',I2,'**2 HARMONICS =' ,F8.3////)
      MMM=1
      MTT=1
      MTTT=NH/10
      MMMM=10
      DO 155 MM=MTT,MTTT
      PRINT 130,(MHA(M),M=MMM,MMMM)
130  FORMAT(1X,110('*')/1X,'*',108X,'*/1X,'*',9X,I2,8X,8(I2,8X),I2,7X,
$'*/1X,'*',108X,'*/1X,'*',108X,'*')
      DO 139 N=1,NH
139  PRINT 140,N,(MROT(N,M),M=MMM,MMMM)
140  FORMAT(1X,'*',1X,I2,2X,10(I7,3X),3X,'*')
      PRINT 150
150  FORMAT(1X,'*',108X,'*/1X,110('*')////)
      MMM=MMMM + 1
      MMMM=MMMM + 10
      DO 933 I=MMM,MMMM
933  MHA(I)=I

```

```

155  CONTINUE
      DO 7735 I=1,10
7735  MHA(I)=0
      DO 7739 N=1,NH
      DO 7739 M=1,NH
      DO 7738 I=1,10
      MM=I*10
      IF(MROT(N,M).LE.MM) GO TO 7737
      GO TO 7738
7737  MHA(I)=MHA(I) + 1
      GO TO 7739
7738  CONTINUE
7739  CONTINUE
      PRINT 7740, PWMAX
7740  FORMAT(///1X,'MAXIMUM POWER =',F9.5///)
      PRINT 7741
7741  FORMAT(1X,'DISTRIBUTION OF POWERS'//1X,'PERCENT OF    RELATIVE'/1X,
$ 'MAX. POWER    FREQUENCY'/)
      HN2=100./(NH*NH)
      DO 7743 I=1,10
      MM=I*10
      M=MM - 9
      IF(I.EQ.1) M=0
      PROP=MHA(I)*HN2
      PRINT 7742, M,MM,PROP
7742  FORMAT(1X,I3,1X,'--',1X,I3,4X,F6.2)
7743  CONTINUE
156  CONTINUE
      IF(NPOR.EQ.0) GO TO 184
C *****
C
C  POROSITY (PORE AREA), SPECIFIC PORE PERIMETER (PORE PERIMETER/SAMPLE
C  AREA), AND AVERAGE ROCK AND PORE DIMENSION ANALYSES
C *****
C  NT ACCUMULATES THE NUMBER OF ROCK-PORE TRANSITIONS FOR ALL PORE
C  ELEMENTS WITHIN THE ARRAY MAT
      NT=0
C  NB ACCUMULATES THE NUMBER OF ROCK-PORE TRANSITIONS OCCURRING ALONG
C  ROWS OR COLUMNS OF THE ARRAY
      NB=0
C  NP ACCUMULATES THE NUMBER OF PORE ELEMENTS IN THE ARRAY
      NP=0
      DO 170 I=1,NRC
      DO 170 J=1,NRC
      IF(MAT(I,J).EQ.-1) NP=NP + 1
      IF(J.EQ.NRC) GO TO 157
      IF(MAT(I,J).NE.MAT(I,J+1)) NB=NB + 1
157  IF(MAT(I,J).NE.-1) GO TO 170
      IF(I.EQ.1) GO TO 158

```

```

      IF(MAT(I,J).NE.MAT(I-1,J)) NT=NT + 1
158  IF(I.EQ.NRC) GO TO 159
      IF(MAT(I,J).NE.MAT(I+1,J)) NT=NT + 1
159  IF(J.EQ.1) GO TO 160
      IF(MAT(I,J).NE.MAT(I,J-1)) NT=NT + 1
160  IF(J.EQ.NRC) GO TO 170
      IF(MAT(I,J).NE.MAT(I,J+1)) NT=NT + 1
170  CONTINUE
C    SS IS THE SPECIFIC PORE PERIMETER
      SS=(NT*RESO)/((NRC*RESO)*(NRC*RESO))
C    POR IS THE POROSITY
      POR=(NP/(NRC*NRC*1.))*100.
      PNUMB=NP
      NROCK=NRC*NRC-NP
C    AXD IS THE AVERAGE PORE DIMENSION NORMAL TO COLUMNS
      AXD=(NP/(NB/2.))*RESO
C    BXD IS THE AVERAGE ROCK DIMENSION NORMAL TO COLUMNS
      BXD=(NROCK/(NB/2.))*RESO
      NB=0
      DO 175 J=1,NRC
      DO 175 I=1,NRC
      IF(I.EQ.NRC) GO TO 175
      IF(MAT(I,J).NE.MAT(I+1,J)) NB=NB + 1
175  CONTINUE
C    AYD IS THE AVERAGE PORE DIMENSION PARALLEL TO COLUMNS
      AYD=(NP/(NB/2.))*RESO
C    BYD IS THE AVERAGE ROCK DIMENSION PARALLEL TO COLUMNS
      BYD=(NROCK/(NB/2.))*RESO
      POREAV = ((AXD + AYD)/2.)/RESO
      NBCUT= POREAV
C    PRINT THE RESOLUTION AND THE RESULTS FOR SS, POR, AYD, BYD, AXD
C    AND BXD
      PRINT 932
      PRINT 180, SS,POR
180  FORMAT(////1X,'SPECIFIC PORE SURFACE AREA = ',F8.3,' MM PER 1 SQU
$ARE MM'///1X,'POROSITY =',F7.2,' PERCENT'//)
      PRINT 182, AYD,AXD
182  FORMAT(/1X,'AVERAGE PORE DIMENSION PARALLEL TO COLUMNS =',F7.3,' M
$M'/1X,'AVERAGE PORE DIMENSION NORMAL TO COLUMNS =',F7.3,' MM')
      AVEAD=(AYD+AXD)/2.
      PRINT 1820, AVEAD
1820 FORMAT(/1X,'AVERAGE PORE DIMENSION =',F7.3)
      PRINT 183, BYD,BXD
183  FORMAT(//1X,'AVERAGE ROCK DIMENSION PARALLEL TO COLUMNS =',F7.3,'
$MM'/1X,'AVERAGE ROCK DIMENSION NORMAL TO COLUMNS =',F7.3,' MM')
      AVEBD=(BYD+BXD)/2.
      PRINT 1830, AVEBD
1830 FORMAT(/1X,'AVERAGE ROCK DIMENSION =',F7.3)
      PRINT 5184,RESO

```



```

5184 FORMAT(///1X,'RESOLUTION =',F7.4,' MM BETWEEN ADJACENT ROCK/PORE P
      $OINTS')
      PRINT 181
184  CONTINUE
      IF(NACA.EQ.0) GO TO 239
C  *****
C
C  TWO-DIMENSIONAL AUTOCORRELATION ANALYSIS
C
C  *****
      COM(1)=1.
      L=1
      K=NRC-1
185  CONTINUE
      MISSUM=0
C  CALCULATIONS FOR A LAG MOVEMENT DIRECTION PERPENDICULAR TO THE
C  COLUMNS. THE COLUMNS IN THE FIRST ARRAY ARE 1 TO K, AND THOSE FOR
C  THE SECOND ARRAY ARE 1 TO NRC. THE ROWS FOR BOTH ARRAYS ARE 1 TO
C  NRC.
      DO 200 J=1,K
      I=J + L
      DO 200 M=1,NRC
      IF(MAT(M,J).NE.MAT(M,I)) MISSUM=MISSUM + 2
200  CONTINUE
C  COM IS THE AREAL MATCHING COEFFICIENT
      COM(L+1)=1. - MISSUM/(K*NRC*2.)
      K=K - 1
      L=L + 1
      IF(L.GT.LAGMAX) GO TO 210
      GO TO 185
C  PRINT THE RESULTS
210  PRINT 932
      PRINT 234
220  FORMAT(1X, 'TWO-DIMENSIONAL AUTOCORRELATION: LAG MOV
      $EMENT PARALLEL TO COLUMNS',///1X,'LAG',5X,'CORRELATION (AMC)'////)
222  CONTINUE
      LL=LAGMAX + 1
      DO 230 I=1,LL
      N=I - 1
      DO 225 J=1,50
225  IOUT(J)=IBLNK
      IX=COM(I)*50.
      DO 227 J=1,IX
227  IOUT(J)=ISTAR
      PRINT 228, N,COM(I),(IOUT(J),J=1,50)
228  FORMAT(2X,I2,11X,F5.3,2X,50A1)
230  CONTINUE
      IF(NPASS.EQ.5) GO TO 239
C  CALCULATIONS FOR A LAG MOVEMENT DIRECTION PARALLEL TO THE COLUMNS.
C  THE ROWS IN THE FIRST ARRAY ARE 1 TO K, AND THOSE IN THE SECOND
C  ARRAY ARE 1 TO NRC. THE COLUMNS FOR BOTH ARRAYS ARE 1 TO NRC

```

```

      L=1
      NPASS=5
      K=NRC-1
231  CONTINUE
      MISSUM=0
      DO 232 M=1,K
      I=M + L
      DO 232 J=1,NRC
      IF(MAT(M,J).NE.MAT(I,J)) MISSUM=MISSUM + 2
232  CONTINUE
      COM(L+1)=1. - MISSUM/(K*NRC*2.)
      K=K-1
      L=L + 1
      IF(L.GT.LAGMAX) GO TO 233
      GO TO 231
C   PRINT THE RESULTS
233  PRINT 101
      PRINT 220
234  FORMAT(1X,          'TWO-DIMENSIONAL AUTOCORRELATION: LAG MOV
      $EMENT PERPENDICULAR TO COLUMNS'///1X,'LAG',5X,'CORRELATION (AMC)'/
      $///)
      GO TO 222
239  CONTINUE
      IF(NQUAD.EQ.0) GO TO 315
C   *****
C
C   QUADRAT POROSITY ANALYSIS
C
C   *****
      NQ=0
      SUMQP=0
      SUMQP2=0
      INC=NRC/3
      NREM=NRC - (INC*3)
C   THE SAMPLE AREA IS DIVIDED INTO NINE APPROX. SQUARE, EQUAL-AREA
C   CELLS. THE POROSITY OF EACH CELL IS DETERMINED.
      DO 300 I=1,3
      I2=INC*I
      I1=I2 - (INC - 1)
      IF(I.EQ.3) I2=I2 + NREM
      DO 290 J=1,3
      J2=INC*J
      J1=J2-(INC-1)
      IF(J.EQ.3) J2=J2 + NREM
      NP=0
      DO 240 N=I1,I2
      DO 240 L=J1,J2
240  IF(MAT(N,L).EQ.-1) NP=NP + 1
      NQ=NQ + 1
      TOT=(I2-I1+1) * (J2-J1+1)*1.

```

```

C   QP IS THE POROSITY OF A SINGLE CELL
      QP(NQ)=(NP/TOT)*100.
      SUMQP=SUMQP + QP(NQ)
290  SUMQP2=SUMQP2 + QP(NQ)*QP(NQ)
300  CONTINUE
C   SDPOR IS THE STANDARD DEVIATION OF THE POROSITY VALUES FOR THE
C   NINE CELLS
      SDPOR=((9.*SUMQP2-SUMQP*SUMQP)/72.)**.5
C   PRINT THE RESULTS
      PRINT 932
      PRINT 310, SDPOR
310  FORMAT(1X,'STANDARD DEVIATION OF QUADRAT POROSITY =',F8.3,' PERCENT
      $T')
315  CONTINUE
      IF(NFREQ.EQ.0) GO TO 892
C   *****
C
C   PORE SIZE DISTRIBUTION AND PORE TORTUOSITY ANALYSES
C   *****
C   ASSIGN VALUES TO THE VARIOUS CONSTANTS AND ACCUMULATOR VARIABLES
      NPORE=0
      NP=0
      NPASS=0
      NPSUM=0
      ISAV=1
      WORSUM=0.
      TORSUM=0.
      IMAX=2
      IMIN=1
      JMAX=2
      JMIN=1
C   INITIALIZE ARRAYS MROT AND MTOR (SET ALL ELEMENTS EQUAL TO 1, ROCK);
C   AND STORE A COPY OF MAT IN THE ARRAY MSAT
      DO 9 I=1,NRC
      DO 9 J=1,NRC
      MROT(I,J)=1
9     MTOR(I,J)=1
      PRINT 932
C   PRINT THE HEADING FOR THE TORTUOSITY ANALYSIS RESULTS
      PRINT 5333
5333  FORMAT(1X,'RESULTS OF THE TORTUOSITY ANALYSIS FOR EACH PORE'///)
      PRINT 5334
5334  FORMAT(5X,'PORE',2X,'NO. OF',2X,'TORTU-',4X,'PORE',3X,'EXTREME PTS
      $.',7X,'EXTREME PTS.'/6X,'NO.',2X,'CYCLES',2X,'OSITY',5X,'SIZE',3X,
      $'ROW',4X,'COL',9X,'ROW',4X,'COL'/19X,'SQUARED'///)
      DMXSUM=0.

```

```

C  SEARCH OUT THE INDIVIDUAL PORES (I.E., SETS OF CONTIGUOUS PORE
C  ELEMENTS IN THE ARRAY MAT). FOR EACH PORE DETERMINE THE NUMBER (NP)
C  PORE ELEMENTS (I.E., SIZE), THE MAXIMUM DIMENSIONS (IN MM) PARALLEL
C  (IMAX-IMIN) AND NORMAL (JMAX-JMIN) TO COLUMNS, AND THE ABSOLUTE
C  MAXIMUM DIMENSION (IN MM).
12  CONTINUE
    IF(NTORT.EQ.0) GO TO 802
C  REINITIALIZE ARRAY MROT (RESET ALL ELEMENTS EQUAL TO 1, ROCK)
    DO 801 I=IMIN,IMAX
    DO 801 J=JMIN,JMAX
801  MROT(I,J)=1
802  CONTINUE
C  SCAN THE ARRAY MAT UNTIL A PORE ELEMENT IS ENCOUNTERED (MAT(I,J) =
C  -1)
    DO 15 I=ISAV,NRC
    DO 15 J=1,NRC
    IF(MAT(I,J).NE.1) GO TO 20
15  CONTINUE
C  CONVERT THE PORE ELEMENT IN MAT TO A ROCK ELEMENT (MAT(I,J); +1 NOT
C  -1) AND CONVERT THE CORRESPONDING ARRAY ELEMENT MROT TO A PORE
C  ELEMENT (MROT(I,J); -1 NOT +1)
20  MAT(I,J)=1
    MROT(I,J)=-1
    ISAV=I-1
    IF(I.EQ.1) ISAV=1
C  NP ACCUMULATES THE NUMBER OF ARRAY ELEMENTS IN A GIVEN PORE.
C  ARRAYS MI AND MJ STORE THE COORDINATES OF THE PORE ELEMENTS IN A
C  GIVEN PORE.
    NP=NP + 1
    MI(NP)=I
    MJ(NP)=J
C  IMAX-IMIN = MAXIMUM NUMBER OF PORE ELEMENTS PARALLEL TO COLUMNS
    IMAX=I
    IMIN=I
C  JMAX-JMIN = MAXIMUM NUMBER OF PORE ELEMENTS NORMAL TO COLUMNS
    JMAX=J
    JMIN=J
C  DEFINE THE SEARCH CONFIGURATION FOR THE IMMEDIATELY CONTIGUOUS ARRAY
C  ELEMENTS.
21  IB=I + 1
    IS=I - 1
    IF(I.EQ.1) IS=1
    IF(I.EQ.NRC) IB=NRC
    JB=J + 1
    JS=J-1
    IF(J.EQ.1) JS=1
    IF(J.EQ.NRC) JB=NRC
C  SEARCH FOR IMMEDIATELY CONTIGUOUS PORE ELEMENTS
    DO 3000 II=IS,IB
    DO 3000 JJ=JS,JB

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        IF(MAT(II,JJ).EQ.-1) GO TO 25
        GO TO 3000
25      NP=NP + 1
        MI(NP)=II
        MJ(NP)=JJ
C      SET THE CONTIGUOUS PORE ELEMENTS EQUAL TO +1 IN MAT AND -1 IN MROT
C      AND UPDATE, IF NECESSARY, THE VALUES OF THE MAXIMUM PORE DIMENSIONS
        MAT(II,JJ)=1
        MROT(II,JJ)=-1
        IF(MI(NP).GT.IMAX) IMAX=MI(NP)
        IF(MI(NP).LT.IMIN) IMIN=MI(NP)
        IF(MJ(NP).GT.JMAX) JMAX=MJ(NP)
        IF(MJ(NP).LT.JMIN) JMIN=MJ(NP)
3000    CONTINUE
        IF(NP.EQ.1) GO TO 4001
        IF(NPASS.EQ.1) GO TO 35
        NPASS=1
C      CONTINUE TO SEARCH FOR IMMEDIATELY CONTIGUOUS PORE ELEMENTS FOR THE
C      PROGRESSIVELY INCREASING NUMBER OF ARRAY ELEMENTS IN A GIVEN PORE
        DO 4000 N=2,NP
            I=MI(N)
            J=MJ(N)
            GO TO 21
35      CONTINUE
4000    CONTINUE
C      NPORE ACCUMULATES THE NUMBER OF INDIVIDUAL PORES IN THE ARRAY MAT.
C      XE = MAXIMUM PORE DIMENSION NORMAL TO COLUMNS.
C      YE = MAXIMUM PORE DIMENSION PARALLEL TO COLUMNS.
C      NE = NUMBER OF ARRAY ELEMENTS IN A GIVEN PORE
C      NPSUM ACCUMULATES THE TOTAL NUMBER OF PORE ELEMENTS IN THE ARRAY MAT
4001    NPORE=NPORE + 1
        XE(NPORE)=((IMAX-IMIN) +1)*RESO
        YE(NPORE)=((JMAX-JMIN) +1)*RESO
        NE(NPORE)=NP
        NPSUM=NPSUM + NP
        NS=0
        IF(NP.EQ.1) GO TO 4003
        GO TO 4010
4003    DMX=1.
C      FIND THE TWO MOST WIDELY SEPARATED PORE ELEMENTS IN A PORE (I.E.,
C      THE TWO EXTREME POINTS: MI1, MJ1 AND MI2, MJ2)
        MI1=MI(1)
        MI2=MI(1)
        MJ1=MJ(1)
        MJ2=MJ(1)
        GO TO 4015
4010    CONTINUE
        DO 715 N=1,NP
            IF((MI(N).EQ.IMAX).OR.(MI(N).EQ.IMIN)) GO TO 710
            IF((MJ(N).EQ.JMAX).OR.(MJ(N).EQ.JMIN)) GO TO 710

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      GO TO 715
710  NS=NS + 1
      MIS(NS)=MI(N)
      MJS(NS)=MJ(N)
715  CONTINUE
      DMX=0.
C    COMPUTE THE DISTANCE BETWEEN ALL POSSIBLE PAIRS OF PORE ELEMENTS IN
C    A PORE USING JUST THOSE ELEMENTS WITH AT LEAST ONE COORDINATE EQUAL
C    TO IMAX, IMIN, JMAX OR JMIN
      DO 720 L=1,NS
      KS=L+1
      IF(KS.GT.NS) GO TO 720
      DO 720 K=KS,NS
      DDD=(( (MIS(L)-MIS(K))*(MIS(L)-MIS(K)) + (MJS(L)-MJS(K))*(MJS(L)-
$MJS(K)))*.5) + 1.
      IF(DDD.GT.DMX) GO TO 717
      GO TO 720
717  DMX=DDD
      MI1=MIS(L)
      MJ1=MJS(L)
      MI2=MIS(K)
      MJ2=MJS(K)
720  CONTINUE
4015 CONTINUE
C    DE = ABSOLUTE MAXIMUM PORE DIMENSION
      DE(NPORE)=DMX*RESO
C
C    BEGIN THE TORTUOSITY ANALYSIS
C
      IF(NTORT.EQ.0) GO TO 895
      NCAT = 0
860  CONTINUE
C    INITIALIZE CONSTANTS AND VARIABLES
      NSTOP=0
      NPASS=0
      NQUIT=0
      NS=1
      NCAT=NCAT + 1
      MI(NS)=MI1
      MJ(NS)=MJ1
      I=MI1
      J=MJ1
      IMIN=MI1
      IMAX=MI1
      JMIN=MJ1
      JMAX=MJ1
C    CONVERT THE FIRST PORE ELEMENT (ONE OF THE EXTREME POINTS) IN MROT
C    TO A ROCK ELEMENT AND CONVERT TO PORE ELEMENTS THE ARRAY ELEMENTS
C    IN MTOR CORRESPONDING TO THE TWO EXTREME POINTS
      MTOR(I,J)=-1

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      MTOR(MI2,MJ2)=-1
      MROT(I,J)=1
      IF((MI1.EQ.MI2).AND.(MJ1.EQ.MJ2)) GO TO 806
      GO TO 808
806  TE(NPORE)=1.
      GO TO 891
808  CONTINUE
C    DEFINE THE SEARCH CONFIGURATION FOR THE IMMEDIATELY CONTIGUOUS
C    ARRAY ELEMENTS
821  NSI(1)=I-1
      NSJ(1)=J
      NSI(2)=I+1
      NSJ(2)=J
      NSI(3)=I
      NSJ(3)=J+1
      NSI(4)=I
      NSJ(4)=J-1
      NSI(5)=I+1
      NSJ(5)=J+1
      NSI(6)=I-1
      NSJ(6)=J-1
      NSI(7)=I+1
      NSJ(7)=J-1
      NSI(8)=I-1
      NSJ(8)=J+1
      NCHK=0
      NCNT=0
C    SEARCH FOR IMMEDIATELY CONTIGUOUS PORE ELEMENTS
      DO 830 LL=1,8
        II=NSI(LL)
        JJ=NSJ(LL)
        IF((II.LT.1).OR.(II.GT.NRC)) GO TO 830
        IF((JJ.LT.1).OR.(JJ.GT.NRC)) GO TO 830
        IF(MROT(II,JJ).EQ.-1) GO TO 825
        GO TO 830
825  MROT(II,JJ)=1
      NS=NS + 1
      MI(NS)=II
      MJ(NS)=JJ
      NCHK=1
      NCNT=NCNT + 1
      IF(II.GT.IMAX) IMAX=II
      IF(II.LT.IMIN) IMIN=II
      IF(JJ.GT.JMAX) JMAX=JJ
      IF(JJ.LT.JMIN) JMIN=JJ
      IF((II.EQ.MI2).AND.(JJ.EQ.MJ2)) NSTOP = NS
830  CONTINUE
      IF(NPASS.EQ.1) GO TO 835
      NPASS=1

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C   CONTINUE TO SEARCH FOR IMMEDIATELY CONTIGUOUS PORE ELEMENTS FOR THE
C   PROGRESSIVELY INCREASING NUMBER OF ARRAY ELEMENTS IN A PORE
      DO 840 N=2,NS
        I=MI(N)
        J=MJ(N)
        GO TO 821
835  CONTINUE
      MTOR(I,J)=-1
      IF(N.EQ.NSTOP) GO TO 850
      IF(NCHK.EQ.0) GO TO 837
      GO TO 840
837  MTOR(I,J)=1
      NQUIT=1
840  CONTINUE
C   THE FLOW PATH IS RESOLVED WHEN NO PORE ELEMENTS WERE DELETED FROM
C   MTOR DURING THE LAST RESOLUTION CYCLE; IF NQUIT IS NOT EQUAL TO
C   ZERO GO TO 860 FOR ANOTHER RESOLUTION CYCLE
      850 IF(NQUIT.EQ.0) GO TO 870
C   STORE THE ABBREVIATED PORE OF MTOR IN MROT FOR THE NEXT RESOLUTION
C   CYCLE
      DO 855 I=IMIN,IMAX
        DO 855 J=JMIN,JMAX
855  MROT(I,J)=MTOR(I,J)
      NCNTS=NCNT
      GO TO 860
870  SUMT=0.
      LL=NS - 1
C   COMPUTE THE FLOW PATH LENGTH
      DO 890 L=1,LL
        IF((MI(L).NE.MI(L+1)).AND.(MJ(L).NE.MJ(L+1))) GO TO 880
        GO TO 881
880  SUMT=SUMT + 1.41421
        GO TO 890
881  SUMT=SUMT + 1.
890  CONTINUE
      DMXSUM=DMXSUM + DMX
C   TE = TORTUOSITY
      TE(NPORE)=((SUMT + 1.)/DMX)**2.
891  TORSUM=TORSUM + NE(NPORE)*TE(NPORE)
      WORSUM=WORSUM + DMX*TE(NPORE)
C   PRINT THE RESULTS OF THE TORTUOSITY ANALYSIS FOR EACH PORE
      PRINT 5331, NPORE,NCAT,TE(NPORE),NE(NPORE),MI1,MJ1,MI2,MJ2
5331  FORMAT(1X,2I7,F10.5,3I7,5X,2I7)
895  CONTINUE
C   REINITIALIZE NP AND NPASS, AND, UNLESS NPSUM = PNUMB, SEARCH OUT
C   ANOTHER INDIVIDUAL PORE AND REPEAT THE ABOVE STEPS.
      NP=0
      NPASS=0
      IF(NPSUM.GE.PNUMB) GO TO 50
      GO TO 12

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50  CONTINUE
    PRINT 932
C   NPORE = THE TOTAL NUMBER OF PORES
    PRINT 982, NPORE
982  FORMAT(1X,'NUMBER OF PORES =',I5////)
    DO 2200 K=1,17
        NESUM(K)=0
2200 NEE(K)=0
C   DETERMINE THE FREQUENCY DISTRIBUTION OF THE NPORE ZLOG VALUES
    DO 800 N=1,NPORE
C   ZNE = NUMBER OF ARRAY ELEMENTS IN THE N TH PORE
        ZNE=NE(N)
C   ZLOG = LOG (TO THE BASE 10) OF ZNE
        ZLOG=ALOG10(ZNE)
        B1=-.25
        DO 270 K=1,17
            B1=B1 + .25
            B2=B1 + .25
            IF((ZLOG.GE.B1).AND.(ZLOG.LT.B2)) GO TO 250
        GO TO 270
250  NEE(K)=NEE(K) + 1
        NESUM(K)=NESUM(K) + NE(N)
        GO TO 800
270  CONTINUE
800  CONTINUE
C   PRINT THE FREQUENCY DISTRIBUTION OF THE NUMBER OF ARRAY ELEMENTS
C   (I.E., SIZE) FOR THE INDIVIDUAL PORES
    PRINT 305
305  FORMAT(1X,'FREQUENCY DISTRIBUTION OF PORE AREAS: LOG10(NO. OF PTS.
    $)')//)
    PRINT 3100
3100 FORMAT(11X,'LOWER',10X,'UPPER',6X,'% OF'/8X,'BOUNDARY',7X,'BOUNDAR
    $Y',6X,'PORE',5X,'FREQ.'/9X,'> OR =',12X,'<',8X,'SPACE'//)
    MXNEE=NEE(1)
    B=-.25
    DO 320 K=1,18
        B=B + .25
        IF(NEE(K).GT.MXNEE) MXNEE=NEE(K)
        LAL(K)=10.**B + .05
320  CONTINUE
        EX=MXNEE
        B1=-.25
        DO 350 K=1,17
            XNPP=PNUMB
            VAR=NESUM(K)/XNPP * 100.
            B1=B1 + .25
            B2=B1 + .25
            DO 330 I=1,70
330  IOUT(I)=IBLNK
            IX=(NEE(K)/EX)*70

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      IF(NEE(K).EQ.0) GO TO 336
      IF((IX.EQ.0).AND.(NEE(K).NE.0)) IX=1
      DO 335 I=1,IX
335  IOUT(I)=ISTAR
336  CONTINUE
      LTL=LAL(K)
      IF(LAL(K).GT.1) LTL=LAL(K) + 1
      IF(K.EQ.2) LTL=2
      PRINT 340, B1,LTL,B2,LAL(K+1),VAR,NEE(K),(IOUT(I),I=1,70)
340  FORMAT(6X,F4.2,' (' ,I5,')',4X,F4.2,' (' ,I5,')',4X,F3.0,4X,I5,5X,
      $ 70A1)
350  CONTINUE
C   NAVEPS = AVERAGE NUMBER OF ARRAY ELEMENTS IN A PORE
      NAVEPS=PNUMB/NPORE
      PRINT 360, NAVEPS,NPSUM
360  FORMAT(///1X,'AVERAGE NO. OF PTS. IN A PORE =' ,I7,10X,'TOTAL NUMB
      $ER OF PORE POINTS =' ,I7)
      AVAREA=NAVEPS*((RESO*RESO*(NRC-1)**2)/(NRC*NRC))
      PRINT 7783, AVAREA
7783 FORMAT(/1X,'AVERAGE AREA OF A PORE (MM**2) =' ,F10.6)
C   PRINT THE FREQUENCY DISTRIBUTION OF THE MAXIMUM PORE DIMENSIONS
C   (PARALLEL AND NORMAL TO COLUMNS, AND ABSOLUTE)
      PRINT 181
181  FORMAT(1H1)
      PRINT 370
370  FORMAT(1X,'FREQUENCY DISTRIBUTION OF MAX. PORE DIMENSIONS PARALLEL
      $ TO COLUMNS (MM)'////)
      NPAP=0
375  CONTINUE
      DO 380 K=1,24
      NESUM(K)=0
380  NEE(K)=0
      DO 420 N=1,NPORE
      B1=-.25
      DO 400 K=1,24
      B1=B1 + .25
      B2=B1 + .25
      IF((YE(N).GE.B1).AND.(YE(N).LT.B2)) GO TO 390
      GO TO 400
390  NEE(K)=NEE(K) + 1
      NESUM(K)=NESUM(K) + NE(N)
      GO TO 420
400  CONTINUE
420  CONTINUE
      PRINT 3100
      MXNEE=NEE(1)
      DO 430 K=1,24
430  IF(NEE(K).GT.MXNEE) MXNEE=NEE(K)
      EX=MXNEE
      B1=-.25

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DO 480 K=1,24
  XNPP=PNUMB
  VAR=NESUM(K)/XNPP * 100.
  B1=B1 + .25
  B2=B1 + .25
  DO 440 I=1,70
440  IOUT(I)=IBLNK
      IX=(NEE(K)/EX)*70
      IF(NEE(K).EQ.0) GO TO 451
      IF((IX.EQ.0).AND.(NEE(K).NE.0)) IX=1
      DO 450 I=1,IX
450  IOUT(I)=ISTAR
451  CONTINUE
      PRINT 460,B1,B2,VAR,NEE(K),(IOUT(I),I=1,70)
460  FORMAT(11X,F5.2,10X,F5.2,7X,F3.0,7X,I3,5X,70A1)
480  CONTINUE
      IF(NPAP.EQ.7) GO TO 555
      IF(NPASS.EQ.3) GO TO 520
      SUMYE=0.
      SUMDE=0.
      SUMXE=0.
      NPASS=3
      DO 490 N=1,NPORE
      SUMYE=SUMYE + YE(N)
      SUMDE=SUMDE + DE(N)
      SUMXE=SUMXE + XE(N)
490  YE(N)=XE(N)
      AVEYE=SUMYE/NPORE
      AVEXE=SUMXE/NPORE
      AVEDE=SUMDE/NPORE
      PRINT 500, AVEYE
500  FORMAT(/////1X,'AVERAGE MAXIMUM PORE DIMENSION =',F6.3,' MM')
      PRINT 181
      PRINT 510
510  FORMAT(1X,'FREQUENCY DISTRIBUTION OF MAX. PORE DIMENSIONS NORMAL T
$O COLUMNS (MM)'////)
      GO TO 375
520  PRINT 500, AVEXE
533  CONTINUE
      PRINT 181
      PRINT 545
545  FORMAT(1X,'FREQUENCY DISTRIBUTION OF MAXIMUM PORE DIMENSIONS (MM)'
$////)
      DO 550 N=1,NPORE
550  YE(N)=DE(N)
      NPAP=7
      GO TO 375
555  PRINT 500, AVEDE
      IF(NTORT.EQ.0) GO TO 892
      PRINT 932

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      IF(NPRNT.EQ.0) GO TO 5342
C   PRINT THE PORE TORTUOSITY MAP
      PRINT 896
896  FORMAT(1X,'PORE TORTUOSITY MAP: FLOW PATHS BETWEEN EXTREME POINTS
      $FOR EACH PORE'////)
      DO 898 I=1,NRC
      DO 897 J=1,NRC
897  IOUT(J)=IBLNK
      DO 893 J=1,NRC
893  IF(MTOR(I,J).EQ.-1) IOUT(J)=ISTAR
      PRINT 935,(IOUT(J),J=1,NRC)
898  CONTINUE
5342 CONTINUE
C   TORSUM = WEIGHTED (BY PORE AREA) AVERAGE TORTUOSITY
C   WORSUM = WEIGHTED (BY ABS. MAX. PORE DIMENSION) AVERAGE TORTUOSITY
      TORSUM=TORSUM/PNUMB
      WORSUM=WORSUM/DMXSUM
      PRINT 894, TORSUM,WORSUM
894  FORMAT(////1X,'WEIGHTED (BY PORE AREA) AVERAGE PORE TORTUOSITY ='
      $,F7.3//1X,'WEIGHTED (BY MAX. PORE DIMENSION) AVERAGE PORE TORTUOS
      $ITY =' ,F7.3)
C   COMPUTE THE TORTUOSITY FOR THREE DISCONTINUOUS FLOW PATHS USING A
C   MODIFICATION OF THE METHOD OF PRESTON AND DAVIS, 1976
C
C   INITIALIZE THE STORAGE ARRAYS FOR THE THREE FLOW PATHS
      NTP(1)=13
      NTP(2)=40
      NTP(3)=66
      NTPS(1)=13
      NTPS(2)=40
      NTPS(3)=66
      TPTH(1)=0.
      TPTH(2)=0.
      TPTH(3)=0.
      NTPAV(1)=0
      NTPAV(2)=0
      NTPAV(3)=0
C   IF THE ARBITRARILY CHOSEN STARTING POINTS FOR THE FLOW PATHS DO
C   NOT CORRESPOND TO PORE POINTS, SHIFT THE STARTING POINTS Laterally
C   (NORMAL TO COLUMNS) TO THE NEAREST PORE POINT
      DO 6017 K=1,3
      L=NTP(K)
      IF(MSAT(1,L).EQ.-1) GO TO 6017
      DO 6010 J=L,NRC
      IF(MSAT(1,J).EQ.-1) GO TO 6011
6010 CONTINUE
      MR=999
      GO TO 6012
6011 MR=J-L
6012 LL=L-1

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        DO 6020 J=1,LL
        JJ=L-J
        IF(MSAT(1,JJ).EQ.-1) GO TO 6013
6020 CONTINUE
        ML=999
        GO TO 6014
6013 ML=L-JJ
6014 IF(ML.GE.MR) GO TO 6015
        NTP(K)=L-ML
        GO TO 6017
6015 NTP(K)=MR + L
6017 CONTINUE
C   PRINT THE HEADING AND FIRST LINE OF THE PORE TORTUOSITY MAP
        PRINT 932
        IF(NPRNT.EQ.0) GO TO 6025
        PRINT 6019
6019 FORMAT(1X,'PORE TORTUOSITY MAP: THREE FLOW PATHS APPROXIMATELY PAR
        $ALLEL TO COLUMNS (MODIFIED METHOD OF PRESTON AND DAVIS, 1976)')
        DO 6021 J=1,NRC
6021 IOUT(J)=IBLNK
        DO 6022 L=1,3
        J=NTP(L)
6022 IOUT(J)=ISTAR
        PRINT 935, (IOUT(J),J=1,NRC)
6025 CONTINUE
C   FOR EACH OF THE THREE FLOW PATHS, MOVE (IN A DIRECTION PARALLEL TO
C   COLUMNS) THROUGH THE ROWS OF THE ARRAY MSAT AND LOCATE THE PORE
C   POINT CLOSEST TO THE PORE POINT ON THE FLOW PATH IN THE PRECEEDING
C   ROW. MEASURE AND ACCUMULATE THE DISTANCE BETWEEN THESE TWO PORE
C   POINTS.
        DO 6500 I=2,NRC
        DO 6400 K=1,3
        L=NTP(K)
        DO 6110 J=L,NRC
        IF(MSAT(I,J).EQ.-1) GO TO 6111
6110 CONTINUE
        MR=999
        GO TO 6112
6111 MR=J-L
6112 LL=L-1
        DO 6120 J=1,LL
        JJ=L-J
        IF(MSAT(I,JJ).EQ.-1) GO TO 6113
6120 CONTINUE
        ML=999
        GO TO 6114
6113 ML=L-JJ
6114 IF((ML.EQ.999).AND.(MR.EQ.999)) GO TO 6115
        GO TO 6150
6115 MR=NRC-L

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      ML=L-1
      IF(ML.GE.MR) GO TO 6118
      NTP(K)=1
      GO TO 6300
6118  NTP(K)=NRC
      GO TO 6300
6150  IF(ML.EQ.MR) GO TO 6155
      GO TO 6170
6155  NC1=(L+MR)-NTPS(K)
      NC1=IABS(NC1)
      NC2=(L-ML)-NTPS(K)
      NC2=IABS(NC2)
      IF(NC1.LE.NC2) GO TO 6160
      NTP(K)=L-ML
      GO TO 6300
6160  NTP(K)=L + MR
      GO TO 6300
6170  IF(ML.LT.MR) GO TO 6180
      NTP(K)=L + MR
      GO TO 6300
6180  NTP(K)=L-ML
6300  NW=NTP(K)-L
      W=(NW*NW + 1)**.5
      TPTH(K)= TPTH(K) + W
      LL=NRC-10
      IF(I.GT.LL) NTPAV(K)=NTPAV(K) + NTP(K)
6400  CONTINUE
C    PRINT THE NEXT LINE OF THE PORE TORTUOSITY MAP
      DO 6405 J=1,NRC
6405  IOUT(J)=IBLNK
      DO 6410 L=1,3
      J=NTP(L)
6410  IOUT(J)=ISTAR
      PRINT 935, (IOUT(J),J=1,NRC)
6500  CONTINUE
C    COMPUTE AND PRINT THE TORTUOSITIES FOR THE THREE FLOW PATHS
      K=NRC-1
      DO 6600 L=1,3
      XNTP = NTPAV(L)/10.
      XM=NTPS(L)-XNTP
      XM=(XM*XM + K*K)**.5
6600  TPTH(L)=TPTH(L)/XM
      AVETP=(TPTH(1) + TPTH(2) +TPTH(3))/3.
      PRINT 6700,(TPTH(L),L=1,3),AVETP
6700  FORMAT(/////1X,'FLOW PATH TORTUOSITIES:',3F10.4,5X,'AVERAGE =',F8.
      $3)
892  CONTINUE
      IF(NORN.EQ.0) GO TO 699

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C *****
C
C DIRECTIONAL ANALYSIS OF PREFERRED PORE ELONGATION ORIENTATION
C
C *****
C   SID=(NRC/2.)
C   NCENT=NRC/2 + 1
C   HYP=(SID*SID + SID*SID)**.5
C THE DIRECTIONAL ANALYSIS OF PORE ELONGATION IS CONFINED TO THE
C CENTRAL PORTION OF THE ARRAY MAT (A CENTERED SQUARE WITH A SIDE
C DIMENSION OF IHYP). THE CORNER POINTS OF THIS CENTERED SQUARE ARE:
C IMIN,JMAX = NRB,NCB; IMIN,JMAX = NRB,NCE; IMAX,JMIN = NRE,NCB; AND
C IMAX,JMAX = NRE,NCE. MAT = MSAT.
C   IHYP=HYP
C   IHYP2=IHYP/2
C   IHYP2=2*IHYP2
C   IF(IHYP2.EQ.IHYP) IHYP=IHYP-1
C   ISID=(NRC-IHYP)/2
C   NRB=ISID + 1
C   NCB=ISID + 1
C   NRE=ISID + IHYP
C   NCE=NRE
C   PI=-.3141592
C COMPUTE THE AVERAGE PORE DIMENSION FOR TEN DIFFERENT DIRECTIONS
C (RELATIVE TO COLUMNS: 0 TO 180 DEGREES WITH A 18 DEGREE INCREMENT)
C   DO 690 K=1,5
C INITIALIZE THE ARRAY MROT (SET ALL ELEMENTS EQUAL TO 1, ROCK)
C   DO 600 I=1,IHYP
C   DO 600 J=1,IHYP
600 MROT(I,J)=1
C THE ARRAY MROT CONTAINS THE ROTATED ELEMENTS OF THE ARRAY MSAT
C   N=0
C   PI=PI + .3141592
C   CT=COS(PI)
C   ST=SIN(PI)
C   CALC=(CT + (ST*ST)/CT)
C ROTATE THE PORE ELEMENTS IN THE CENTRAL PORTION OF MSAT. STORE THE
C NEW COORDINATES IN THE ARRAYS XIX AND YJY.
C   DO 610 I=NRB,NRE
C   DO 610 J=NCB,NCE
C   N=N + 1
C   XI=(I-NCENT)*(-1.)
C   YJ=(J-NCENT)*1.
C   ZOT=(XI - (YJ*ST)/CT)/CALC
C   XIX(N)=ZOT/(-1) + NCENT
C   ZOT=(YJ + (XI*ST)/CT)/CALC
610 YJY(N)=ZOT + NCENT
C   L=L + 1
C TRANSFER THE INFORMATION IN XIX AND YJY TO MROT.
C   DO 630 I=1,IHYP

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DO 630 J=1,IHYP
L=L + 1
IX=XIX(L)
IF(IX.LT.1) IX=1
JY=YJY(L)
IF(JY.LT.1) JY=1
IX1=IX + 1
JY1=JY + 1
DMIN=2.
C THE ARRAY ELEMENTS OF MROT ARE ASSIGNED A VALUE OF -1 (PORE) IF THE
C NEAREST ROTATED ELEMENT OF MAT IS A PORE ELEMENT
DO 620 II=IX,IX1
DO 620 JJ=JY,JY1
DIST=((II-XIX(L))*(II-XIX(L)) + (JJ-YJY(L))*(JJ-YJY(L)))*.5
IF(DIST.LT.DMIN) GO TO 611
GO TO 620
611 DMIN=DIST
ISAV=II
JSAV=JJ
620 CONTINUE
IF(MSAT(ISAV,JSAV).EQ.-1) MROT(I,J)=-1
630 CONTINUE
C FIND THE AVERAGE OF THE SQUARE OF THE LONGER THAN AVE PORE SEGMENTS
C IN MROT PARALLEL TO THE ROWS (AXDD) AND COLUMNS (AYDD)
INTS=0
SUMNB=0.0
DO 4655 I=1,IHYP
DO 4650 J=1,IHYP
IF(J.EQ.IHYP) GO TO 4642
GO TO 4643
4642 IF(MROT(I,IHYP).EQ.-1) GO TO 4645
GO TO 4650
4643 CONTINUE
IF((MROT(I,J).NE.MROT(I,J+1)).AND.(MROT(I,J+1).EQ.-1)) JSAV =J+1
IF((J.EQ.1).AND.(MROT(I,1).EQ.-1)) JSAV = 1
IF((MROT(I,J).NE.MROT(I,J+1)).AND.(MROT(I,J).EQ.-1)) GO TO 4645
GO TO 4650
4645 NB = J - JSAV + 1
IF(NB.LE.NBCUT) GO TO 4650
INTS=INTS + 1
SUMNB=SUMNB + NB*NB
4650 CONTINUE
4655 CONTINUE
IF(INTS.EQ.0) INTS=1
AXDD(K)= (SUMNB/INTS)*RESO
INTS= 0
SUMNB=0.0
DO 5655 J=1,IHYP
DO 5650 I=1,IHYP
IF(I.EQ.IHYP) GO TO 5642

```



```

      GO TO 5643
5642 IF(MROT(IHYP,J).EQ.-1) GO TO 5645
      GO TO 5650
5643 CONTINUE
      IF((MROT(I,J).NE.MROT(I+1,J)).AND.(MROT(I+1,J).EQ.-1)) JSAV =I+1
      IF((I.EQ.1).AND.(MROT(1,J).EQ.-1)) JSAV=1
      IF((MROT(I,J).NE.MROT(I+1,J)).AND.(MROT(I,J).EQ.-1)) GO TO 5645
      GO TO 5650
5645 NB = I - JSAV + 1
      IF(NB.LE.NBCUT) GO TO 5650
      INTS=INTS + 1
      SUMNB=SUMNB + NB*NB
5650 CONTINUE
5655 CONTINUE
      IF(INTS.EQ.0) INTS=1
      AYDD(K) = (SUMNB/INTS)*RESO
      ANG5(K)=PI*57.2958
690 CONTINUE
C PRINT THE RESULTS
      DMAX=0.
      DMIN = AXDD(1)
      DO 665 K=1,5
        IF(AYDD(K).GT.DMAX) DMAX=AYDD(K)
        IF(AXDD(K).GT.DMAX) DMAX=AXDD(K)
        IF(AYDD(K).LT.DMIN) DMIN=AYDD(K)
        IF(AXDD(K).LT.DMIN) DMIN=AXDD(K)
665 CONTINUE
      DIFF = DMAX - DMIN
      N=0
      PRINT 932
      PRINT 670
670 FORMAT(1X,'ANALYSIS OF PREFERRED PORE ELONGATION ORIENTATION'////)
      PRINT 671
671 FORMAT(10X,'ANGLE BETWEEN',4X,'AVE. OF THE',21X,'*',9X,'*',12X,'*'
$ /10X,'THE COLUMNS ',4X,'SQUARE OF THE',4X,'(1) *** (2-5) * (
$6) * (7-10) */10X,'AND THE MEAN',4X,'LONGER THAN AVE',19X,'*'
$,7X,'*',10X,'*/10X,'SURED DIRECTION',2X,'PORE SEGMENTS'//)
      DO 675 K=1,5
        ANG90=90.-ANG5(K)
        DO 666 I=1,80
966 IOUT(I)=IBLNK
        IX = (1. - (DMAX-AXDD(K))/DIFF) * 80
        IF(IX.EQ.0) IX=1
        DO 667 I=1,IX
967 IOUT(I)=ISTAR
        N=N + 1
        AXDD(K)=AXDD(K)/DMIN + .0001
675 PRINT 676,N,ANG90,AXDD(K),(IOUT(I),I=1,80)
676 FORMAT(9X,I2,4X,F3.0,10X,F9.3,3X,80A1)
      DO 680 K=1,5

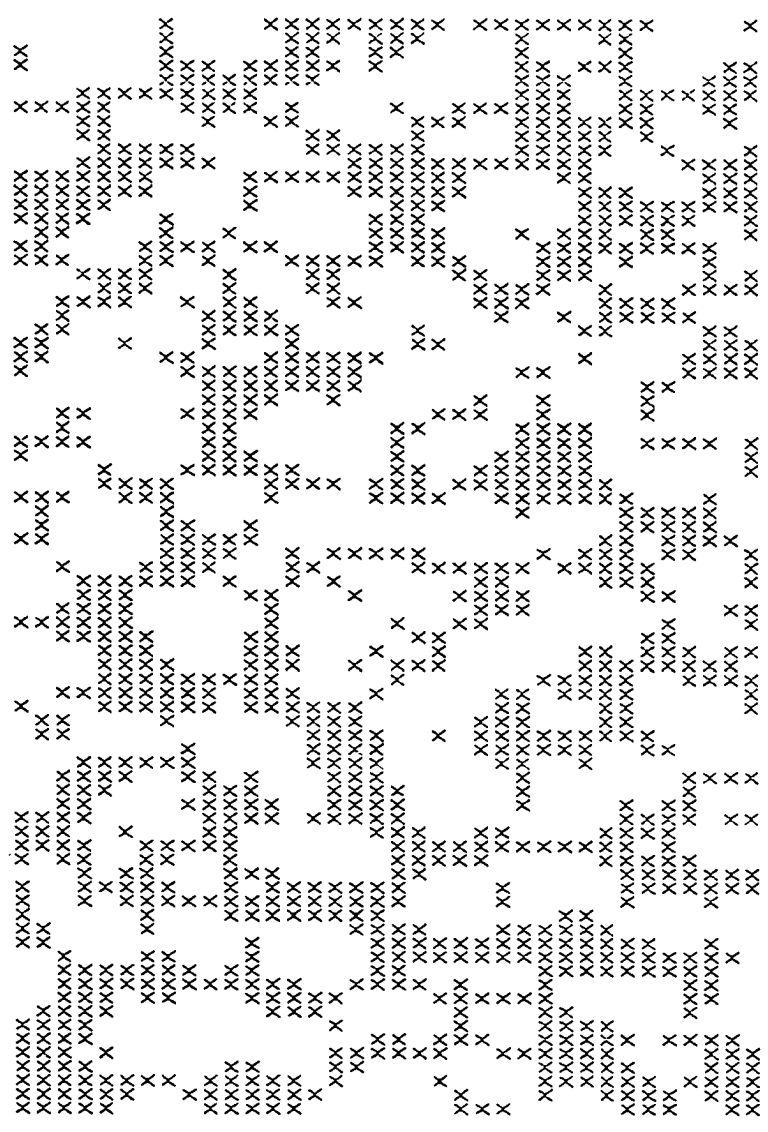
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```
      DO 678 I=1,80
678   IOUT(I)=IBLNK
      IX = (1. - (DMAX-AYDD(K))/DIFF) * 80
      IF (IX.EQ.0) IX=1
      DO 679 I=1,IX
679   IOUT(I)=ISTAR
      N=N + 1
      AYDD(K)=AYDD(K)/DMIN + .0001
680   PRINT 676,N,ANGS(K),AYDD(K),(IOUT(I),I=1,80)
699   CONTINUE
      PRINT 540
540   FORMAT(/////1X,'NORMAL END OF JOB')
      STOP
      END
```

Part II: Output

*
* *****
* *
* * D3-15 *
* *
* *****
*

ROCK (BLANK) / PORE (X) MAP



*

DOUBLE FOURIER POWER SPECTRUM

20 X 20 HARMONICS

ROCK/PORE MATRIX ELEMENTS: MEAN = 0.1152 AND VARIANCE = 0.9869

THE PERCENTAGE OF THE TOTAL VARIANCE EXPLAINED BY THE 20**2 HARMONICS = 60.197

*****											*	
*											*	
*		1	2	3	4	5	6	7	8	9	10	*
*												*
*	1	6	6	39	14	9	2	13	8	25	30	*
*	2	14	23	13	44	22	13	19	20	11	34	*
*	3	9	14	27	18	13	31	5	33	32	29	*
*	4	15	32	2	30	25	3	38	16	10	68	*
*	5	9	9	46	19	20	9	18	16	1	8	*
*	6	22	9	70	6	3	15	19	6	21	39	*
*	7	5	21	28	12	4	4	24	17	28	20	*
*	8	9	21	28	1	19	9	11	14	18	46	*
*	9	15	24	11	22	12	26	27	8	11	5	*
*	10	20	5	37	31	11	16	11	9	42	11	*
*	11	30	58	11	14	20	22	23	17	4	24	*
*	12	6	1	35	17	4	20	54	3	10	9	*
*	13	5	8	12	16	37	2	9	19	7	14	*
*	14	16	9	11	13	3	2	28	21	15	5	*
*	15	15	9	18	12	8	6	8	3	2	4	*
*	16	8	8	3	9	8	1	10	3	1	3	*
*	17	4	11	2	12	4	8	2	11	5	3	*
*	18	7	15	5	2	12	6	2	7	3	16	*
*	19	13	11	7	7	3	0	3	4	4	3	*
*	20	9	1	3	5	2	13	4	7	3	5	*
*****											*	

#											#	
#	11	12	13	14	15	16	17	18	19	20	#	
#											#	
#											#	
#	1	60	21	11	5	18	1	2	6	3	3	#
#	2	21	20	23	20	18	14	25	5	14	6	#
#	3	43	56	9	3	27	1	0	10	4	10	#
#	4	11	54	27	1	34	6	2	6	10	17	#
#	5	7	3	25	20	14	11	8	9	9	8	#
#	6	24	34	16	3	7	3	8	1	0	5	#
#	7	1	35	9	14	5	3	6	2	7	8	#
#	8	100	8	16	10	1	16	4	4	4	4	#
#	9	38	9	1	16	19	8	10	13	8	3	#
#	10	1	18	7	0	26	10	2	12	8	3	#
#	11	17	8	11	3	9	0	5	2	3	1	#
#	12	18	7	6	7	9	6	2	3	4	11	#
#	13	26	7	11	4	6	1	6	7	3	1	#
#	14	4	4	3	10	8	2	8	3	5	2	#
#	15	2	7	1	9	5	5	0	0	2	5	#
#	16	2	4	4	2	8	6	3	4	2	1	#
#	17	2	2	0	2	0	3	2	4	3	1	#
#	18	5	2	3	1	5	15	2	2	8	7	#
#	19	8	9	15	2	2	4	6	1	11	4	#
#	20	0	6	1	6	1	3	3	4	0	1	#

MAXIMUM POWER = 0.01217

DISTRIBUTION OF POWERS

PERCENT OF MAX. POWER	RELATIVE FREQUENCY
0 -- 10	61.25
11 -- 20	22.50
21 -- 30	9.00
31 -- 40	4.00
41 -- 50	1.25
51 -- 60	1.25
61 -- 70	0.50
71 -- 80	0.0
81 -- 90	0.0
91 -- 100	0.25

*
*

SPECIFIC PORE SURFACE AREA = 21.858 MM PER 1 SQUARE MM

POROSITY = 44.24 PERCENT

AVERAGE PORE DIMENSION PARALLEL TO COLUMNS = 0.085 MM

AVERAGE PORE DIMENSION NORMAL TO COLUMNS = 0.077 MM

AVERAGE PORE DIMENSION = 0.081

AVERAGE ROCK DIMENSION PARALLEL TO COLUMNS = 0.107 MM

AVERAGE ROCK DIMENSION NORMAL TO COLUMNS = 0.098 MM

AVERAGE ROCK DIMENSION = 0.102

RESOLUTION = 0.0254 MM BETWEEN ADJACENT ROCK/PORE POINTS

 *

TWO-DIMENSIONAL AUTOCORRELATION: LAG MOVEMENT PERPENDICULAR TO COLUMNS

LAG	CORRELATION (AMC)
0	1.000
1	0.706
2	0.551
3	0.491
4	0.475
5	0.499
6	0.517
7	0.528
8	0.514
9	0.504
10	0.487
11	0.488
12	0.485
13	0.494
14	0.508
15	0.514
16	0.504
17	0.491
18	0.481
19	0.492
20	0.515
21	0.531
22	0.529
23	0.518
24	0.522
25	0.511
26	0.499
27	0.491
28	0.494
29	0.505
30	0.511
31	0.531
32	0.525
33	0.510
34	0.505
35	0.501
36	0.509
37	0.508
38	0.502
39	0.498

LAG	CORRELATION (AMC)
0	1.000
1	0.732
2	0.579
3	0.511
4	0.489
5	0.492
6	0.499
7	0.518
8	0.520
9	0.504
10	0.489
11	0.492
12	0.496
13	0.491
14	0.491
15	0.498
16	0.507
17	0.503
18	0.506
19	0.496
20	0.505
21	0.512
22	0.521
23	0.518
24	0.508
25	0.508
26	0.510
27	0.511
28	0.519
29	0.512
30	0.514
31	0.509
32	0.501
33	0.494
34	0.498
35	0.505
36	0.520
37	0.525
38	0.531
39	0.533

 *

STANDARD DEVIATION OF QUADRAT POROSITY = 4.268 PERCENT

 *

RESULTS OF THE TORTUOSITY ANALYSIS FOR EACH PORE

PORE NO.	NO. OF CYCLES	TORTUOSITY SQUARED	PORE SIZE	EXTREME ROW	PTS. COL	EXTREME ROW	PTS. COL
1	110	1.52209	2642	79	1	1	73
2	2	1.00000	5	1	30	3	28
3	2	1.09912	7	1	42	3	45
4	3	1.00000	8	1	48	4	51
5	1	1.00000	2	1	76	1	77
6	1	1.00000	1	6	56	6	56
7	2	1.00000	3	20	57	21	56
8	2	1.09912	5	21	3	24	1
9	1	1.00000	1	21	28	21	28
10	1	1.00000	2	24	16	24	17
11	1	1.00000	2	25	54	26	54
12	1	1.00000	1	28	55	28	55
13	1	1.00000	4	31	49	34	49
14	2	1.00000	3	35	37	36	36
15	1	1.00000	2	38	10	38	11
16	4	1.15042	18	42	58	47	53
17	1	1.00000	2	45	76	46	76
18	1	1.00000	1	55	45	55	45
19	1	1.00000	1	55	56	55	56
20	5	1.06008	27	56	35	62	40
21	1	1.00000	1	56	53	56	53
22	1	1.00000	1	57	44	57	44
23	1	1.00000	2	75	26	75	27
24	4	1.08251	11	76	79	79	75
25	2	1.11313	6	77	35	79	34
26	1	1.00000	1	79	14	79	14
27	1	1.00000	2	79	40	79	41

*

NUMBER OF PORES = 27

FREQUENCY DISTRIBUTION OF PORE AREAS: LOG10(NO. OF PTS.)

LOWER BOUNDARY > OR =	UPPER BOUNDARY <	% OF PORE SPACE	FREQ.
0.0 (1)	0.25 (1)	0.	8 *****
0.25 (2)	0.50 (3)	1.	9 *****
0.50 (4)	0.75 (5)	1.	3 *****
0.75 (6)	1.00 (10)	1.	3 *****
1.00 (11)	1.25 (17)	0.	1 *****
1.25 (18)	1.50 (31)	2.	2 *****
1.50 (32)	1.75 (56)	0.	0
1.75 (57)	2.00 (100)	0.	0
2.00 (101)	2.25 (177)	0.	0
2.25 (178)	2.50 (316)	0.	0
2.50 (317)	2.75 (562)	0.	0
2.75 (563)	3.00 (1000)	0.	0
3.00 (1001)	3.25 (1778)	0.	0
3.25 (1779)	3.50 (3162)	96.	1 *****
3.50 (3163)	3.75 (5623)	0.	0
3.75 (5624)	4.00 (10000)	0.	0
4.00 (10001)	4.25 (17782)	0.	0

AVERAGE NO. OF PTS. IN A PORE = 102 TOTAL NUMBER OF PORE POINTS = 2761

AVERAGE AREA OF A PORE (MM**2) = 0.064151

FREQUENCY DISTRIBUTION OF MAX. PORE DIMENSIONS PARALLEL TO COLUMNS (MM)

LOWER BOUNDARY > OR =	UPPER BOUNDARY <	% OF PORE SPACE	FREQ.	
0.00	0.25	4.	26	*****
0.25	0.50	0.	0	
0.50	0.75	0.	0	
0.75	1.00	0.	0	
1.00	1.25	0.	0	
1.25	1.50	0.	0	
1.50	1.75	0.	0	
1.75	2.00	0.	0	
2.00	2.25	96.	1	**
2.25	2.50	0.	0	
2.50	2.75	0.	0	
2.75	3.00	0.	0	
3.00	3.25	0.	0	
3.25	3.50	0.	0	
3.50	3.75	0.	0	
3.75	4.00	0.	0	
4.00	4.25	0.	0	
4.25	4.50	0.	0	
4.50	4.75	0.	0	
4.75	5.00	0.	0	
5.00	5.25	0.	0	
5.25	5.50	0.	0	
5.50	5.75	0.	0	
5.75	6.00	0.	0	

AVERAGE MAXIMUM PORE DIMENSION = 0.133 MM

FREQUENCY DISTRIBUTION OF MAX. PORE DIMENSIONS NORMAL TO COLUMNS (MM)

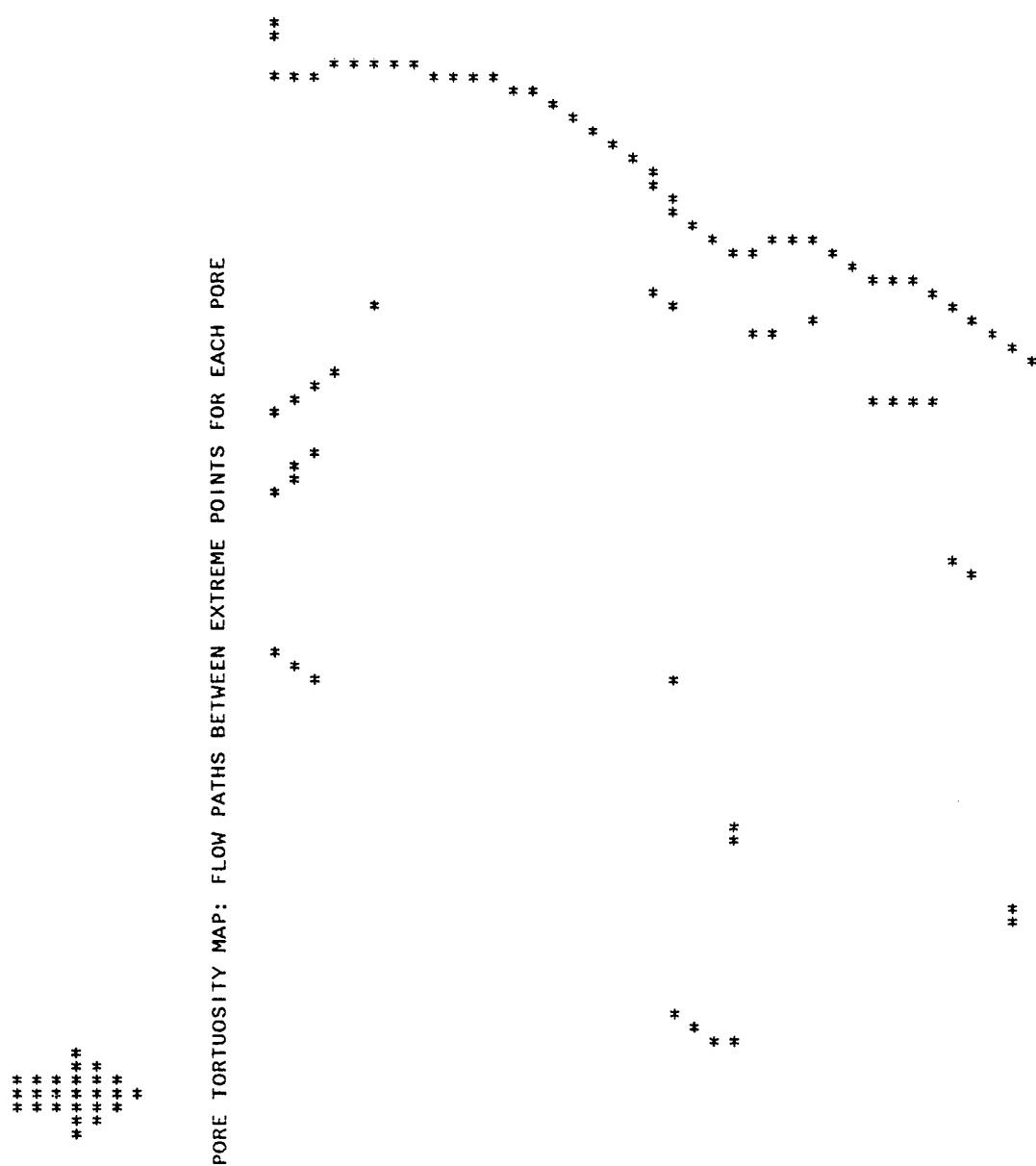
LOWER BOUNDARY > OR =	UPPER BOUNDARY <	% OF PORE SPACE	FREQ.	
0.00	0.25	4.	26	*****
0.25	0.50	0.	0	
0.50	0.75	0.	0	
0.75	1.00	0.	0	
1.00	1.25	0.	0	
1.25	1.50	0.	0	
1.50	1.75	0.	0	
1.75	2.00	0.	0	
2.00	2.25	96.	1	**
2.25	2.50	0.	0	
2.50	2.75	0.	0	
2.75	3.00	0.	0	
3.00	3.25	0.	0	
3.25	3.50	0.	0	
3.50	3.75	0.	0	
3.75	4.00	0.	0	
4.00	4.25	0.	0	
4.25	4.50	0.	0	
4.50	4.75	0.	0	
4.75	5.00	0.	0	
5.00	5.25	0.	0	
5.25	5.50	0.	0	
5.50	5.75	0.	0	
5.75	6.00	0.	0	

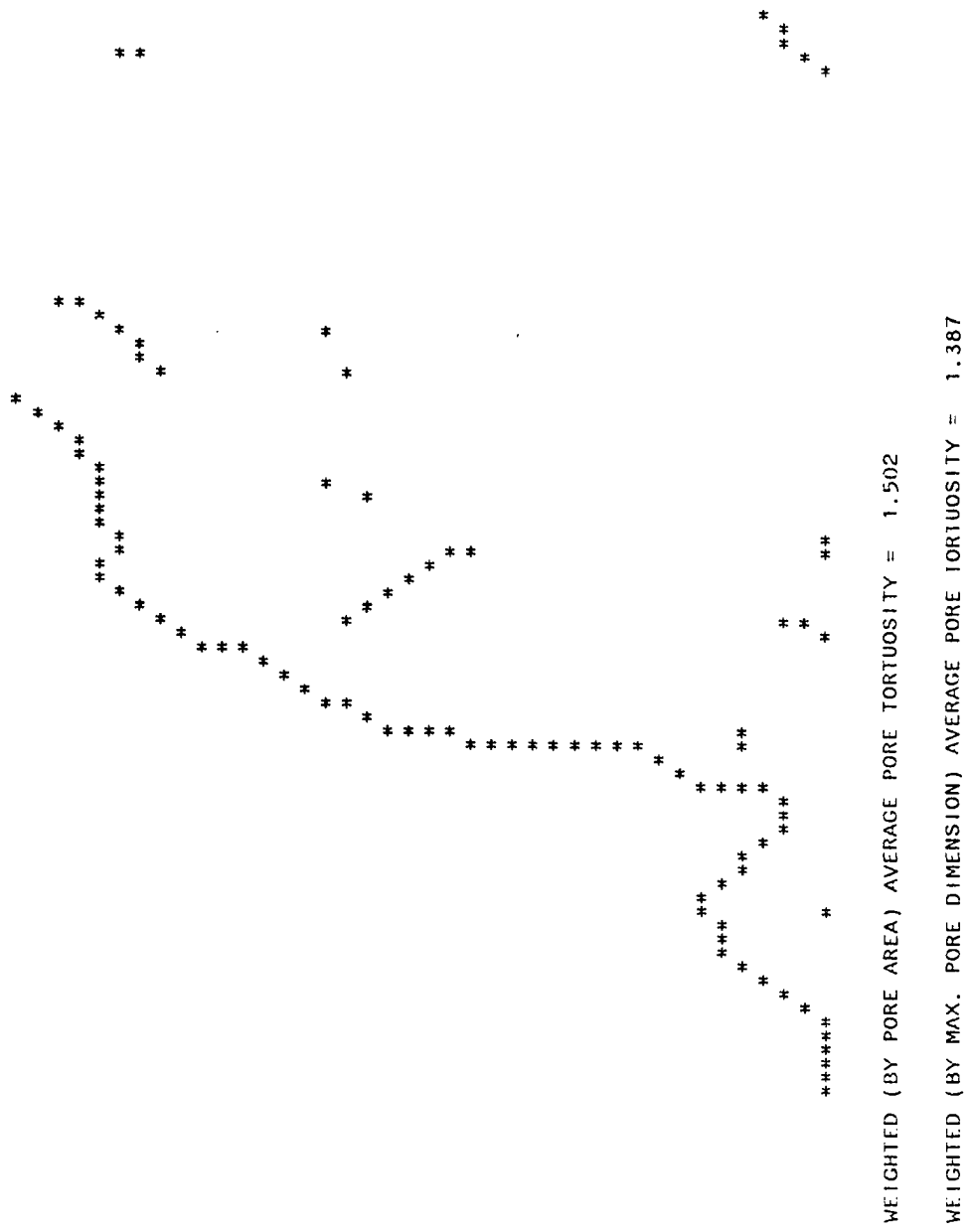
AVERAGE MAXIMUM PORE DIMENSION = 0.130 MM

FREQUENCY DISTRIBUTION OF MAXIMUM PORE DIMENSIONS (MM)

LOWER BOUNDARY > OR =	UPPER BOUNDARY <	% OF PORE SPACE	FREQ.	
0.00	0.25	4.	26	*****
0.25	0.50	0.	0	
0.50	0.75	0.	0	
0.75	1.00	0.	0	
1.00	1.25	0.	0	
1.25	1.50	0.	0	
1.50	1.75	0.	0	
1.75	2.00	0.	0	
2.00	2.25	0.	0	
2.25	2.50	0.	0	
2.50	2.75	96.	1	**
2.75	3.00	0.	0	
3.00	3.25	0.	0	
3.25	3.50	0.	0	
3.50	3.75	0.	0	
3.75	4.00	0.	0	
4.00	4.25	0.	0	
4.25	4.50	0.	0	
4.50	4.75	0.	0	
4.75	5.00	0.	0	
5.00	5.25	0.	0	
5.25	5.50	0.	0	
5.50	5.75	0.	0	
5.75	6.00	0.	0	

AVERAGE MAXIMUM PORE DIMENSION = 0.172 MM

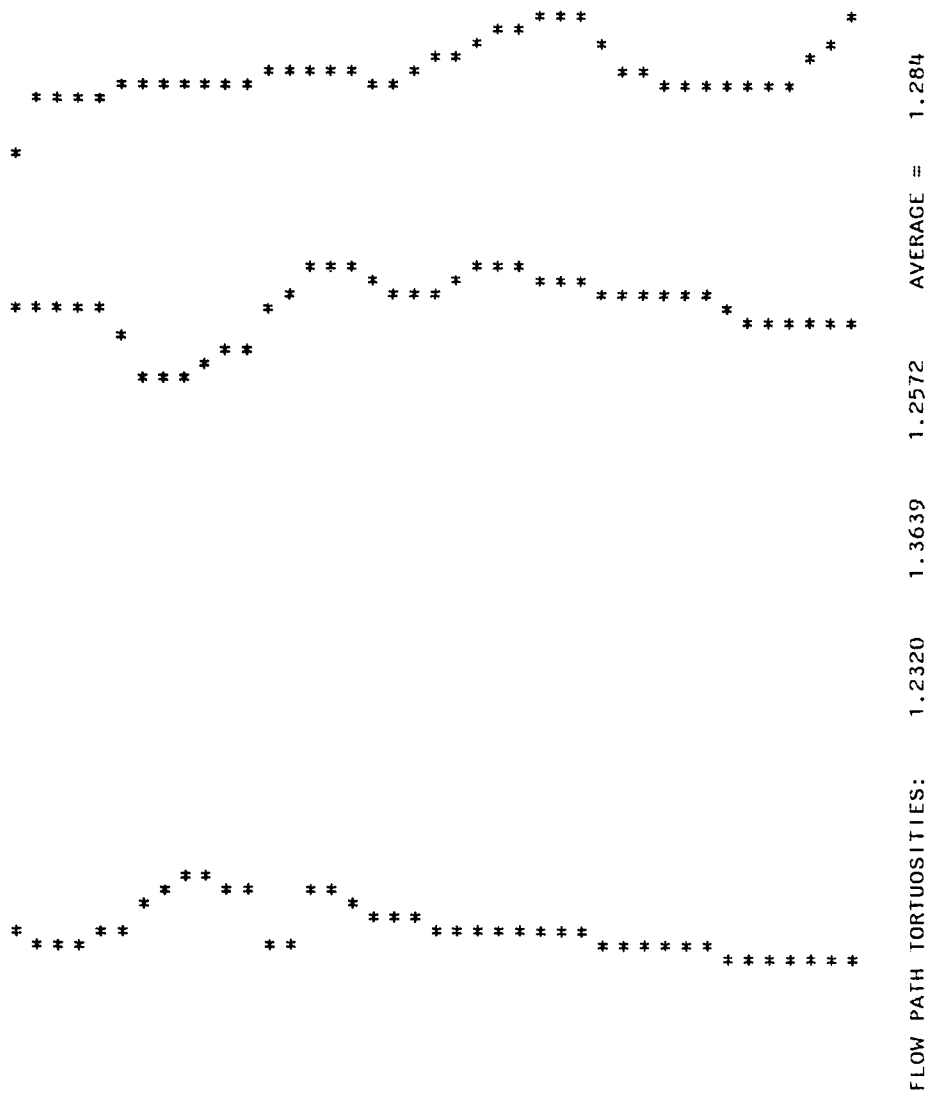




*

PORE TORTUOSITY MAP; THREE FLOW PATHS APPROXIMATELY PARALLEL TO COLUMNS (MODIFIED METHOD OF PRESTON AND DAVIS, 1976)





*

ANALYSIS OF PREFERRED PORE ELONGATION ORIENTATION

ANGLE BETWEEN THE COLUMNS AND THE MEA- SURED DIRECTION	AVE. OF THE SQUARE OF THE LONGER THAN AVE PORE SEGMENTS	(1) ***	(2-5) *	(6) *	(7-10) *	*
1 90.	1.044	*****				
2 72.	1.000	*				
3 54.	1.066	*****				
4 36.	1.140	*****				
5 18.	1.298	*****				
6 0.	1.240	*****				
7 18.	1.172	*****				
8 36.	1.135	*****				
9 54.	1.108	*****				
10 72.	1.004	*				

NORMAL END OF JOB

APPENDIX M

COMPUTATIONAL RESULTS FOR THE PORE GEOMETRY ANALYSES

EXPLANATORY NOTE

- 1) The analyzed rock-pore matrices are illustrated in Appendix K.
- 2) Rock-pore matrices 'B2-16 // S.' and 'D5-16 // S.' are oriented normal to bedding and parallel to strike. The top and bottom margins of the matrices are parallel to bedding and to strike.
- 3) Rock-pore matrices 'B2-16 // B.' and 'D5-16 // B.' are oriented parallel to bedding. The left and right margins of the matrices are parallel to the direction of dip. The laminae dip towards the lower margin of the matrices.
- 4) All other rock-pore matrices are oriented normal to bedding and parallel to dip. The left and right margins of the matrices are parallel to bedding. The laminae dip towards the lower margin of the matrices.
- 5) The nine test patterns are intended to simulate rock-pore matrices oriented normal to bedding and parallel to dip.
- 6) The horizontal and vertical distance between adjacent rock and pore points (RES0) is 0.0254 millimeters for the two AB1 samples, the two D3 samples and five of the AR1 samples (AR1-4c excluded). The interpoint distance is 0.0508 millimeters for all other samples and the test patterns.

Part I: Porosity, Specific Surface Area, Tortuosity and Number of Pores

Sample	Porosity (percent)	Standard Deviation of Quadrat Porosity	Specific Surface Area (mm ⁻¹)	Weighted Average Individual Pore Tortuosity		Average Preston- Davis ¹ Tortuosity	Number of Individual Pores
				By Area	By Maximum Dimension		
B2-20	41.02	9.48	6.479	2.377	2.128	1.377	8
B2-7	37.30	3.38	8.333	1.588	1.543	1.483	22
B2-9	42.03	3.23	8.718	1.380	1.351	1.384	22
B2-1	40.89	5.06	8.860	1.306	1.295	1.331	18
B2-16A	41.45	4.88	9.153	1.761	1.624	1.427	19
B2-16B	40.70	3.26	9.204	2.344	1.864	1.370	20
B2-16//S.	38.55	8.91	9.122	1.560	1.452	1.494	27
B2-16//B.	40.01	3.88	9.052	1.586	1.534	1.399	17
B1-15	44.85	3.13	14.780	2.433	1.956	1.404	39
B1-16	50.83	4.05	13.645	1.554	1.471	1.329	21
AB1-1d1	18.15	5.56	10.743	1.209	1.242	3.551	83
AB1-1d2	19.48	5.26	11.257	1.216	1.220	3.220	86
D5-10	44.74	3.26	12.550	1.372	1.333	1.288	43
D5-15	45.17	2.01	13.102	1.877	1.591	1.289	49
D5-16A	50.31	3.83	12.538	1.287	1.307	1.279	20
D5-16B	49.70	3.86	12.941	1.407	1.376	1.349	31
D5-16//S.	48.37	2.85	12.626	1.819	1.813	1.441	26
D5-16//B.	49.78	3.26	13.064	1.347	1.315	1.174	28
D3-15	44.24	4.27	21.858	1.502	1.387	1.279	27
D3-19	43.12	3.44	22.085	1.450	1.324	1.226	28
AD2-1e	30.33	3.97	10.298	1.351	1.369	1.852	129
AD2-1f	28.33	3.18	9.292	1.368	1.358	1.950	105
R5-23	45.75	3.23	13.257	1.402	1.471	1.367	25
R5-25	46.32	2.81	14.269	1.698	1.625	1.331	26
R5-21	47.64	1.42	11.664	1.315	1.306	1.316	12

Part I: (Continued)

Sample	Porosity (percent)	Standard Deviation of Quadrat Porosity	Specific Surface Area (mm ⁻¹)	Weighted Average Individual Pore Tortuosity		Average Preston- Davis Tortuosity ¹	Number of Individual Pores
				By Area	By Maximum Dimension		
R5-34	47.83	1.76	14.033	1.878	1.645	1.313	32
AR1-4c	21.45	3.51	7.191	1.268	1.293	2.230	123
AR1-5c	25.96	3.53	13.456	1.230	1.228	2.195	80
AR1-14	21.94	3.64	12.692	1.235	1.231	3.040	99
AR1-15a	17.96	7.80	10.920	1.163	1.174	2.663	104
AR1-18	18.35	5.79	10.100	1.164	1.179	2.392	96
AR1-22c	16.79	4.28	10.497	1.140	1.181	2.666	101
RAN-1	18.88	1.31	6.037	1.194	1.205	2.928	78
RAN-2	36.89	2.77	7.665	1.278	1.233	1.726	38
RAN-3	51.61	6.77	13.292	1.455	1.466	1.345	59
CASE1-P	25.60	3.85	7.116	1.000	1.000	1.807	64
CASE1-OB	45.22	4.43	5.504	1.308	1.314	1.799	11
CASE2-P	12.83	1.19	5.709	1.124	1.124	1.838	81
CASE2-OB	40.07	3.00	6.248	1.515	1.440	1.965	14
CASE3-P	48.93	3.09	5.296	1.323	1.323	1.263	2
CASE3-OB	25.70	1.28	7.226	1.398	1.347	2.032	50

¹Each pore path was tracked in a direction roughly parallel to the left and right margins of the rock-pore matrices.

Part II: Pore Size					Measures Based on Individual Pores					
Sample	Measures Based on the Entire Pore Pattern									
	Average Pore Dimension (mm)			Average Maximum Pore Dimension (mm)						
	Parallel to Right Margin	Normal to Right Margin	Mean (overall)	Parallel to Right Margin	Normal to Right Margin	Mean (overall)				
							Parallel to Right Margin	Normal to Right Margin	Average Pore Area (mm ²)	
B2-20	0.272	0.237	0.254	0.391	0.341	0.366	0.648	0.737	0.933	0.8050
B2-7	0.190	0.170	0.180	0.319	0.285	0.302	0.520	0.423	0.590	0.2642
B2-9	0.206	0.181	0.194	0.285	0.250	0.268	0.293	0.291	0.383	0.2994
B2-1	0.189	0.181	0.185	0.273	0.261	0.267	0.381	0.398	0.506	0.3547
B2-16A	0.185	0.177	0.181	0.261	0.251	0.256	0.369	0.356	0.450	0.3421
B2-16B	0.185	0.169	0.177	0.270	0.247	0.259	0.384	0.475	0.556	0.3195
B2-16//S.	0.175	0.164	0.170	0.279	0.261	0.270	0.380	0.371	0.469	0.2239
B2-16//B.	0.170	0.184	0.177	0.255	0.275	0.265	0.332	0.329	0.442	0.3673
B1-15	0.124	0.119	0.122	0.153	0.146	0.150	0.231	0.237	0.296	0.1786
B1-16	0.153	0.145	0.149	0.148	0.141	0.145	0.310	0.356	0.444	0.3800
AB1-1d1	0.069	0.067	0.068	0.309	0.300	0.305	0.106	0.112	0.136	0.0082
AB1-1d2	0.068	0.070	0.069	0.287	0.300	0.294	0.116	0.112	0.145	0.0085
D5-10	0.147	0.138	0.143	0.182	0.171	0.177	0.261	0.285	0.345	0.1610
D5-15	0.147	0.130	0.139	0.179	0.157	0.168	0.206	0.202	0.261	0.1434
D5-16A	0.165	0.156	0.161	0.163	0.154	0.159	0.272	0.290	0.376	0.3950
D5-16B	0.160	0.148	0.154	0.162	0.149	0.156	0.244	0.236	0.310	0.2516
D5-16//S.	0.155	0.152	0.154	0.165	0.162	0.164	0.293	0.305	0.388	0.2918
D5-16//B.	0.153	0.152	0.153	0.154	0.153	0.154	0.256	0.245	0.333	0.2767
D3-15	0.085	0.077	0.081	0.107	0.098	0.103	0.133	0.130	0.172	0.0642
D3-19	0.083	0.074	0.079	0.109	0.098	0.104	0.151	0.167	0.206	0.0604
AD2-1e	0.118	0.117	0.118	0.272	0.269	0.271	0.234	0.232	0.290	0.0352
AD2-1f	0.124	0.120	0.122	0.314	0.303	0.309	0.254	0.264	0.324	0.0402
R5-23	0.143	0.133	0.138	0.169	0.158	0.164	0.311	0.341	0.434	0.2868
R5-25	0.135	0.125	0.130	0.156	0.145	0.151	0.328	0.297	0.391	0.2792

Sample	Part II: (Continued)				Measures Based on Individual Pores			
	Measures Based on the Entire Pore Pattern				Measures Based on Individual Pores			
	Average Pore Dimension (mm)				Average Maximum Pore Dimension (mm)			
	Parallel to Right Margin	Normal to Right Margin	Mean (overall)	Parallel to Right Margin	Normal to Right Margin	Mean (overall)	Parallel to Right Margin	Average Pore Area (mm ²)
R5-21	0.170	0.158	0.164	0.186	0.173	0.180	0.440	0.6214
R5-34	0.143	0.130	0.137	0.156	0.142	0.149	0.238	0.2340
AR1-4c	0.123	0.116	0.120	0.451	0.424	0.438	0.199	0.0252
AR1-5c	0.079	0.075	0.077	0.226	0.214	0.220	0.140	0.0126
AR1-14	0.070	0.068	0.069	0.248	0.244	0.246	0.111	0.0082
AR1-15a	0.068	0.063	0.066	0.312	0.290	0.301	0.088	0.0063
AR1-18	0.076	0.070	0.073	0.337	0.311	0.324	0.089	0.0069
AR1-22c	0.067	0.062	0.065	0.330	0.305	0.318	0.090	0.0063
RAN-1	0.123	0.127	0.125	0.530	0.545	0.538	0.304	0.0377
RAN-2	0.190	0.195	0.192	0.325	0.334	0.330	0.504	0.1509
RAN-3	0.160	0.151	0.156	0.150	0.142	0.146	0.196	0.1358
CASE1-P	0.144	0.144	0.144	0.418	0.418	0.418	0.451	0.0604
CASE1-OB	0.327	0.331	0.329	0.396	0.401	0.398	1.372	0.6440
CASE2-P	0.127	0.070	0.099	0.860	0.474	0.667	0.157	0.0226
CASE2-OB	0.263	0.251	0.257	0.393	0.375	0.384	1.183	0.4478
CASE3-P	0.371	0.368	0.370	0.387	0.384	0.386	4.013	3.8415
CASE3-OB	0.143	0.142	0.142	0.412	0.410	0.411	0.473	0.0805

Part III: Double Fourier Analyses
Most Powerful Sinusoid Pairs³

Sample	% of Total Var.1	Max.2 Power ² (x10)	First				Second					
			V. 4 Har.	λ_V (mm)	H. 6 Har.	λ_H (mm)	λ_H (mm)	% of Max.8	V. 8 Har.	λ_V (mm)	H. 8 Har.	λ_H (mm)
B2-20	71.3	0.293	3	1.32	3	1.32	100	4	0.99	2	1.98	65
B2-7	63.9	0.124	2	1.98	8	0.50	100	6	0.66	1	3.96	96
B2-9	66.7	0.119	3	1.32	4	0.99	100	5	0.79	1	3.96	95
B2-1	65.9	0.163	5	0.79	8	0.50	100	1	3.96	3	1.32	68
B2-16A	65.8	0.105	8	0.50	6	0.66	100	1	3.96	9	0.44	99
B2-16R	66.0	0.119	1	3.96	8	0.50	100	6	0.66	4	0.99	99
B2-16//S.	63.5	0.131	1	3.96	2	1.98	100	2	1.98	1	3.96	89
B2-16//B.	65.7	0.150	8	0.50	4	0.99	100	12	0.33	2	1.98	79
B1-15	44.7	0.049	13	0.30	18	0.22	100	4	0.99	17	0.23	92
B1-16	49.0	0.051	4	0.99	8	0.50	100	8	0.50	17	0.23	88
AB1-1d1	64.9	0.100	2	0.99	4	0.50	100	2	0.99	1	1.98	83
AB1-1d2	65.4	0.090	1	1.98	3	0.66	100	7	0.28	2	0.99	91
D5-10	54.5	0.087	2	1.98	12	0.33	100	13	0.30	2	1.98	81
D5-15	52.0	0.082	5	0.79	8	0.50	100	6	0.66	4	0.99	90
D5-16A	54.7	0.087	8	0.50	3	1.32	100	8	0.50	11	0.36	98
D5-16B	51.5	0.070	3	1.32	8	0.50	100	11	0.36	1	3.96	93
D5-16//S.	53.3	0.066	10	0.40	9	0.44	100	13	0.30	5	0.79	89
D5-16//B.	52.7	0.064	7	0.57	9	0.44	100	14	0.28	7	0.57	90
D3-15	60.2	0.122	8	0.25	11	0.18	100	6	0.33	3	0.66	70
D3-19	59.8	0.100	9	0.22	5	0.40	100	4	0.50	11	0.18	77
AD2-1e	55.2	0.066	8	0.50	4	0.99	100	3	1.32	5	0.79	95
AD2-1f	58.2	0.088	11	0.36	4	0.99	100	8	0.50	5	0.79	70
R5-23	51.0	0.059	5	0.79	17	0.23	100	10	0.40	2	1.98	88
R5-25	45.0	0.052	14	0.28	13	0.30	100	1	3.96	17	0.23	85
R5-21	59.0	0.098	10	0.40	5	0.79	100	11	0.36	4	0.99	79

Part III: (Continued)

Most Powerful Sinusoid Pairs³

Sample	% of Total Var.	Max. 2 Power (x10)	First					Second				
			V. 4 Har.	λ_V (mm)	H. 6 Har.	λ_H (mm)	% of 8 Max.	V. Har.	λ_V (mm)	H. Har.	λ_H (mm)	% of Max.
R5-34	47.1	0.067	1	3.96	12	0.33	100	11	0.36	6	0.66	76
AR1-4c	58.1	0.072	6	0.66	2	1.98	100	3	1.32	2	1.98	92
AR1-5c	65.3	0.096	5	0.40	6	0.33	100	2	0.99	5	0.40	94
AR1-14	64.0	0.147	3	0.66	1	1.98	100	2	0.99	1	1.98	75
AR1-15a	61.1	0.166	2	0.99	4	0.50	100	4	0.50	1	1.98	78
AR1-18	66.0	0.197	1	1.98	1	1.98	100	7	0.28	3	0.66	46
AR1-22c	64.4	0.204	1	1.98	3	0.66	100	5	0.40	5	0.40	43
RAN-1	63.8	0.248	5	0.79	6	0.66	100	8	0.50	2	1.98	61
RAN-2	68.9	0.170	3	1.32	2	1.98	100	9	0.44	1	3.96	94
RAN-3	51.2	0.188	1	3.96	4	0.99	100	2	1.98	1	3.96	62
CASE1-P	10.4	0.335	8	0.50	8	0.50	100	16	0.25	16	0.25	52
CASE1-OB	69.1	1.25	7	0.57	2	1.98	100	1	3.96	8	0.50	55
CASE2-P	28.0	0.382	5	0.79	8	0.50	100	4	0.99	8	0.50	73
CASE2-OB	73.2	0.987	1	3.96	8	0.50	100	2	1.98	8	0.50	76
CASE3-P	10.3	0.506	11	0.36	8	0.50	100	6	0.66	16	0.25	22
CASE3-OB	66.9	0.396	5	0.79	2	1.98	100	3	1.32	8	0.50	82

Part III: (Continued)

Most Powerful Sinusoid Pairs

Sample	Third					Fourth				
	V. Har.	λ_V (mm)	H. Har.	λ_H (mm)	% of Max.	V. Har.	λ_V (mm)	H. Har.	λ_H (mm)	% of Max.
B2-20	2	1.98	6	0.66	64	5	0.79	5	0.79	61
B2-7	2	1.98	5	0.79	88	3	1.32	4	0.99	88
B2-9	3	1.32	2	1.98	94	7	0.57	8	0.50	91
B2-1	5	0.79	4	0.99	67	5	0.79	6	0.66	57
B2-16A	2	1.98	6	0.66	94	7	0.57	6	0.66	89
B2-16B	7	0.57	7	0.57	86	5	0.79	8	0.50	81
B2-16//S.	9	0.44	3	1.32	64	1	3.96	1	3.96	62
B2-16//B.	9	0.44	1	3.96	78	1	3.96	8	0.50	69
B1-15	19	0.21	1	3.96	81	11	0.36	2	1.98	79
B1-16	4	0.99	5	0.79	87	9	0.44	3	1.32	82
AB1-1d1	1	1.98	1	1.98	78	4	0.50	1	1.98	77
AB1-1d2	7	0.28	1	1.98	90	1	1.98	1	1.98	82
D5-10	1	3.96	3	1.32	73	10	0.40	7	0.57	63
D5-15	2	1.98	5	0.79	69	2	1.98	14	0.28	62
D5-16A	13	0.30	2	1.98	70	11	0.36	3	1.32	69
D5-16B	4	0.99	5	0.79	77	13	0.30	4	0.99	67
D5-16//S.	2	1.98	1	3.96	88	7	0.57	13	0.30	85
D5-16//B.	7	0.57	6	0.66	88	2	1.98	13	0.30	88
D3-15	4	0.50	10	0.20	68	1	1.98	11	0.18	60
D3-19	2	0.99	6	0.33	75	3	0.66	8	0.25	75
AD2-1e	1	3.96	8	0.50	85	7	0.57	4	0.99	82
AD2-1f	2	1.98	13	0.30	66	4	0.99	8	0.50	61
R5-23	2	1.98	11	0.36	76	6	0.66	7	0.57	71
R5-25	18	0.22	3	1.32	79	5	0.79	12	0.33	77
R5-21	11	0.36	5	0.79	75	9	0.44	8	0.50	62

Part III: (Continued)

Most Powerful Sinusoid Pairs

Sample	Third					Fourth				
	V. Har.	λ_V (mm)	H. Har.	λ_H (mm)	% of Max.	V. Har.	λ_V (mm)	H. Har.	λ_H (mm)	% of Max.
R5-34	6	0.66	12	0.33	72	3	1.32	9	0.44	70
AR1-4C	2	1.98	4	0.99	81	3	1.32	6	0.66	62
AR1-5C	8	0.25	4	0.50	84	4	0.50	2	0.99	78
AR1-14	1	1.98	5	0.40	62	7	0.28	1	1.98	50
AR1-15a	2	0.99	11	0.18	65	5	0.40	6	0.33	37
AR1-18	2	0.99	9	0.22	41	3	0.66	1	1.98	40
AR1-22c	3	0.66	5	0.40	38	5	0.40	6	0.33	38
RAN-1	13	0.30	8	0.50	53	3	1.32	8	0.50	49
RAN-2	7	0.57	4	0.99	75	8	0.50	7	0.57	71
RAN-3	3	1.32	4	0.99	56	1	3.96	2	1.98	48
CASE1-P	8	0.50	16	0.25	10	16	0.25	8	0.50	10
CASE1-OB	2	1.98	8	0.50	40	3	1.32	1	3.96	26
CASE2-P	14	0.28	8	0.50	56	20	0.20	8	0.50	14
CASE2-OB	6	0.66	2	1.98	72	9	0.44	1	3.96	35
CASE3-P	18	0.22	8	0.50	9	17	0.23	8	0.50	8
CASE3-OB	9	0.44	1	3.96	78	2	1.98	10	0.40	70

Part III: Footnotes

- ¹Percent of the total variance accounted for by the 400 sinusoid pairs.
- ²Power (in absolute terms) of the single most powerful sinusoid pair.
- ³Results for the four most powerful sinusoid pairs.
- ⁴Harmonic number for sinusoids with vertical ridge axes (i.e., parallel to the left and right margins—and columns—of the rock-pore matrices).
- ⁵Wavelength (in millimeters) for the vertically oriented sinusoids:
 $\lambda_V = (78 \cdot \text{RESO}) / (\text{V. Har.})$ where RESO is the distance between adjacent rock and pore points.
- ⁶Harmonic number for sinusoids with horizontal ridge axes (i.e., parallel to the top and bottom margins—and rows—of the rock-pore matrices).
- ⁷Wavelength (in millimeters) for the horizontally oriented sinusoids:
 $\lambda_H = (78 \cdot \text{RESO}) / (\text{H. Har.})$.
- ⁸Relative power of the sinusoid pairs expressed as the percent of the power for the single most powerful sinusoid pair.

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Part IV: Footnotes

- ¹Results for the correlogram where the direction of lag movement is horizontal or parallel to the top and bottom margins of the rock-pore matrices (and perpendicular to bedding for most matrices).
- ²Results for the correlogram where the direction of lag movement is vertical or parallel to the left and right margins of the rock-pore matrices (and parallel to bedding for most matrices).
- ³Y—yes, repetitions are visible in the correlogram; and N—no, repetitions are not visible.
- ⁴Maximum ratio of the similarity coefficients for the adjacent correlogram peaks and troughs of the observed repetition (peak/trough).
- ⁵Number of lags spanned by the repetition (i.e., the repeat interval).
- ⁶Wavelength (in millimeters) of the repetition: $\lambda = (\text{no. lags}) \cdot \text{RESO}$ where RESO is the distance between adjacent rock and pore points.
- ⁷Angle and height for the three largest peaks in the histogram plot of average pore dimension (i.e., the average of the squared lengths of the pore segments longer than the overall average pore dimension in Part II of this appendix) versus traverse orientation; for many rock-pore matrices only two peaks are present.
- ⁸Pore orientation relative to the margins of the rock-pore matrices: 0, oriented parallel to the left and right margins; 18-72, oriented diagonally from upper right to lower left; 90, oriented perpendicular to the left and right margins; and 108-162, oriented diagonally from lower right to upper left.
- ⁹Ratio of the average pore dimension for the peak to the minimum average pore dimension for any orientation.

Part IV: (Continued)

Autocorrelation										Pore Orientation ⁷					
Horizontal Lags ¹					Vertical Lags ²					1st Peak		2nd Peak		3rd Peak	
Sample	Rep's ³		If yes		λ ⁶	Rep's		If yes		Angle ⁸	Height ⁹	Angle	Height	Angle	Height
	?	P/T ⁴	no. lags	?		P/T	no. lags	λ							
R5-23	N	1.06	—	—	—	N	1.03	—	—	90	1.28	36	1.27	0	1.24
R5-25	N	1.06	—	—	—	N	1.06	—	—	0	1.38	144	1.17	90	1.13
R5-21	N	1.07	—	—	—	N	1.09	—	—	0	1.39	90	1.27	54	1.26
R5-34	N	1.08	—	—	—	N	1.06	—	—	0	1.47	90	1.23	108	1.16
AR1-4c	N	1.03	—	—	—	N	1.03	—	—	126	1.24	90	1.21	18	1.19
AR1-5c	N	1.05	—	—	—	N	1.04	—	—	54	1.26	90	1.23	126	1.17
AR1-14	N	1.06	—	—	—	N	1.03	—	—	108	1.38	54	1.10	0	1.07
AR1-15a	N	1.03	—	—	—	N	1.06	—	—	0	1.75	126	1.21	90	1.12
AR1-18	N	1.03	—	—	—	N	1.02	—	—	54	1.31	162	1.15	—	—
AR1-22c	N	1.02	—	—	—	N	1.03	—	—	0	1.75	72	1.30	—	—
RAN-1	Y	1.19	11	0.56	—	N	1.10	—	—	54	1.44	90	1.08	144	1.06
RAN-2	N	1.07	—	—	—	Y	1.13	10	0.51	126	1.19	0	1.14	54	1.10
RAN-3	N	1.10	—	—	—	N	1.03	—	—	162	1.47	36	1.24	90	1.08
CASE1-P	Y	1.52	10	0.51	—	Y	1.52	10	0.51	0	1.65	90	1.65	—	—
CASE1-OB	Y	1.59	10	0.51	—	Y	2.19	11	0.56	108	3.67	0	1.97	—	—
CASE2-P	Y	1.35	10	0.51	—	Y	1.29	17	0.86	0	10.60	90	2.02	—	—
CASE2-OB	Y	1.90	10	0.51	—	N	1.29	—	—	18	2.57	90	1.98	—	—
CASE3-P	Y	1.39	10	0.51	—	Y	2.99	14	0.71	90	31.91	0	2.72	—	—
CASE3-OB	Y	1.22	10	0.51	—	Y	1.20	8	0.41	0	1.67	90	1.32	—	—

APPENDIX N

ANNOTATED LISTING AND OUTPUT EXAMPLE
FOR THE FORTRAN IV COMPUTER PROGRAM 'CORMAT'

Part I: Program

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C *****
C *      *
C * CORMAT *
C *      *
C *****
C
C
C THE CORMAT PROGRAM TAKES A DATA SET CONSISTING OF NS (MAX.=200)
C SAMPLES WITH NV (MAX.=75) VARIABLES AND COMPUTES THE CORRELATION
C MATRIX (BASED ON BIVARIATE LEAST SQUARES POLYNOMIAL REGRESSION).
C FOR EACH PAIR OF VARIABLES THE FOLLOWING INFORMATION IS PROVIDED IN
C THE MATRIX: THE PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS FOR
C THE FIRST (LINEAR/STRAIGHT LINE), SECOND (QUADRATIC/PARABOLIC CURVE)
C AND THIRD (CUBIC/DOUBLE PARABOLIC CURVE) DEGREE POLYNOMIALS; THE
C RESULTS OF A F TEST FOR EACH REGRESSION TERM (EXPRESSED AS THE CON-
C FIDENCE LEVEL AT WHICH THE TERM CAN BE CONSIDERED STATISTICALLY
C SIGNIFICANT; THE NUMBER OF SAMPLES USED IN THE CALCULATIONS; AND
C THE CURVATURE AND ORIENTATION OF THE SECOND DEGREE POLYNOMIAL CURVE
C (I.E., THE QUADRATIC CURVE TYPE). FOR EACH VARIABLE PAIR, THE DEPENDENT
C VARIABLE IS INDICATED AT THE TOP OF THE COLUMN AND THE INDEPENDENT
C VARIABLE IS INDICATED ON THE LEFT SIDE OF THE ROW.
C
C THE CODES FOR THE QUADRATIC CURVE TYPE (QCT) ARE AS FOLLOWS:
C
C 1 *      ** * 3 **      * 5 *      *
C   *      * *      *      *      *      *
C   *      *      *      *      *      *
C **      * 2      ** 4 *      *      * 6 *
C
C CURVE TYPES 5 AND 6 CAN BE FURTHER INTERPRETED AS FOLLOWS:
C
C L TERM = SIG      *
C R SIGN = +      *
C QCT = 5 A      * *
C              **
C
C L TERM = SIG      *
C R SIGN = -      *
C QCT = 5 B      * *
C              **
C
C L TERM = NOT SIG  *      *
C R SIGN = + OR -  *      *
C QCT = 5 C      * *
C              **
C
C L TERM = SIG      **
C R SIGN = +      * *
C QCT = 6 A      *
C              *
C

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C   L TERM = SIG           **
C   R SIGN = -             *  *
C   QCT = 6 B              *
C                           *
C
C   L TERM = NOT SIG       **
C   R SIGN = + OR -        *  *
C   QCT = 6 C              *  *
C                           *  *
C
C ***** CONTROL AND DATA CARDS *****
C
C ***** CONTROL CARD 1 *****
C   NS (COLS 1-3, RIGHT-JUSTIFIED INTEGER) = NUMBER OF SAMPLES
C   NV (COLS 6-7, RIGHT-JUSTIFIED INTEGER) = NUMBER OF VARIABLES
C   MISVAL (COL 10): SET EQUAL TO 1 IF ALL ZERO VALUES ARE TO BE
C                     CONSIDERED MISSING VALUES (LEAVE BLANK OTHERWISE)
C                     OR SET EQUAL TO 2 IF ALL VALUES EQUAL TO NSKIP
C                     ARE TO BE CONSIDERED MISSING VALUES
C   NSKIP (COLS 15-20, RIGHT-JUSTIFIED INTEGER) = NUMERICAL CODE FOR
C                     MISSING VALUES (LEAVE BLANK IF MISVAL NOT EQUAL
C                     TO 2)
C ***** CONTROL CARD 2 *****
C   COLS 1-80 = FORTRAN FORMAT (ENCLOSED IN PARENTHESES) FOR THE
C               VARIABLE NAME CONTROL CARD WHICH FOLLOWS
C ***** CONTROL CARD 3 (MAY REQUIRE MORE THAN ONE CARD) *****
C   NAMES OF THE NV VARIABLES(MAX. OF 4 CHARACTERS PER NAME)
C ***** CONTROL CARD 4 *****
C   COLS 1-80 = FORTRAN FORMAT (ENCLOSED IN PARENTHESES) FOR THE SAMPLE
C               NAME/NUMBER AND THE NV VARIABLE VALUES; THE FORMAT
C               STATEMENT BEGINS AS FOLLOWS: (2A4,.....)
C ***** DATA CARDS *****
C   COLS 1-8 = SAMPLE NAME/NUMBER (FIRST CARD ONLY IF THERE ARE MORE
C               THAN ONE CARD PER SAMPLE)
C   COLS 9-80 = VARIABLE VALUES (IF THERE ARE MORE THAN ONE CARD PER
C               SAMPLE USE COLS 1-80 FOR ALL ADDITIONAL CARDS)
C
C
C   DIMENSION NSS(75,75), NQC(75,75)
C   DIMENSION X(200,75),A(200),B(200),R(75,75),R2(75,75),R3(75,75)
C   DIMENSION VN(75), NP(75,75),NP2(75,75),NP3(75,75),C(5),Y(5)
C   DIMENSION RT(10),SSRG1(10),SSRG2(10),FF(10),NZ(5)
C   DIMENSION FMT1(20),FMT2(20),COEF(5),ID1(200),ID2(200)
C   REAL*8 SUMB,SSR,SST,SSD,SSRG1,SSRG2,DMS
C READ THE CONTROL AND DATA CARDS
C   READ 1, NS,NV,MISVAL,NSKIP
C 1   FORMAT(I3,2X,I2,2X,I1,4X,I6)
C     NPOLY=3
C     NCYCLE=0

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      READ 2, FMT1
2    FORMAT(20A4)
      READ(5,FMT1)  (VN(I),I=1,NV)
      READ 2, FMT2
      DO 3 I=1,NS
3    READ(5,FMT2) ID1(I),ID2(I),(X(I,J),J=1,NV)
      PRINT 450
450  FORMAT('1')
      PRINT 820
820  FORMAT(/////59X,17('*')/59X,'*',15X,'*'/59X,'* DATA MATRIX */59
      $X,'*',15X,'*'/59X,17('*')/65X,'*****'/66X,'****'/67X'*/'////)
C    PRINT THE DATA SET
      LL=-11
      NVSET=NV/12
      NXT=NVSET * 12
      IF(NXT.LT.NV) NVSET=NVSET + 1
      DO 850 K=1,NVSET
      LL=LL + 12
      LLL=LL + 11
      IF(LLL.GT.NV) LLL=NV
      PRINT 824, (VN(J),J=LL,LLL)
824  FORMAT(/1X, 'SAMPLE ',3X,12(3X,A4,3X))
      PRINT 350
      DO 830 I=1,NS
      PRINT 825, ID1(I),ID2(I),(X(I,J),J=LL,LLL)
825  FORMAT(1X,A4,A4,1X,12(F9.4,1X))
830  CONTINUE
850  CONTINUE
C    INITIALIZE THE CORRELATION COEFFICIENT (R,R2,R3), CONFIDENCE LEVEL
C    (NP,NP2,NP3), SAMPLE NUMBER (NSS) AND QUADRATIC CURVE TYPE (QCT)
C    MATRICES
      DO 4 I=1,NV
      DO 4 J=1,NV
      R(I,J)=0.
      NP(I,J)=0
      R2(I,J)=0.
      R3(I,J)=0.
      NP2(I,J)=0
      NP3(I,J)=0
      IF(I.EQ.J) GO TO 410
      GO TO 415
410  R(I,J)=1.
      NP(I,J)=1
      R2(I,J)=1.
      NP2(I,J)=2
      R3(I,J)=1.
      NP3(I,J)=3
      NSS(I,J)=9999
415  CONTINUE
4    CONTINUE

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      NONE=1
      NV3=NV
      NV2=NV - 1
230  CONTINUE
      IF(NCYCLE.EQ.0) GO TO 235
      NONE=2
      NV2=NV
      LZ=1
235  CONTINUE
C   PERFORM CALCULATIONS FOR ALL POSSIBLE VARIABLE PAIRS
      DO 200 I=NONE,NV2
      IF(NCYCLE.EQ.0) GO TO 240
      NV3=I-1
      GO TO 250
240  LZ=I + 1
250  CONTINUE
      DO 180 J=LZ,NV3
      NUMS=0
C   IF ZERO VALUES ARE CONSIDERED MISSING VALUES, DELETE SAMPLES WITH
C   MISSING VALUES FROM THE CALCULATIONS FOR A VARIABLE PAIR
      DO 5 MM=1,NS
      IF(MISVAL.EQ.2) GO TO 461
      GO TO 480
461  NTEMP1=X(MM,I)
      NTEMP2=X(MM,J)
      IF((NTEMP1.EQ.NSKIP).OR.(NTEMP2.EQ.NSKIP)) GO TO 5
480  CONTINUE
      IF(MISVAL.NE.1) GO TO 400
      NTEMP1=X(MM,I)*10000.
      NTEMP2=X(MM,J)*10000.
      IF((NTEMP1.EQ.0).OR.(NTEMP2.EQ.0)) GO TO 5
400  NUMS=NUMS + 1
      A(NUMS)=X(MM,I)
      B(NUMS)=X(MM,J)
      5  CONTINUE
C   COMPUTE THE MEAN FOR THE DEPENDENT VARIABLE
      SUMB=0.
      DO 6 LL=1,NUMS
      6  SUMB=SUMB + B(LL)
      BMEAN=SUMB/NUMS
      NSLOPE=1
C   FIND THE MIN AND MAX VALUES FOR THE INDEPENDENT VARIABLE
      AAMIN=A(1)
      AAMAX=A(1)
      DO 10 LL=1,NUMS
      IF(A(LL).LT.AAMIN) GO TO 7
      GO TO 8
      7  AAMIN=A(LL)
      GO TO 10
      8  IF(A(LL).GT.AAMAX) AAMAX=A(LL)

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10  CONTINUE
    CINC=(AAMAX-AAMIN)/25.
C   FIND THE REGRESSION AND CORRELATION COEFFICIENTS FOR THE FIRST,
C   SECOND AND THIRD DEGREE POLYNOMIALS
    DO 100 N=1,NPOLY
        NTERMS=N + 1
        CALL POLFIT(A,B,NUMS,NTERMS,COEF)
        SSR=0.
        SST=0.
        SSD=0.
        IF(N.NE.1) GO TO 59
        IF(COEF(2)) 55,59,59
55   NSLOPE=-1
59   CONTINUE
C   DETERMINE THE CURVATURE AND ORIENTATION OF THE SECOND DEGREE
C   POLYNOMIAL CURVE
    IF(N.NE.2) GO TO 560
    C(1)=AAMIN
    C(2)=AAMIN + CINC
    C(3)=AAMAX - CINC
    C(4)=AAMAX
    DO 502 L=1,4
502  Y(L)=COEF(1) + COEF(2)*C(L) + COEF(3)*C(L)*C(L)
        NSET=0
        IF((Y(1).LT.Y(2)).AND.(Y(3).LT.Y(4))) GO TO 510
        IF((Y(1).GT.Y(2)).AND.(Y(3).GT.Y(4))) GO TO 520
        IF((Y(1).GT.Y(2)).AND.(Y(4).GT.Y(3))) GO TO 530
        IF((Y(1).LT.Y(2)).AND.(Y(4).LT.Y(3))) NSET=6
        GO TO 540
510  CL=Y(2)-Y(1)
        CR=Y(4)-Y(3)
        NSET=2
        IF(CL.LT.CR) NSET=1
        GO TO 540
520  CL=Y(1)-Y(2)
        CR=Y(3)-Y(4)
        NSET=4
        IF(CL.GT.CR) NSET=3
        GO TO 540
530  NSET=5
540  CONTINUE
560  CONTINUE
        NQC(I,J)=NSET
        DO 50 L=1,NUMS
            BP=0.
            DO 40 M=1,N
                MM=M + 1
40   BP=BP + COEF(MM)*(A(L)**M)
            BP=BP + COEF(1)
            SSR=SSR + (BP-BMEAN)**2

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      SST=SST + (B(L)-BMEAN)**2
      SSD=SSD + (B(L)-BP)**2
50  CONTINUE
      RT(N)=(SSR/SST)**.5
      SSRG1(N)=SSR
      IF(N.EQ.1) GO TO 60
      SSRG2(N)=SSRG1(N) - SSRG1(N-1)
      GO TO 100
60  SSRG2(N)=SSRG1(N)
100  CONTINUE
      DMS=SSD/(NUMS-4)
C   CALCULATE F STATISTICS FOR THE THREE REGRESSION TERMS
      DO 65 N=1,NPOLY
65  FF(N)=SSRG2(N)/DMS
C   TEST THE SIGNIFICANCE OF THE THREE REGRESSION TERMS
      NSN = NUMS
      CALL FTEST(NSN,FF,NZ)
C   STORE THE CALCULATION RESULTS FOR A VARIABLE PAIR IN THE CORRELATION
C   COEFFICIENT, CONFIDENCE LEVEL AND SAMPLE NUMBER MATRICES
      R(I,J)=RT(1)
      R2(I,J)=RT(2)
      R3(I,J)=RT(3)
      IF(NSLOPE.EQ.-1) R(I,J)=R(I,J)*(-1.)
      NP(I,J)=NZ(1)
      NP2(I,J)=NZ(2)
      NP3(I,J)=NZ(3)
      NSS(I,J) = NUMS
180  CONTINUE
200  CONTINUE
      IF(NCYCLE.EQ.0) GO TO 202
      GO TO 210
202  NCYCLE=1
      GO TO 230
210  CONTINUE
C   PRINT THE CORRELATION MATRIX
      PRINT 450
      PRINT 220
220  FORMAT(/////53X,24('*')/53X,'*',22X,'*'/53X,'* CORRELATION MATRIX
$   */53X,'*',22X,'*'/53X,24('*')/63X,'*****'/64X,'***'/65X,'*'/)
      NV4=NV + 14
      DO 300 L=15,NV4,15
      LL=L-14
      LLL=L
      IF(NV.LT.L) LLL=NV
      PRINT 301, (VN(K),K=LL,LLL)
301  FORMAT(1X, 7X,15(2X,A4,2X))
      PRINT 350
      DO 305 I=1,NV
      PRINT 302, VN(I), (R(I,J),J=LL,LLL)
302  FORMAT(1X,A4,3X,15(1X,F6.3,1X))

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311 PRINT 303, (NP(I,J),J=LL,LLL)
303 FORMAT(8X,15(2X,'(',I2,')',2X))
PRINT 308,(R2(I,J),J=LL,LLL)
308 FORMAT(8X,15(1X,F6.3,1X))
PRINT 340,(NP2(I,J),J=LL,LLL)
340 FORMAT(8X,15(2X,'(',I2,')',2X))
PRINT 320,(NQC(I,J),J=LL,LLL)
320 FORMAT(8X,15(2X,'QCT=',I1,1X))
PRINT 310, (R3(I,J),J=LL,LLL)
310 FORMAT(8X,15(1X,F6.3,1X))
PRINT 340,(NP3(I,J),J=LL,LLL)
PRINT 460, (NSS(I,J),J=LL,LLL)
460 FORMAT(8X,15(2X,I3,3X))
PRINT 350
350 FORMAT(//1X)
305 CONTINUE
IF(LLL.EQ.NV) GO TO 370
300 CONTINUE
370 PRINT 381
381 FORMAT(///1X,'NOTE: VARIABLES ACROSS THE TOP OF THE CORRELATION M
$ATRIX ARE DEPENDENT; THOSE ALONG THE LEFT SIDE ARE INDEPENDENT')
STOP
END
SUBROUTINE POLFIT(X,Y,NPTS,NTERMS,A)
C THE POLFIT SUBROUTINE PERFORMS BIVARIATE LEAST SQUARES POLYNOMIAL
C REGRESSION (MODIFIED FROM BEVINGTON, 1969, PP. 140-142)
DOUBLE PRECISION SUMX,SUMY,XTERM,YTERM,ARRAY
DIMENSION X(1),Y(1),A(1)
DIMENSION SUMX(50),SUMY(50),ARRAY(10,10)
C ACCUMULATE THE WIGHTED SUMS
11 NMAX=2*NTERMS - 1
DO 13 N=1,NMAX
13 SUMX(N)= 0.
DO 15 J=1,NTERMS
15 SUMY(J)= 0.
21 DO 50 I=1,NPTS
XI=X(I)
YI=Y(I)
41 XTERM=1.
DO 44 N=1,NMAX
SUMX(N)=SUMX(N) + XTERM
44 XTERM=XTERM * XI
45 YTERM= YI
DO 48 N=1,NTERMS
SUMY(N)=SUMY(N) + YTERM
48 YTERM=YTERM * XI
50 CONTINUE
C CONSTRUCT MATRICES AND CALCULATE COEFFICIENTS
51 DO 54 J=1,NTERMS
DO 54 K=1,NTERMS

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      N=J+K-1
54  ARRAY(J,K)=SUMX(N)
      DELTA=DETERM(ARRAY,NTERMS)
      IF(DELTA) 61,57,61
57  DO 59 J=1,NTERMS
59  A(J)=0.
      GO TO 80
61  DO 70 L=1,NTERMS
62  DO 66 J=1,NTERMS
      DO 65 K=1,NTERMS
      N=J+K-1
65  ARRAY(J,K)=SUMX(N)
66  ARRAY(J,L)=SUMY(J)
70  A(L)=DETERM (ARRAY,NTERMS) / DELTA
80  RETURN
      END
      FUNCTION DETERM(ARRAY,NORDER)
C   THE DETERM FUNCTION SUBPROGRAM COMPUTES THE DETERMINANT OF A
C   SYMMETRICAL TWO-DIMENSIONAL SQUARE MATRIX (FROM BEVINGTON, 1969,
C   P. 294)
      DOUBLE PRECISION ARRAY,SAVE
      DIMENSION ARRAY(10,10)
10  DETERM=1.
11  DO 50 K=1,NORDER
      IF(ARRAY(K,K)) 41,21,41
21  DO 23 J=K,NORDER
      IF(ARRAY(K,J)) 31,23,31
23  CONTINUE
      DETERM=0.
      GO TO 60
31  DO 34 I=K,NORDER
      SAVE=ARRAY(I,J)
      ARRAY(I,J)=ARRAY(I,K)
34  ARRAY(I,K)=SAVE
      DETERM= - DETERM
41  DETERM = DETERM * ARRAY(K,K)
      IF(K-NORDER) 43,50,50
43  K1=K + 1
      DO 46 I=K1,NORDER
      DO 46 J=K1,NORDER
46  ARRAY(I,J)=ARRAY(I,J) - ARRAY(I,K)*ARRAY(K,J)/ARRAY(K,K)
50  CONTINUE
60  RETURN
      END
      SUBROUTINE FTEST(N,FF,NP)
C   THE FTEST SUBROUTINE DETERMINES THE STATISTICAL SIGNIFICANCE OF
C   EACH REGRESSION TERM (MODIFIED FROM DORRER, 1968)
      DOUBLE PRECISION W, Z, P, D
      DIMENSION FF(10), NP(5)
      NF = N -4

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```
NB = 2*(NF/2) - NF + 2
DO 100 I = 1,3
W = FF(I) * (1./NF)
Z = 1 / (1+W)
IF(NB.EQ.2) GO TO 10
P = W**.5
Y = .3183099
D = Y * (Z/P)
P = 2 * Y * DATAN(P)
GO TO 20
10  P = (W*Z)**.5
    D = .5 * P * (Z/W)
20  Y = 2 * (W/Z)
    NS = NB + 2
    DO 50 J = NS,NF,2
    D = D * Z * (1 + (1./(J-2)))
50  P = P + D * (Y/(J-1))
    IF(P.GT..99) P=.99
    NP(I) = P * 100
100 CONTINUE
    RETURN
    END
```

Part II: Output

```

*****
*                                     *
*   DATA MATRIX   *
*                                     *
*****
*****
*****
*
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SAMPLE	MEAN	SORT	FI	PS-P	SSA	APD	T-PD
B2-20	0.8100	0.4100	64.7000	45.4000	6.4790	0.2540	1.3800
B2-7	1.3600	0.3400	57.4000	38.3000	8.3330	0.1800	1.4830
B2-9	1.4300	0.3700	53.4000	36.5000	8.7180	0.1940	1.3840
B2-1	1.3900	0.4000	46.7000	39.4000	8.8600	0.1850	1.3310
B2-16B	1.4500	0.3400	62.4000	40.5000	9.1780	0.1790	1.3980
B1-15	2.5500	0.2600	52.9000	41.4000	14.7800	0.1220	1.4040
B1-16	2.3200	0.3200	53.9000	39.1000	13.6450	0.1490	1.3290
D5-10	2.3200	0.3200	52.9000	41.7000	12.5500	0.1430	1.2880
D5-15	2.2400	0.3100	47.4000	42.3000	13.1020	0.1390	1.2890
D5-16B	2.3700	0.3900	50.6000	44.9000	12.7390	0.1570	1.3140
D3-15	2.8700	0.2000	47.7000	44.0000	21.8580	0.0810	1.2790
D3-19	2.8600	0.2300	48.2000	42.2000	22.0850	0.0790	1.2260
R5-23	2.2800	0.4500	56.2000	40.8000	13.2570	0.1380	1.3670
R5-25	2.3800	0.3600	58.2000	45.8000	14.2690	0.1300	1.3310
R5-21	2.1600	0.3100	56.5000	46.7000	11.6640	0.1640	1.3160
R5-34	2.5100	0.3000	50.3000	45.5000	14.0330	0.1370	1.3130
R5-27	2.9600	0.4100	0.0	45.0000	0.0	0.0	0.0
R5-29	3.0600	0.4200	0.0	48.4000	0.0	0.0	0.0

 * CORRELATION MATRIX *

	MEAN	SORT	FI	PS-P	SSA	APD	T-PD
MEAN	1.000 (1)	-0.322 (78)	-0.584 (98)	0.474 (97)	0.902 (99)	-0.940 (99)	-0.653 (99)
	1.000 (2)	0.352 (42)	0.586 (17)	0.600 (92)	0.967 (99)	0.942 (74)	0.683 (64)
	QCT=0	QCT=5	QCT=3	QCT=5	QCT=5	QCT=4	QCT=6
	1.000 (3)	0.370 (34)	0.680 (87)	0.689 (89)	0.990 (99)	0.983 (99)	0.685 (18)
	*** 18	18	16	18	16	16	16
SORT	-0.322 (81)	1.000 (1)	0.440 (89)	0.063 (18)	-0.743 (99)	0.705 (99)	0.420 (87)
	0.477 (85)	1.000 (2)	0.471 (48)	0.198 (51)	0.867 (99)	0.768 (89)	0.465 (55)
	QCT=5	QCT=0	QCT=6	QCT=5	QCT=5	QCT=6	QCT=6
	0.515 (58)	1.000 (3)	0.471 (2)	0.206 (16)	0.875 (59)	0.805 (81)	0.465 (0)
	18	*** 18	16	18	16	16	16
FI	-0.584 (98)	0.440 (88)	1.000 (1)	0.092 (25)	-0.569 (96)	0.615 (98)	0.606 (98)
	0.686 (89)	0.440 (0)	1.000 (2)	0.213 (49)	0.573 (22)	0.669 (76)	0.636 (60)
	QCT=6	QCT=2	QCT=0	QCT=5	QCT=4	QCT=5	QCT=6
	0.691 (29)	0.446 (23)	1.000 (3)	0.270 (43)	0.574 (11)	0.681 (45)	0.651 (47)
	16	16	*** 16	16	16	16	16
PS-P	0.474 (94)	0.063 (19)	0.092 (26)	1.000 (1)	0.272 (73)	-0.152 (45)	-0.433 (90)
	0.500 (50)	0.373 (84)	0.277 (65)	1.000 (2)	0.501 (90)	0.484 (91)	0.518 (75)
	QCT=6	QCT=5	QCT=5	QCT=0	QCT=6	QCT=5	QCT=5
	0.525 (50)	0.391 (35)	0.402 (70)	1.000 (3)	0.580 (76)	0.515 (51)	0.578 (70)
	18	18	16	*** 18	16	16	16

SSA	0.902	-0.743	-0.569	0.272	1.000	-0.942	-0.687
	(99)	(99)	(97)	(70)	(1)	(99)	(99)
	0.993	0.756	0.586	0.299	1.000	0.970	0.689
	(99)	(52)	(47)	(37)	(2)	(99)	(20)
	QCT=6	QCT=4	QCT=3	QCT=6	QCT=0	QCT=3	QCT=3
	0.993	0.758	0.666	0.500	1.000	0.980	0.698
	(29)	(22)	(83)	(86)	(3)	(97)	(40)
	16	16	16	16	***	16	16
APD	-0.940	0.705	0.615	-0.152	-0.942	1.000	0.583
	(99)	(99)	(98)	(47)	(99)	(1)	(97)
	0.942	0.755	0.625	0.303	0.988	1.000	0.626
	(61)	(83)	(37)	(71)	(99)	(2)	(66)
	QCT=4	QCT=6	QCT=1	QCT=5	QCT=3	QCT=0	QCT=6
	0.967	0.770	0.665	0.588	0.988	1.000	0.628
	(98)	(57)	(68)	(94)	(8)	(3)	(19)
	16	16	16	16	16	***	16
T-PD	-0.653	0.420	0.606	-0.433	-0.687	0.583	1.000
	(98)	(91)	(98)	(89)	(99)	(98)	(1)
	0.667	0.626	0.633	0.479	0.764	0.672	1.000
	(46)	(93)	(59)	(57)	(90)	(85)	(2)
	QCT=3	QCT=6	QCT=2	QCT=6	QCT=5	QCT=6	QCT=0
	0.671	0.627	0.672	0.510	0.772	0.672	1.000
	(24)	(10)	(68)	(50)	(45)	(0)	(3)
	16	16	16	16	16	16	***

APPENDIX 0

INTERCORRELATIONS AMONG GRAIN SIZE, PACKING
AND PORE GEOMETRY PARAMETERS

Pair No.	Variables ¹		Sign. Level ¹ for Terms ²	Polynom. Degree ³ (99% SL)	Correlation ⁴ Coefficients		Strength of Quad. Corr. ⁵	Sign of Linear Corr. ⁶	Quad. Curve Type ⁷	Data Set ⁸	
	Response	Predictor			r _L	r _Q					
											L
AMONG GRAIN SIZE PARAMETERS											
1	KURT	SKEW	99	96	1	.585	.671	W	+	5A	AMA
2	KURT	MEAN	99	37	1	.510	.518	*	-	4	AMA
AMONG GRAIN SIZE AND PACKING PARAMETERS											
3	MC-P	MEAN	99	73	1	.586	.612	VW	+	5A	AMA
AMONG GRAIN SIZE AND PORE GEOMETRY PARAMETERS											
4	ARD	MEAN	99	94	1	.988	.991	VS	-	3	NAM
5	SSA	MEAN	99	99	2	.902	.967	VS	+	5A	NAM
6	APD	MEAN	99	74	1	.940	.942	S	-	4	NAM
7	SDQP	MEAN	99	99	2	.587	.876	M	-	5B	NAM
8	SSA	SORT	99	99	2	.743	.867	M	-	5B	NAM
9	AMPD	MEAN	99	65	1	.828	.837	M	-	3	NAM
10	APD	SORT	99	89	1	.705	.768	VW	+	6A	NAM
11	DG-P	MEAN	99	92	1	.632	.696	*	+	6A	NAM
12	T-PD	MEAN	99	64	1	.653	.683	*	-	6B	NAM
13	APA	MEAN	99	34	1	.665	.669	*	-	3	NAM
AMONG PACKING PARAMETERS											
14	FI	CI	99	41	1	.966	.967	VS	-	3	NAM
15	PKEF	PS-P	99	16	1	.928	.928	S	+	2	AM
16	PS-P	MC-P	99	98	1	.716	.830	M	+	6A	AM
AMONG PACKING AND PORE GEOMETRY PARAMETERS											
17	PS-P	DG-P	99	45	1	.918	.920	VS	+	2	NAMA
18	AMPD	FI	99	86	1	.765	.811	W	+	1	NAM
19	AMPD	CI	99	87	1	.754	.803	W	-	5B	NAM
20	SDQP	FI	97	99	2*	.417	.778	W	+	5C	NAM
21	SDQP	CI	99	99	2	.528	.770	VW	-	5B	NAM

Pair No.	Variables ¹		Sign. Level for Terms ²		Polynom. Degree ³ (99% SL)	Correlation Coefficients ⁴		Strength of Quad ⁵ Corr.	Sign of Linear Corr. ⁶	Quad. Curve Type ⁷	Data Set ⁸
	Response	Predictor	L	Q		r ^L	r ^Q				
AMONG PACKING AND PORE GEOMETRY PARAMETERS (continued)											
22	T-MD	CI	99	94	1	.614	.739	VW	-	5B	NAM
23	ARD	CI	99	89	1	.626	.720	VW	-	5B	NAM
24	APA	FI	99	69	1	.670	.703	*	+	1	NAM
25	APA	CI	99	75	1	.616	.660	*	-	5B	NAM
26	T-PD	CI	99	54	1	.634	.653	*	-	4	NAM
AMONG PORE GEOMETRY PARAMETERS											
27	T-AR	T-MD	99	33	1	.977	.977	VS	+	2	NAMA
28	DG-P	T-PD	99	99	2	.914	.972	VS	-	5B	NAMA
29	APD	AMPD	99	98	1	.929	.943	VS	+	2	NAMA
30	APA	AMPD	99	24	1	.930	.931	VS	+	1	NAMA
31	PNUM	T-PD	99	99	2	.752	.897	S	+	6A	NAMA
32	APD	APA	99	95	2	.873	.891	S	+	2	NAMA
33	ARD	SSA	99	99	2	.829	.889	S	-	5B	NAMA
34	APA	PNUM	99	99	2	.761	.879	S	-	5B	NAMA
35	DG-P	PNUM	99	89	1	.859	.867	S	-	3	NAMA
36	DG-P	APA	99	99	2	.653	.856	S	+	6A	NAMA
37	AMPD	PNUM	99	99	2	.661	.850	S	-	5B	NAMA
38	APD	PNUM	99	99	2	.667	.828	M	-	5B	NAMA
39	SDQP	APD	20	99	2*	.033	.821	M	+	5C	NAMA
40	DG-P	T-AR	99	99	2	.550	.789	M	+	6A	NAMA
41	SDQP	AMPD	68	99	2*	.134	.787	M	+	5C	NAMA
42	T-PD	APD	99	99	2	.673	.782	M	-	5B	NAMA
43	DG-P	T-MD	99	99	2	.553	.776	M	+	6A	NAMA
44	T-PD	APA	99	99	2	.600	.772	M	-	5B	NAMA
45	SDQP	T-MD	46	99	2*	.086	.768	M	+	5C	NAMA
46	DG-P	APD	99	99	2	.635	.763	M	+	6A	NAMA
47	DG-P	AMPD	99	99	2	.568	.758	M	+	6A	NAMA

Pair No.	Variables ¹		Sign. Level for Terms ²		Polynom. Degree ³ (99% SL)	Correlation 4 Coefficients		Strength of Quad. Corr. ⁵	Sign of Linear Corr. ⁶	Quad. Curve Type ⁷	Data Set ⁸
	Response	Predictor	L	Q		r _L	r _Q				
AMONG PORE GEOMETRY PARAMETERS (continued)											
48	T-PD	AMPD	99	99	2	.594	.758	M	-	5B	NAMA
49	ARD	DG-P	99	87	1	.723	.756	M	-	6B	NAMA
50	T-PD	T-AR	99	99	2	.531	.753	M	-	5B	NAMA
51	T-PD	T-MD	99	99	2	.537	.728	W	-	5B	NAMA
52	ARD	T-PD	99	98	1	.556	.685	W	+	6A	NAMA
53	T-MD	AMPD	99	44	1	.666	.671	W	+	1	NAMA
54	PNUM	T-AR	99	98	1	.527	.660	W	-	5B	NAMA
55	APD	T-MD	99	65	1	.646	.659	VW	+	2	NAMA
56	ARD	PNUM	99	98	1	.560	.658	VW	+	5A	NAMA
57	APA	SDQP	50	99	2*	.108	.654	VW	+	5C	NAMA
58	PNUM	T-MD	99	92	1	.542	.621	VW	-	5B	NAMA
59	APA	T-MD	99	21	1	.620	.621	VW	+	1	NAMA
60	APD	T-AR	99	82	1	.560	.605	VW	+	6A	NAMA
61	SDQP	T-AR	11	99	2*	.026	.575	VW	+	5C	NAMA
62	AMPD	T-AR	99	60	1	.553	.571	*	+	2	NAMA
63	ARD	T-MD	59	99	2*	.152	.549	*	-	5C	NAMA
64	APA	T-AR	99	43	1	.531	.541	*	+	2	NAMA
65	ARD	APA	45	99	2*	.111	.537	*	-	5C	NAMA
66	ARD	T-AR	79	99	2*	.224	.536	*	-	5C	NAMA
67	ARD	SDQP	99	30	1	.518	.523	*	+	2	NAMA

- ¹The response (dependent) and predictor (independent) variables; see text for code definitions.
- ²The significance level for the linear (L) and quadratic (Q) regression terms; based on the F test results.
- ³The degree of the polynomial regression model which best characterizes the relationship between the two variables at the 99 percent significance level; the numeric codes refer to models described in the text — 1 (Equation 31), 2 (Equation 33) and 2* (Equation 32).
- ⁴The absolute value of the linear correlation coefficient ($|r_L|$), and the quadratic correlation coefficient (r_Q); $0 \leq |r_L|$, $r_Q \leq 1.0$.
- ⁵The strength of quadratic correlation relative to the critical r value for the 99 percent significance level; the alphabetic codes refer to correlation intervals described in the text — VS (very strong), S (strong), M (moderate), W (weak), VW (very weak), and * (no significant correlation); the critical r values for the four data sets are — .712 (NAM), .677 (AM), .574 (NAMA) and .555 (AMA).
- ⁶The sign of the linear correlation coefficient.
- ⁷The quadratic curve type; (see Table 14 for code definitions); the A, B and C subdivisions of the quadratic curve types 5 and 6 are based on the 99 percent significance level for the linear regression term.
- ⁸The data set used for the calculations; see text for code definitions.

APPENDIX P

SAMPLING AND SAMPLE PREPARATION PROCEDURES

Part I: Epoxy Impregnation Procedure for
Unconsolidated Sand

- 1) Prepare a horizontal surface immediately adjacent to the sampling site for the loose grains. For horizontal laminae, a few millimeters of undisturbed sand is left on top of the lamina of interest. This insures that the grains in this lamina will not be disturbed during impregnation. For foreset laminae, the horizontal surface will necessarily cut through the lamina of interest.
- 2) Lightly place a small aluminum pie tin (8.4 centimeter diameter base and 2.5 centimeters deep) with a densely perforated bottom on the prepared horizontal surface. This tin will act as a holding reservoir for the epoxy which will seep through the perforations into the underlying sand. For the foreset laminae, the tin is placed astride the trace of the lamina of interest (see Plate 1). The portion of this lamina within a few millimeters of the base of the tin is doubtless disturbed; however, the thin section analyses are performed only on the deeper portions of the lamina.
- 3) Gently pack sediment (preferably moist and clayey) around the base of the pie tin. This will prevent epoxy in the tin from leaking out onto the prepared horizontal surface.
- 4) Cut vertical faces in the sand on two or more sides of the pie tin (i.e., carve a pedestal out of the sand underlying the tin). This allows air to readily escape from the sand during impregnation.
- 5) Mix up from 100 to 200 milliliters of Epon 815 epoxy (Miller-Stephenson Chemical Co., Danbury, Conn.) in a separate container.

The epoxy mixture consists of 95.5 parts (by volume) of Epon Resin 815, 11 parts Diethylenetriamine (DTA, a hardner), and 4.5 parts of Butyl Glycidyl Ether (BGE, a 'reactive diluent' which reduces the viscosity of the epoxy mixture). From experiments performed by the author and from the vendor's product literature it was found that this epoxy has the following properties.

a) The maximum absolute viscosity of the fluid epoxy is approximately 4 poise at room temperature (this is about 3 times greater than the viscosity of heavy machine oil). In any impregnation procedure it is desirable that the viscosity of the epoxy be as low as possible. In general, however, the lower the viscosity of the fluid epoxy, the softer the solid 'cured' epoxy. It is important that the solid epoxy be hard enough to permit thin sectioning. Thus a reasonable compromise between hardness and viscosity must be sought. With this in mind, Epon 815, out of the many epoxys tested, was found to be the most suitable.

b) The specific gravity of the fluid epoxy is about 1.15. It is assumed here that the downward percolating epoxy does not disturb the grains. Since many pore volumes of water had already passed through the sand prior to impregnation, it seems unlikely that the slower moving fluid epoxy—with a specific gravity near that of water—could cause any further disturbance of the grains.

c) The fluid epoxy is less 'wetting' than water. Interstitial water in the sand is, consequently, not completely expelled during impregnation. This property of the epoxy is not desirable.

d) The epoxy is able to penetrate and cure properly in sand with small amounts of fresh interstitial water (i.e., in slightly 'damp' sand). However, in sand with large amounts of fresh interstitial water or in sand with any amount of saline interstitial water the epoxy usually failed to cure properly. It never hardened sufficiently to permit thin-sectioning.

e) During curing the epoxy generates heat. The initial and maximum temperatures in the curing epoxy were experimentally determined to be: for epoxy alone in a cup, 22°C (initial) and over 100°C (maximum); for impregnated dry sand, 21°C (initial) and 36°C (maximum); and for impregnated damp sand, 19°C (initial) and 31°C (maximum). The maximum temperature attained in a sand during curing is too low for any boiling in the epoxy to have occurred. Thus the impregnation cannot cause any grain disturbance through heat-driven convective currents or turbulence in the fluid epoxy.

f) At room temperature epoxy left in a cup will harden in about 30 minutes and will achieve a complete cure (i.e., reach maximum hardness) in about 7 days. A complete cure

can be obtained more quickly, however, by heating the epoxy in an oven at 60°C for several hours. If the epoxy has been poured into a dry sand and the weather is warm, the impregnated sample will be sufficiently hard to allow handling after about 6 hours. If, on the other hand, the sand is damp and the weather is cool it may be 24 hours before the impregnated sample can be handled. If the air temperature is below about 5°C (41°F) the epoxy will not harden for several days.

g) The volume of the cured epoxy is 3 to 5 percent less than the original volume of the fluid epoxy. Experiments show that nearly all the volume reduction occurs during the 'gel stage' immediately prior to hardening. This slight volume reduction probably does not disturb the grains. The only effect seems to be that the contracting epoxy partially evacuates some of the pores.

h) The thickness of the zone of impregnated sand beneath the pie tin is quite variable. For fine-grained, damp sand the penetration is one inch or less. For coarse-grained, dry sand the penetration is up to a few inches.

i) Colored dyes may be added to the colorless epoxy mixture in order to visually enhance the pore space. It was observed, however, that the presence of a dye interfered slightly with the curing of the epoxy. For this reason no dye was used.

6) Pour the epoxy into the pie tin. Allow up to 24 hours for the epoxy to harden sufficiently before the impregnated sand sample is removed.

Part II: Straining Procedure for Thin Sections

1) A solvent-soluble dye is added to an organic solvent at room temperature. Enough dye is added to saturate the solvent.

There are two considerations in the selection of the dye and solvent. First, the dye should readily dissolve in the solvent. Second, the epoxy in the thin section should not dissolve in the solvent. As it turns out, the solvents for which the dyes are most soluble are also the ones most damaging to the epoxy. Thus some compromise between dye and epoxy solubility is necessary with the latter, of course, being the most important consideration. After experimentation with numerous dyes and solvents the following were selected for use in this study: Orasol Red B dye (CIBA-GEIGY Corp., Ardsley, New York) and Benzene, a common laboratory solvent.

2) Immerse the thin section in the benzene-dye solution for 24 hours. A longer soaking time will not significantly increase the coloration but may damage the epoxy.

The effect of the benzene is apparently to expand the molecular structure of the epoxy. The dye then enters the epoxy (via diffusion) through the enlarged surface openings (CIBA-GEIGY Corp. technical consultant, personal communication). Depending on the brand of epoxy, the coloration will be a shade of either red or pink.

3) Remove the thin section from the benzene-dye solution, and rinse with water. The epoxy will be soft and rubbery to the

Part III: Treatment Procedures for Unconsolidated
Sands and Indurated Sandstones

Treatment of Unconsolidated Sand

- 1) The samples were immersed, with occasional stirring, in 200 milliliters of 10 percent hydrochloric acid for 48 hours. This treatment removed any shell or carbonate rock fragments.
- 2) The acid was poured off and the samples were then flushed repeatedly with tap water. The clay and fine silt size particles were decanted between flushings. Before decanting, the beakers containing the sand were allowed to stand for at least 5 minutes. All medium silt and coarser grains would settle through the 10 centimeter deep beakers within this period. After the allotted time, the water was carefully poured off. The addition and decanting of water was repeated until the water remained relatively clear.
- 3) The samples were flushed repeatedly with scalding hot water to remove remaining soluble salts.
- 4) The dried samples were immersed in Bromoform, a 'heavy liquid' with a specific gravity of 2.89. This treatment separated the 'heavy' and 'light' mineral grains. All subsequent texture and grain packing analyses utilized only the light mineral fraction. Both the heavy and light mineral fractions were washed repeatedly with acetone to remove Bromoform residue adhering to the grain surfaces.

Disaggregation and Treatment of
Indurated Sandstone

- 1) The samples were broken up as much as possible with the fingers. Some of the harder pieces were wrapped in a thick rubber sheath and crushed with pliers.
- 2) The samples were boiled in 10 percent hydrochloric acid for one hour in order to remove calcite cement.
- 3) The samples were washed and dried, and broken up further with the fingers.
- 4) The samples were immersed, with occasional stirring, for 6 weeks in 200 milliliters of 20 percent hydrochloric acid containing 5 grams of stannous chloride (SnCl_2). The stannous chloride reduces the iron in iron oxide stains and cements, making them more readily solubilized by the acid (Carver, 1971b, p. 432).
- 5) The samples were washed and dried, and broken up further with the fingers.
- 6) The samples were repeatedly washed and the clay and fine silt size particles were decanted (see Step 2 in the treatment of unconsolidated sand).
- 7) The samples were spread uniformly and thinly (a couple of particles thick) over a hard rubber mat. A hand-held roller with a hard rubber surface was passed repeatedly over the sediment

in an effort to reduce each sample to its original component grains. The sediment was periodically examined under a binocular microscope. If grain aggregates were still visible, the sediment was broken up further with the roller.

8) The samples were repeatedly washed and the clay and fine silt size particles were decanted.

9) The samples were boiled in 10 percent hydrochloric acid for 30 minutes. This treatment helped to disperse and remove any clay adhering to the grain surfaces (the acid tends to leach aluminum from the clay structure).

10) The samples were repeatedly washed and the clay and fine silt size particles were decanted.

11) The samples were again examined with a binocular microscope. If grain aggregates were still visible steps 7 and 8 were repeated.