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M.S.

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GENESIS AND DEPOSITIONAL HISTORY OF THE EATON SANDSTONE, GRAND LEDGE, MICHIGAN

by

Richard James Hudson

AN ABSTRACT

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MASTER OF SCIENCE

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Approved____

AN ABSTRACT RICHARD JAMES HUDSON

This paper presents the results of a mechanical, statistical and petrographic analysis of the Eaton sandstone of the Pennsylvanian system. This formation, very limited in outcrop area, is exposed in the immediate vicinity of Grand Ledge, Michigan. As a consequence of this study, interpretations as to the environmental and depositional aspects of the formation were made. These interpretations are subsequently compared with those of W. A. Kelly, professor of Geology at Michigan State University.[1]

Sieve analysis data revealed the excellent sorting of the Eaton sandstone. In the insoluble residue determination, the insolubles were almost exclusively predominant. The heavy mineral analysis was marked by a high proportion of zircon in each of the samples. The final phase of this study indicated generally progressive increases in sphericity and roundness in northeasterly and northwesterly directions.

The interpretations drawn from this analysis are that the source of the Eaton sandstone lay in a southerly direction, and that the Eaton was deposited in a continental environment. The latter interpretation is in accord with that postulated by Kelly.

ACKNOWLEDGMENTS

At the outset, I would like to express my appreciation to the members of my guidance committee, Dr. Kelly and Dr. Sandefur. Dr. Kelly suggested this study, helped the author collect samples, and offered suggestions throughout the progress of the paper. Dr. Sandefur supervised the mechanical analysis, and also offered timely suggestions.

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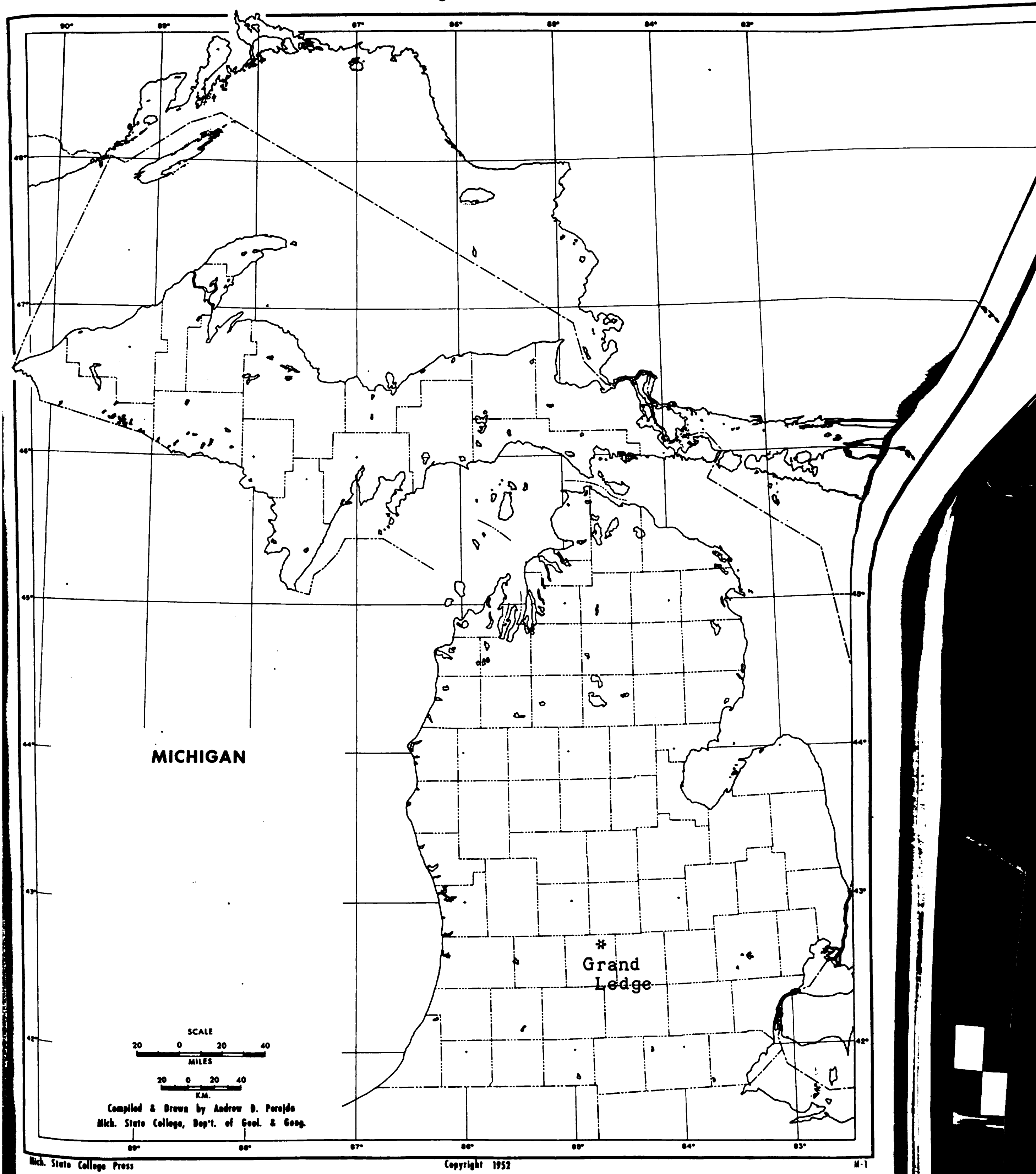
The advice of Dr. Zinn and Dr. Trow in guiding the author to this type of study is also highly appreciated.

Figure 1


MICHIGAN
Grand Ledge
SCALE
20 0 20 40
MILES
20 0 20 40
KM.
Compiled & Drawn by Andrew D. Perejda
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M-1

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Investigation of coal bearing and related strata of the Pennsylvanian system in Michigan has been carried on since the discovery of coal near Jackson, Michigan in 1835. Down through the years, these strata have been classified and reclassified by A. C. Lane, W. M. Gregory, W. F. Cooper, R. A. Smith, R. B. Newcombe and W. A. Kelly, among others.[2] Throughout these classifications, degrees of uncertainty have existed as to problems of correlation, source rock character, source rock location and sedimentary environment.

Of the many Pennsylvanian horizons, one particularly lending itself to sedimentary analysis is the Eaton sandstone which outcrops in the vicinity of Grand Ledge, Michigan. I have thus chosen the Eaton sandstone as the object of this study in an attempt to throw some light on the problems involved in the classification of the Pennsylvanian stratigraphy of Michigan.

GENERAL INFORMATION

Various methods of sedimentary analysis have been employed in the correlation, stratigraphic position, and classification of sediments. At present, however, added emphasis is being placed on the adaptation of these methods to include environmental and depositional interpretation.

In spite of numerous studies, there remains much disagreement and uncertainty regarding the interpretation of the various statistical curves,[3] and in the application of sphericity and roundness studies to sedimentary problems.[4] However, the rigorous examination of quantitative data gathered from the analyses of sediments of known origin is continually rendering greater validity to interpretations based on statistical criteria. Synthetic studies of sedimentary conditions are also proving valuable in this regard.

One type of study related to the quantitative determinations referred to above involves the analysis of sedimentary features of formations visible in surface exposure. Here, the cross-bedding, ripple marks, fossils and other criteria often establish the directional and environmental aspects of deposition. The latter mode of analysis serves as a basis of comparison for conclusions based on quantitative laboratory determinations.

The Pennsylvanian outcrops in the Grand Ledge area are the most extensive of the system in Michigan. Numerous stratigraphic and environmental studies of its composite formations, including the Eaton sandstone, have been made by Kelly. In such studies, the criteria mentioned in the preceding paragraph, i.e., cross-bedding, fossils and ripple marks, were the basis for the interpretation of the depositional aspects of these strata.

The formation involved in this investigation forms the ledges, or bluffs, of the Grand River and its tributaries in the northern part of Eaton and the southern part of Clinton counties. The name, Eaton sandstone, was proposed for this formation by Kelly. According to him, it is post-Saginaw and a member of the Grand River Group. Its true stratigraphic relation to other sandstones, such as the Woodville, Ionia or other strata of this group outcropping elsewhere, has not been determined. Exposures of the Eaton sandstone have not been found outside the Grand Ledge area.

The Eaton is a porous, buff-colored sandstone, having a maximum thickness in outcrop of 50 feet. The lower contact of this formation with the channel shale of the underlying Saginaw group is highly undulating, the elevation of this contact varying between 795 and 830 feet above sea level.[5] The upper surface of the Eaton is bounded by glacial drift.

SAMPLE SELECTION

Source of Samples

The sandstone samples used in this study were obtained from the bluffs of the Grand River and its tributaries in the northern part of Eaton county. The area encompassing this study lies in Section 2 and 3, T4N, R5W (map in pocket part).

Location of Individual Samples

Sample 1 — Section 2

Location: Corner of bluff at intersection of Grand River and tributary.

Sample 2 — Section 2

Location: Ten feet southeast of sample 1.

Sample 3 — Section 2

Location: 80 feet southeast of sample 1.

Sample 4 — Section 2

Location: 300 feet southeast of sample 1.

Sample 5 — Section 2

Location: 100 feet southwest of sample 1.

<u>Sample 6</u> Section 2

Location: 200 feet southwest of sample 1.

<u>Sample 7</u> Section 3

Location: Quarry of Grand Ledge Face Brick Company, 3/4 miles N 32° W of sample 1.

<u>Sample 8</u> Section 3

Location: In narrow ravine formed by one of the tributaries of Grand River, 1 mile N 50° W of sample 1.

Method of Sampling

As this study includes the directional aspects of deposition, samples were selected in a manner which would provide control in two directions lying approximately at right angles to each other. The close proximity of samples 1 and 2 was deemed advisable in view of the selection of sample 1 as the reference base. Throughout the selection, an attempt was made to secure samples similar in lithology and vertical position in the formation.

LABORATORY PROCEDURE

General

Mechanical, petrographic and statistical methods of study were employed in this analysis. Included are the determination of weight percentages and quartile measures of sorted sieve sizes; roundness and sphericity measurement of quartz grains; insoluble residue determination; and a heavy mineral analysis, including frequency distribution and percentage of heavy as against light constituents in each sample.

Disaggregation of Test Samples

As all of the samples were highly indurated, a pestle served as the primary means of disaggregation.. In this process, grinding was avoided as a precaution against the possibility of fracturing of the individual grains. Further disaggregation was effected by treating the samples with 6N hydrochloric acid and 30 percent hydrogen peroxide solutions. The samples, thus immersed, were then heated gently for a period of two hours. Alkalies were not added to the samples for disaggregation purposes because of their possible effect on the mineral grains.[6] Subsequent microscopic examination revealed the absence of fracture or aggregation of the individual mineral grains.

Weighing of Test Samples

A chemical balance was employed for the weighing out of 100.00 gram portions of each sample.

Sieve Fractionation

In the initial procedure, sieve size 28 was the first to retain any sample material. Thus, sieve sizes 28, 35, 48, 65, 100 and 150 were used in the first fractionation. As more than 10 grams of samples 2 and 3 passed through sieve size 150, sieve sizes 200, 230, 270 and 325 were employed to complete the fractionation. All of the samples were subjected to this second fractionation to effect uniformity in the accuracy of the cumulative curves based on this analysis. Each grade size was then weighed and recorded, and the fractions below sieve size 65 were retained in separate containers for possible future reference.

Insoluble Residue Determination

Five grams of each sample, previously subjected only to the initial crushing process, were placed in a 250 ml. beaker and treated with 25 ml. of 6N hydrochloric acid and 1 ml. of methyl alcohol. The beakers were then covered, and the samples thus treated were left undisturbed for 30 minutes. One hundred ml. of distilled water were then added to each sample, and the resulting mixture heated to the boiling point.

The contents of each beaker were allowed to cool, after which they were passed through separate filter papers which had previously been weighed. The residue remaining on the filter paper was then washed several times with 6 N hydrochloric acid and distilled water. After complete drying the filter papers and associated residue were weighed, the weights being recorded.

Heavy Mineral Identification

This phase of the analysis involved a primary separation of the heavy and light constituents which passed through Tyler sieve size 65, but were retained on sieve size 100. This separation was effected with pure bromoform ($CHBr_3$), a heavy liquid having a specific gravity of 2.87 at 20°C.[7] This is quite sufficient for a separation of quartz (sp. gr. 2.66) and feldspar (sp. gr. 2.70) from the heavy minerals.

The apparatus employed in the above separation included an upper funnel with attached rubber tubing and stop-cock. A lower funnel, fitted with filter paper, previously weighed, to retain the heavy minerals and a beaker to collect the bromoform completed the apparatus.

The individual samples were initially dispersed in the upper funnel which had been half filled with pure bromoform. Following thorough agitation of the samples, more bromoform was added to release any mineral grains which had adhered to the sides of the funnel during the stirring process. The

samples were subsequently allowed to remain undisturbed until the "heavies" had settled to the bottom of the funnel. The stop-cock was then loosened allowing the heavies to pass through the upper funnel onto the filter paper emplaced in the lower funnel. After the contents of the lower funnel had been thoroughly washed with ethyl alcohol, sufficient time was alloted for complete drying of this portion of the sample. The filter papers and the included heavy constituents were then weighed, these weights also being recorded.

The remaining bromoform and suspended light constituents were then decanted into clean filter paper which had been weighed before being fitted into the lower funnel. The light fractions were then washed thoroughly with ethyl alcohol, dried and weighed. These weights were also recorded.

The heavy constituents were mounted on separate slides in a medium of piperine (n = 1.66). Excess piperine was removed from the edges of the cover glasses with xylol. The prepared slides were then carefully examined with the aid of a polarizing microscope. The main purposes of this examination were the identification of the constituent minerals and the percentage determination of each species present. The primary objectives of this phase of the study were determinations of source rock and environmental factors rather than correlation.

Determination of Sphericity and Roundness

The light minerals collected from the heavy mineral separations were also mounted in piperine. Employing a petrographic microscope and mirror, the grain images were then projected onto a white surface preparatory to measurement with Wadell's circular scale. This scale consists of a series of concentric circles differing in radius by 2 mm. The magnification and projection facilitated the measurement of the diameter of the smallest circumscribing circle (I), the diameter of the largest inscribed circle (i), and the radius of curvature of the various corners (r) of the grains examined. These values were then substituted into the roundness and sphericity formulas of Riley.[2]

According to Riley, the sphericity of a quartz grain is expressed by the ratio $\frac{i}{I}$ where I and i are the circle diameters referred to in the preceding paragraph.

Roundness is calculated by the formula $\frac{\sum(\frac{r}{i})}{N}$, where r is the radius of curvature of a given corner of the quartz grain under consideration, i the diameter of the largest inscribed circle as above, and N the number of corners in a given plane.

The sphericity and roundness of the various samples were thus determined in a procedure which involved the measurement of I, i, and r for 100 grains of each sample.

ANALYSIS AND INTERPRETATION OF DATA

Sieve Analysis

The method employed in this statistical summary of sieve analysis data is based on quartiles obtained graphically from the cumulative curve.[9] The quartiles are determined by following the 25, 50, and 75 percent lines on the graph to the right until they intersect the cumulative curve, and then reading the values on the size scale which lie directly below the intersections. The graph paper used in Figures 2 to 9 is semi-logarithmic to facilitate reading of interpolated values.

The second quartile, associated with the 50 percent line, is termed the median diameter. Since the median diameter represents the middle-most grain, with an equal weight frequency of grains on both sides, it is the average grain diameter of the sediment.

The degree of sorting is defined statistically as the extent to which grains spread on either side of the average diameter. The wider the spread, the poorer the sorting. The sorting coefficient, S_o, as developed by Trask (1932) is defined as the square root of the ratio of the larger quartile (the 25 percent value, Q_1) to the smaller quartile (the 75 percent value, Q_3):

$$S_o = \sqrt{Q_1 / Q_3}$$

The median diameter and sorting coefficient give some indication of the conditions under which a given clastic sediment is formed. The former value, although conclusive authority is still lacking, is generally associated with current capacity.

The sorting coefficient is an index of the range of conditions present in the transporting fluid (range of velocity, rate of change of velocity, degree of turbulence, et cetera) and to some extent reflects the distance of transportation. According to Trask (1932),[10] well sorted marine sediments have S_o values less than 2.5; moderately sorted sediments, values ranging from 2.5 to 4.0; and poorly sorted sediments, values larger than 4.0.

A third statistical measure, skewness, indicates the relative degree to which the grains spread out on either side of the median diameter. The significance of this factor, as is the case with the median diameter, remains subject to controversy.

In the Eaton sandstone, the sorting coefficient varies from 1.11 to 1.25 (Table I). According to Trask these values would normally indicate well sorted marine sediments. It is possible, however, that such excellent sorting might result from channel deposition where lengthy transportation and moderate loads were accompanied by a low rate of decrease of velocity.[11] The Pottsville sandstone, also Pennsylvanian, outcropping in Powell county, Kentucky, illustrates this possibility. Though generally considered to be a channel deposit,[12] the Pottsville displays a high degree of sorting in this locality.

In regard to classification of the Eaton sandstone, the predominant grain size in all of the test samples lies between .250 and .500 millimeters. Thus, according to Wentworth's classification, the Eaton would be termed a medium sand.[13]

TABLE I

SIEVE ANALYSIS DATA

Included in this table are the weights of that part of the sample retained by each sieve, the percentage those weights bear to the total sample, and the cumulative percentage or total weight percentage that would be retained on a given sieve if those above had been removed.

<u>Sample 1</u>:

Weight of test sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	9.270	9.32	9.32
35	11.490	11.53	20.85
48	49.835	50.06	70.91
65	18.510	18.59	89.50
100	6.420	6.45	95.95
150	2.435	2.44	98.39
200	1.100	1.11	99.50
230	.205	.20	99.70
270	.095	.10	99.80
325	.100	.10	99.90
> 325	.090	.10	100.00
	99.550 gms.	100.00%	
Sieve Loss	.450 gms.		
Per Cent Loss:	.45%		

Sample 2:

Weight of test sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	1.865	1.88	1.88
35	7.105	7.14	9.02
48	66.135	66.54	75.56
65	10.840	10.90	86.46
100	4.610	4.64	91.10
150	3.005	3.02	94.12
200	1.355	1.36	95.48
230	.650	.65	96.13
270	.540	.54	96.67
325	.670	.67	97.34
> 325	2.640	2.66	100.00
	99.415 gms.	100.00%	
Sieve Loss	.585 gms.		
Per Cent Loss:	.59%		

Sample 3:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	3.415	3.43	3.43
35	2.800	2.81	6.24
48	35.400	35.58	41.82
65	37.860	38.05	79.87
100	10.155	10.20	90.07
150	3.800	3.82	93.89
200	1.405	1.40	95.29
230	.180	.18	95.47
270	.495	.50	95.97
325	.710	.71	96.68
> 325	3.315	3.32	100.00
	99.535 gms.	100.00%	

Sieve Loss .465 gms.

Per Cent Loss: .47%

Sample 4:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	9.625	9.66	9.66
35	6.775	6.80	16.46
48	44.730	44.93	61.49
65	17.855	17.93	79.42
100	6.540	6.56	85.98
150	4.325	4.34	90.32
200	2.070	2.08	92.40
230	.490	.49	92.89
270	.845	.84	93.73
325	1.200	1.20	94.93
> 325	5.155	5.17	100.00
	99.610 gms.	100.00%	

Sieve Loss: .390 gms.

Per Cent Loss: .39%

Sample 5:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	6.355	6.38	6.38
35	5.765	5.79	12.17
48	38.205	38.35	50.52
65	25.755	25.88	76.40
100	8.230	8.26	84.66
150	4.765	4.79	89.45
200	2.235	2.25	91.70
230	.675	.68	92.38
270	.780	.78	93.16
325	2.355	2.37	95.53
> 325	4.450	4.47	100.00
	99.565 gms.	100.00%	

Sieve Loss: .435 gms.

Per Cent Loss: .44%

Sample 6:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	5.275	5.30	5.30
35	9.380	9.42	14.72
48	48.965	49.16	63.88
65	29.845	29.95	93.83
100	2.315	2.32	96.15
150	1.365	1.38	97.53
200	1.105	1.11	98.64
230	.350	.35	98.99
270	.400	.40	99.39
325	.195	.20	99.59
> 325	.410	.41	100.00
	99.605 gms.	100.00%	

Sieve Loss: .395 gms.

Per Cent Loss: .40%

Sample 7:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	3.200	3.21	3.21
35	8.820	8.86	12.07
48	61.280	61.54	73.61
65	11.050	11.10	84.71
100	5.080	5.11	89.82
150	3.265	3.28	93.10
200	1.960	1.97	95.07
230	.370	.37	95.44
270	.390	.39	95.83
325	.630	.63	96.46
> 325	3.520	3.54	100.00
	99.565 gms.	100.00%	

Sieve Loss: .435 gms.

Per Cent Loss: .44%

Sample 8:

Weight of Test Sample: 100 gms.

Mesh / in.	Weight Retained gms.	Weight %	Cumulative %
28	1.395	1.41	1.41
35	1.865	1.88	3.29
48	15.045	15.13	18.42
65	54.915	55.20	73.62
100	15.840	15.92	89.54
150	4.530	4.55	94.09
200	1.545	1.56	95.65
230	1.035	1.04	96.69
270	.240	.24	96.93
325	.470	.47	97.40
> 325	2.590	2.60	100.00
	99.470 gms.	100.00%	

Sieve Loss: .530 gms.

Per Cent Loss: .53%

Figure 2

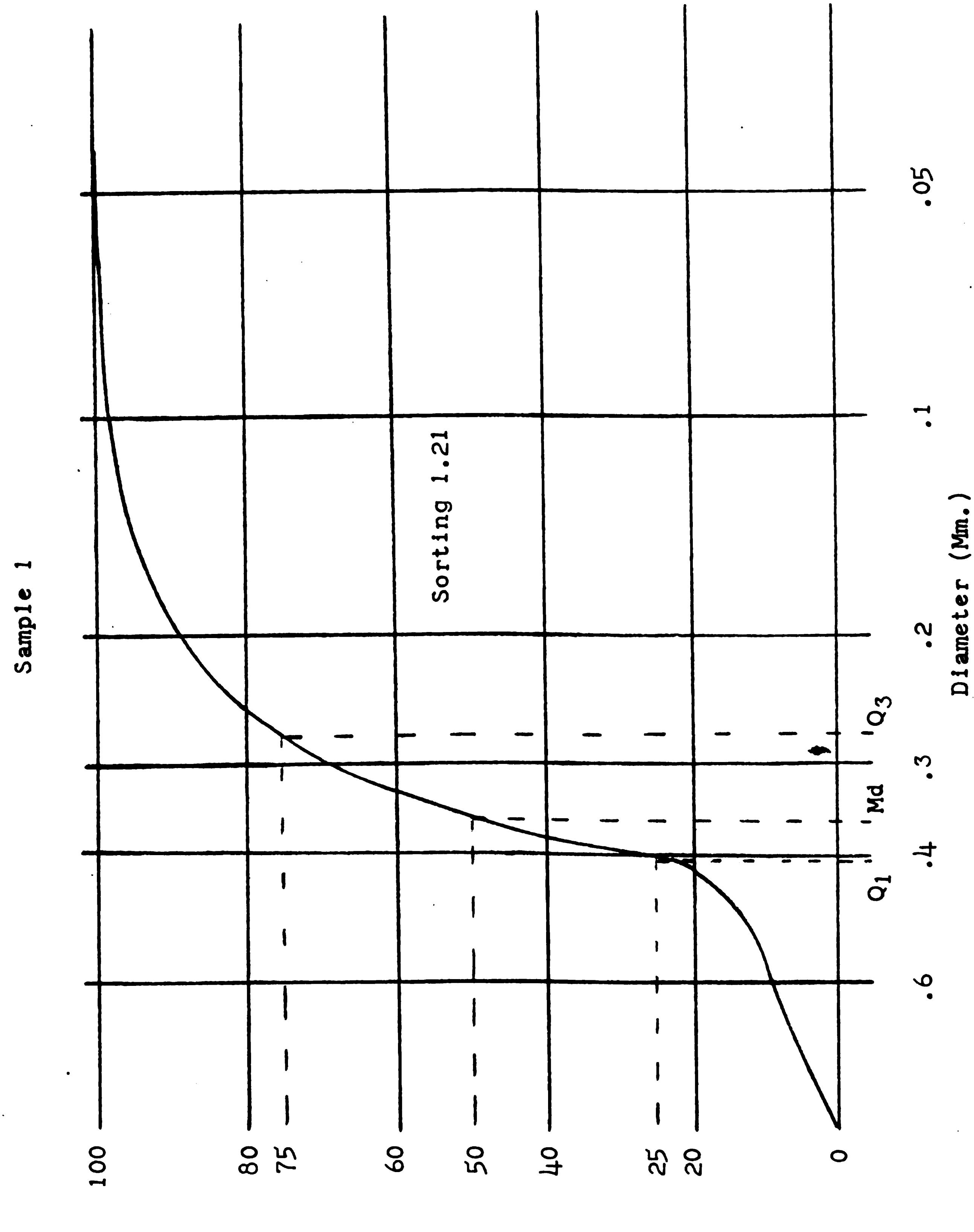
Sample 1
Sorting 1.21
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q_1
Md
Q_3
100
80
75
60
50
40
25
20
0

Figure 3

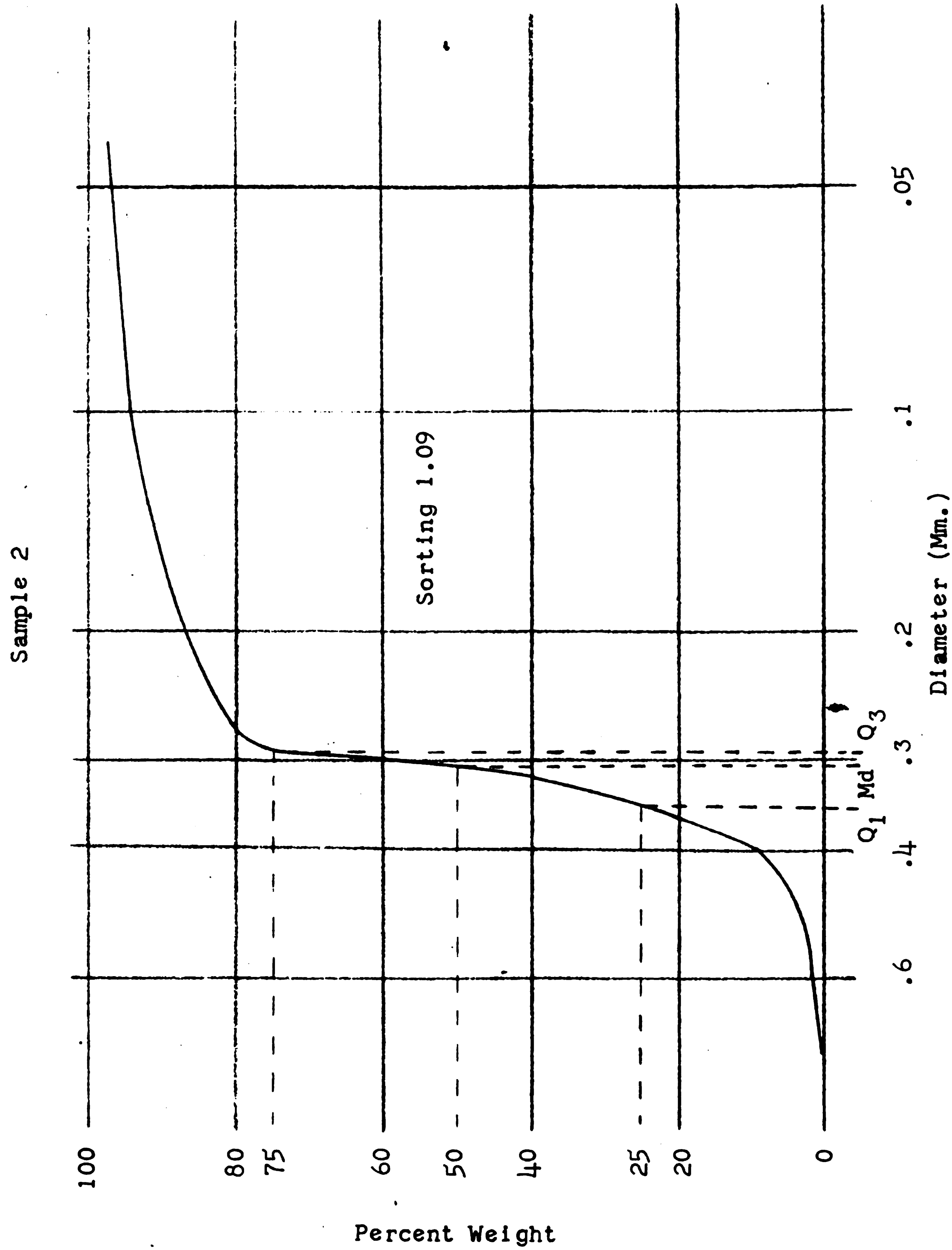
Sample 2
Sorting 1.09
Percent Weight
100
80
75
60
50
40
25
20
0
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q3
Md
Q1

Figure 4

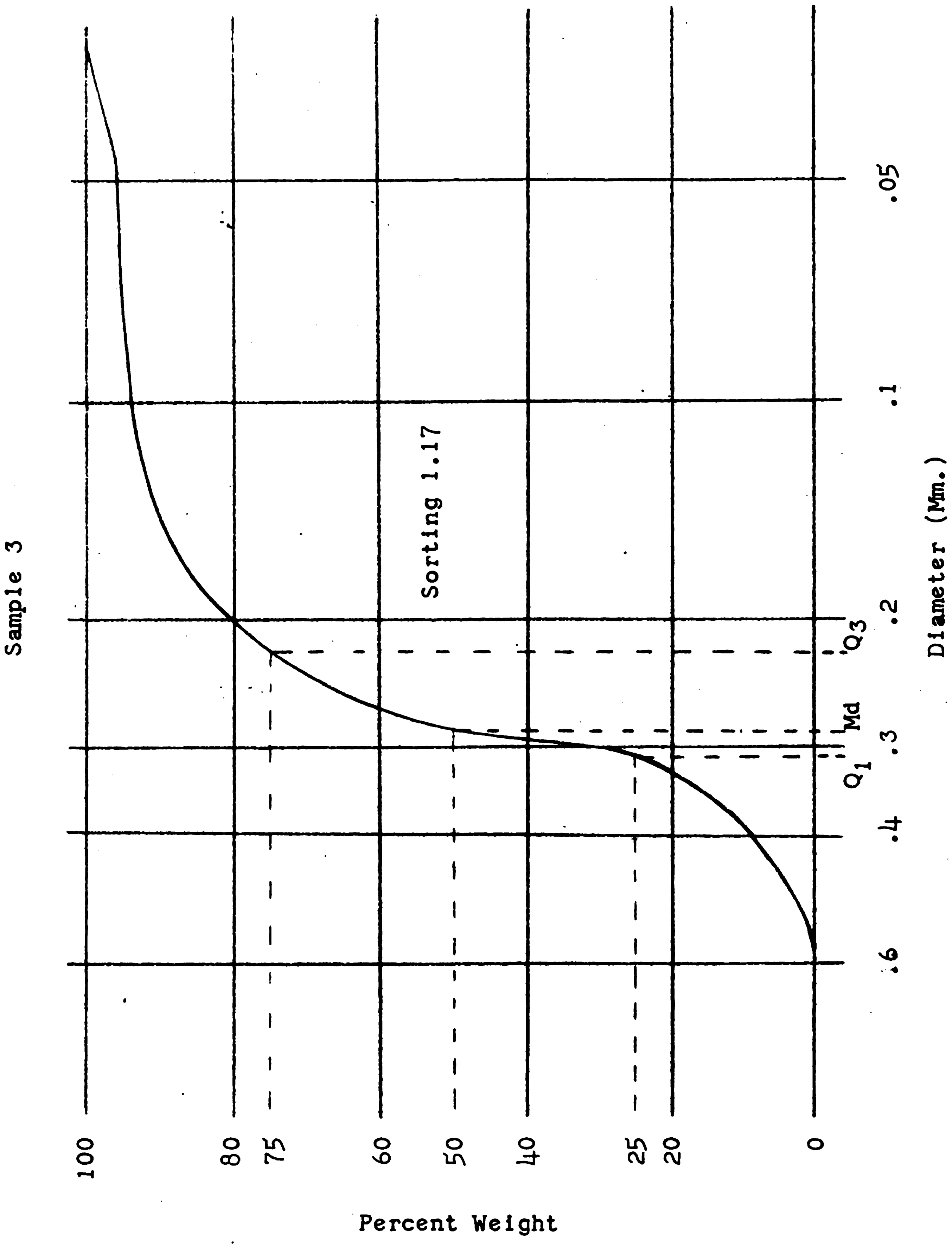
Sample 3
Sorting 1.17
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q_3
Md
Q_1
100
80
75
60
50
40
25
20
0
Percent Weight

Figure 5

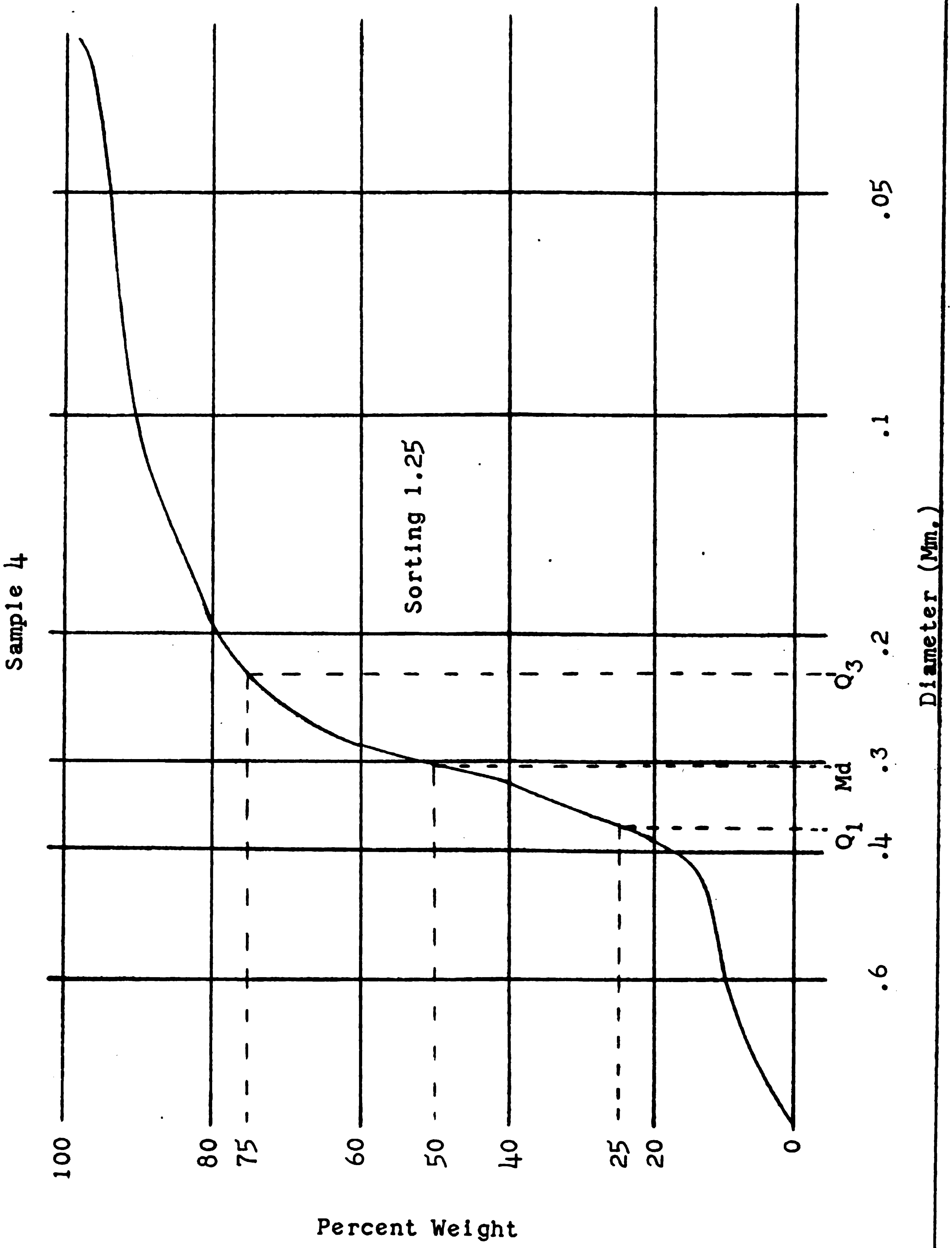
Sample 4
Sorting 1.25
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q_3
Md
Q_1
100
80
75
60
50
40
25
20
0
Percent Weight

Figure 6

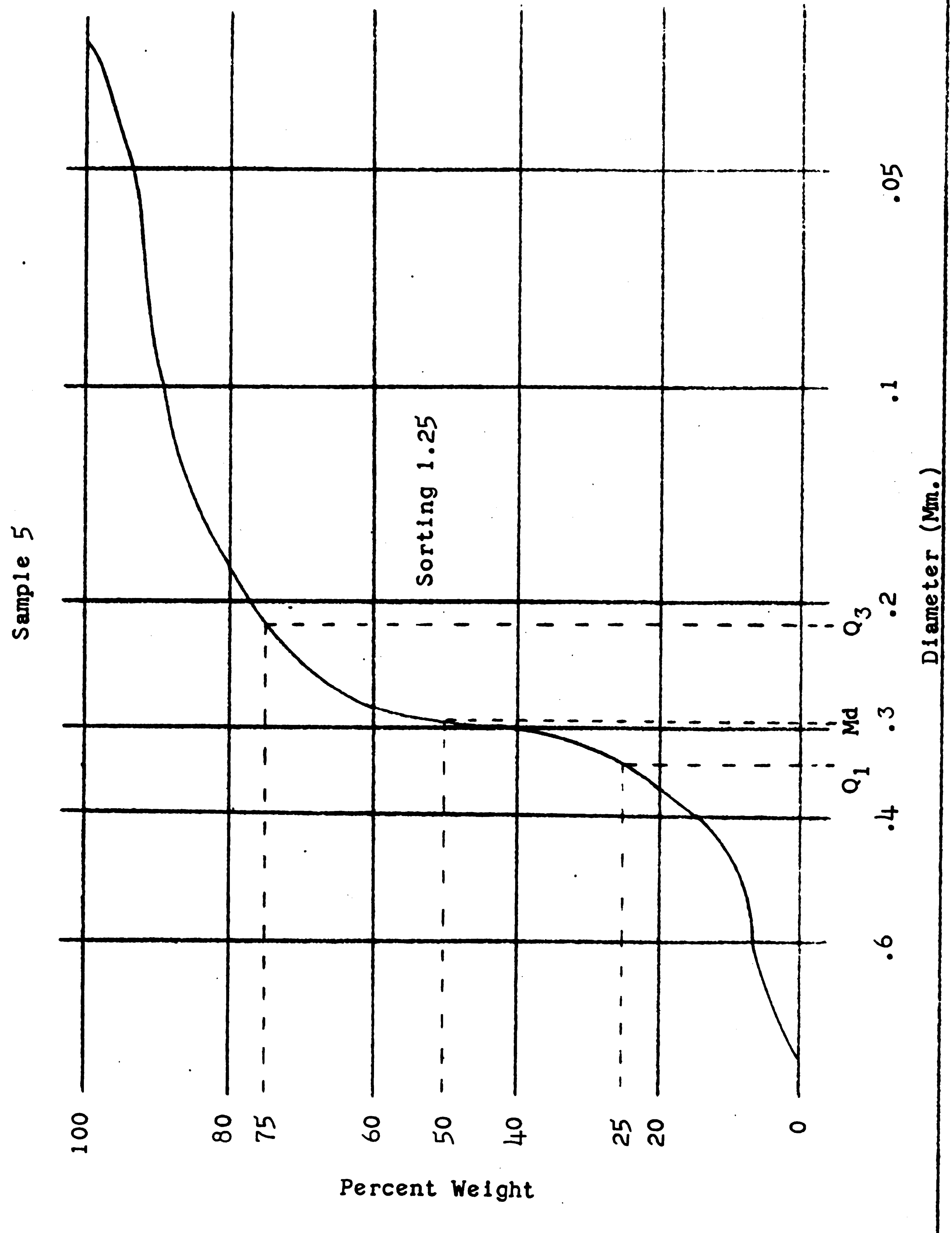
Sample 5
Sorting 1.25
Percent Weight
100
80
75
60
50
40
25
20
0
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q_3
Md
Q_1

Figure 7

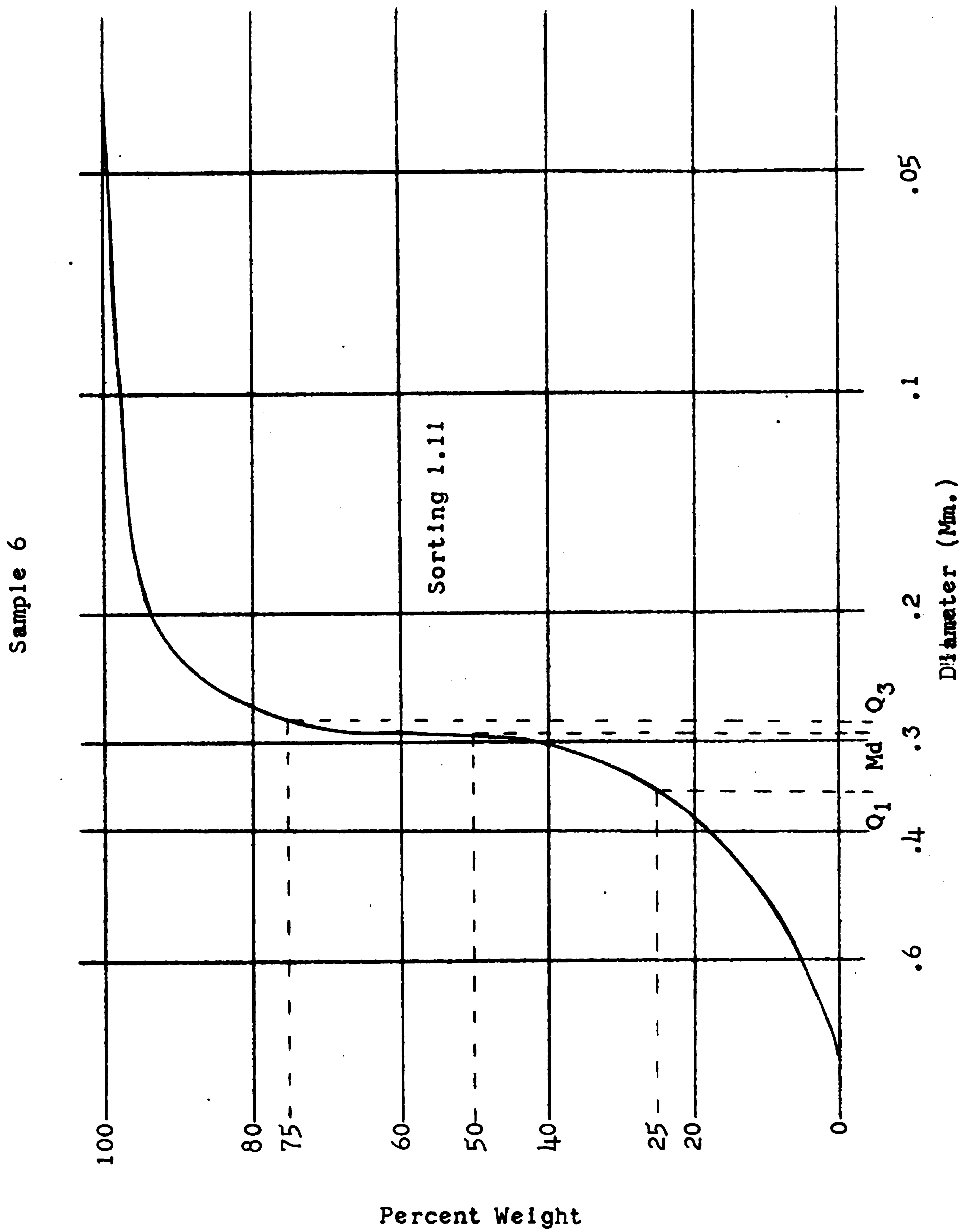
Sample 6
Sorting 1.11
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q3
Md
Q1
100
80
75
60
50
40
25
20
0
Percent Weight

Figure 8

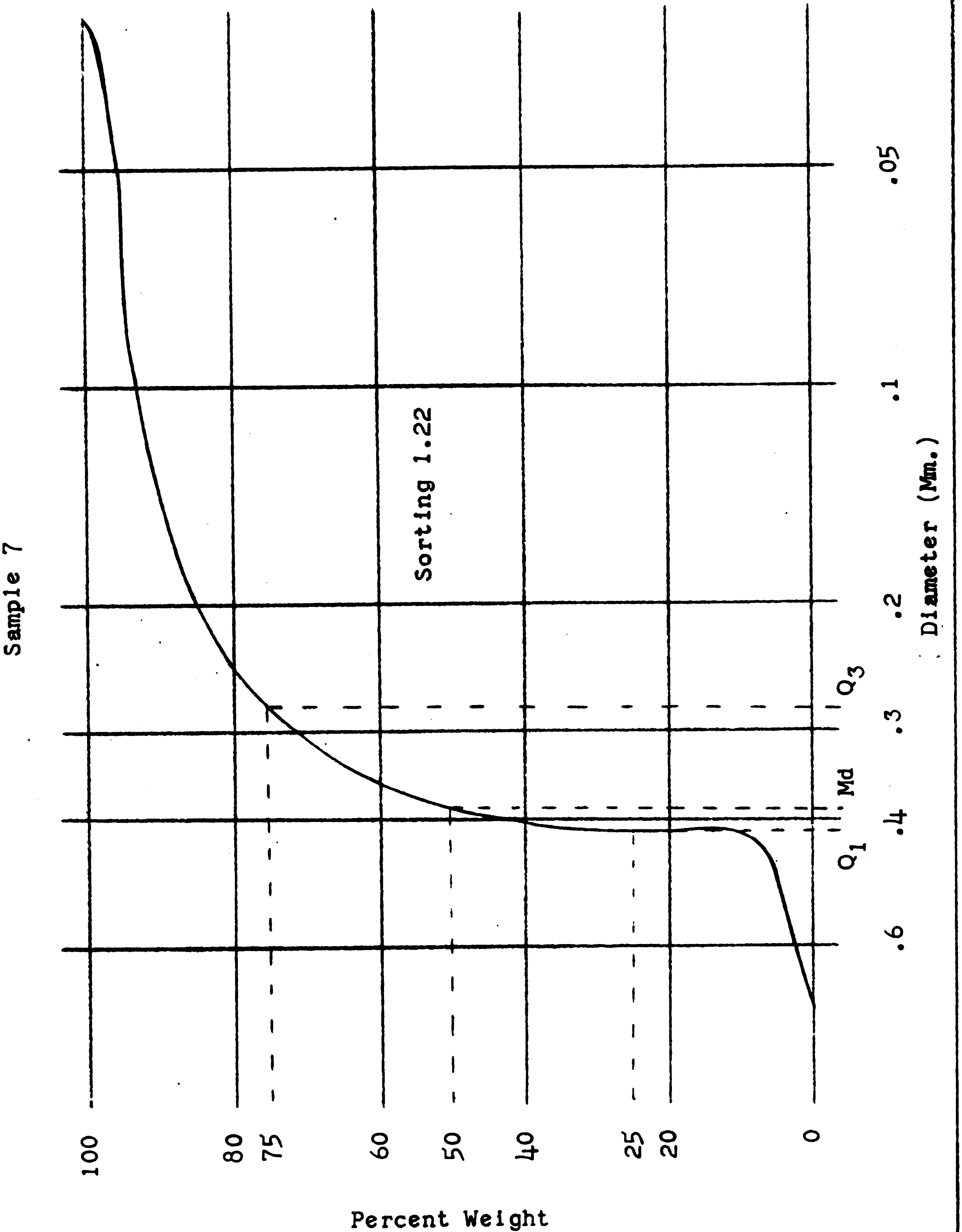
Sample 7
Sorting 1.22
.05
.1
.2
.3
.4
.6
Diameter (Mm.)
Q_3
Md
Q_1
100
80
75
60
50
40
25
20
0
Percent Weight

Figure 9

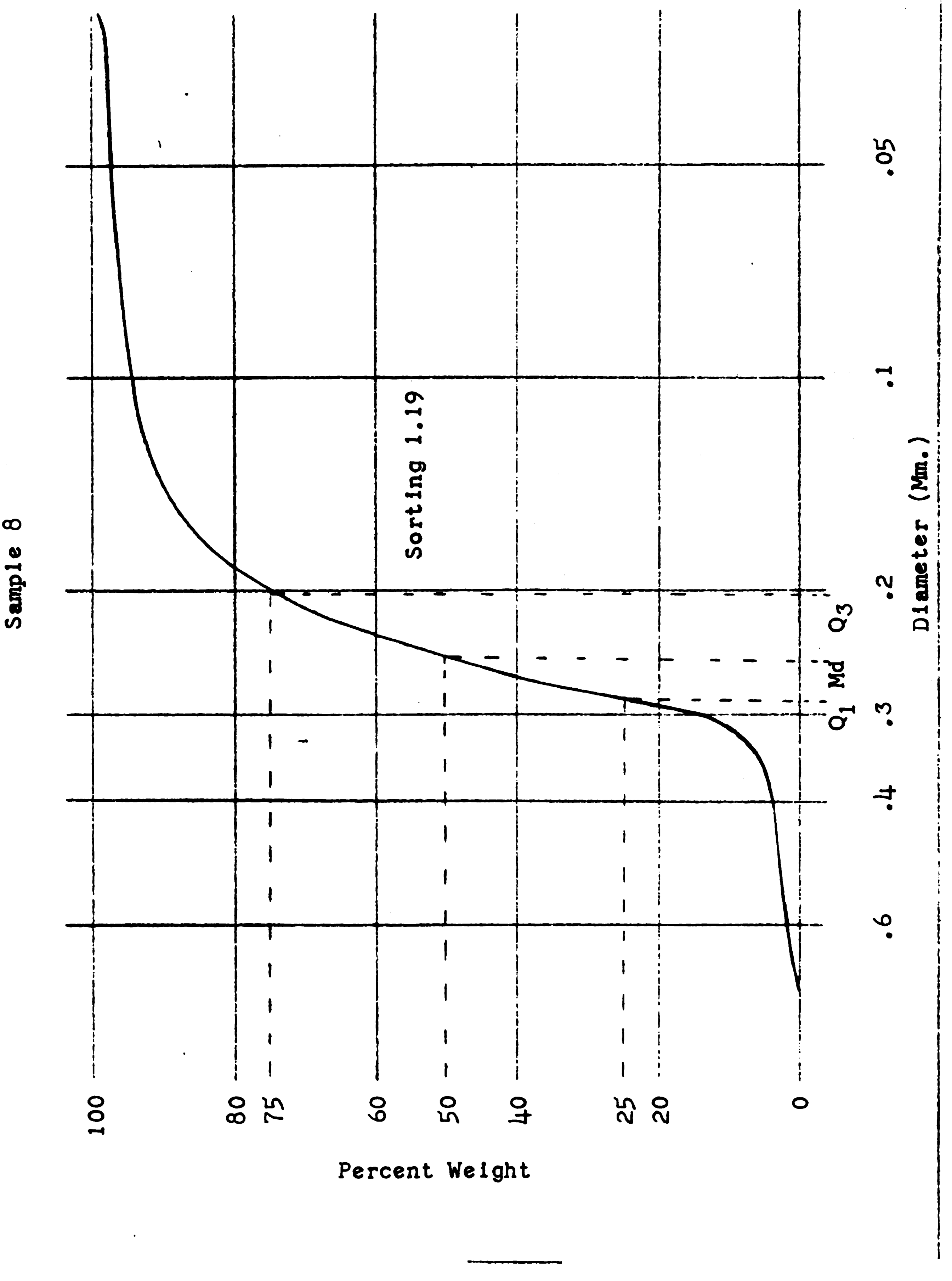
Sample 8
Sorting 1.19
Diameter (Mm.)
.05
.1
.2
.3
.4
.6
Q_1
Md
Q_3
100
80
75
60
50
40
25
20
0
Percent Weight

TABLE I

Part 2

The values in this part of Table I, referred to under "Analysis and Interpretation of Data" were obtained by plotting cumulative percentage against sieve size on semi-logarthmic graph paper.

Samples	Md	Q_1	Q_3	S_o	Skg	Log S_o
1	.362	.410	.280	1.21	1.07	.083
2	.310	.351	.295	1.09	1.07	.038
3	.285	.311	.225	1.17	1.08	.071
4	.317	.382	.244	1.25	1.03	.098
5	.297	.340	.218	1.25	1.09	.097
6	.296	.350	.286	1.11	.936	.044
7	.390	.420	.283	1.22	1.14	.086
8	.254	.287	.204	1.19	1.05	.074

Insoluble Residues

The quantity of soluble material in the Eaton serves as a measure of the calcareous cement in this sandstone. In the Eaton, the soluble material varied from .5 to 5.6 percent of the entire sample (Table II). Thus, as previously indicated in the disaggregation process, as well as in sphericity and roundness determination, the cement is largely siliceous.

Heavy Mineral Analysis

The heavy constituents of the Eaton sandstone varied from 1.5 to 3 percent of the entire sample (Table III). This small proportion of "heavies" would tend to indicate a secondary source for the Eaton.[14] As the components of a particular rock type are reworked, unstable minerals, such as hornblende and biotite tend to break down as a result of the weathering process, and thus the heavy mineral content of a sediment is inversely proportional to the sedimentary generation.

Another important consideration in the heavy mineral analysis involves the mineral suites present and the frequency of the individual suite minerals (Table IV). Zircon is the predominant "heavy" in each of the samples, varying from 66.7 percent of the "heavy" content in sample 1 to 88.6 percent in sample 8. Tourmaline is also quite prominent in each of the samples, ranging from 6.9 percent in sample 2 to 16.1 percent in sample 1. Garnet and cassiterite are the only other

TABLE II

INSOLUBLE RESIDUE DATA BASED ON 5 GM. SAMPLE

Sample No.	Gms.	% Insoluble
<u>Sample 1</u>		
Weight of filter paper	1.020	
Weight of filter paper and residue	5.870	
Weight of residue	4.850	97
<u>Sample 2</u>		
Weight of filter paper	1.030	
Weight of filter paper and residue	5.845	
Weight of residue	4.815	96.5
<u>Sample 3</u>		
Weight of filter paper	1.020	
Weight of filter paper and residue	5.995	
Weight of residue	4.975	99.5
<u>Sample 4</u>		
Weight of filter paper	1.070	
Weight of filter paper and residue	5.965	
Weight of residue	4.895	97.9
<u>Sample 5</u>		
Weight of filter paper	1.030	
Weight of filter paper and residue	5.750	
Weight of residue	4.720	94.4
<u>Sample 6</u>		
Weight of filter paper	1.055	
Weight of filter paper and residue	5.825	
Weight of residue	4.770	95.4
<u>Sample 7</u>		
Weight of filter paper	1.020	
Weight of filter paper and residue	5.845	
Weight of residue	4.825	96.5
<u>Sample 8</u>		
Weight of filter paper	1.040	
Weight of filter paper and residue	5.960	
Weight of residue	4.920	98.4

"heavies" occurring consistently in significant amounts, the former varying from 1 percent in sample 4 to 14 percent in sample 2, and the latter from 2 percent in sample 1 to 12 percent in sample 6. Kyanite and staurolite are present in minor amounts in all of the test samples, but monazite, also occurring sporadically, is absent from samples 2 and 3.

The high proportion of zircon to the other heavy minerals in each sample is likely an indication of thorough weathering, rather than a reflection of the mineral content in the original source rock. Zircon, as well as the rest of the above mentioned suite minerals, generally occurs in very minor amounts in igneous rocks, and an attempt to hypothesize an igneous rock with zircon occurring in such relative prominence as indicated by the suite percentages, seems hardly feasible. However, Dryden and Dryden,[15] in a study of the comparative rates of weathering of heavy minerals, found that zircon is much more resistant to weathering than a number of other species. Arbitrarily establishing the resistance of garnet as 1, they compiled the following table based on a study of the Maryland-Pennsylvania region.

Zircon	100
Tourmaline	80
Sillimanite	40
Monazite	40
Chloritoid	20
Kyanite	7

Hornblende 5

Staurolite 3

Garnet (taken as) . . . 1

Hypersthene 1-

Thus, if resistance to weathering is accepted as the major determinant of the heavy mineral assemblage of the Eaton sandstone, zircon occurred in considerably greater proportion than tourmaline or monazite in the original source rock. In reference to Table IV, the proportion of zircon in the original source rock but slightly exceeded that of kyanite and staurolite, while that of garnet sizeably surpassed the original proportion of zircon.

Another consideration involves the effect of transportation on a given heavy mineral assemblage. Prior to a study by Russell,[16] it was generally assumed that there also existed a definite, well defined transportation resistance series among the "heavies." In this series, garnet was believed to be highly resistant to the effects of transportation, while the amphiboles and pyroxenes were assumed to be rapidly eliminated by breakage and decomposition during transportation. In Russell's analysis, based on samples collected from the Mississippi River between Cairo, Illinois and the Gulf of Mexico (approximately 1100 miles), marked progressive downstream changes in mineral composition were lacking. Though a slight downstream decrease in pyroxene was noted, no trend whatever in the percentage of amphibole was discernible. Russell concluded, therefore, that the pyroxenes and amphiboles were more resistant to abrasion and far more persistent than previously assumed. Also, if they were absent from a sediment, it is likely that this sediment was derived from a source already free of these species, or that they had been dissolved from the sediment subsequent to its deposition. Thus, in general, preferential effects in regard to composition as a result of transportation appear to be quite insignificant.

Another application of the heavy mineral data deals with the consideration of whether the immediate source rock of the original sediment was an igneous or metamorphic rock. It also furnishes an indication of the mineral content of the original source rock. Regarding the former, the presence of garnet, kyanite and staurolite indicates a period of dynamometamorphism in the ultimate conversion process. As for mineral content of the original source rock, the occurrence of zircon and monazite attest to a rather acid igneous rock.

Thorough reworking of the original sediment is postulated, due to the high degree of roundness expressed by the mineral zircon. The presence of relatively well-rounded tourmaline grains supports this contention.[17]

TABLE III

RELATIVE PERCENTAGES OF HEAVY AND LIGHT CONSTITUENTS OF EATON SANDSTONE BASED ON 1 GM. SAMPLE (H-HEAVY MINERALS, L-LIGHT MINERALS)

Sample No.	H Gms.	% H	% L
Sample 1			
Weight of filter paper	1.040		
Weight of filter paper and constituent	1.065		
Weight of constituent	.025	2.5	97.5
Sample 2			
Weight of filter paper	1.060		
Weight of filter paper and constituent	1.085		
Weight of constituent	.025	2.5	97.5
Sample 3			
Weight of filter paper	1.010		
Weight of filter paper and constituent	1.030		
Weight of constituent	.020	2.0	98.0
Sample 4			
Weight of filter paper	1.065		
Weight of filter paper and constituent	1.085		
Weight of constituent	.020	2.0	98.0
Sample 5			
Weight of filter paper	1.015		
Weight of filter paper and constituent	1.045		
Weight of constituent	.030	3.0	97.0
Sample 6			
Weight of filter paper	1.015		
Weight of filter paper and constituent	1.040		
Weight of constituent	.025	2.5	97.5
Sample 7			
Weight of filter paper	.995		
Weight of filter paper and constituent	1.010		
Weight of constituent	.015	1.5	98.5
Sample 8			
Weight of filter paper	1.040		
Weight of filter paper and constituent	1.070		
Weight of constituent	.030	3.0	97.0

TABLE IV

HEAVY MINERAL FREQUENCY DISTRIBUTION OF EATON SANDSTONE

Included are the recorded values derived from the isolation and identification of the heavy minerals in the eight samples on which conclusions relative to the heavy mineral content of the Eaton are based.

Sample 1

Mineral	No. of Grains	Mineral %
Zircon	58	66.7
Tourmaline	14	16.1
Garnet	8	9.2
Cassiterite	2	2.3
Kyanite	1	1.1
Staurolite	2	2.3
Monazite	2	2.3
Total Grains	87	100.0

Sample 2

Mineral	No. of Grains	Mineral %
Zircon	448	88.5
Tourmaline	35	6.9
Garnet	14	2.8
Cassiterite	6	1.2
Kyanite	2	.4
Staurolite	1	.2
Total Grains	506	100.0

TABLE IV (Continued)

Sample 3

Mineral		No. of Grains	Mineral %
Zircon		128	71.9
Tourmaline		28	15.7
Garnet		12	6.7
Cassiterite		7	3.9
Kyanite		1	.6
Staurolite		2	1.2
	Total Grains	178	100.0

Sample 4

Mineral		No. of Grains	Mineral %
Zircon		370	87.1
Tourmaline		39	9.2
Garnet		1	.2
Cassiterite		5	1.2
Kyanite		7	1.6
Staurolite		1	.2
Monazite		2	.5
	Total Grains	425	100.0

Sample 5

Mineral		No. of Grains	Mineral %
Zircon		441	87.8
Tourmaline		42	8.4
Garnet		8	1.6
Cassiterite		5	1.0
Kyanite		3	.6
Staurolite		2	.4
Monazite		1	.2
	Total Grains	502	100.0

TABLE IV (Continued)

Sample 6

Mineral		No. of Grains	Mineral %
Zircon		463	87.3
Tourmaline		41	7.8
Garnet		5	.9
Cassiterite		12	2.3
Kyanite		1	.2
Staurolite		6	1.1
Monazite		2	.4
	Total Grains	530	100.0

Sample 7

Mineral		No. of Grains	Mineral %
Zircon		456	86.7
Tourmaline		40	7.6
Garnet		9	1.7
Cassiterite		8	1.5
Kyanite		6	1.1
Staurolite		3	.6
Monazite		4	.8
	Total Grains	526	100.0

Sample 8

Mineral		No. of Grains	Mineral %
Zircon		452	88.6
Tourmaline		39	7.7
Garnet		10	1.9
Cassiterite		3	.6
Kyanite		3	.6
Staurolite		2	.4
Monazite		1	.2
	Total Grains	510	100.0

Sphericity and Roundness

The sphericity and roundness of the Eaton sandstone should lend an indication as to the direction of deposition and as to the environment in which this sandstone was deposited.

Sphericity, the first characteristic to be considered, is, in part, a function of the relation between the surface area and volume of a particle. A sphere has the least surface area of any shaped particle for a given volume, and as the shape departs from that of a sphere, the ratio of surface area to volume increases. This relation affects the resistance which the particle offers to movement by a fluid. If movement is by suspension, grains of low sphericity tend to be concentrated downcurrent and at the site of final deposition. On the other hand, if movement is dominantly by rolling, there is a tendency toward the opposite result, as grains of high sphericity roll more easily and rapidly than flatter grains of low sphericity, and thus tend to outdistance the flatter ones.[18]

In general, the sphericity of pebbles increases with the distance of travel, thus giving an indication that rolling is the more prominent means of transport as a sediment approaches sand grade. Russell and Taylor (1937), however, observed a decrease in sphericity of Mississippi River sands downstream from Cairo.[19]

As defined by Wadell (1932)[20] roundness is expressed as:

$$\frac{\text{Average radius of corners and edges}}{\text{Radius of maximum inscribed circle}}$$

When the corners and edges are sharp, the average radius is small and the roundness low; but when the average radius of the corners approaches that of the inscribed circle, the roundness value approaches its maximum of 1.0.

Roundness of pebbles increases in the direction of transport in the absence of severe breakage. Large angular particles, moreover, tend to round more rapidly than small ones. Rapidity of rounding is also influenced by the hardness of the particles under consideration. Limestone pebbles thus tend to round quite rapidly, while chert pebbles may remain quite angular for great distances of travel.

In considering the directional aspect of deposition as interpreted from this particular analysis, the sphericity of the Eaton increased in a northwesterly direction, varying progressively, with the exception of sample 2, from .572 in sample 4 to .647 in sample 1 (Table V). Sphericity also increased in a northeasterly direction, varying progressively from 559 in sample 6 to .647 in sample 1. The roundness increased successively in a northwesterly direction with a figure of .087 being recorded for sample 4 and that of .221 for sample 1 (Table V). As was the case in the sphericity determination, the roundness also increased toward the northeast, varying from .083 in sample 6 to .221 in sample 1.

Sample 2 also as above, alone had an anomalous value.

Samples 7 and 8 represent the only other known outcrops of the Eaton sandstone. Anomalous values were recorded for both samples, with the possible exception of a sphericity value of .656 for sample 8. The roundness in both cases was .103, while the sphericity of sample 7 was .605.

Since, as noted above, sphericity and roundness generally increase in the direction of transport, deposition of the Eaton would be inferred to have proceeded in a northerly, possibly a northeasterly, direction. This inference is based on the fact that although sphericity and roundness increased in both northeasterly and northwesterly directions, the increase toward the northeast was slightly sharper. Thus, the relatively small sphericity increase in sample 8 may, in part, be attributed to a greater divergence from the actual direction of deposition than was the case in the consideration of samples 1 and 4.

Any environmental interpretation would seemingly have to be based on sphericity and roundness studies of deposits of known origin. Krumbein and Sloss[21] have compiled such data covering a variety of depositional environments. In their tabulation, however, roundness alone showed an environmental variation. The roundness of marine sediments evaluated therein varied from .60 - .65, while that of sediments of continental origin ranged from .30 - .35. Thus, using the above tabulation as a basis for evaluation, the Eaton sandstone, in which the roundness varied from .083 in sample 6 to .236 in sample 2, would be considered a continental, as opposed to a marine sediment.

TABLE V

SPHERICITY AND ROUNDNESS DATA

Herein are recorded values of sphericity and roundness of the Eaton which serve as the basis for directional and environmental interpretations.

<u>Sample 1</u>

Sphericity: .647 Roundness: .221

<u>Sample 2</u>

Sphericity: .613 Roundness: .236

<u>Sample 3</u>

Sphericity: .618 Roundness: .156

<u>Sample 4</u>

Sphericity: .572 Roundness: .087

<u>Sample 5</u>

Sphericity: .617 Roundness: .106

<u>Sample 6</u>

Sphericity: .559 Roundness: .083

<u>Sample 7</u>

Sphericity: .605 Roundness: .103

<u>Sample 8</u>

Sphericity: .656 Roundness: .103

SUMMARY

In Kelly's analysis of the Eaton sandstone, a continental origin was proposed for this formation.[22] This interpretation, as referred to previously, was based on megascopic characteristics, such as cross-bedding, ripple marks, fossils, et cetera. In the quantitative analysis completed by the writer, a similar interpretation is generally indicated.

Sieve analysis data reveals the excellent degree of sorting present in the formation. However, sorting such as present herein, although generally characteristic of sediments of marine origin, might result from channel deposition where lengthy transportation and moderate loads were accompanied by a low rate of decrease of velocity.

In the insoluble residue determination, negative values may be of some significance. A substantial content of calcareous material, generally indicative of marine sedimentation, was not in evidence in any of the samples.

The results of the heavy mineral analysis reveal that either the Eaton sandstone is not a first generation sediment, or that if it is the result of a single cycle of sedimentation, its depositional environment was one receiving sediments from an area of thorough weathering. Transportational effects (Russell) are considered to be of minor importance in determining the heavy mineral content of a sediment.

The sphericity and roundness study made possible both depositional and environmental interpretations. Progressive changes in both sphericity and roundness indicated that deposition proceeded in a northerly direction. As for the environmental interpretation, roundness alone proved to be significant. Consistent with recorded values of roundness for the Eaton and the tabulation by Krumbein and Sloss,[23] would be an interpretation of this formation as having a continental origin.

Thus, the results gathered from the quantitative methods employed in the writer's analysis tend to support Kelly's findings regarding the depositional environment of the Eaton sandstone, and yield data indicating an inference as to the direction of deposition of this formation.

RECOMMENDATIONS FOR FURTHER STUDY

Further study of the Pennsylvanian formations near Grand Ledge should include quantitative analyses of the cyclical formations exposed in that area. The Ionia sandstone, outcropping in the Grand River valley near Ionia, and the Woodville sandstone which outcrops in Jackson county should also be studied quantitatively. Interpretations resulting from these analyses should provide additional bases of comparison, which in turn may aid in alleviating some problems of classification of the Pennsylvanian in Michigan.

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