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A Study of Particle Size Distribution in North Dakota Clays

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A STUDY OF PARTICLE SIZE DISTRIBUTION IN NORTH DAKOTA CLAYS

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This thesis, presented by Arthur Irvin Vigard, in partial fulfillment of the requirements for the degree of Master of Science, is hereby approved by the Committee on Instruction in charge of his work.

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A STUDY OF PARTICLE SIZE DISTRIBUTION IN NORTH DAKOTA CLAYS.

A. Introduction

The study of particle size distribution of clays has been attracting considerable attention in recent years because it seems evident that such properties of clays as plasticity, permeability, capillarity, adsorption and moisture content are largely determined by the size of the particles making up that clay. A clay having too little colloidal material lacks plasticity and is referred to by the ceramic chemist as weak, lean or sandy, while if it has too much it is called fat, strong and sticky. A moderate plasticity is desirable. Norton and Hodgdon[1] argue, however, that it is not proved that colloidal particles are necessary to plasticity. Such factors as the presence of protective colloids (e.g. humus), salts and the pH value[3] apparently also influence the properties of the clay. We do know[2], however, that if the fine particles of a plastic clay are all removed the clay loses its plasticity. It seems certain that the size of the particles has some effect, since grinding increases the plasticity, while the addition of coarser grains decreases it.

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1 Norton, F.H.& Hodgdon, F.B.; Jour. Amer.Cer.Soc. 15,191-205(1932)

2 Searle, A.B. --The Chemistry & Physics of Clays" page 260 D. Van Nostrand Co. New York

3 Beeman, Norvil--Jour. Amer. Cer. Soc. 14, 72-87 (1931)

According to the hypothesis most generally accepted, clays consist essentially of hydrated aluminum silicate whose crystalline particles are coated with a stable, water-attracting surface. These particles are of varying degrees of fineness. Most clays, if not all, contain detached colloidal particles. When mixed with water clays are capable of being molded under a low pressure and retain their shape on removal of the pressure. Their chemical and physical properties vary with the geological processes which have produced them.

Purpose of the Investigation.

A survey of the clay deposits of North Dakota has been carried on by the School of Mines of the University of North Dakota under the supervision of Mr. W. E. Budge. The manufacture of clay products has been developed to a limited extent within the state, the most successful being in the vicinities of Dickinson, Hebron and Grand Forks. The use of North Dakota clays in pottery has been developed at the School of Mines, and a pottery project is under consideration at Mandan.

The investigation here presented contemplates a measurement of the particle size distribution of clays now in use in the ceramic industries of North Dakota, as well as a number of clays under investigation at the School of Mines; and a comparison of this information with any properties of these clays so far as they have been determined by use and study.

Theory of Sedimentation.

A mixture of clay and water consists of a wide variety of sizes of clay particles suspended in the liquid. Several forces immediately begin to act on these suspended particles. One of these is the force of gravity, which acts downward and is constant in a given locality. The actual downward pull is determined by the mass of the suspended body. Another force is the buoyant effect, or lifting force of the liquid, which at the same time tends to move the body upward. The combination of these two forces, or the net effect of gravity, is given in the equation:

$$G = \frac{4}{3}\pi r^3(d_1 - d_2)g \qquad (1)$$

π = 3.1416

r = radius of particle in cm. (assuming the particle to be a sphere)

d_1 = density of particle

d_2 = density of the fluid

g = force in dynes exerted by gravity upon a body

A third factor must be considered in sedimentation. When a body begins to move as a result of gravity and buoyancy, a retarding force is developed due to the friction between the body and the fluid. This is due to the viscosity of the liquid, and is expressed in dynes in the following equation:

$F = 6\pi nrv$

n = viscosity

r = radius

v = velocity of settling, cm/sec.

The effect of friction acts in opposition to the net effect of gravity, that is, upward.

When the force of liquid friction is equal to the net effect of gravity, or F = G, the rate of fall of the body will be constant, and

$$6\pi nrv = \frac{4}{3}\pi r^3(d_1 - d_2)g \qquad (2)$$

or

$$v = \frac{2r^2(d_1 - d_2)\,g}{9n} \qquad (3)$$

This equation is the usual mathematical expression of Stoke's Law.

Fig. 1. Graphic Representation of Vertical Forces Acting On A Body In Suspension.

Gravity is the downward force, and the retarding or resistance to flow is the upward force.

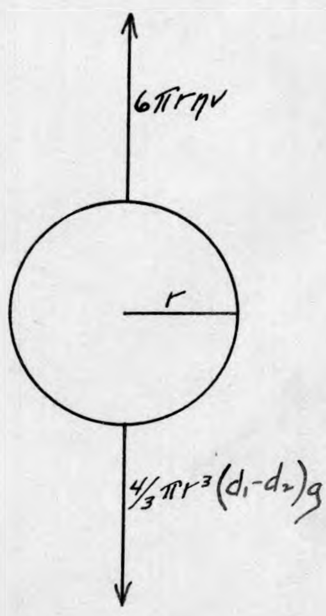

Figure 1.

Since the rate of fall is proportional to the square of the radius of the particle, it is evident that as the particles in the suspension become smaller, the rate of sedimentation decreases very greatly.

When the particles in a suspension become so small that they come in the colloidal range, 5 millimicrons to 200 millimicrons, Stoke's Law appears not to apply. This has been popularly believed to be because the net force of gravity is made ineffective by the bombardment of the suspended particles by the molecules in the liquid phase, but it appears more likely[1,2] to be due to the great susceptibility of these minute particles to convection currents.

The radius of a spherical particle can be calculated from its rate of settling by using the following formula derived from equation (3):

$$r^2 = \frac{9}{2} \frac{nh}{(d_1 - d_2)\ 60\ gt} \qquad (4)$$

r = radius of a spherical particle

n = viscosity of medium

h = distance of sedimentation, cm.

d_1 = specific gravity of dispersed phase

d_2 = specific gravity of dispersing medium

g = gravitational constant---980 dynes

t = time, minutes

[1] Kraemer, E. O. Colloid Symposium Monograph 5, 81

[2] Burton, E. F. in Bogue's "Colloidal Behavior" Vol. I, p. 123

The distance h is measured from the top of the medium to the top of the sedimentation pan.

Let us consider what happens when a gram of solid settles out of a liquid medium.[1] First let us take a meterial whose particles are all of the same size and which completely settle out in ten minutes. Curve 1, Fig. 2, shows that the rate of settling is constant, being a straight line.

Now let us take one gram of material every particle of which settles out half as fast -- that is, in 20 minutes. Curve 2 illustrates the rate as constant and a straight line as before.

Similarly, curves 3 and 4 illustrate the rates for two other imaginary products with every particle of one size, but settling out in 50 and 100 minutes, respectively.

Now let us take one gram of a 50:50 mixture of No. 2 and No. 3 product and settle it out under conditions as above. In 20 minutes all of No. 2, or 0.50 gram, and two-fifths of No. 3, or 0.20 gram, or in all 0.70 gram, will have settled out. In 50 minutes the remainder, or 0.3 gram, of No. 3 will have settled out. The lineABC, Fig. 2, Section2, is the curve for the mixture. An extension of line BC cuts the vertical axis at 0.5, which is the amount of each size.

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1 Calbeck, J. H. and Harner, H.R. Journ. Ind. & Eng. Chem. 19: 58-61 (1927)

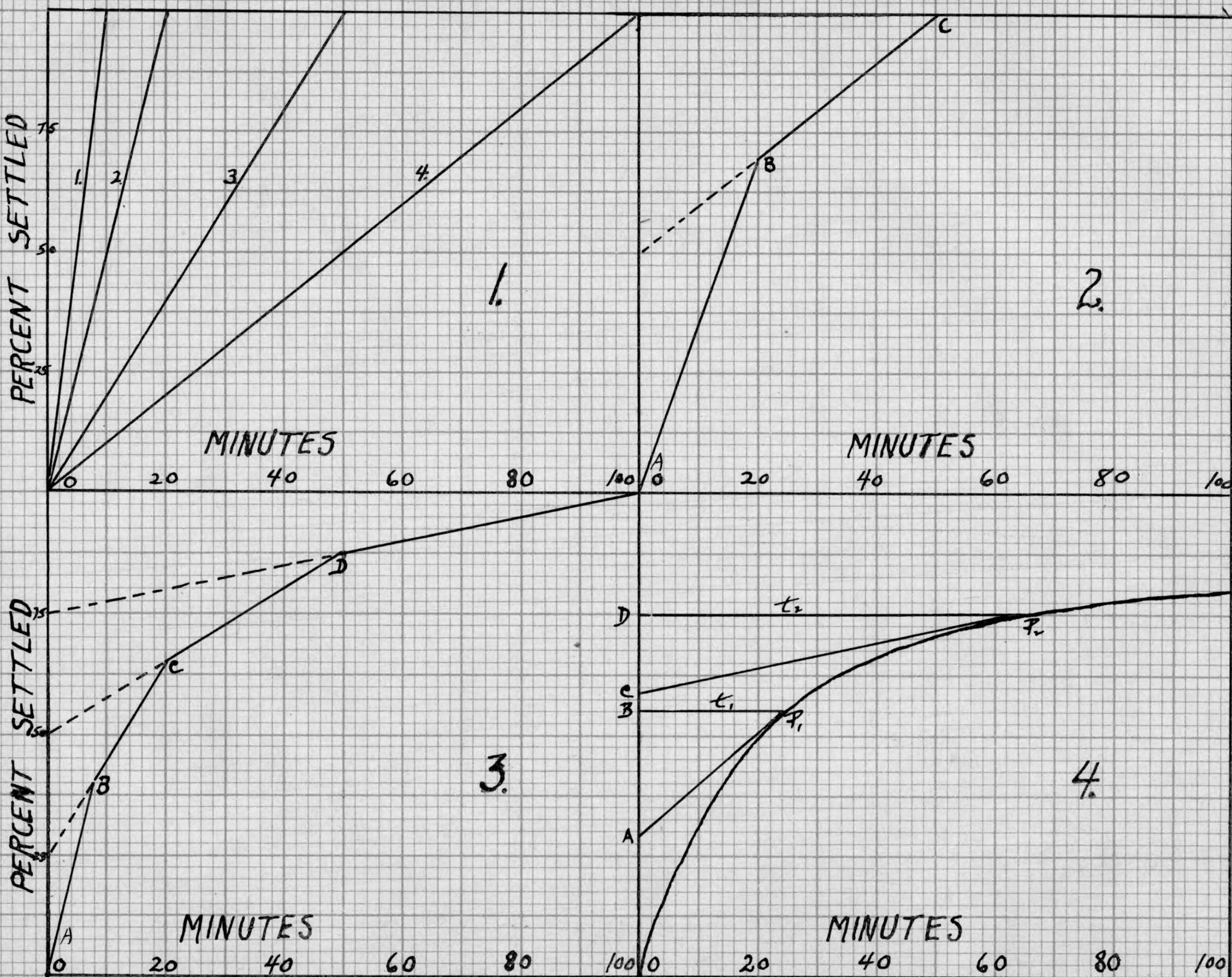
PERCENT SETTLED
75
50
25
1.
2.
3.
4.
MINUTES
0
20
40
60
80
100
A
B
C
D
t₁
t₂
P₁
P₂

Figure 2.

Now suppose all four of the materials are mixed in equal proportions, so that there are 0.25 gram of each in the sample. The settling will then occur as follows:

First 10 minutes

	Gram
All of No. 1	0.25
½ of No. 2	0.125
1/5 of No. 3	0.050
1/10 of No. 4	0.025
Total	0.450

Second 10 minutes

All that settled in first 10 min.	0.450
½ of No. 2	0.125
1/5 of No. 3	0.050
1/10 of No. 4	0.025
Total	0.650

Next 30 minutes

All that settled in first 20 min.	0.650
3/5 of No. 3	0.15
3/10 of No. 4	0.075
Total at end of 30 min.	0.875
Total at end of 100 min.	1.000

Plotting these results we obtain curve ABCDE (Fig. 2, Section 3). The settling proceeds at a constant rate until all of the largest size has settled out and then changes abruptly and continues at a constant rate until all the second largest size has settled out, breaks again, and so on until all has settled out. Extensions of the lines BC, CD, and EF cut the vertical axis so as to divide it into sections of each 0.25 gram, or the exact original weight of each of the different size particles. Similarly, if there had been unequal amounts of each of the four sizes the sections on the vertical axis would have been proportional to these amounts.

An ordinary clay is not made up like the mixture of definite particle sizes, but has a gradient of sizes ranging from the finest to the coarsest. Curve 4, Figure 2, shows a typical sedimentation curve. From the conditions of the experiment the radii corresponding to the different times may be calculated from Stokes' Law and marked along the time axis.

Now let us consider any point on the curve, as P_1, which defines the total amount of sedimentation that has occurred in time t_1. The amount, Y, is composed of two parts, one part, S, which contains all particles that have completely settled out--i.e., have radii greater than 2 microns--and a second part containing particles of smaller size, only a fraction of which have settled out. The rate of settling of this fraction is the slope of the tangent to the curve at the point P_1, or the derivative dY/dt, and the weight of this fraction equals tdY/dt.

Obviously Y equals $S + t \frac{dY}{dt}$

But $t\frac{dY}{dt}$ at time $t_1 = t_1\frac{BA}{t_1}$ or BA

Then S equals OA

Therefore the tangent to the curve at any point cuts off a section of the Y axis which defines the weight of those particle sizes that have completely settled out in the time indicated by the point.

Similarly, if we consider the sedimentation after time t_2 the slope of the tangent P_2C is the rate of settling for the fraction that has not settled out at time t_2 and tdY/dt at time t_2 is equal to DC, and the weight of these particle sizes completely settled out is OC.

Therefore, the section OA indicates the weight of particles having radii greater than 2 microns, AC, those having radii between 2 microns and 1.5 microns, and CD all having radii less than 1.5 microns.

Methods of Sedimentation Measurement.

In general there are three methods that have been employed successfully in making sedimentation measurements, namely:

1. The Centrifugal Method, which is adaptable to extremely fine material which settles very slowly under gravity.

2. The method of measuring the rate of change in the density of a suspension at a fixed point of a sedimentation system.

3. The determination of sedimentation gravimetrically.

The first method, namely the use of the centrifuge, has been used extensively by Svedberg,[1] Nichols[3] and Liebe[2] at the University of Wisconsin, and also by Svedberg and Rinde[4,5] at the University of Upsala, Sweden. This method is particularly suitable where the material to be examined is made up of particles of extreme fineness, especially colloidal materials, where gravity would fail to give satisfactory results.

The material to be studied is placed in a high speed centrifuge, and at periodic intervals is examined, without stopping the centrifuge, thru a small window provided for the purpose.

Method 2 has been applied in several ways. One of these determinations is described by Schurecht[6] who made use of the fact that a weight or plummet weighs less in a slip of high clay content than with a low clay content. Thus as the particles fell to the bottom of a container of the clay and water mixture the variations of specific gravity were determined at regular intervals of time, measurements being taken at the same depth in the container for all readings.

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[1] Svedberg, The. & Nichols, J. B.----Jour. Am. Chem. Soc. 45: 2910-17 (1923)
[2] Nichols, J. B. & Liebe, H. C.-----Colloid Symp. Mon. Vol. 3 268-284 (1925) Chem. Cat. Co.
[3] Nichols, J. B. Coll. Symp. Mon. Vol. VI, 287-308 (1928) Chem. Cat. Co.
[4] Svedberg, The. & Rinde, H. Jour. Amer. Chem. Soc. 45, 943-954 (1923)
[5] Svedberg, The. & Rinde, H.;Jour. Amer. Chem. Soc. 46, 2677-93 (1924)
[6] Schurecht, H. G. ; Jour. Amer. Cer. Soc. 4, 812-21 (1921)

Beeman[1] also employs this method for determining the effect of pH concentration on the sedimentation of clay.

Another device based on method 2, devised by Ostwald and Von Hahn[2], consists of a U-tube, in one arm of which is placed the suspension to be studied and in the other arm the pure medium. The operation of this instrument depends on the fact that the suspension is heavier than the medium, and the latter therefore stands at a higher level. As the dispersed phase settles the suspension becomes lighter and the difference of level in the two arms decreases.

Kelly[3] modified this apparatus so as to make it suitable for less concentrated suspensions. His device differs from Ostwald's in that the measuring tube, in which the pure medium is placed, is bent in its upper part, making a slight angle with the horizontal. Thus small variations in the height of the medium, as the weight of the suspension decreases, produce large variations in the position of the meniscus in the bent section of the capillary arm.

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[1] Beeman, Norval, Jour. Amer. Cer. Soc., 14, 72-87, (1931)
[2] Ostwald, Wo. & Von Hahn---Kolloid Zeit., 32, 60 (1923)
[3] Kelly, W.J., Jour. Ind. Eng. Chem., 16, 928-30 (1924) and
Coll. Symp. Mon., Vol. 2, 29-36 (1925)

Another device based on the determination of density is the method of Robinson[1] and modified by Thomas, Jennings and Gardner,[2] where a small quantity of the suspension (2 c.c.) is drawn off at regular intervals at a definite depth and analyzed for its solid content. The latter investigators recommended nephelometric methods[3] for the estimation of the quantity of particles, but this method has not proved to be reliable.

The third general method of sedimentation measurements is a gravimetrical determination. This method consists of a sedimentation cylinder near the bottom of which is suspended a thin plate or pan suspended from one arm of a sensitive balance. Oden[4] appears to have been the originator of this device. The times for small increases of weights were noted, and from this data accumulation curves were prepared. From these curves "histograms"[5] are drawn, which show the percentage by weight as an area.

Oden's device was improved by Svedberg & Rinde[4] thru various steps involving automatic recording devices and electrical control of the weighing.

Calbeck and Harner[5] have done extensive work on paint pigments using this method of determining the particle size.

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[1]Robinson, G.W., Jour. Agri. Science, 12, 306-21 (1922)
[2]Jennings, D.S., Thomas, M.D., Gardner, W. Soil Science 14, 485-99, (1922)
[3]J. Ind. Eng. Chem., 7, 343 (1918)
[4]Oden, Sven----Alexander's "Colloid Chem." Vol. I, 861-901 Chem. Cat. Co. (1926)
[5]Calbeck, J.H.& Harner, H.R., Jour. Ind. Eng. Chem. 19, 58 (1927)

Holmes and Niver[1] have varied this method by the use of a Jolly Balance to support the sedimentation pan, instead of suspending it from one arm of a lever balance.

The gravimetric method of sedimentation measurement has been adopted in this investigation because of the wide range of particle sizes which can be handled.

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[1] Holmes, H. N. & Niver, E.-----Lab. Manual for Coll. Chem. Harry N. Holmes, p. 10-11 (J. Wiley & Sons, Pub.)

B. Method and Procedure

<u>Sources of Materials</u>: The clays used in making this investigation were, with several exceptions, obtained from the ceramics department of the School of Mines of the University of North Dakota. These clays were obtained largely in the southwestern part of North Dakota, and in many instances are clays that are being used in ceramic industries in the vicinities of Hebron and Dickinson. A number of others were obtained by Professor W. E. Budge in making surveys of clay deposits thruout this state. One sample was obtained from the deposits of the Red River Valley Brick Corporation near Grand Forks.

<u>Preparation of Materials</u>: CLAYS: The clays were individually crushed and sifted thru a 100 mesh sieve to remove lumps and coarse sand. The density of each clay sample was determined by measuring the volume of a weighed quantity of the clay dispersed in water in a pycnometer flask. Each clay was examined microscopically and the maximum radius of each sample was determined by a micrometer eyepiece, which had been previously calibrated.

WATER: All mixtures (which we shall call slips) were made up with freshly distilled water.

<u>APPARATUS</u>: The apparatus used in this investigation is shown in Figure 3. This was made by rebuilding an analytical

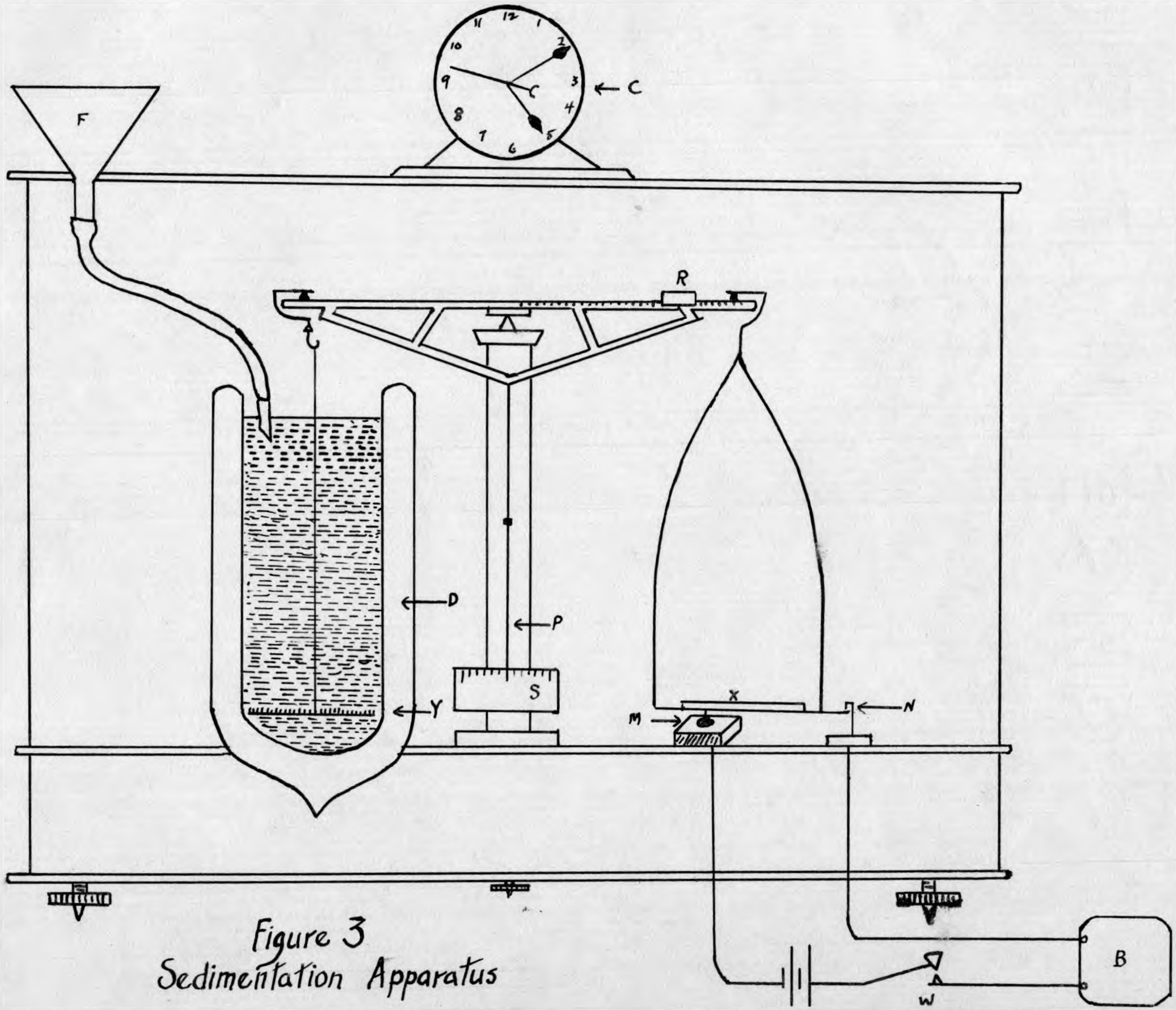

Figure 3
Sedimentation Apparatus

balance to a form suitable for sedimentation measurements. The left pan of the balance was removed and in its place a small copper pan, Y, of slightly less than 3.5 c.m. diameter was suspended from a fine wire. D is a Dewar vacuum flask, unsilvered, and about 19 cm. long and 4 cm. inside diameter. This is used as a settling chamber in which is suspended pan Y. The funnel F is provided for pouring the slip into the settling chamber. The construction of the apparatus was based on the descriptions of Oden[1] and Calbeck and Harner[2].

The balance was adjusted so that the beam could swing freely thru a very small angle, and so the pointer P could swing a very small distance to the left of the center mark on the scale S. An arrangement was made on pan X so that an electric buzzer B sounded when the pointer swung from the left past the center mark. This arrangement gave greater accuracy in noting the exact instant the pointer reached the center mark than could be obtained by judging with the eye, and at the same time also eliminated the necessity of such close attention to the apparatus during a series of readings.

The contact for operating the buzzer in this case consisted of a fine wire soldered to the bottom of pan X and so arranged that it dipped into a drop of mercury in a hollowed depression in a plaster block. The mercury was connected by a

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[1]Oden, Sven----Alexander's "Colloid Chem." Vol. I, 861-909 Chem. Cat. Co. (1927)

[2]Calbeck, J.H. & Harner, H.R.-----Jour. Ind. Eng. Chem. 19, 58 (1927)

wire to two dry cells. The right side of pan X was arranged so that as it rose when the pointer swung to the right, it came in contact with a stiff piece of wire just as the pointer reached the center mark. This piece of wire was also connected in the circuit with the dry cells and the buzzer, and the buzzer was caused to sound. When a weight was added to pan X the contact was broken and the buzzer stopped sounding.

The pans X and Y were adjusted so that they balanced exactly when the Dewar flask D was filled to an index mark with distilled water. The water was then removed and the flask and pan Y replaced without disturbing the adjustment of the balance.

A 10 mg. weight was placed on pan X before pouring the slip into the Dewar flask, so that when the suspension was added the pointer was to the left of the center point.

The slip was thoroly agitated for one half hour with a mechanical mixer. Boyoucos[1] finds that mixing in this manner does in 10 minutes what an ordinary shaker requires 24 hours to accomplish. The temperature was adjusted to 25° Centigrade.

The slip was quickly poured into the suspension chamber thru the funnel F. The exact time in seconds was noted on the electric clock C and recorded. The clay began to settle out on pan Y and the pointer slowly began to swing to the right. When it reached the center point the buzzer sounded and the time was noted. Another 10 mg. weight was placed on pan X and the pointer again moved to the left, but slowly moved to the right till the

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[1] Boyoucos, Geo.-----Science, 60, 16 (1927)

buzzer again sounded, and so on till no more clay settled out. After the first few readings the size of the weight added was reduced to 5 mg. and when the sedimentation neared completion 2mg. or 1mg. weights were used. The rider could also be used.

Description of Measurements: Since the larger particles settled most rapidly the interval between the first readings was very brief, but as the size range settling became smaller the intervals became longer. The readings were extended as long as accurate readings could be obtained. In the case of some of the clays it was not possible to obtain a complete sedimentation, since they remained slightly turbid after long periods of standing. In those cases the data excludes that portion which did not settle out.

From the data obtained by recording weights and time sedimentation curves were prepared for each clay, such as the one shown in Figure 4. Time was plotted along the X axis and weight along the Y axis and a curve was drawn. The radii corresponding to the different times was marked along the time axis. For instance, in one case of yellow clay from Dickinson, Figure 4 and Table 13, the value of t was determined from equation (4) for the radius 10.0 microns.

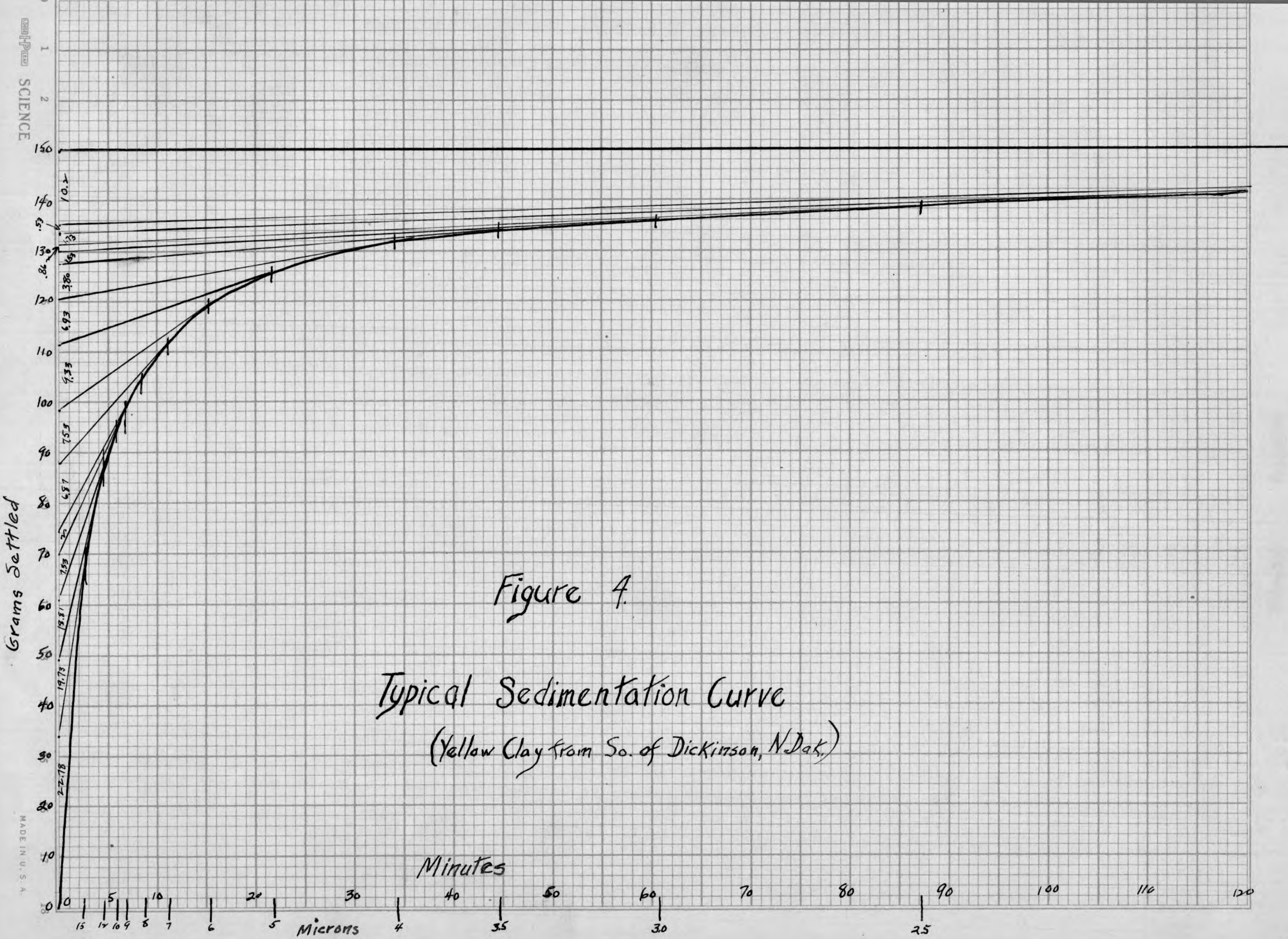

Figure 4.

Typical Sedimentation Curve

(Yellow Clay from So. of Dickinson, N.Dak.)

If $r^2 = \frac{9}{2} \frac{nh}{(d_1 - d_2)gt}$ (4)

by collecting all values which for any one case are constant we have:

$$\frac{9}{2} \frac{nh}{(d_1 - d_2)g} = K$$

therefore $r_2 = \frac{K}{t}$

or $t = \frac{K}{r_2}$ (5)

But n = .00894 (abs. viscosity of water at 25°C.)

h = 13 cm.

d_1 = 2.622 g. (determined by pycnometer method.)

d_2 = 1.0 g.

g = gravity constant.

t = time, minutes.

r = radius, cm.

Therefore in the case of Yellow Clay from So. Dickinson

$K = 5.47 \times 10^{-6}$

and $t = \frac{5.47 \times 10^{-6}}{0.001^2}$ = 5.47 minutes if r = 10 microns.

Similarly for the other radii, using the value K, the time t was calculated. These radii were then located along the sedimentation curve, and tangents were drawn to cut the Y axis. The slope of each tangent represents the rate of settling of that particular size particle, and the tangent to any point on the curve cuts off a section on the Y axis which represents the weight of those particle sizes that have completely settled out in that time. Therefore the sections cut off by the tangents on the Y axis represent the weight of the particles which have the size range between the radii represented by points on the curve.

The sedimentation curves must be accurately drawn, and were made on rolls of large cross-section paper, 26 x 40 inches, and the tangents were drawn as accurately as possible.

Tables 1 to 17 were prepared from the sedimentation curves drawn for the various clays. r is the radius, taken at intervals from the curve. The values t were determined by equation (5) for each radius. dr represents the radius intervals. Total weights of sedimentation from beginning to any time t are given in column S. The values s were determined by the points on the Y axis cut by tangents from points of various values of r on the sedimentation curve, and ds represents the differences between these weights, or the distribution of particle size by weight. dS gives the distribution of particle size by percent. Thus in table 13 for value r = 10.0 the position on the time axis would be 5.47 minutes in column t. dr is 1.0 which represents the radius interval between 10.0 microns and 11.0 microns. The tangent from this point on the sedimentation curve cuts the Y axis at 69.5, which means that 69.5 mg. of material of all size ranges larger than 10 microns has settled out. ds is 6.2 since this is the difference between 69.5 and 63.3 mg. This 6.2 mg. is 4.13% of the original amount of 150 mg. and is called dS. The column $\frac{dS}{dr}$ represents the function obtained when dS, which in this case is 4.13, is divided by the value dr which is 1.0. For the radius of 10 microns it is 4.13.

Histograms are prepared for each clay. These were made by taking the radii as abscissas and the function $\frac{dS}{dr}$ as ordinates. The column $\frac{dS}{dr}$ gives the functions to be used as ordinates for each radius interval shown in column r. The entire area under the rectangles represents 100% of the weight of the clay deposited. The vertical broken line that divides the area into two equal parts is called the "median" or "weight mean radius". Half of the weight of the clay has radii greater and half smaller than the median. The median for each clay was determined by drawing, from the point on the Y axis representing one half the weight of the material settled, a line tangent to the curve. The point on the curve touched by the tangent gave the time equal to the radius which is the median, and r can be calculated from equation (5).

The particle size weight which has the highest $\frac{dS}{dr}$ function is called the "mode" and represents the size occurring in the greatest weight.

The histograms are useful in comparing the particle size range and distribution for the various clays, and the comparison of these with other characteristics enable the prediction of still other properties.

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TABLE I

Clay 101 from Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.3112	42.6					
1.41	20.0	22.6	24.0	24.0	14.550	.644
2.2	16.0	4.0	48.0	24.0	14.550	3.6375
2.5	15.0	1.0	63.8	15.8	9.580	9.580
2.88	14.0	1.0	67.5	3.7	2.242	2.242
3.34	13.0	1.0	72.2	4.7	2.850	2.850
3.918	12.0	1.0	74.6	2.4	1.455	1.455
4.66	11.0	1.0	78.3	3.7	2.242	2.242
5.647	10.0	1.0	81.3	3.0	1.818	1.818
6.94	9.0	1.0	84.1	2.8	1.696	1.696
8.8	8.0	1.0	87.1	3.0	1.818	1.818
11.49	7.0	1.0	88.5	1.4	0.848	0.848
15.64	6.0	1.0	96.0	7.5	4.540	4.540
22.26	5.0	1.0	98.6	2.6	1.575	1.575
35.08	4.0	1.0	103.3	4.7	2.850	2.850
45.8	3.5	0.5	110.5	7.2	4.370	8.740
62.7	3.0	0.5	121.3	10.8	6.540	13.080
90.25	2.5	0.5	124.5	3.2	1.938	3.876
140.8	2.0	0.5	127.9	3.4	2.310	4.620
250.4	1.5	0.5	137.0	9.1	5.520	11.040
564.7	1.0	0.5	148.8	11.8	7.150	14.300
	0.0	1.0	165.0	16.2	9.825	9.825
				165.0	100 .267	

TABLE II

Clay 201 from Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.29	43.7					
.35	40.0					
.62	30.0					
1.40	20.0	23.7	42.0	42.0	26.73	1.13
2.49	15.0	5.0	55.5	13.5	8.51	1.71
2.86	14.0	1.0	60.0	4.5	2.86	2.86
3.31	13.0	1.0	66.6	6.6	4.20	4.20
3.90	12.0	1.0	68.8	2.2	1.40	1.40
4.63	11.0	1.0	71.7	2.9	1.845	1.845
5.60	10.0	1.0	85.5	13.8	8.78	8.78
6.92	9.0	1.0	89.0	3.5	2.10	2.10
8.75	8.0	1.0	98.0	9.0	5.73	5.73
11.42	7.0	1.0	101.6	3.6	2.29	2.29
15.55	6.0	1.0	109.4	7.8	4.97	4.97
22.41	5.0	1.0	121.9	12.5	7.97	7.97
35.00	4.0	1.0	125.6	3.7	2.357	2.357
45.70	3.5	0.5	132.0	6.4	4.07	8.14
62.2	3.0	0.5	135.2	3.2	2.037	4.074
89.6	2.5	0.5	141.3	6.1	3.88	7.76
140.0	2.0	0.5	143.1	1.8	1.145	2.29
249.2	1.5	0.5	150.6	7.5	4.77	9.54
	0.00	1.5	157.0	6.4	4.07	2.71
				157.0	99.714	

TABLE III
Clay 202 from Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
2.66	14.364					
5.48	10.0	4.364	40.8	40.8	22.05	5.06
6.77	9.0	1.0	52.3	11.5	6.22	6.22
8.57	8.0	1.0	64.0	11.7	6.33	6.33
11.18	7.0	1.0	73.0	9.0	4.86	4.86
15.23	6.0	1.0	79.8	6.8	3.67	3.67
21.91	5.0	1.0	86.2	6.4	3.458	3.458
34.28	4.0	1.0	99.8	13.6	7.35	7.35
44.75	3.5	0.5	114.7	14.9	8.05	16.10
60.9	3.0	0.5	116.0	1.3	.703	1.406
87.7	2.5	0.5	119.7	3.7	1.998	3.996
136.8	2.0	0.5	130.5	10.8	5.84	11.68
243.7	1.5	0.5	136.4	5.9	3.185	6.370
	0.0	1.5	185.0	48.6	26.26	17.50
				185.0	99.981	

TABLE IV

Clay 301 from Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
2.183	15.87					
2.51	15.0	0.87	33.5	33.5	20.3	2.33
2.89	14.0	1.0	5.0	11.5	6.88	6.88
3.35	13.0	1.0	62.6	17.6	10.52	10.52
3.94	12.0	1.0	70.0	7.4	4.43	4.43
4.7	11.0	1.0	82.7	12.7	7.60	7.60
5.67	10.0	1.0	90.5	7.8	4.67	4.67
6.99	9.0	1.0	103.0	12.5	7.48	7.48
8.84	8.0	1.0	112.0	9.0	5.88	5.88
11.55	7.0	1.0	122.8	10.8	6.47	6.47
15.72	6.0	1.0	130.7	7.9	4.73	4.73
22.63	5.0	1.0	137.6	6.9	4.13	4.13
35.4	4.0	1.0	141.8	4.2	2.51	2.51
46.3	3.5	0.5	146.0	4.2	2.51	5.02
62.9	3.0	0.5	151.5	5.5	3.29	6.58
90.7	2.5	0.5	157.0	5.5	3.29	6.58
141.6	2.0	0.5	165.0	8.0	4.78	9.56
	0.0	2.0	167.0	2.0 167.0	1.196 100.666	.598

TABLE V

Clay 501 from Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.94	24.2					
1.375	20.0	4.2	21.0	21.0	17.48	4.16
2.45	15	5.0	27.5	6.5	5.42	1.084
3.26	13.0	2.0	31.0	3.5	2.92	1.46
3.83	12.0	1.0	35.0	4.0	3.33	3.33
5.51	10.0	2.0	38.70	3.7	3.08	1.54
6.8	9.0	1.0	41.8	3.1	2.58	2.58
8.61	8.0	1.0	44.5	2.7	2.25	2.25
11.24	7.0	1.0	46.6	2.1	1.75	1.75
15.29	6.0	1.0	50.1	3.5	2.92	2.92
22.1	5.0	1.0	64.1	14.0	11.67	11.67
34.41	4.0	1.0	68.7	4.6	3.83	3.83
44.9	3.5	0.5	71.8	3.1	2.58	5.16
61.2	3.0	0.5	76.0	4.2	3.50	7.00
88.2	2.5	0.5	84.3	8.3	6.92	13.84
137.6	2.0	0.5	90.4	6.1	5.08	10.16
245.0	1.5	0.5	101.7	11.3	9.43	18.86
551.0	1.0	0.5	111.9	10.2	8.50	17.00
720.0	0.00	1.0	120.0	8.1	6.75	6.75
				120.0	99.99	

TABLE VI

Clay No. 302

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.171	56.5					
.2188	50.0					
.874	25.0					
2.43	15.0	41.5	56.0	56.0	43.10	1.036
3.79	12.0	3.0	64.8	8.8	6.77	2.28
4.52	11.0	1.0	71.4	6.6	5.07	5.07
5.47	10.0	1.0	81.2	9.8	7.53	7.53
6.74	9.0	1.0	83.4	2.2	1.69	1.69
8.53	8.0	1.0	86.9	3.5	2.69	2.69
11.14	7.0	1.0	90.6	3.7	2.84	2.84
15.17	6.0	1.0	93.8	3.2	2.46	2.46
21.88	5.0	1.0	99.7	5.9	4.53	4.53
34.2	4.0	1.0	102.8	3.1	2.38	2.38
44.7	3.5	0.5	106.8	4.0	3.08	6.16
60.7	3.0	0.5	111.1	4.3	3.30	6.60
87.4	2.5	0.5	116.5	5.4	4.15	8.30
136.4	2.0	0.5	118.5	2.0	1.54	3.08
302.4	0.00	2.0	130.0	11.5	8.85	4.425
				130.0	99.98	

TABLE VII

Clay 1001 from Hebron

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.789	26.0					
1.333	20.0	6.0	18.0	18.0	10.590	1.765
2.372	15.0	5.0	34.5	16.5	9.710	1.942
3.158	13.0	2.0	42.5	8.0	4.710	2.355
3.705	12.0	1.0	49.3	6.8	4.000	4.000
4.41	11.0	1.0	55.0	5.7	3.350	3.350
5.34	10.0	1.0	60.7	5.7	3.350	3.350
6.58	9.0	1.0	71.9	11.2	6.590	6.590
8.34	8.0	1.0	77.8	5.9	3.472	3.472
10.88	7.0	1.0	84.7	6.9	4.061	4.061
14.83	6.0	1.0	88.6	3.9	2.292	2.292
21.35	5.0	1.0	96.6	8.0	4.711	4.711
33.33	4.0	1.0	102.4	5.8	3.412	3.412
43.6	3.5	0.5	106.7	4.3	2.531	5.062
59.4	3.0	0.5	108.9	2.2	1.294	2.588
85.4	2.5	0.5	114.0	5.1	3.000	6.000
133.3	2.0	0.5	122.1	8.1	4.772	9.544
237.2	1.5	0.5	129.5	7.4	4.350	8.700
534.0	1.0	0.5	138.6	9.1	5.351	10.702
	0.0	1.0	170.0	31.4	18.452	18.452
				170.0	100.000	

TABLE VIII

Clay 1101 from Hebron

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
1.18	22.3					
4.18	12.0	10.3	11.1	11.1	9.490	.855
4.84	11.0	1.0	14.0	2.9	2.478	2.478
5.87	10.0	1.0	17.7	3.7	3.160	3.160
7.24	9.0	1.0	19.8	2.1	1.795	1.795
9.18	8.0	1.0	22.6	2.8	2.393	2.393
11.98	7.0	1.0	30.3	7.7	6.580	6.580
16.30	6.0	1.0	39.2	8.9	7.610	7.610
23.5	5.0	1.0	53.3	14.1	12.050	12.050
36.65	4.0	1.0	63.0	9.7	8.290	8.290
47.80	3.5	0.5	69.6	6.6	5.640	11.280
65.30	3.0	0.5	72.0	2.4	2.050	4.100
93.8	2.5	0.5	74.3	2.3	1.964	3.928
146.5	2.0	0.5	86.8	12.5	10.680	21.360
261.0	1.5	0.5	93.4	6.6	5.640	11.280
	0.0	1.5	117.0	23.6	20.160	13.540
				117.0	99.990	

TABLE IX

Clay 1201 from Hebron

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.75	27.1					
3.81	12.0	15.1	19.1	19.1	13.64	.904
4.53	11.0	1.0	23.6	4.5	3.21	3.21
5.48	10.0	1.0	28.2	4.6	3.28	3.28
6.77	9.0	1.0	35.7	7.5	5.36	5.36
8.57	8.0	1.0	38.8	3.1	2.22	2.22
11.18	7.0	1.0	44.8	6.0	4.28	4.28
15.23	6.0	1.0	52.3	7.5	5.36	5.36
21.91	5.0	1.0	59.6	7.3	5.21	5.21
34.28	4.0	1.0	68.5	8.9	6.35	6.35
44.75	3.5	0.5	74.0	5.5	3.93	7.86
60.90	3.0	0.5	80.8	6.8	4.86	9.72
87.7	2.5	0.5	92.0	11.2	8.01	16.02
136.8	2.0	0.5	100.2	8.2	5.86	11.72
243.7	1.5	0.5	107.1	6.9	4.93	9.86
548.0	1.0	0.5	121.3	14.2	10.14	20.28
	0.0	1.0	140.0	18.7	13.37	13.37
				140.0	100.01	

TABLE X

Clay 1301 from Hebron

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.824	26.0					
5.570	10.0	16.0	41.8	41.8	24.58	1.545
6.88	9.0	1.0	54.2	12.4	7.30	7.30
8.71	8.0	1.0	66.0	11.8	6.94	6.94
11.36	7.0	1.0	77.1	11.1	6.53	6.53
15.46	6.0	1.0	88.0	10.9	6.41	6.41
22.15	5.0	1.0	105.4	17.4	10.23	10.23
34.8	4.0	1.0	114.2	8.8	5.175	5.175
45.4	3.5	0.5	115.7	1.5	.883	1.766
61.9	3.0	0.5	119.2	3.5	2.052	4.104
89.1	2.5	0.5	121.9	2.7	1.588	3.176
139.2	2.0	0.5	134.9	13.0	7.64	15.280
247.5	1.5	0.5	148.3	13.4	7.89	15.780
557.0	1.0	0.5	163.9	15.6	9.185	18.370
	0.0	1.0	170.0	6.1	3.58	3.580
				170.0	99.992	

TABLE XI

Clay 2101, Mottled from Taylor

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.366	39.7					
2.56	15.0	24.7	34.8	34.8	19.880	.804
2.94	14.0	1.0	38.8	4.0	2.282	2.282
3.41	13.0	1.0	46.5	7.7	4.400	4.400
4.00	12.0	1.0	58.0	11.5	6.580	6.580
4.76	11.0	1.0	64.3	6.3	3.590	3.590
5.76	10.0	1.0	76.3	12.0	6.860	6.860
7.12	9.0	1.0	83.0	6.7	3.830	3.830
8.99	8.0	1.0	90.7	7.7	4.400	4.400
11.75	7.0	1.0	98.6	7.9	4.502	4.502
16.14	6.0	1.0	105.0	6.4	3.660	3.660
23.20	5.0	1.0	110.5	5.5	3.142	3.142
35.47	4.0	1.0	118.0	7.5	4.280	4.280
47.00	3.5	0.5	123.3	5.3	3.030	6.060
63.80	3.0	0.5	130.0	6.7	3.830	7.660
92.20	2.5	0.5	132.8	2.8	1.600	3.200
143.80	2.0	0.5	135.9	3.1	1.770	3.540
256.00	1.5	0.5	144.1	8.2	4.680	9.360
576.0	1.0	0.5	160.5	16.4	9.380	18.760
	0.0	1.0	175.0	14.5	8.280	8.280
				175.0	99.975	

TABLE XII

Red Clay from South of Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.539	32.25					
1.40	20.0	12.25	32.0	32.0	20.000	1.632
2.49	15.0	5.0	36.2	4.2	2.625	.524
5.60	10.0	5.0	47.5	11.3	7.070	1.414
6.92	9.0	1.0	51.3	3.8	2.373	2.373
8.74	8.0	1.0	59.0	7.7	4.810	4.810
11.42	7.0	1.0	63.8	4.8	4.000	3.000
15.56	6.0	1.0	68.3	4.5	2.810	2.810
22.40	5.0	1.0	75.5	7.2	4.500	4.500
35.00	4.0	1.0	82.0	6.6	4.125	4.125
45.70	3.5	0.5	86.9	4.8	3.000	6.000
62.45	3.0	0.5	90.2	3.3	2.063	4.126
89.70	2.5	0.5	95.5	5.3	3.312	6.624
140.00	2.0	0.5	100.8	5.3	3.312	6.624
249.20	1.5	0.5	120.0	19.2	12.000	24.000
560.00	1.0	0.5	134.4	14.4	9.000	18.000
	0.0	1.0	160.0	25.6	16.000	16.000
				160.0	100.000	

TABLE XIII

Yellow Clay from South of Dickinson

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
1.588	18.55					
2.13	16.0	2.55	31.8	31.8	21.18	8.37
2.43	15.0	1.0	34.2	2.4	1.60	1.60
2.788	14.0	1.0	38.3	4.1	2.73	2.73
3.23	13.0	1.0	43.8	5.5	3.67	3.67
3.79	12.0	1.0	48.8	5.0	3.33	3.33
4.52	11.0	1.0	63.3	14.5	9.68	9.68
5.47	10.0	1.0	69.5	6.2	4.13	4.13
6.74	9.0	1.0	72.5	3.0	2.00	2.00
8.53	8.0	100	76.0	3.5	2.33	2.33
11.14	7.0	1.0	86.3	10.3	6.87	6.87
15.17	6.0	1.0	97.6	11.3	7.53	7.53
21.88	5.0	1.0	111.6	14.0	9.33	9.33
34.20	4.0	1.0	122.0	10.4	6.93	6.93
44.70	3.5	0.5	127.7	5.7	3.80	7.60
60.70	3.0	0.5	130.0	2.3	1.53	3.06
87.40	2.5	0.5	131.3	1.3	0.86	1.72
136.40	2.0	0.5	132.1	0.8	0.53	1.06
243.0	1.5	0.5	134.7	2.6	1.73	3.46
	0.000	1.5	150.0	15.3	10.20	6.8
				150.0	99.96	

TABLE XIV

Clay from coal mine at Beulah

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
2.094	17.2					
2.21	16.0	1.2	20.0	20.0	12.500	10.41
2.57	15.0	1.0	21.7	1.7	1.062	1.062
3.92	12.0	3.0	22.5	0.8	0.5000	0.1666
4.67	11.0	1.0	24.7	2.2	1.374	1.374
5.65	10.0	1.0	26.9	2.2	1.374	1.374
6.95	9.0	1.0	29.6	2.7	1.687	1.687
8.83	8.0	1.0	31.5	1.9	1.188	1.188
11.53	7.0	1.0	34.3	2.8	1.750	1.750
15.7	6.0	1.0	39.0	4.7	2.939	2.939
22.58	5.0	1.0	48.9	9.9	6.180	6.180
35.30	4.0	1.0	56.1	7.2	4.500	4.500
46.20	3.5	0.5	62.7	6.6	4.125	8.250
62.80	3.0	0.5	67.1	4.4	2.750	5.500
90.40	2.5	0.5	75.9	8.8	5.500	11.000
141.20	2.0	0.5	101.4	25.5	15.925	31.850
251.00	1.5	0.5	112.6	11.2	7.000	14.000
565.00	1.0	0.5	124.0	11.4	7.130	14.260
	0.0	1.0	160.0	36.0	22.500	22.500
				160.0	99.984	

TABLE XV

Clay from Horse Nose Butte

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.59	24.3					
1.354	20.0	4.3	38.4	38.4	24.000	5.580
2.41	15.0	5.0	55.0	16.6	10.370	2.072
5.42	10.0	5.0	62.9	7.9	4.940	0.988
6.68	9.0	1.0	68.2	5.3	3.312	3.312
8.47	8.0	1.0	72.7	4.5	2.815	2.813
11.05	7.0	1.0	82.0	9.3	5.820	5.820
15.05	6.0	1.0	90.0	8.0	5.000	5.000
21.68	5.0	1.0	97.8	7.8	4.870	4.870
33.88	4.0	1.0	112.4	14.6	9.130	9.130
44.25	3.5	0.5	121.4	9.0	5.625	11.250
60.25	3.0	0.5	126.0	4.6	2.877	5.754
86.70	2.5	0.5	131.9	5.9	3.688	7.376
135.40	2.0	0.5	139.9	8.0	5.000	10.000
241.00	1.5	0.5	143.8	3.9	2.438	4.876
	0.0	1.5	160.0	16.2	10.120	6.740
				160.0	100.003	

TABLE XVI
Clay from Red River Valley Brick Corporation

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
.788	25.8					
1.31	20.0	5.8	40.0	40.0	25.0000	4.3100
1.60	18.0	2.0	49.0	9.0	5.6250	2.8130
1.81	17.0	1.0	64.0	15.0	9.3750	9.3750
2.05	16.0	1.0	78.5	14.5	9.0625	9.0625
2.335	15.0	1.0	84.3	5.8	3.6250	3.6250
2.67	14.0	1.0	98.0	13.7	8.5625	8.5625
3.10	13.0	1.0	102.9	4.9	3.0625	3.0625
3.64	12.0	1.0	105.0	2.1	1.3125	1.3125
4.33	11.0	1.0	111.3	6.3	3.9375	3.9375
5.25	10.0	1.0	114.7	3.4	2.1250	2.1250
6.48	9.0	1.0	117.9	3.2	2.0000	2.0000
8.72	8.0	1.0	120.9	3.0	1.8750	1.8750
10.71	7.0	1.0	122.2	1.3	0.8187	0.8187
14.58	6.0	1.0	124.9	2.7	1.6875	1.6875
21.30	5.0	1.0	126.5	1.6	1.0000	1.0000
32.80	4.0	1.0	127.0	0.5	0.3125	0.3125
42.80	3.5	0.5	127.4	0.4	0.2500	0.5000
58.40	3.0	0.5	128.1	0.7	0.4575	0.9150
84.00	2.5	0.5	128.8	0.7	0.4575	0.9150
131.2	2.0	0.5	129.4	0.6	0.3750	0.7500
233.5	1.5	0.5	132.5	3.1	1.9375	3.8750
525.0	1.0	0.5	143.0	10.5	6.5620	13.1240
	0.0	1.0	160.0	17.0	10.6250	10.6250
				160.0	100.0457	

TABLE XVII

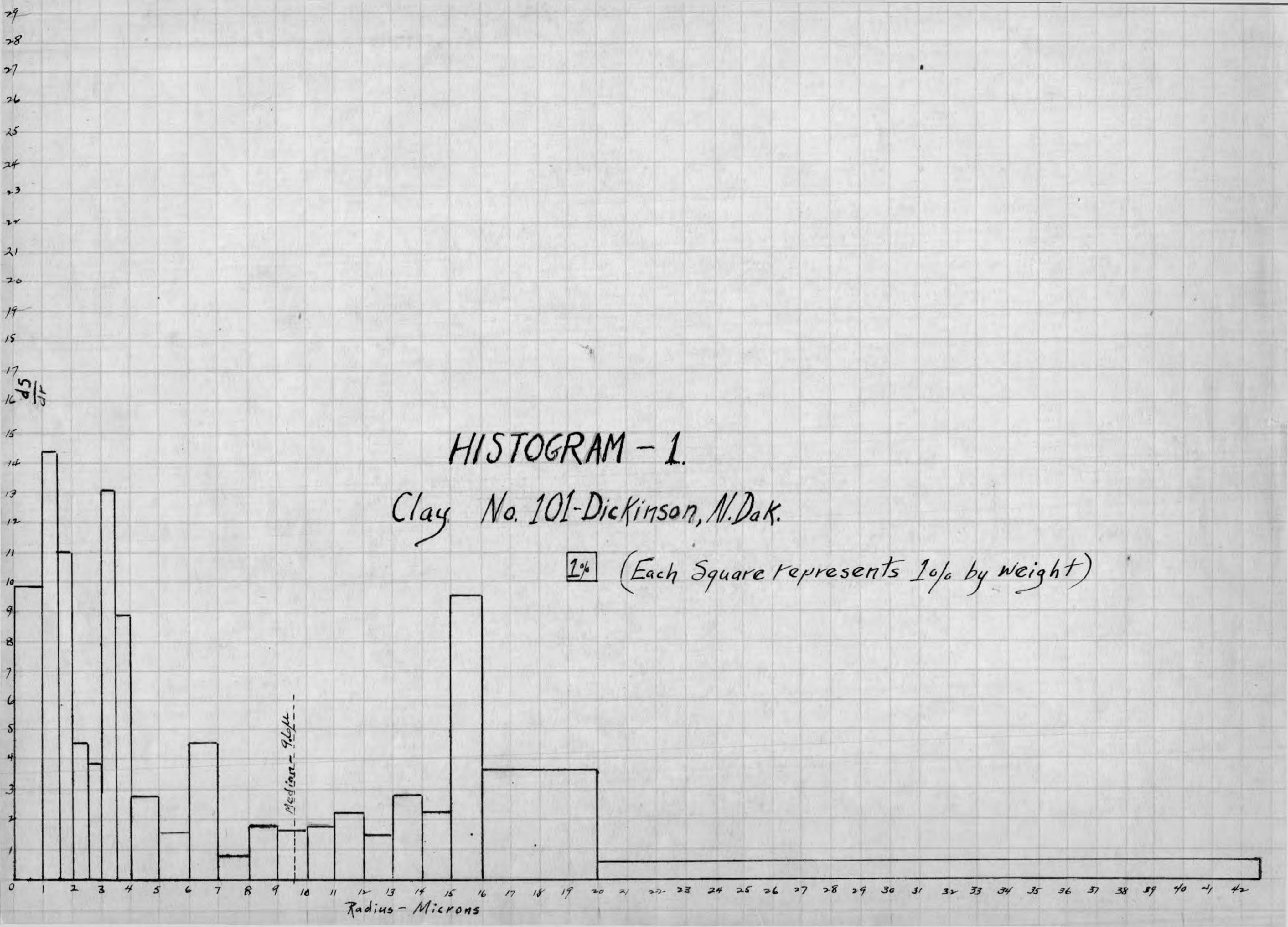
Clay #02 from Southeart (Bentonite)

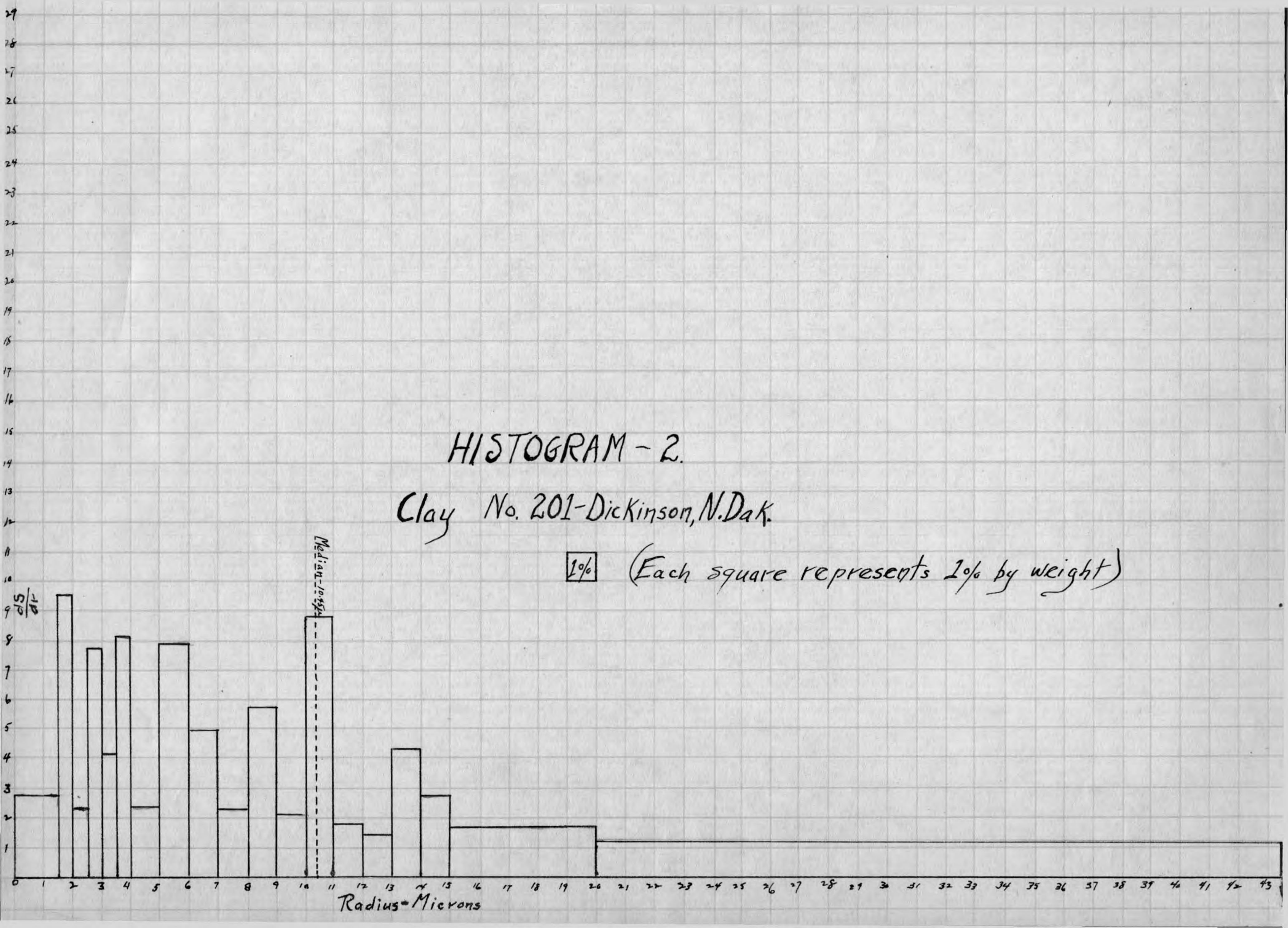
t	r	dr	s	ds	dS	$\frac{dS}{dr}$
1.586	19.75					
2.75	15.0	4.75	25.9	25.9	18.500	3.894
4.30	12.0	3.0	40.8	14.9	10.640	3.547
5.12	11.0	1.0	45.8	5.0	3.538	3.538
6.19	10.0	1.0	52.0	6.2	4.425	4.425
7.63	9.0	1.0	59.9	7.9	5.640	5.640
9.67	8.0	1.0	62.5	2.6	1.856	1.856
12.62	7.0	1.0	69.1	6.6	4.720	4.720
17.18	6.0	1.0	79.0	9.9	7.070	7.070
24.67	5.0	1.0	87.0	8.0	5.720	5.720
38.70	4.0	1.0	90.9	3.9	2.792	2.792
50.5	3.5	0.5	93.8	2.9	2.071	4.142
68.7	3.0	0.5	95.7	1.9	1.357	2.714
98.4	2.5	0.5	100.9	5.2	3.712	7.424
154.6	2.0	0.5	109.9	9.0	6.425	12.850
275.0	1.5	0.5	118.0	8.1	5.780	11.560
619.0	1.0	0.5	124.6	6.6	4.720	9.440
	0.0	1.0	140.0	15.4	11.0	11.000
				140.00	99.946	

TABLE XVIII

Johnson-Porter Ball Clay (Tennessee)

t	r	dr	s	ds	dS	$\frac{dS}{dr}$
5.44	8.35					
5.92	8.0	.35	11.3	11.3	7.540	21.54
7.73	7.0	1.0	14.9	3.6	2.400	2.400
10.52	6.0	1.0	19.5	4.6	3.066	3.066
15.16	5.0	1.0	26.2	6.7	4.470	4.470
23.73	4.0	1.0	32.9	6.7	4.470	4.470
31.0	3.5	0.5	38.4	5.5	3.662	7.324
42.2	3.0	0.5	46.5	8.1	5.400	10.800
60.7	2.5	0.5	51.4	4.9	3.268	6.536
94.9	2.0	0.5	64.7	13.3	8.870	17.740
168.8	1.5	0.5	79.0	14.3	9.540	19.080
379.0	1.0	0.5	101.4	22.4	14.935	29.870
	0.0	1.0	150.0	48.6	32.420	32.420
				150.0	100.041	


HISTOGRAM - 1.
Clay No. 101-Dickinson, N.Dak.
1% (Each Square represents 1% by weight)
Median - 9.6μ
Radius - Microns
ds/dr



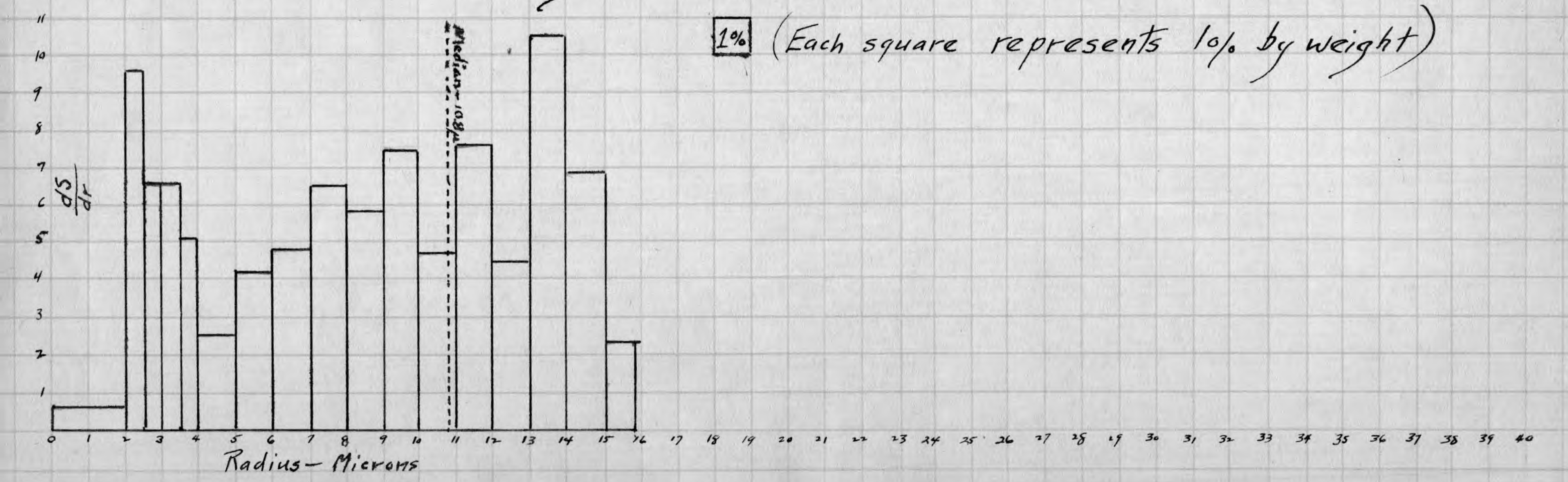
HISTOGRAM - 2.
Clay No. 201-Dickinson, N.Dak.
1% (Each square represents 1% by weight)
Median-10.45μ
Radius-Microns

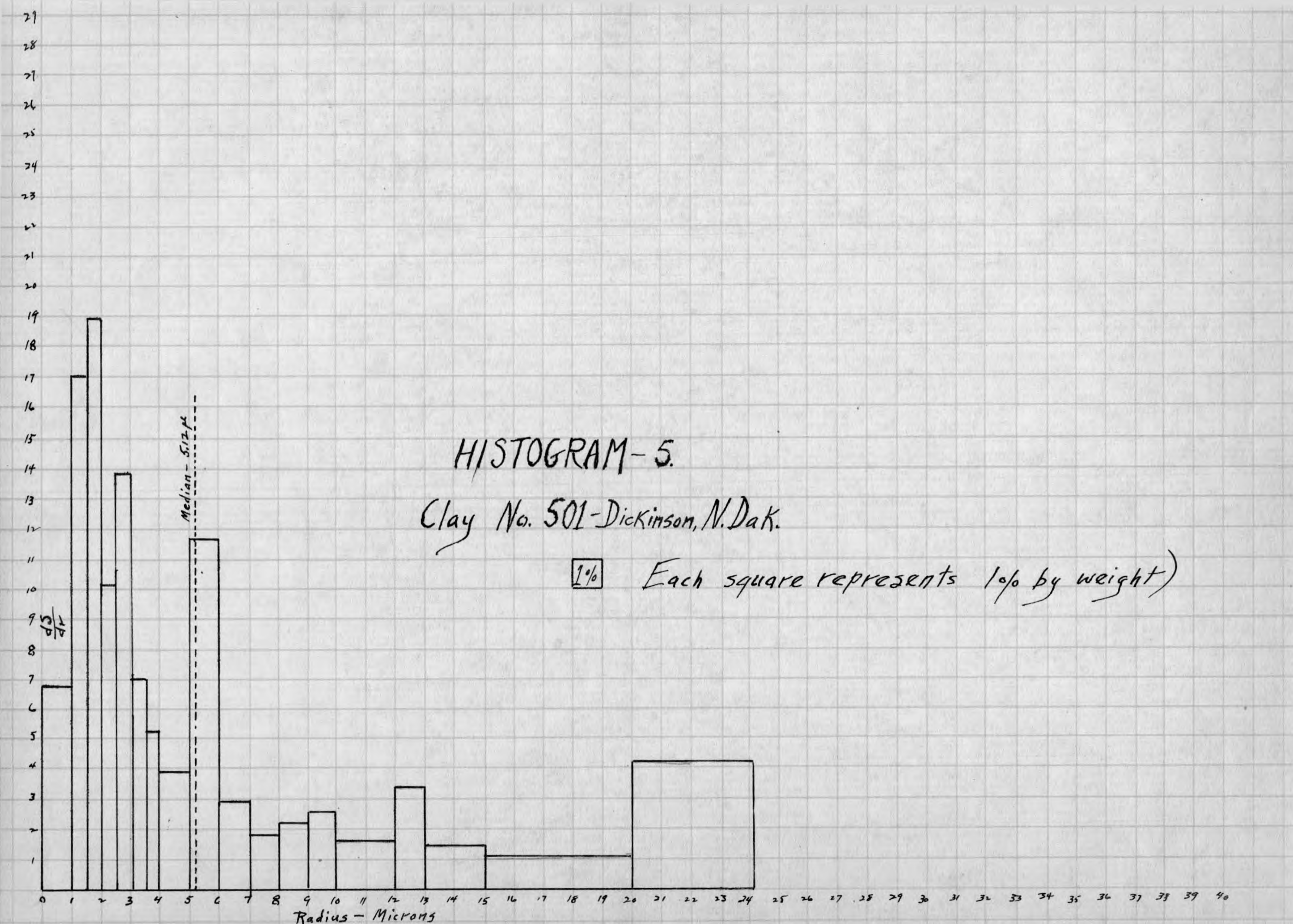
HISTOGRAM -3.

Clay No. 202-Dickinson, N.Dak.

HISTOGRAM - 4.

Clay No. 301 - Dickinson, N. Dak.



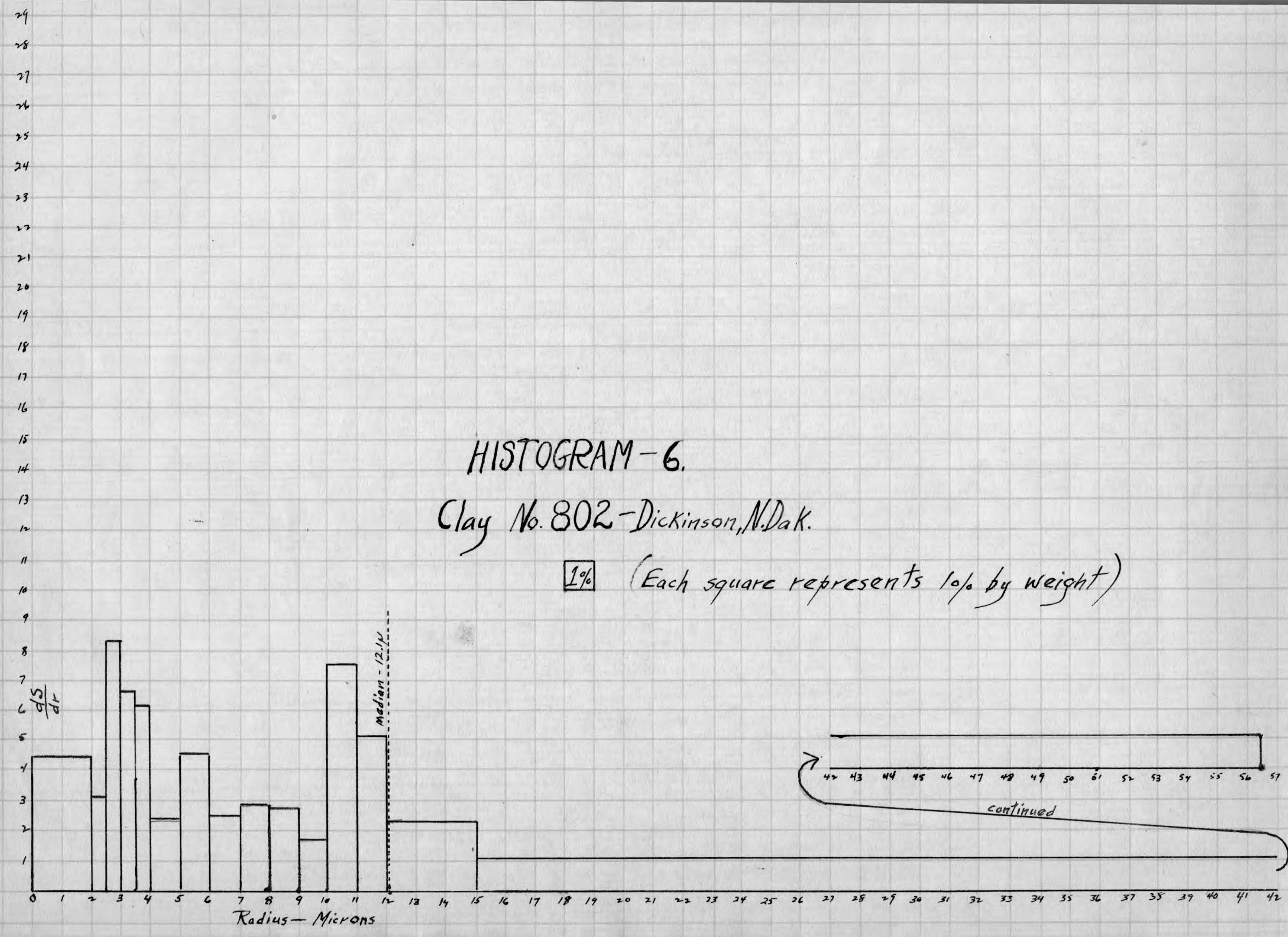


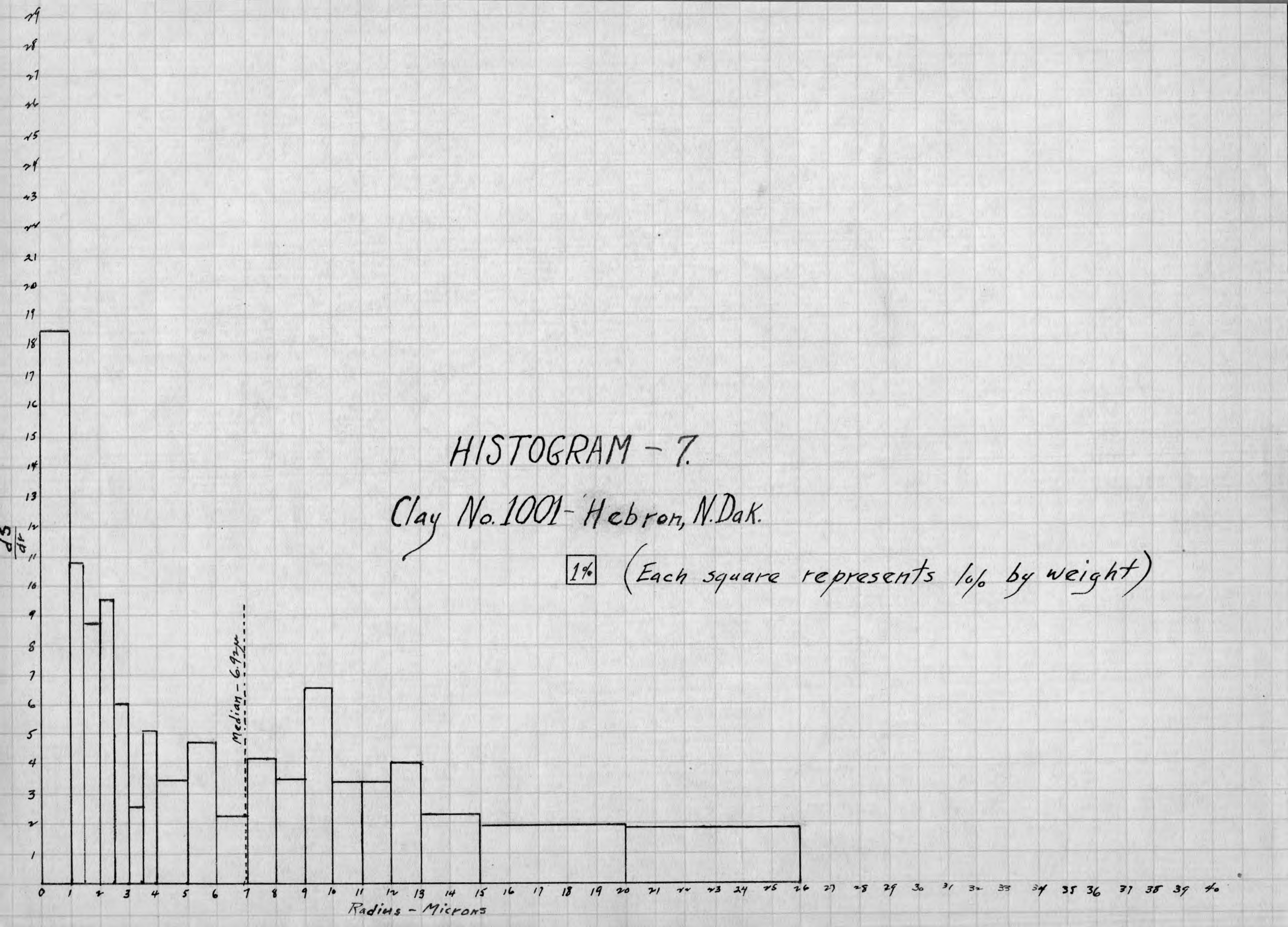
HISTOGRAM - 5.
Clay No. 501 - Dickinson, N. Dak.
1% Each square represents 1% by weight)
Median - 5.12μ
Radius - Microns

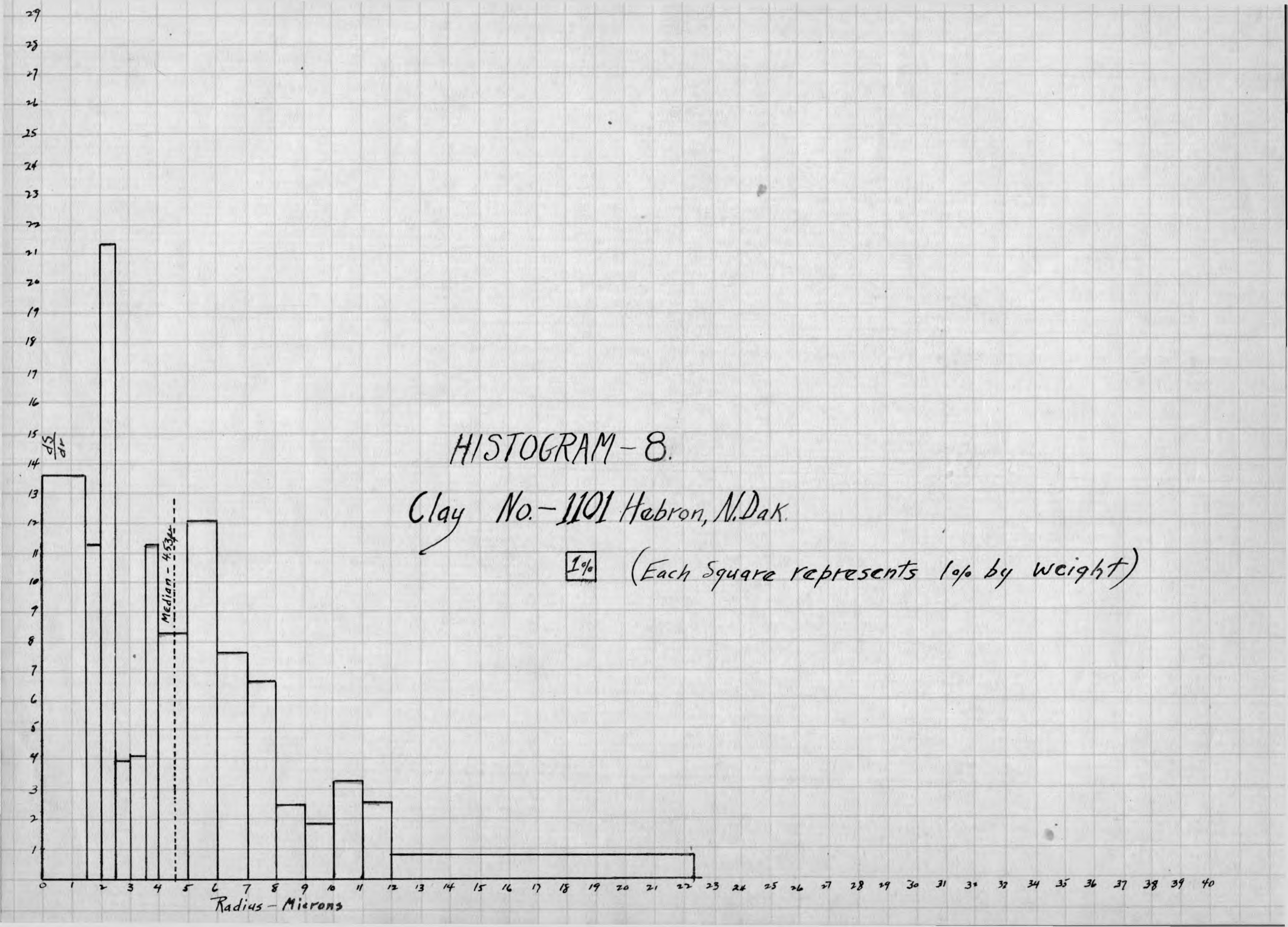
HISTOGRAM-6.

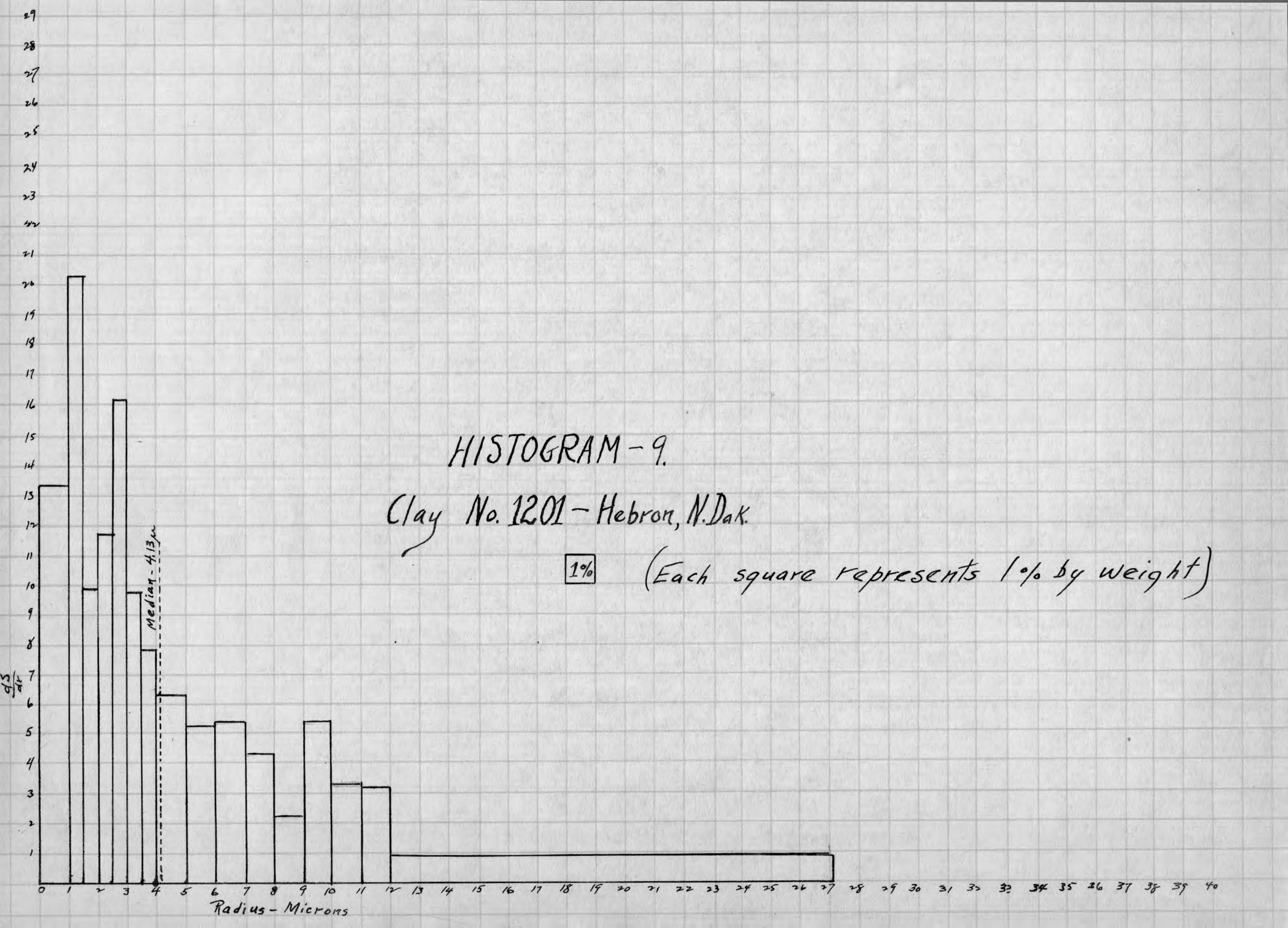
Clay No. 802-Dickinson, N.Dak.

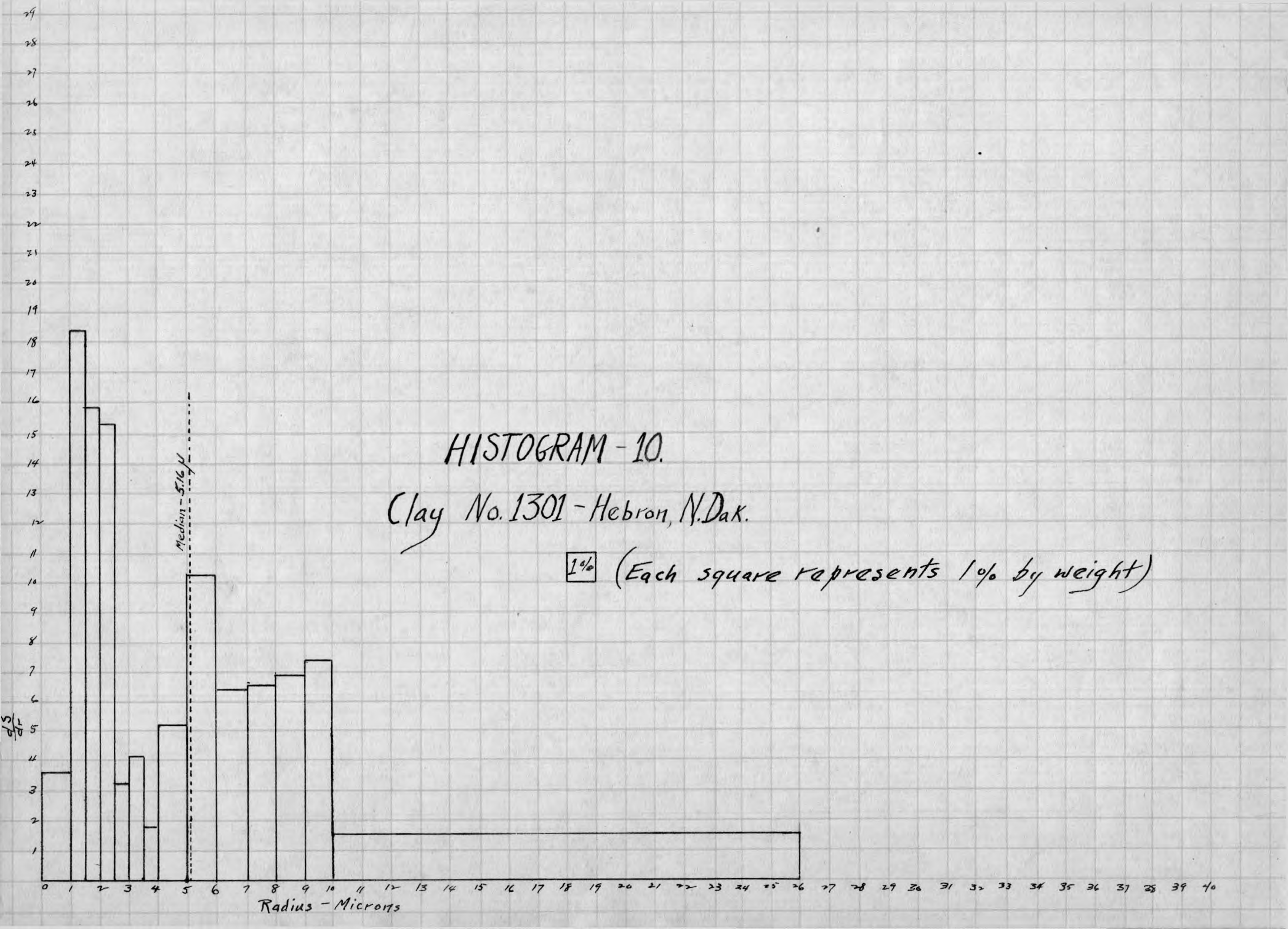
1% (Each square represents 1% by weight)



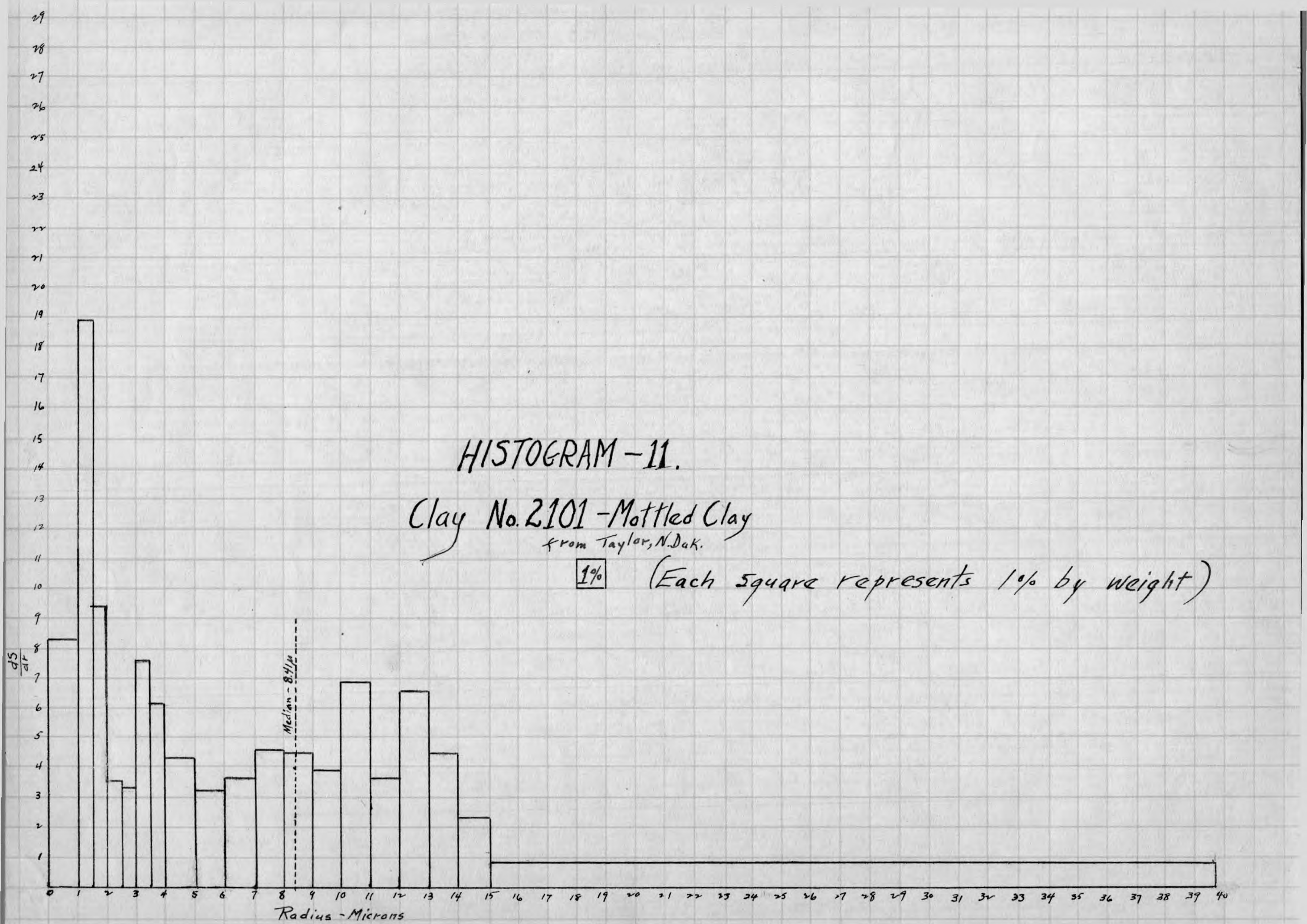

HISTOGRAM - 7.
Clay No. 1001 - Hebron, N. Dak.
1% (Each square represents 1% by weight)
Median - 6.92μ
ds/dr
Radius - Microns

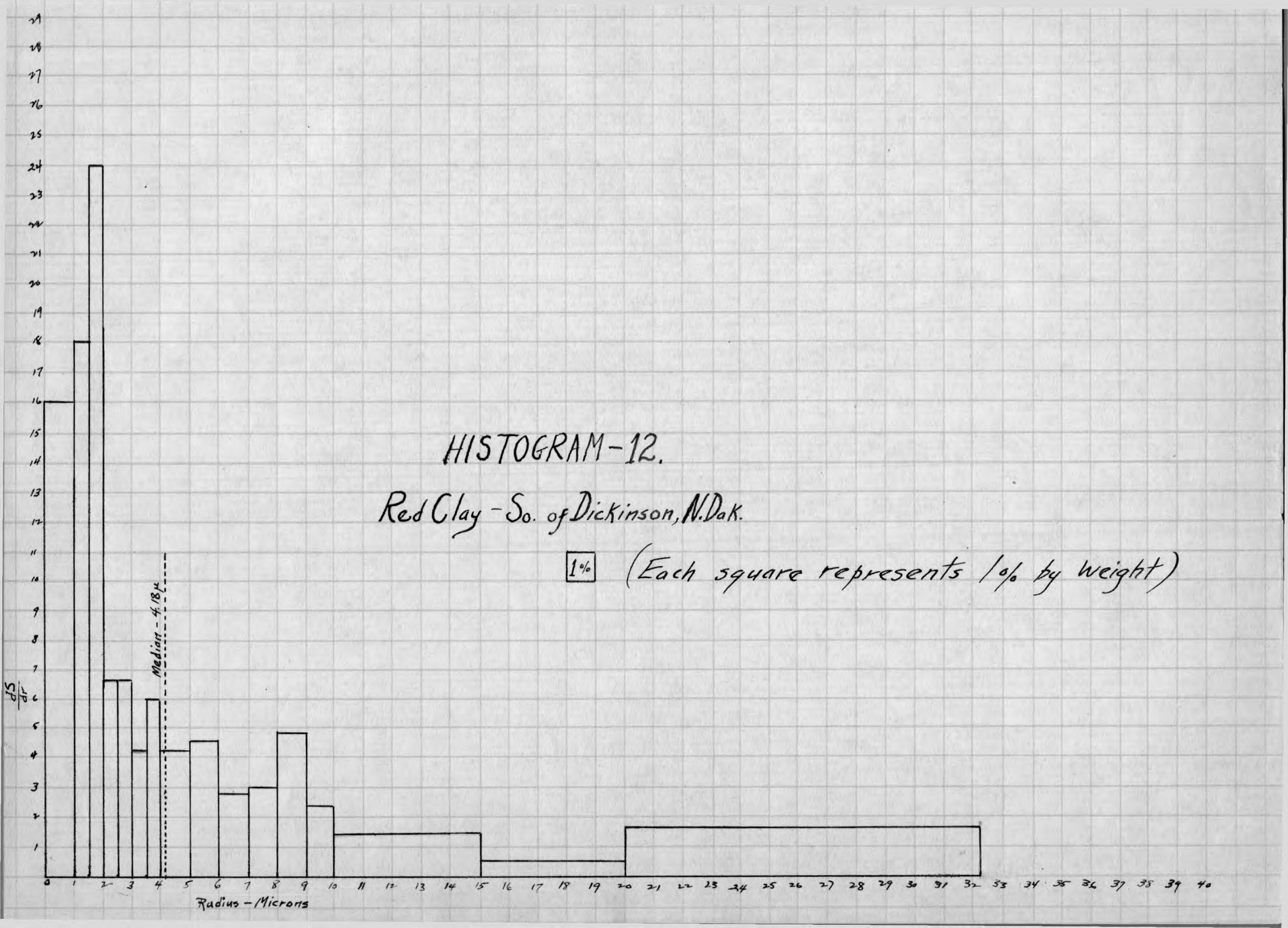

HISTOGRAM - 8.
Clay No. - 1101 Hebron, N. Dak.
1%
(Each Square represents 1% by weight)
Median - 4.53μ
dS/dr
Radius - Microns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 34 35 36 37 38 39 40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29


HISTOGRAM - 9.
Clay No. 1201 - Hebron, N. Dak.
1%
(Each square represents 1% by weight)
Median - 4.13μ
ds/dr
Radius - Microns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29



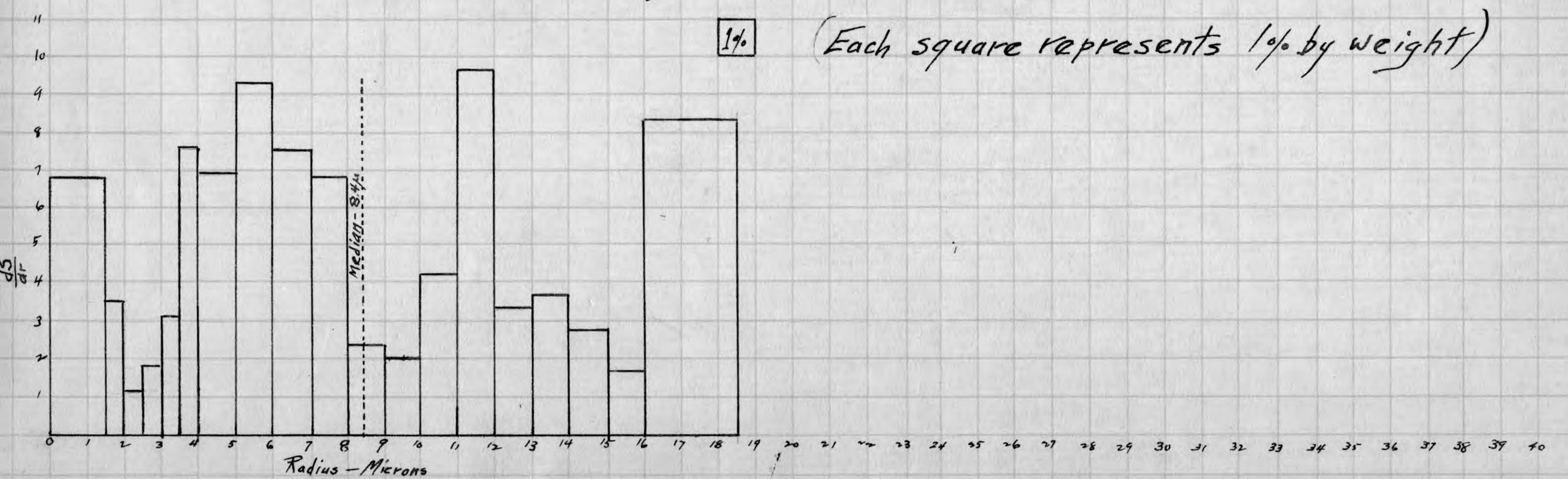
HISTOGRAM - 10.
Clay No. 1301 - Hebron, N. Dak.
1% (Each square represents 1% by weight)
Median - 5.16 μ
Radius - Microns

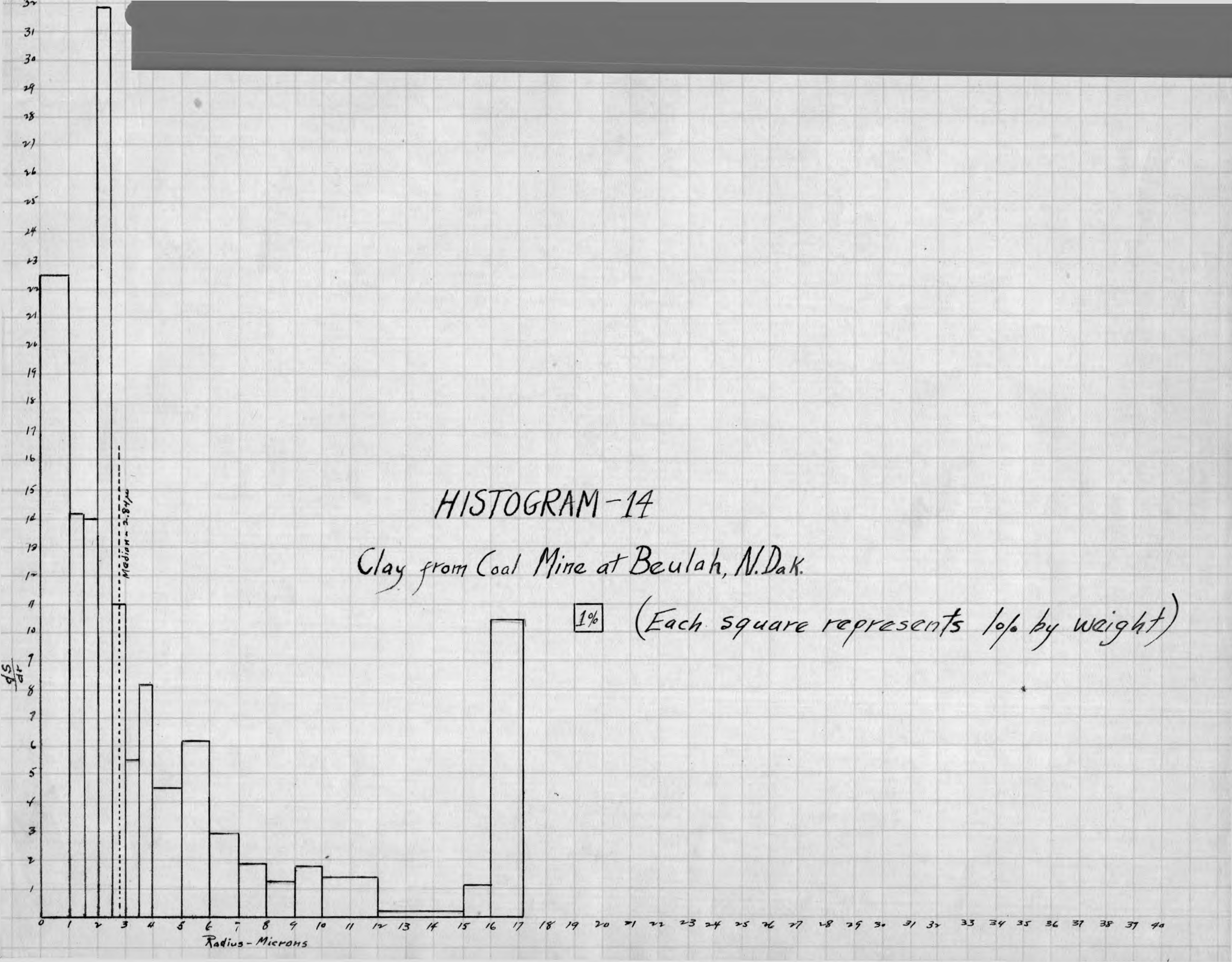

HISTOGRAM - 11.
Clay No. 2101 - Mottled Clay
from Taylor, N.Dak.
1%
(Each square represents 1% by weight)
dS/dr
Median - 8.41μ
Radius - Microns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

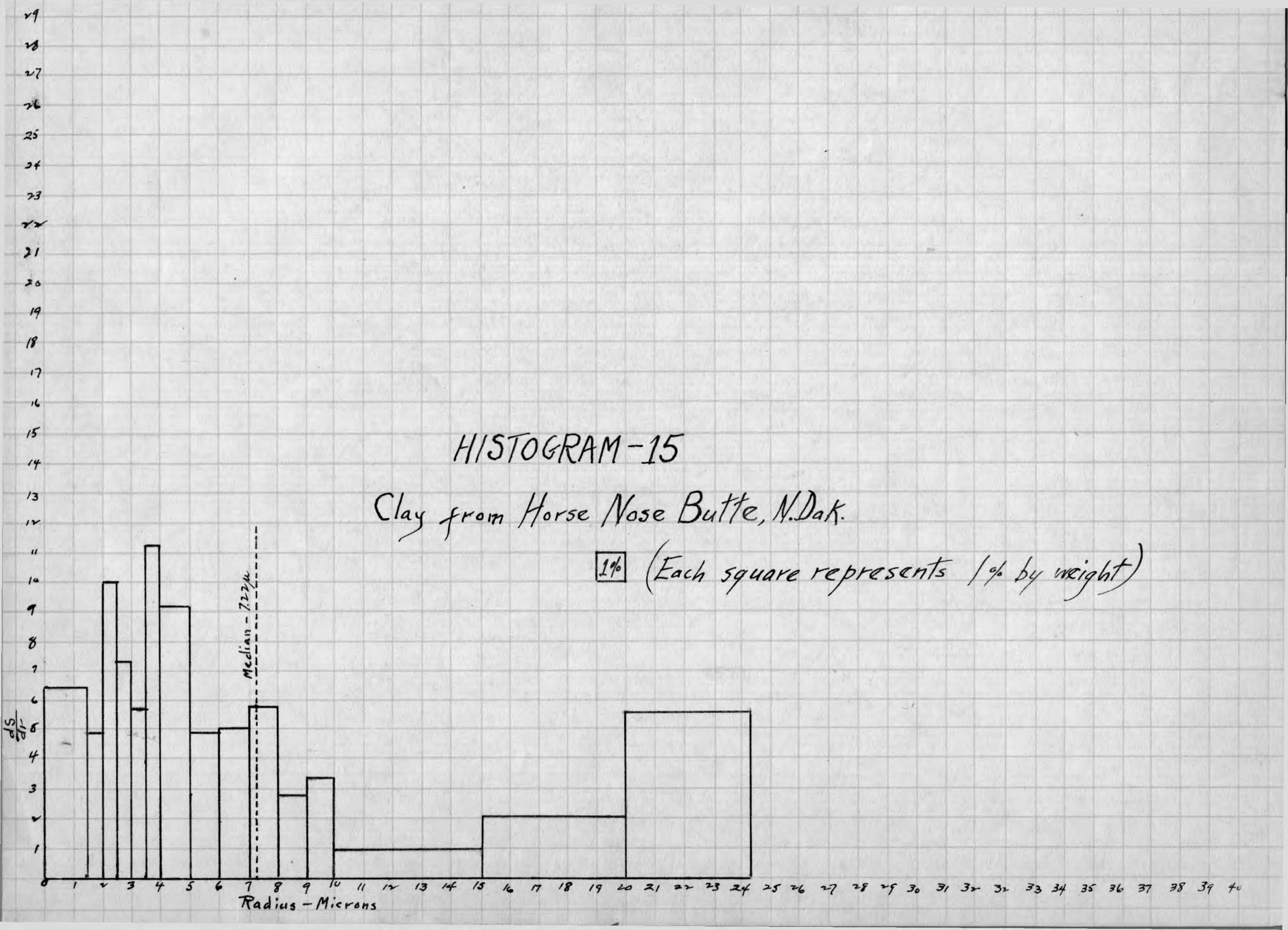

HISTOGRAM-12.
Red Clay - So. of Dickinson, N.Dak.
1%
(Each square represents 1% by weight)
Median - 4.18μ
dS/dr
Radius - Microns

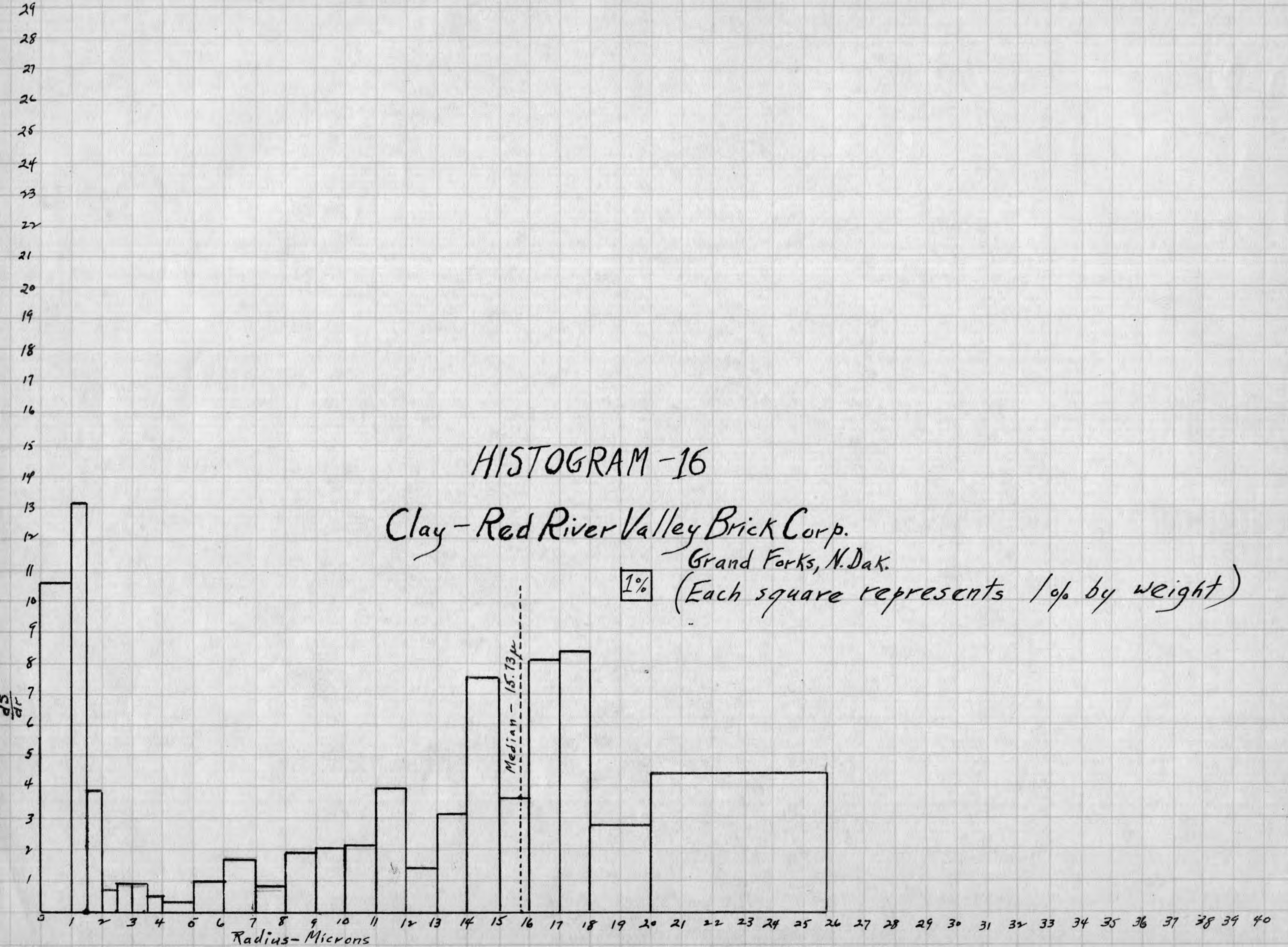
HISTOGRAM - 13.

Yellow Clay - So. of Dickinson, N. Dak.




HISTOGRAM-14
Clay from Coal Mine at Beulah, N.Dak.
1%
(Each square represents 1% by weight)
Median - 2.84μ
dS/dr
Radius - Microns

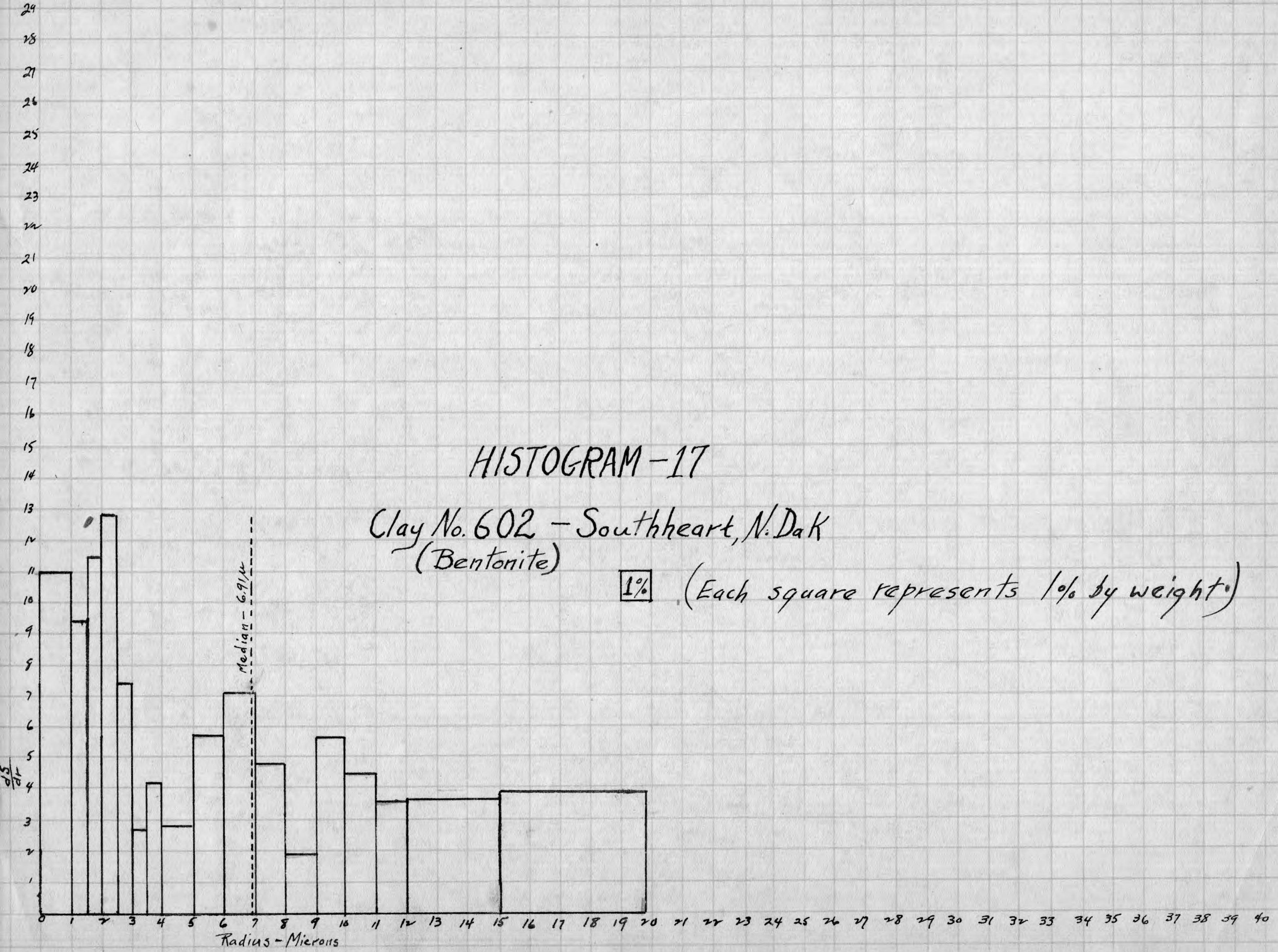

HISTOGRAM-15
Clay from Horse Nose Butte, N.Dak.
1% (Each square represents 1% by weight)
Median - 7.22μ
Radius - Microns
dS/dr

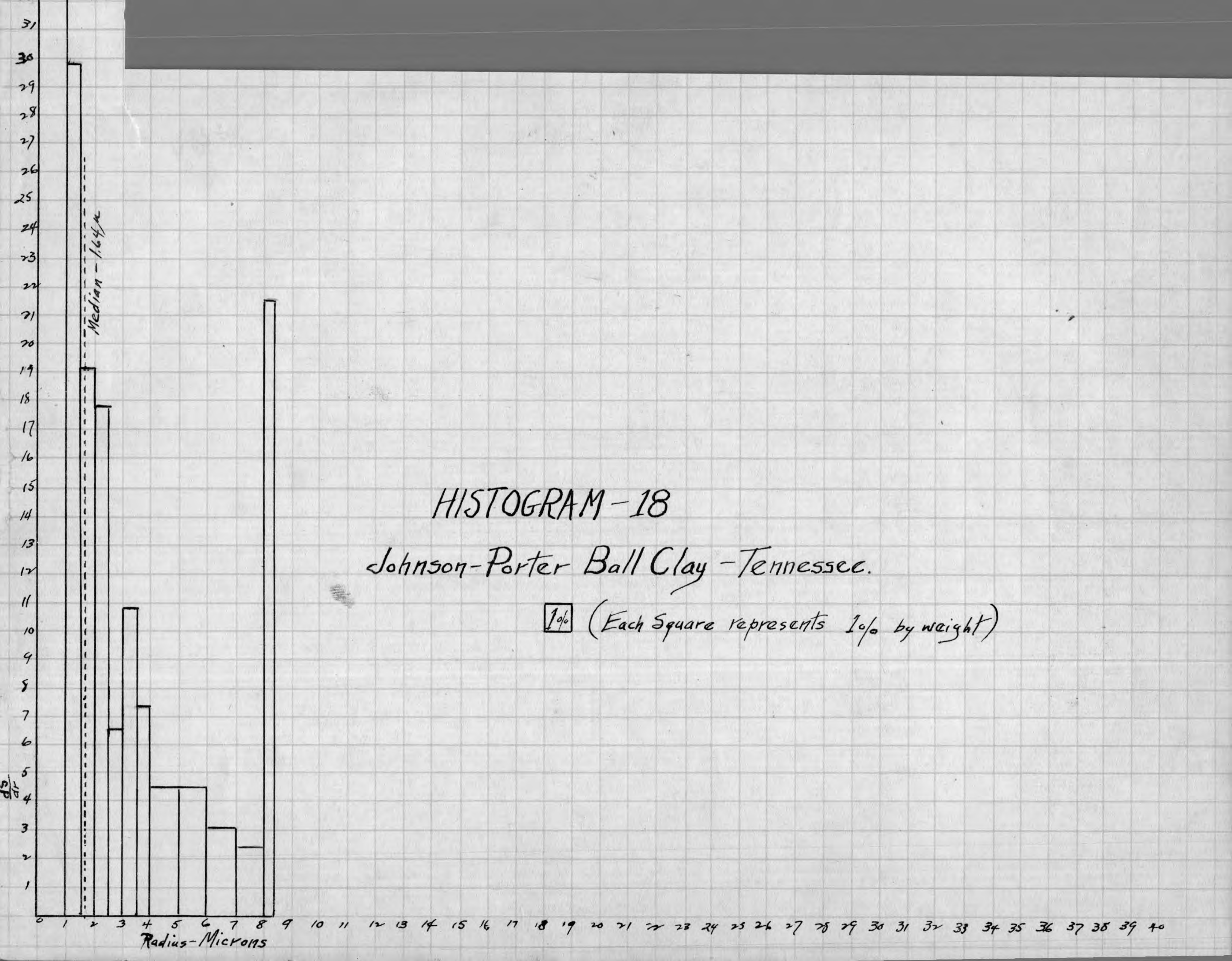

HISTOGRAM - 16
Clay - Red River Valley Brick Corp.
Grand Forks, N. Dak.
1%
(Each square represents 1% by weight)
Median - 15.73μ
Radius - Microns
ds/dr
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40

HISTOGRAM - 17

Clay No. 602 - Southheart, N. Dak
(Bentonite)

1% (Each square represents 1% by weight.)




HISTOGRAM - 18
Johnson-Porter Ball Clay - Tennessee.
1% (Each Square represents 1% by weight)
Median - 1.64 μ
ds/dr
Radius - Microns
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

D. Comparison With Other Data.

THE KNOWN PROPERTIES OF THE CLAYS UNDER INVESTIGATION ARE:

1. Clay 101 from Dickinson:

Color - light gray; Density 2.554

Maximum radius - 42.6 microns

Minimum radius - less than 1 micron

Median radius - 9.6 microns

Mode - 1.0 - 1.5 microns

Plasticity - good; Linear drying shrinkage - 6.1%

Slight turbidity after 48 hours.

Use - brick, tile, pottery

2. Clay 201 from Dickinson:

Color - light gray; Density - 2.585

Maximum radius - 43.7 microns

Minimum radius - less than 1.5 microns

Median radius - 10.45 microns

Mode - 1.5 - 2.0 microns

Plasticity - not determined

Slight turbidity after 24 hours

3. Clay 202 from Dickinson:

Color - light gray; Density - 2.62 g.

Maximum radius - 14.364 microns

Minimum radius - less than 1.5 microns

Median radius - 4.55 microns

Mode - less than 1.5 microns

Plasticity - fair

Use - brick, tile; not good in pottery or casting; cracks

Slight turbidity after 24 hours.

4. Clay 301 from Dickinson:

Color - deep yellow; Density - 2, 57 g.

Maximum radius - 15.87 microns

Minimum radius - less than 2.0 microns

Median radius - 10.8 microns

Mode - 13.0 - 14.0 microns

5. Clay 501 from Dickinson

Color - light gray; Density - 2.612 g.

Maximum radius - 24.2 microns

Minimum radius - less than 1 micron

Median radius - 5. 12 microns

Mode - 1.5 - 2.0 microns

Plasticity - good; Linear drying shrinkage - 4.7%

Slight turbidity after 24 hours

Use - brick, tile, pottery

6. Clay 802

Color - medium dark gray; Density - 2.623 g.

Maximum radius - 56.5 microns

Minimum radius - less than 2 microns

Median radius - 12.1 microns

Mode - 2.5 - 3.0 microns

7. Clay 1001 from Hebron Brick Company:

Color - medium gray; Density 2.66 g.

Maximum radius - 26.0 microns

Minimum radius - less than 1 micron

Median radius - 6.92 microns

Mode - less than 1 micron

Plasticity - good; Linear drying shrinkage - 4.3%

Use - brick, tile, pottery

8. Clay 1101 from Hebron:

Color - brownish gray; Density - 2.514 g.

Maximum radius - 22.3 microns

Minimum radius - less than 1.5 microns

Median radius - 4.53 microns

Mode - 2.0 - 2.5 microns

Slight turbidity after 24 hours

9. Clay 1201 from Hebron:

Color - medium yellow; Density - 2.62 g.

Maximum radius - 27.1 microns

Minimum radius - less than 1 micron

Median radius - 4.135 microns

Mode - 1.0 - 1.5 microns

Plasticity - good; Linear drying shrinkage - 7.2%

Use - brick

Very slight turbidity after 24 hours

10. Clay 1301 from Hebron

Color - medium yellow; Density - 2.584 g.

Maximum radius - 26.0 microns

Minimum radius - less than 1.0 microns

Median radius - 5.166 microns

Mode - 1.0 - 1.5 microns

Plasticity - good; Linear drying shrinkage - 7.0%

11. Clay 2101 Mottled Clay from Taylor:

Color - light yellowish gray; Density - 2.546 g.

Maximum radius - 39.7 microns

Minimum radius - less than 1 micron

Median radius - 8.41 microns

Mode - 1.0 - 1.5 microns

Plasticity - good; Linear drying shrinkage 7.0%

Pink color after firing

Use - pottery, brick

Slight turbidity after 24 hours

12. Clay - Red from south of Dickinson:

Color - pink; Density - 2.585 g.

Maximum radius - 32.25 microns

Minimum radius - less than 1.0 micron

Median radius - 4.18 microns

Mode - 1.5 - 2.0 microns

Turbid after 24 hours

13. Clay - Yellow from south of Dickinson:

Color - bright yellow; Density - 2.522 g.

Maximum radius - 18.55 microns

Minimum radius - less than 1.5 microns

Median radius - 8.4 microns

Mode - 11.0 - 12.0 microns

14. Clay - From coal mine at Beulah:

Color - dark gray; Density - 2.57 g.

Maximum radius - 17.2 microns

Minimum radius - less than 1.0 micron

Median radius - 2.84 microns

Mode - less than 1 micron

Evidences of certain sizes of particles absent in range evidenced by striations in sedimentation tube.

15. Clay - from Horse Nose Butte:

Color - yellowish gray; Density - 2.64 g.

Maximum radius - 24.3 microns

Minimum radius - less than 1.5 microns

Median radius - 7.22 microns

Mode - 3.5 - 4.0 microns

Slight turbidity after 24 hours

16. Clay - from Red River Valley Brick Corporation of Grand Forks:

Color - light brown; Density - 2.692 g.

Maximum radius - 25.8 microns

Minimum radius - less than 1.0 microns

Median radius - 15.73 microns

Mode - 1.0 - 1.5 microns

Sandy clay; traces of mica

Microscopic examination shows many particles approximately 20 microns

Use - brick, tile

17. Clay - 602 from Southheart (Bentonite):

Color - light yellow; Density - 2.434 g.

Maximum radius - 19.75 microns

Minimum radius - less than 1.0 micron

Median radius - 6.91 micron

Mode - 2.0 - 2.5 microns

Turbid after 48 hours

Discussion Of The Results and Possibilities

From the above data and from the histograms we might make some comparisons. The average median for the clays investigated, Tables I to XVII, inclusive, is approximately a radius of 7.53 microns. That is, on the average, half of the weight of clay is of a particle size greater than 7.53 microns. Of the seventeen clays included in this investigation seven had a median higher than the average and ten lower than average.

Higher	Lower
No. 101	No. 202
No. 201	No. 501
No. 301	No. 1001
No. 802	No. 1101
No. 2101	No. 1201
Yellow from Dickinson	No. 1301
Red River Valley	Red from Dickinson
	Beulah
	Horse Nose Butte
	No. 602

Of those clays in the higher group only three showed turbidity after standing 24 hours, namely, 101, 201, 2101. This indicates the presence of colloidal particles, or at least extreme fineness. It is interesting to note that two of these, 101 and 2101 are reported as very plastic by the School of Mines. No measurements have been made on 201, except that when mixed with water it shows evidences of fair plasticity. From a study of the histograms we should expect the other members of the higher group to show medium to poor plasticity. The medians for Clays 301 and 802 are high, and both of them, together with the Yellow from Dickinson and the Red River Valley Clay, show considerable evidence of being sandy, both upon microscopic examination and in the fact that their histograms show large values in the upper range of their particle size. The Red River Valley clay was very sandy, and lacks plasticity and is classed as a loam. Such a clay is desirable for brick and tile.

Of the clays listed in the group, the medians of which are lower than average, every one remained turbid after long standing, showing extremely fine particles present. Four from this group are reported by the School of Mines as having good plasticity, namely clays 501, 1001, 1201 and 1301. The histo-grams of these clays show a large weight of fine particles. Another, clay 202, is reported as ohly fairly plastic. This might be accounted for by the fact that its histogram shows an increase in the weight of particles in the coarser range of sizes, and microscopic examination confirms this to be sand. The Horse Nose Butte clay and Beulah clay show evidences of sandiness, both microscopically and from their histograms. Altho no data on plasticity is available for the remaining clays in this group, from a study of the histograms it seems reasonable to predict that the Red clay from Dickinson, No. 1101, No. 602 and the Beulah clay should have good plasticity, and the Horse Nose Butte Clay at least fair plasticity.

Table XVIII and Histogram 18 give the particle size range for Johnson Porter Tennessee Ball clay. This clay has great plasticity, in fact, is actually sticky. It will be noted its particle size median is low and there are large weights in the smaller range of radii.

Data on linear drying shrinkage was available for only six clays and was considered insufficient for arriving at any conclusions regarding the relation of this property to particle size distribution.

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Summary

1. The theory of sedimentation has been discussed, and its application to systems having a large gradient of sizes has been studied.

2. The various methods employed in measuring particle size distribution have been reviewed, namely

a. The Centrifuge method.

b. The method of measuring the rate of change of density.

c. The Gravimetric method.

3. The apparatus for the measurement of particle size distribution by the gravimetric method has been described; likewise the materials and their preparation, and the description of the measurements.

4. Tables and Histograms for each clay studied in this investigation have been prepared, and are included in this thesis.

5. A comparison has been made between the data obtained in this investigation with other data available with reference to the clays used.

6. The application of this data is discussed.

Acknowledgment

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To Miss Freda Hammers of the Ceramic Arts department for her assistance.