

Dep. Col.
Thesis
F863

DEPOSITORY
COLLECTION
NOT TO BE
TAKEN

AN EXPERIMENTAL STUDY OF VARVES AND VARVE DEPOSITION.

BY

HORACE J. FRASER B. SC.

#####

Presented in partial fulfilment of the requirements for
the Master of Science degree in the University of Manitoba.

April 1927.

M.Sc.

THE UNIVERSITY OF MANITOBA
LIBRARY

Table of Contents.

Introduction.

1. The Nature of Varves.

- A. Collection of Samples.
- B. Chemical Analysis.
- C. Results of Chemical Analysis.
- D. Discussion of Chemical Analyses.
- E. Mechanical Analysis.
- F. Results of Mechanical Analyses.
- G. Discussion of Results of Mechanical Analyses.
- H. Chemical and Mechanical Differences between the Two Bands of a Varve.

2. The Conditions that Control Varve Deposition.

- A. Some Experiments on the Sedimentation of Boulder and Varve Clay.
- B. Experiments on the Settling of Various Sized Sand Particles under Different Temperature Conditions.
- C. Experiments on the Settling of Silt and Clay Particles under Different Temperature Conditions.
- D. Experiments on the Settling of Varved Clay under Different Temperature Conditions.
- E. Experiments on the Deposition of Clay under Definite Temperature Conditions.
- F. Experiments on Flocculation at Low Temperatures.
- G. Experiments on Flocculation at Low Temperatures using Partially Deflocculated Material.
- H. Experiments on Flocculation at High Temperatures.
- I. Experiments on the Relative Rate of Flocculation at High and Low Temperatures.
- J. Application of Results.

K. Some Conditions Essential for the Formation of Diatactic Varves.

L. Summary.

.....

A STUDY OF VARVES.

INTRODUCTION.

It has only been within very recent years that geologists have turned their attention to a detailed study of the processes and products of sedimentation. One phase of sedimentation, the seasonal banding of post-glacial clays and the value of this banding in establishing the duration of post-glacial time, has been rather fully investigated by Swedish workers.

(1)
In 1841, Hitchcock discussed the banding of the clays in the Valley of the Connecticut and pointed out that invariably the coarser material was at the bottom of each band, and that there was a gradual increase in fineness upwards, until at the top of the band there was exceedingly fine clay. He suggested that each layer might represent an annual deposit.

(2)
Baron de Geer, in studying the banding of the post-glacial clays of Sweden was the first to give proof that each band represented a year's deposition: consequently by correlating the annual layers in different parts of the country and counting the total number he was able to give a correct estimate of the duration of post-glacial time. He found that approximately 12,000 years were required for the ice to leave Southern Sweden.

The name varve, from the Swedish word varv meaning a periodic iteration of layers, has been applied by Baron de Geer to such annual layers of clay and silt.

1. Hitchcock, E. Final Report on the Geology of Mass. 2 vols.

Amherst, Northampton, 1841.

Sayles ⁽³⁾ has confirmed Hitcock's statement that the banding of the clays of the Valley of the Connecticut represent seasonal deposition, but he further states that the clays were laid down in a glacial lake and also suggests a similar explanation for the banding of the Squantum tillite of Boston. Recently numerous attempts have been made to explain similar periodic banding in old consolidated rocks, as being due to seasonal deposition.

Sauramo ⁽⁴⁾ and Antevs ⁽⁵⁾, who were students of de Geer's, have added valuable contributions to our knowledge of varve structure. Sauramo was able to work out the rate of retreat of the ice from Southern Finland and to give us a general idea of the climatic changes that took place during the retreat of the ice. Antevs made a similar study of the varve sediments of the New England States and found that the average rate of retreat of the last ice sheet from these states was one mile in twenty - two years. At a later date he continued these studies in Canada, and published a memoir ⁽⁶⁾ in which he gives a theoretical discussion of the method of origin of varved glacial clay. In concluding his discussion,

2. Geer, Gerard de, A Geochronology of the last 12,000 years.
Compte rendus long. Geol. intern. 11, 1910, 1912, p.241 - 253.
3. Sayles, R. W. Mem. Mus. Comp. Zool. Harvard, 47, 1. 1919.
4. Sauramo, M. Bull. No. 50, Commission Geologique de Finlande.
5. Antevs, E. The Recession of the last ice sheet in New England,
American Geographical Society Research Series, No. 11.
6. Antevs, E. The Retreat of the last ice sheet in Eastern Canada,
Mem., 146, Canadian Geological Survey.

Antevs states that " the role of each condition and factor for the formation of the varved glacial clay is not well known ".

In the following paper, certain analyses and results are presented and discussed in an attempt to ascertain the relative values of some of the factors which affect the formation of varved glacial clay. In order to carry out this investigation it was thought necessary to first make a chemical and mechanical study of varved material, so that the relationship of the two bands might be better understood.

1. THE NATURE OF VARVES.

A. Collection of Samples.

Samples of varved clay were obtained from two localities; the Trapper claim on Herb lake, and from the northeast shore of Cross lake. These varved clays are both due to deposition in Lake Agassiz. The localities are 400 miles apart, and no correlation can be attempted in the light of the present knowledge of deposition in that lake. The elevation at Cross lake is 1050 feet, and at the Herb lake occurrence it is 945 feet, but the present elevation does not indicate the relative positions at the time of deposition, as there has been a differential uplift of the northern area since the ice retreated.

The section obtained from Herb lake was 48 inches long. 215 varves were counted in a section of 38 inches, the section above this was badly contorted. The average thickness of each varve was approximately .2 inches of which about $\frac{1}{3}$ was fine material. There was a considerable variation in the size of the varves, those at the bottom of the section being considerably thicker than those at the top.

The Cross lake varves were much thicker, varying from $\frac{1}{2}$ to $\frac{3}{4}$ of an inch in thickness, of which about $\frac{1}{10}$ of an inch was fine material.

The material was sampled as follows.

Sample 1. Included the lower 3 inches of the Herb lake section.

Sample 2. Taken 15 - 18 inches from the bottom of the Herb lake section.

Sample 3. Taken 30 - 33 inches from the bottom of the Herb lake section.

Sample 4. Was a representative sample of the Cross lake section.

B. Chemical Analysis.

Equal amounts of each sample were taken and separated, as well as could be done by eye, into the light and dark portions. The separate portions were then levigated in an agate mortar, thoroughly mixed and dried at a temperature of 110°C. After drying the samples were preserved in a desiccator.

The system of analysis followed was that prescribed by H. S. Washington in his book, "The Chemical Analysis of Rocks".

C. Results of Chemical Analysis.

Sample.	1		2		3		4	
	A	B	C	D	E	F	G	H
SiO ₂	50.30	49.48	50.04	50.94	49.30	50.22	69.38	54.65
Fe ₂ O ₃	7.59	8.46	7.48	8.45	7.16	7.59	3.90	6.94
Al ₂ O ₃	13.67	15.48	17.18	18.05	17.55	20.06	15.76	20.94
CaO	9.76	7.68	7.64	6.48	7.82	4.96	4.38	2.84
MgO	4.62	5.18	5.37	5.01	3.94	3.79	.85	2.69
K ₂ O	2.47	2.74	2.86	3.09	2.66	2.78	2.11	2.29
Na ₂ O	.39	.54	1.28	1.41	1.36	1.42	2.10	1.20
Ignition	11.21	10.20	8.91	7.23	9.80	8.46	2.00	8.16
	100.01	100.12	100.76	100.66	99.59	99.28	100.46	99.71

A, C, E, G are the lighter or coarser parts of the varves.

Certain general differences in composition between the coarser and finer bands are worthy of note. The finer fraction of the varve contains a larger percentage of ferric oxide, alumina, and potash, and has lesslime than the corresponding coarser fraction. The silica content seems variable, as does that of the oxides of magnesium and sodium. In the sample from Cross lake the high percentage of silica in the coarser fraction is due to the large amount of quartz silt in the sample. There is a greater loss by ignition in the coarser fraction, except in the Cross lake sample, where the low loss on ignition is probably due to the high silica content of the sample.

D. Discussion of Chemical Analyses.

The silica, alumina, and iron oxide may have been transported in the form of a silicate, as a colloid, or both. The portion carried as a silicate would be distributed in the two fractions according to the size of particle, whereas the portion carried colloiddally would remain in suspension until flocculated. Tamm ⁽⁸⁾ has found that there is a concentration of minerals such as biotite in the fine fraction of the varve. This might explain the increase of alumina and iron oxide in this layer. If a large percentage of the silica is carried colloiddally, there should be a concentration of it in the fine layer. This concentration however, would be offset by the deposition of quartz sand in the coarser fraction. The deduction from the analyses is that the silica, other than sand, is combined, presumably in the hydrated form, at least with the alumina and probably in part with the lime. An exception to this is the Cross lake material, in which the silica,

8. Tamm, Olof, Experimental Studies in Chemical Processes in the Formation of Glacial Clay. , Sveriges Geologiska Undersokning, Arsbok 18, 1924, No 5.

especially in the coarser portion, is present as quartz silt or sand.

The larger percentage of potash in the fine band is due to its absorption by the fine, probably colloidal material in this layer.

A considerable percentage of the calcium is present as the carbonate, as is shown by the ready effervescence of the clay when treated with hydrochloric acid. It is noteworthy that the lime content of the Herb lake varves is higher than that of the Cross lake material. Both are outside the limestone area, but the Herb lake sediments may have received more direct contributions from the glacial scourings from the limestone lying west of Hudson Bay.

There is no apparent variation in chemical composition from top to bottom of the Herb lake section.

E. Mechanical Analysis.

For this analysis representative samples of samples 1,3, and 4 were taken.

Five gram samples were placed in bottles containing distilled water to which 5 mcs. of ammonia had been added. These were placed in a mechanical agitator and shaken for six hours. The clay portions were separated by centrifuging, the silt by elutriation and the sands by screens. For the sand grades, 50 gram samples were taken.

The particles of each grade were measured microscopically and few varied from the following sizes.

Coarse sand.	over 0.5	mm.
Fine sand .	.05	-.5 "
Silt.	.005	-.05 "
Coarse clay.	.001	-.005 "
Fine clay.	.000	-.001 "

F. Results of Mechanical Analysis.

Coarse sand.	-----	-----	-----	-----	Trace	-----
Fine sand.	2.85	1.99	1.96	1.60	6.34	1.00
Silt.	54.52	30.64	32.18	16.21	82.26	4.83
Coarse clay.	24.11	20.35	25.96	27.32	6.69	26.66
Fine clay.	18.55	47.08	39.83	55.45	4.76	67.87
	-----	-----	-----	-----	-----	-----
	100.03	100.06	99.93	100.58	100.05	100.36

G. Discussion of Results.

These analyses show that there is a grading between the coarser and finer fractions of the varve. The difference in mechanical composition is not so marked in the Herb lake sections, which are composed of fine material, but is very noticeable in the coarser Cross lake varves. In all the samples there is a definite concentration of the fine clay in the upper or finer fraction. In the Cross lake sample this grading is very definite, not only in the fine and coarse clay fractions but even in the silt and sand fractions.

These mechanical analyses represent the physical state of the clay at the time of examination. While some of the particles may have increased in size since the time of deposition, it is unlikely that any have become smaller. Consequently this grading into fine and coarse portions is due to processes operating during the period of deposition, and not to any subsequent changes.

From these analyses curves have been drawn in which the logarithmic value of the size of grain is plotted against total percentages. This method of representation has been adopted in plotting mechanical analyses because it gives a clearer representation of the finer fractions than is ordinarily obtained.

For comparison with the above analyses, there is given in Graph 1, curves for mechanical analyses of a typical lake Winnipeg clay ⁽⁹⁾, a gray drift clay from Hutchinson, Minn., ⁽¹⁰⁾ and a typical unlaminate lake clay from Heron lake in Minn. ⁽¹¹⁾

A comparison of these curves definitely proves that there is a grading in varved material that does not exist in other types of deposits. This grading is well illustrated in the Cross lake varves where for the coarser fraction the curve ascends nearly vertically within silt limits, whereas in the finer fraction it ascends within the fine clay limits. This grading is present in the Herb lake material although there is not such a marked difference in the size of particle in the two bands. The typical lake Agassiz clay does not show grading. Instead the curve continues uniformly through the silt, coarse clay, and fine clay areas. This clay, however, is finely laminated so that such an analysis really represents the average of the two fractions. The curve for the gray drift definitely shows a lack of grading in that material. This sample has a larger percentage of coarse and fine sand than is found in the varved clays. The curve for the Heron lake clay shows some grading in the silt fraction.

9. Maynard, J.E., The Clays of the Lake Agassiz Basin, M.Sc. Thesis, April 1925.
10. Grout, F.F., Relation of Texture and Composition of Clays, Bul. Geol. Soc. of Am. Vol. 36, 1925, p. 393.
11. Ibid.

A consideration of the analyses of the Herb lake material shows that if a comparison of the average mechanical composition of sample 1 with sample 3 is made, there is a definite increase in fineness of material towards the top of the section. The figures are as given.

	Sample 1 (A B)	Sample 2 (E F)
Coarse sand.	2.42	1.78
Fine sand.	42.58	24.19
Silt.	22.23	26.64
Coarse clay.	32.81	47.64
Fine clay.		
	<hr/> 100.04	<hr/> 100.25

This would apparently indicate a withdrawal of the ice front, with consequently less deposition of material, from the locality at which this material was sedimenting. This coarse material is ordinarily deposited shortly after entering the lake and only the finer material is carried to the distant parts of the lake.

A count of the varves in this section indicates that 160 seasons elapsed between the time that the last varve was deposited in sample 1 and the first varve deposited in sample 3. This time would be sufficient for a considerable withdrawal of the ice front, under suitable climatic conditions. The evidence of a retreat of the ice front is further borne out by the size of the varves. Those of sample 1 average .37 inches in thickness, those of sample 3 average about .19 inches.

14. Chemical and Mechanical Differences between the Two Bands of a Varve.

1. There is a definite increase of ferric oxide, alumina, and potash in the finer fraction.
2. There is a definite decrease in lime in the finer fraction.
3. Sodium oxide and magnesium oxide appear to increase in the finer fraction.

4. Silica appears variable.
5. There is a very definite grading in the two bands.

Accordingly when the origin of varved clay is considered, it is necessary to look for processes which will give these differences between the two bands.

11. The Conditions that Control Varve Deposition.

In the above paragraphs , chemical and mechanical analyses of typical varved clays have been presented. From these analyses differences of both a chemical and mechanical nature have been shown to exist between the two bands that compose a varve. The next problem to be considered is that of the nature of the factors which affect the formation of varves. What are the conditions that control the deposition of varves? In the following paragraphs , experimental work is presented in an effort to ascertain the nature and value of some of the factors affecting varve formation.

A. Some Experiments on the Sedimentation of Boulder and Varve Clay.

1. A quantity of boulder clay was passed through a 20 mesh screen to remove all coarse material. The clay was then shaken in distilled water to which some ammonia had been added. This material was then divided, half of it being placed in a glass cylinder 14 inches high, which contained distilled water, the other half in a similar cylinder containing tap water. The contents of the cylinders were then well shaken and placed in a room at 24°C. In 47 days the sedimentation was practically complete although the liquid above the deposit was still slightly turbid.

In the cylinder containing distilled water the deposit showed an indistinct color division at about the middle. The bottom half of the deposit was darker and coarser than the upper half. The deposit

appeared gradational from coarser particles at the bottom to finer ones at the top.

In the other cylinder no color division could be made in the deposit although the sand at the bottom of the cylinder appeared darker than the rest of the deposit. The material was the same color as the original boulder clay. There was apparently a perfect gradation in size from the coarse material at the bottom to the fine at the top.

2. A quantity of varved material was treated in a similar manner. The material in the cylinder containing tap water appeared to settle much more rapidly, this difference in the rate of settling being most noticeable for the finer sizes. 68 days later the deposits were examined.

In the cylinder of tap water the sedimentation had been completed. A color division could be made about the middle of the deposit, the darker coarser material forming the bottom half of the deposit.

The cylinder of distilled water was still turbid, but an ink mark on a piece of paper could be readily seen through the suspension. The deposit appeared gradational in composition with no indication of varvidity. The color division was not as distinct as in the other cylinder.

In these experiments the following conditions existed. The clay was only partially deflocculated, and was in a condition somewhat comparable to that of clay being carried in suspension by rivers. The water in which the deposition occurred, had a low concentration, or else was relatively free from electrolytes. The sedimentation occurred at fairly high temperatures. The processes of deposition were undisturbed by any currents in the water, except possible convection currents caused by slight differences in temperature in different parts of the cylinder.

B. Conclusions

1. Under these conditions the order of settling of the clay particles is a function of their size.
2. Deposits formed under these conditions showed no indication of settling in two or more parts, rather, the deposit showed a continuously increasing fineness upwards.
3. The sedimentation was more rapid in tap water than in distilled water, especially for the finer sizes. The presence of electrolytes in the tap water would cause flocculation and precipitation of the finer material.
4. With this material and under these conditions the coarser material was darker in color.

B. Experiments on the Settling of Various Sized Sand Particles under Different Temperature Conditions.

When particles settle in an undisturbed liquid at constant temperature, they rapidly attain a constant maximum velocity, when the acceleration of normal falling is balanced by the resistance of the liquid. Their velocity of fall does not follow any mathematical formula but varies with their density, size, shape and the temperature of the water.

(12)
Holmes gives the following approximate formulae for some of the sizes.

For grains larger than .5 mms. $v^2 = d(S.G. - 1)$.

For grains smaller than .2 mms. $V = d^2(S.G. - 1)$.

Where V is the velocity of fall, d the diameter and S.G. the specific gravity of the particle.

Grains between .5 and .2 mms settle with a velocity which agrees with neither of the theoretical formulae given.

A. Apparatus and Material.

In order to obtain some information regarding the effect of temperature on the velocity of settling, the following apparatus was constructed.

A straight glass tube five feet long with an inner diameter of 1.5 cms. was placed in an outer glass tube five feet long having an inner diameter of 3.5 cms. In the lower end of the outer tube was placed a rubber cork through which a piece of glass tubing and a nail passed. The nail fitted into a small hole in the cork of the inner tube, thus steadying the inner tube. The inner tube was held at the upper end by a cork which fitted tightly into the outer tube. Through this stopper was passed a glass tube. Water at constant temperature was pumped through the outer tube. By adjusting the temperature in the supply tank it was found possible to keep a constant temperature in the inner tube.

It was found that particles dropped into the water in the inner tube attained a constant velocity before reaching the first mark on the tube, the mark being about twelve inches from the upper end of the inner tube. Tests were made on the velocity of fall of a sand grain over one foot intervals, at different positions along the tube, and were found to be in very close agreement.

The sand selected for use was from Black island in Lake Winnipeg. This sand contains 96.5 - 98.5 % silica. It was the best rounded sand, in each and every grade, obtainable. A quantity of this sand was passed through a series of screens. The greatest diameters in each grade were measured microscopically and the average size calculated. The sizes used were:

12. Holmes, A., Petrographic Methods and Calculations, p. 205.

Sand	Size in Spaces	Average	Size in Millimeters.
Stopped by 40 mesh screen.	44 - 25	34.5	.436
60	25 - 17	21.0	.266
80	17 - 13	15.0	.190
100	13 - 10	11.5	.145
150	10 - 7	8.5	.107
200	7 - 6	6.5	.082

Under the microscope one space equals .01266 mms.

B. Method and Results.

Representative samples of each grade were taken for the experiments. For the larger sizes an individual grain was dropped into the inner tube and the time taken by it to settle the lower four feet in the tube was measured. Twenty five measurements were taken for each grade. With the finer sizes a small number of grains were dropped into the water and one moving at about the average rate was timed. These measurements were first carried out at a temperature of 2.7°C., then at 10.6 and 20.0°C. The results obtained are tabulated.

<u>Size of Particle</u>	<u>Average time , in seconds, to fall four feet.</u>		
	<u>2.7°</u>	<u>10.6°</u>	<u>20.0°</u>
.436 mms.	17.8	17.2	17.6
.266	29.2	27.8	26.4
.190	52.6	47.4	41.5
.145	97.6	84.2	73.3
.107	131.0	109.4	93.0
.082	197.5	169.0	146.0

These values were first plotted using the time of fall as ordinate and the temperature as abscissa. It was found that the values for each size fall on a straight line, none of the values varying from this line by more than .5 seconds, except for size .107 mms. at 10.6° C. with an error of 2 seconds. From the graph it appeared that the time of fall for any size would have a maximum value at 0° and continuously decrease to 20° C.

For compactness a second graph was constructed. In this the differences in time of fall for each size at different temperatures were plotted as ordinates and the temperatures as abscissae. In this graph the slope of the line for each size gives a measure of the amount of retardation produced by a change of temperature.

To prove the absence of a maximum retardation at 4° C., some measurements for the finer sizes were made at 4° and at 6.2°. The values obtained were as follows.

<u>Size.</u>	<u>Average time, in seconds, to fall four feet.</u>	
	<u>4.0°</u>	<u>6.2°</u>
.082		183.7
.107	126.5	122.3
.145	91.5	90.5

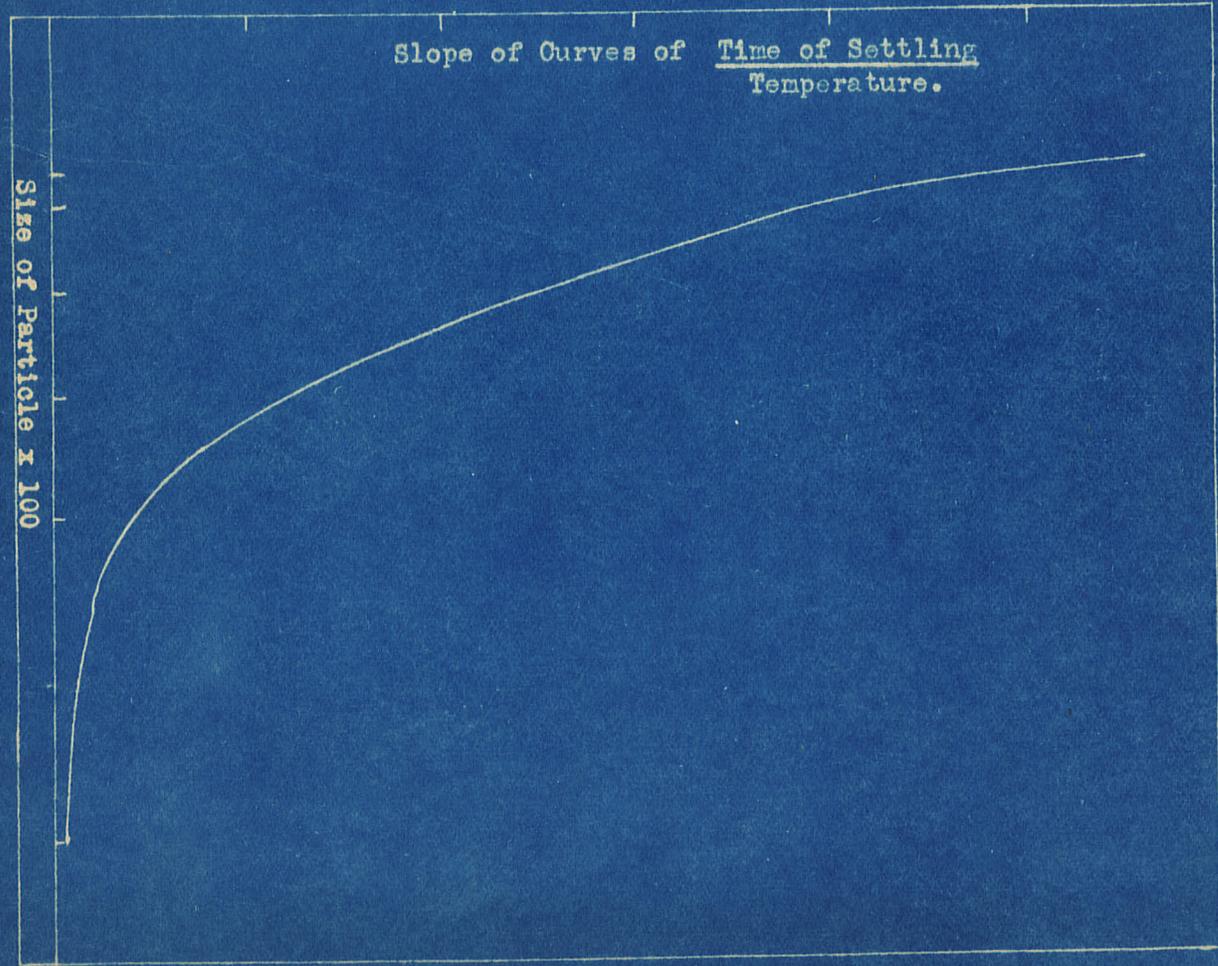
C. Discussion of Results.

These values fall on the straight lines already plotted and prove conclusively that there is not a maximum retardation at 4°, but that it occurs at 0° C. This proves that density of the water is not the controlling factor in the retardation of the fall of these particles, since the density curve has a maximum at 4°. It would appear that the viscosity of the water is an important factor in determining the velocity of the falling particle. The specific surface of a particle, i.e.,

2.



3.



The absolute surface of the entire disperse phase

The total volume of the disperse phase

increases directly as the size decreases. Hence with decreasing size of particle, the resistance to its fall by the water becomes proportionally greater.

The retardation observed for any particular size is probably due to the difference in the viscosity and density of the water at different temperatures. If the entire group of particles are taken into consideration, the differences in retardation for different sizes is probably a combined effect due to increasing density and viscosity of the water together with the increasing resistance, of the water, to the settling of the particle which has an increasing specific surface as the size decreases.

In the next graph is plotted as ordinate the slope, i.e.,
Difference, in seconds, of time of fall, of the lines in the previous

Temperature

graph, and the size of particle as abscissa.

This curve appears to have two asymptotic branches. As the size of particle decreases the retardation appears to become increasingly greater until the colloidal sizes are reached, when the particle remains indefinitely suspended. With coarser sizes as the specific surface decreases the temperature retardation becomes smaller and smaller until it becomes relatively negligible.

It is interesting to note that the sizes of material dealt with in this experiment, are all within the limits, in size, of fine sand.

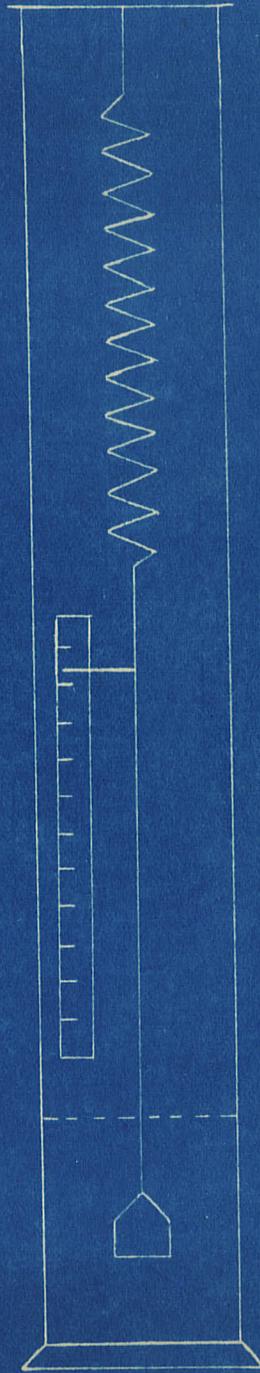


Fig. 1.

C. Experiments on the Settling of Silt and Clay Particles under Different Temperature Conditions.

A. Apparatus and Material.

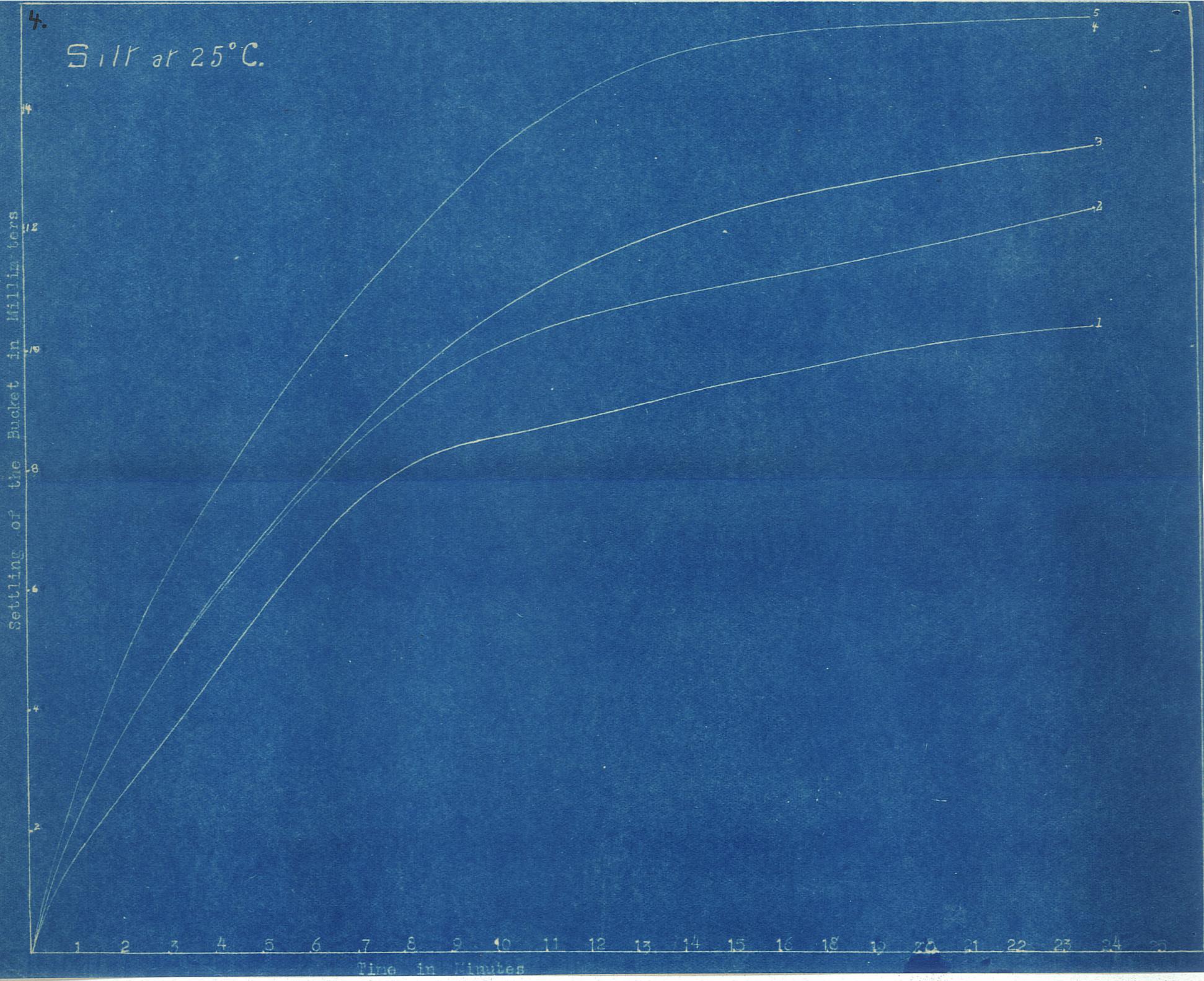
Despite the magnifying effect of the sedimentation tubes it was found impractical to measure the time of fall of particles much smaller than .082 mms. by this method, since the difficulty of following the course of a single particle was too great to permit of accurate results. With the purpose of obtaining comparative results for the smaller grades of material the following apparatus was constructed.

A diagram of the apparatus is given in figure 1. A small glass bucket $9/16$ in. in diameter, with very thin edges, was suspended on a very sensitive spring in a glass cylinder 14 inches high, having an inside diameter of $1 \frac{7}{8}$ inches. The bucket was attached to the spring by means of a fine steel wire which had a pointer fastened to it. This pointer extended over a millimeter scale. 100 ccs. of water was placed in the cylinder, forming a column of liquid $2 \frac{6}{16}$ inches high. The wire holding the bucket was adjusted so that the bucket was suspended 26 mms. from the surface of the liquid and in the center of the cylinder. When a half gram aluminum weight was placed in the bucket, the pointer registered a sinking of 22.8 mms. On carefully testing the apparatus it was found that the expansion of the spring, as recorded by the change in position of the pointer, was directly proportional to the tension, (Hooke's Law), over limits sufficiently wide for the purpose of this experiment.

A quantity of varved clay was thoroughly deflocculated by shaking. By means of the ordinary and supercentrifuge for the finer sizes and sedimentation in tall cylinders for the larger sizes, samples were obtained

4.

S.I.R. at 25°C.



which consisted of particles of the following sizes.

Silt	.05	-	.005
Coarse clay	.005	-	.001
Fine Clay	.001	-	.000

These sizes were carefully measured with a microscope. The size of the silt and coarse clay fractions could be determined accurately, and it was found that the particles were all within the limits given, with the exception of a few mica flakes which were larger. The fine clay was more difficult to separate and measure, but few of its grains were larger than .001 mms.

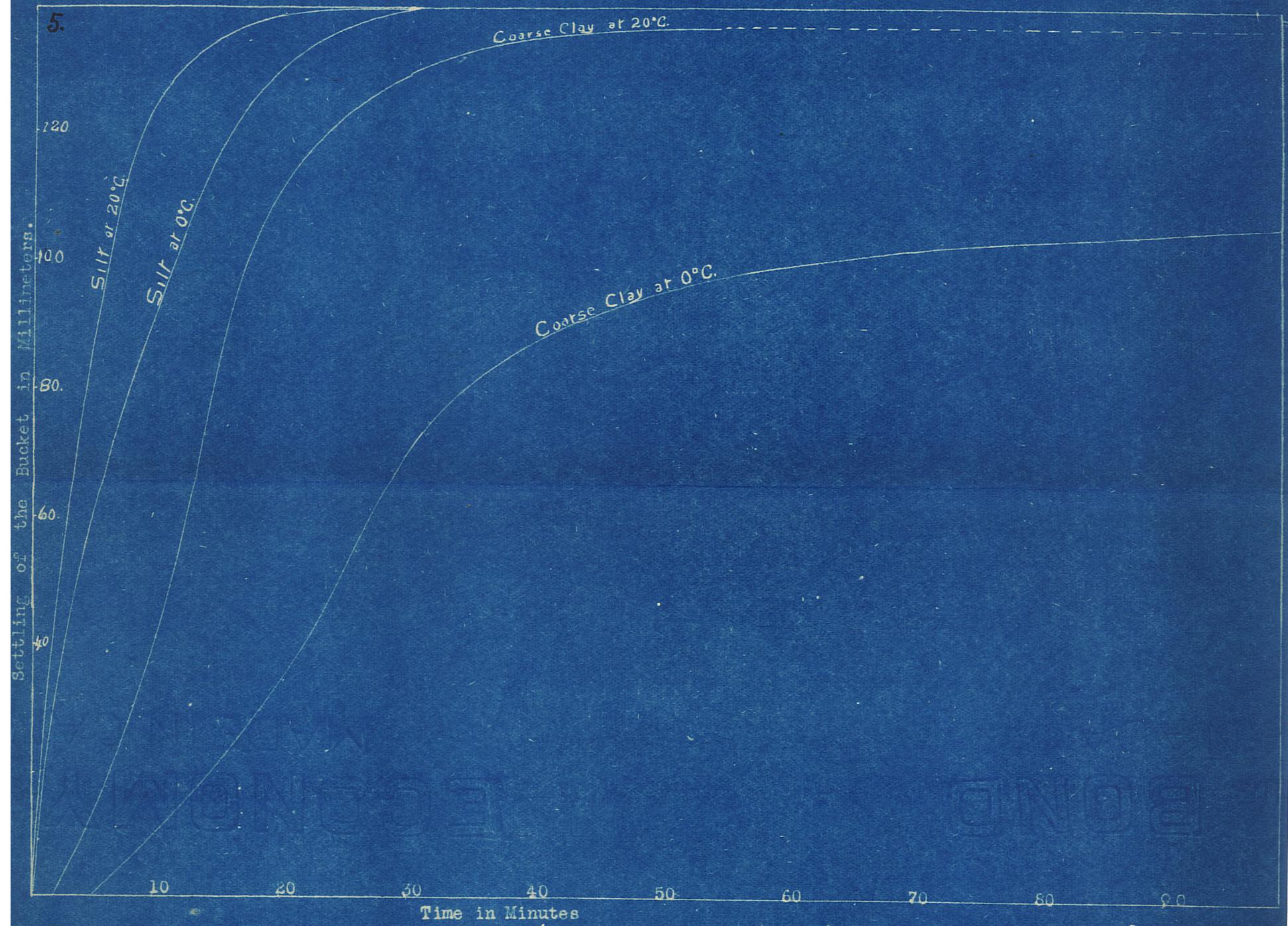
These samples were made up to standard suspensions having the same amount of solid, .0567 grams, per cubic centimeter.

B. Method.

100 cc. samples at 20°C., of these suspensions were used in making determinations. Care was taken that the material was deflocculated before the experiment began. The cylinder and sample were placed in a thermostat adjusted to the required temperature. When the contents of the cylinder had attained constant temperature, the material was thoroughly shaken, the cylinder replaced in the thermostat and the bucket hung in the suspension. The water bath was constantly stirred and the cylinder fixed so that there was no vibration. At definite time intervals, readings of the pointer were taken with the aid of a magnifying glass, and recorded in millimeters. Experiments were carried out at 25°, 20° and 0°C.

C. Results.

Graph 4 shows the results of five successive determinations made on one sample of silt. This sample did not contain the same amount of



material as the standard suspensions. After each determination the spring and bucket were removed, the silt retained in the bucket was returned to the cylinder, and the contents shaken for three minutes. Twenty four readings were made at one minute intervals.

The curves show an increasing rapidity of deposition with successive sedimentation. This is probably due to partial flocculation which was not entirely removed by the agitation given. Determinations 4 and 5 show the reproducibility of the results. The values for these two determinations are practically the same over the entire curve. It can be seen that the curve representing the first measurement is the best representation of the rate of falling of unflocculated silt.

In graph 5 are given the comparative rates of settling of silt and coarse clay at 20° and 0°C . The samples used contained equal amounts of material. For the 0°C . determinations an ice-water mixture was used.

D. Discussion of Results.

The retardation by temperature of the time of falling is not so much more in the silt, especially the coarser sizes, at 0° than it is at 20° . However in the finer fractions it attains considerable proportions. This is shown by a consideration of the last particles to fall into the bucket when the pointer reaches 7.0 mms. on the scale. If a line is drawn parallel to the abscissa from the 7.0 mm. point on the ordinate, it will cut both the silt curves. At this point in each experiment the bucket contained equal weights of material which had settled from columns of suspension having the same diameter and height. The assumption is made that the average particle falling into the bucket at this time has, in each case, fallen the same distance and is the same size.

The maximum distance that such a particle can have fallen is 43

mms., since the bucket is 10 mms deep, started 26 mms from the surface of the liquid and has settled 7 mms. At 20° the particles fell this maximum distance in about 4 minutes whereas at 0° it required 6.8 minutes. This gives a difference in the time of falling of 2.8 minutes over a maximum distance of fall of 43 mms. If the retardation in the time of fall between 20° and 0° is calculated for a distance of four feet it is found to be:

$$\frac{48 \times 25.4}{43} \times 2.8 = 79.4 \text{ minutes or } 4,764 \text{ seconds.}$$

since 1 inch equals 25.4 millimeters.

Assuming an equal distribution of sizes throughout the range of the silt and that these particles settle in the order of their sizes, the particles falling on the bucket when it has settled 7 mms. should be particles having the average velocity of fall of particles within the silt limits, since the total settling caused by the sample of silt was 14.0 mms.

The curves for the coarse clay show that with low temperatures the velocity of fall of this material is much less than that of silt. As the fine sizes are approached the curves of the coarse clay diverge greatly, so that here the difference in the time of fall of the particles would be very considerable.

If the same assumptions and construction are made as for the silt, then the particles at 20° fell in 13.8 minutes, while those at 0° fell in 30.3 minutes, giving a difference between the two temperatures of 16.5 minutes.

Using the same assumptions and calculating in the same manner as before,
the result is :

$$\frac{48 \times 25.4}{46} \times 16.5 = 437.3 \text{ minutes or } 26,238 \text{ seconds.}$$

retardation for a particle of the average size of coarse clay.
Fine clay settled so slowly that measurements were not carried
out with it.

E. Tabulation of Results.

If the results so far obtained are tabulated and brought to a
unit value as the difference in time of fall between temperatures of 0°
and 20°C. over a distance of one foot, the result is as given.

Size.	Difference, in seconds.
.436 mms.	.10
.266	.75
.190	3.00
.145	6.75
.107	10.50
.082	14.25
Particles of average silt size.	1191.00
Particles of average coarse clay size.	6559.50

Graph 3 shows that as the finer sizes are approached the curve
becomes more and more nearly parallel to the vertical axis, so that it is
to be expected that the differences in the time of fall for the small
sizes will become very great. A maximum is reached for particles of
colloidal dimensions since particles of this size remain indefinitely
suspended.

For the silt and coarse clay sizes the figures given are relative and since there are so many assumptions necessary for their calculation, the values given are approximate. Nevertheless they serve to give some idea of the very important effect that temperature has on the velocity of fall of small particles.

D. Experiments on the Settling of Varved Clay under Different Temperature

Conditions.

A sample of typical Herb lake varve clay was obtained. The material was thoroughly deflocculated and samples made up of approximately the same weight per cubic centimeter as those used in the previous experiments.

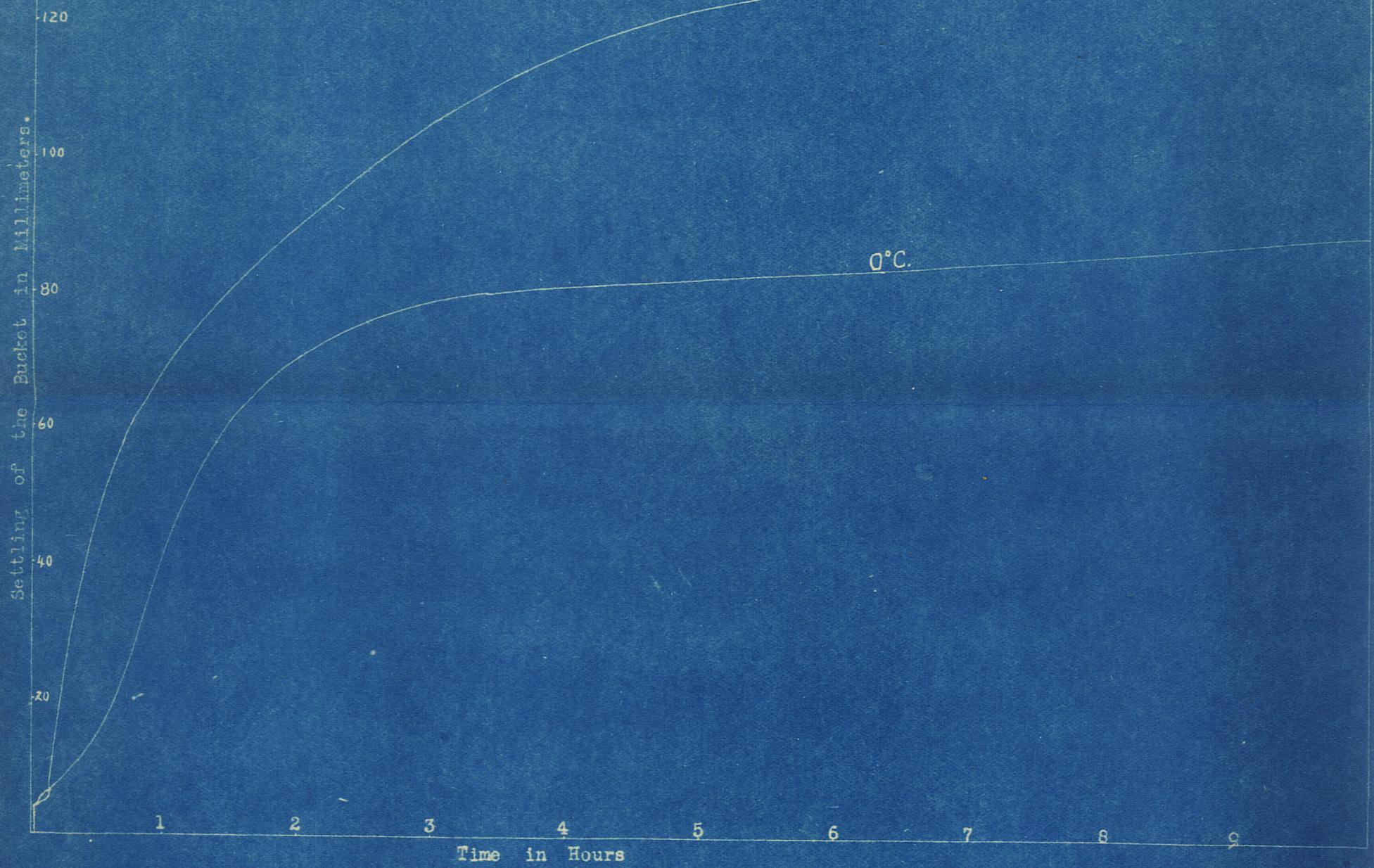
This sample consisted mostly of clay, with some silt but very little sand.

The results are plotted on graph 6. The curves soon begin to diverge appreciably. For the smaller sizes the retardation becomes very great, as can be seen by a comparison of the slopes of the two curves towards the right hand side of the graph. Because of experimental difficulties, the measurements were not carried out to completion, but were made over a period of ten hours only.

This graph shows very clearly the important effect that temperature has on the deposition of clay. The effect is not very noticeable when the material is coarse, but for the finer grades temperature is probably the most important factor affecting the deposition of unflocculated clay particles.

6.

Herb Lake Varve Clay



E. Experiments on the Deposition of Clay under Definite Temperature

Conditions.

A. Apparatus.

A zinc tank was made having a length of 24 in., width 12 in., depth 15 in. Inside this tank was constructed a second smaller tank with a length of 18 in., width of 12 in., depth 7 in., measured from the top of the outer tank. Through the bottom of the inner tank four holes were cut of sufficient size to allow glass cylinders to be set on the bottom of the outer tank. The space around the cylinders was then sealed and the inner tank made watertight. An illustration of this apparatus is given in figure 2, where A and F are the outer and inner tanks, E the cylinders.

In each tank was placed an electric heater B and a thermocontrol C. The one in the lower tank was adjusted to 4°C . the other to 9°C . Vigorous circulation in each tank was obtained by passing a stream of compressed air through the airlines D.

The apparatus was filled with water and placed outside where the temperature varied from 0 to -20°F . It was found that under these conditions, the tanks were held at the required temperatures by the controls provided, and that the variations of temperature within the tank were very small. However it was necessary to adjust the temperature of the upper tank to $.5^{\circ}\text{C}$. in order to prevent freezing of the material in the upper part of the cylinders.

Three of the cylinders were filled with tap water and a fourth with distilled water, and allowed to come to constant temperature. The temperature at various levels in the cylinders was tested and found to be the same as that of the outside bath, except for a region at the boundary of the upper and lower tanks.

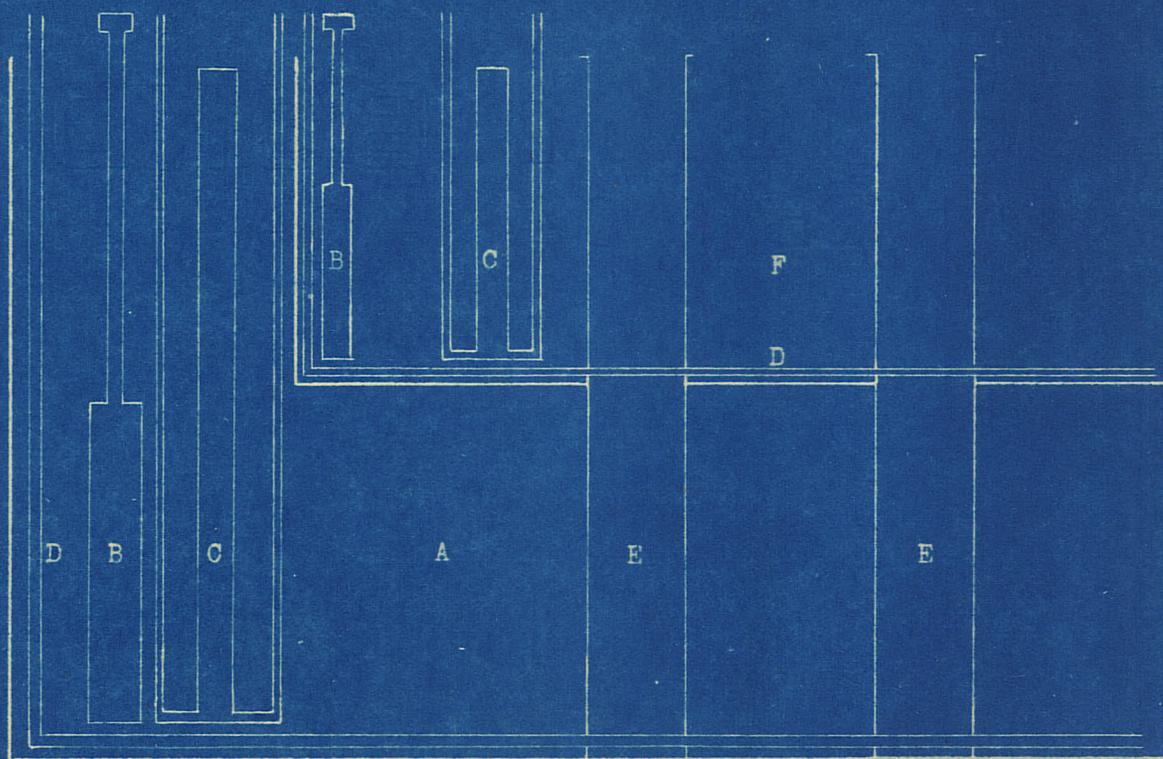


Fig. 2.

This apparatus was designed to reproduce as nearly as possible on an experimental scale the temperature conditions of a glacial lake.

B. Method and Results.

Cylinder 1. This cylinder contained distilled water. A glass tube extended about half way down the cylinder. Through this tube was passed a gentle stream of air, sufficient to keep the contents of the upper part of the cylinder in constant agitation. To this cylinder was added a quantity of deflocculated Herb lake clay containing a small amount of added sand. Agitation in the cylinder was continued for 42 hours, then stopped. After 192 hours the cylinder was removed from the tank and examined.

The coarse material was at the bottom and was well sorted. Its upper boundary was definitely marked. Above this came a layer of finer material with a fairly distinct boundary between itself and a darker finer grained layer above. The experiment would seem to show that when there is a decided difference in the size of the particles in the supply of material, there will be a complete separation, but when the sizes are gradational, the deposit will be gradational but will be much better sorted than under ordinary temperate conditions.

Cylinder 2. This cylinder contained tap water. To it was added a quantity of clay which was allowed to settle undisturbed for 192 hours. On examination it showed a light colored lower band with a darker band above, the boundary between the two being fairly distinct. The cylinder was placed in a room for a number of days. There was a distinct line marking the change in conditions, the material subsequently depositing as a uniform band of light colored sediment.

Cylinder 3. This cylinder contained tap water. At five successive

intervals quantities of deflocculated clay were added. The deposit showed five distinct sets of bands, each set having a lower light and an upper dark part. The contact between the light and dark bands of each set was not as distinct as that between the dark and light bands of different sets. Each set of one light and one dark band corresponds to an addition of material. It could be seen that the lower band of each set was coarser than the upper darker band.

Experiments were carried on at room temperature, 20°C., using similar cylinders containing tap water and adding samples of the same clay at successive intervals. Bands could be discerned, each addition of material being marked by a deposit of coarse material. The deposit from each addition of material however, showed no indication of a division into two components.

F. Experiments on Flocculation at Low Temperatures.

A. Material.

As actual sea water was not readily available a solution was made up according to analyses given by Grabau ⁽¹³⁾. This solution contained per 1000 ccs.

Sodium chloride	27.213	grams.
Magnesium chloride	3.807	"
Magnesium sulfate	1.658	"
Calcium sulfate	1.260	"
Potassium sulfate	.863	"
Calcium carbonate	.123	"
Magnesium bromide	.076	"

13. Grabau, A., Principles of Stratigraphy, p 147.

Using this solution as a standard, cylinders were filled with solutions having a salinity of 1, $1/2$, $1/4$, $1/8$, $1/16$, $1/25$, $1/32$, $1/50$, $1/64$, $1/90$, 0, that of normal sea water.

The clay used in the experiments was completely deflocculated. Its composition was approximately 50% silt, 40% coarse clay, and 10% fine clay. The cylinders were placed in a tank having a temperature of 4°C . Equal quantities of the clay were added to each cylinder at three successive intervals of one hour. After the last addition sedimentation was allowed to proceed for 118 hours. On examination the results were as follows.

B. Results.

Cylinder of 0 salinity solution. The deposit consisted of two thick layers, a whitish silt layer below and an upper dark layer, with a sharp boundary between the two. The lower silt layer showed three sets of alternating light and dark bands, the boundary between an upper dark band of one set and the lower light band of the succeeding set being much more distinct than the boundary between a light and dark band of the same set. The period of sedimentation between successive additions was not sufficient to allow the clay to settle, so that it appeared in a layer, showing increasing fineness upwards, above the silt. The suspension in the cylinder was very turbid 20 hours after the last addition of material and remained so for several days. There was no indication of flocculation in the deposit.

Cylinder of $1/90$ salinity solution. There was a deposit of 10mm., with 2 mm. of silt at the bottom showing two sets of bands, above this the material was flocculated.

Cylinder of $1/64$ salinity solution. 1.5 mms. of silt showing indistinct banding was at the bottom. Above this was 3.5 mms. of darker clay, having a lower sharp boundary with the silt. The lower part of this layer appeared homogeneous and very fine grained. It graded upwards into a layer of 1.5 mms. which consisted of various sized flocculated masses.

Cylinder of $1/50$ salinity solution. A layer of about 1mm. of silt, showing no indication of banding, was on the bottom. Above this the material was flocculated. The entire deposit, however, had a banded appearance, having three sets of layers. These sets consisted of a lower layer of light colored, relatively fine grained appearing material, with an upper component of darker colored material consisting of flocculated masses which gave the deposit a coarse grained appearance. The boundary between light and dark layers of one set was gradational, between dark and light layers of succeeding sets was sharp. Under the microscope the material in the lower light colored band appeared coarser in grain than the upper flocculated band which consisted of flocculated masses of fine grained material.

Cylinder of $1/32$ salinity solution. There was very little silt at the bottom. A layer of 1.5 mms of homogeneous material graded upwards into flocculated material indistinctly showing this flocculation banding.

Cylinder of $1/25$ salinity solution. There was a deposit of 9 mms., with no silt at the bottom. The flocculation banding was very distinct. From the bottom of the deposit the layers measured as follows. Light 1.75 mms. Dark 1.25 mms., Light 1.75 mms., Dark 1.25 mms., Light 1.75 mms., Dark 1.25 mms.

Cylinder of $1/16$ salinity solution. Banded but less distinctly so than in the previous cylinder. The lower two bands were fairly distinct.

Cylinders of $1/8$ and $1/4$ salinity solution. Flocculation banding was fairly distinct in the first cylinder but much less so in the second.

Cylinders of $1/2$ and 1 salinity solution. The material appeared fairly uniform throughout with little or no banding or apparent arrangement of material.

G. Experiments on Flocculation at Low Temperatures using Partially Deflocculated Material.

Experiments were carried out under similar temperature conditions as above, using Cross lake material that was only partially deflocculated. The suspension was added at successive intervals to cylinders containing distilled water.

The material sedimented very rapidly. The deposit showed no indications of banding except for an irregular layer of black material marking the end of each period of sedimentation. This black material was undeflocculated fine clay which constitutes the upper portion of the Cross lake varves.

H. Flocculation Experiments at Higher Temperatures.

Similar flocculation experiments were carried out at room temperatures using the same type of material and the same concentrations of electrolytes as those used for the experiments grouped under F.

The flocculation banding was most marked at a salinity of $1/25$ but was quite definite at a salinity of $1/150$ and indicated at a salinity of $1/8$. With a salinity of $1/2$ the deposit formed from the first addition was banded but subsequent deposits were homogeneous.

In the cylinders containing distilled water there was a division between the silt and clay components. Sets of bands could be distinguished corresponding to the different additions of material, but there was not the distinct boundaries between light and dark layers of each band that are

found in deposits formed at low temperature. The material remaining in suspension after the coarser grades had sedimented, flocculated and was deposited in a uniform layer.

To a cylinder containing 500 ccs. of $1/25$ normal sea water, 40 ccs. of the clay suspension were added in a continuous stream over a period of fifteen minutes. The resulting deposit showed distinctly the flocculation banding.

I. Experiments on the Relative Rate of Flocculation at High and Low Temperatures.

A cylinder containing 500 ccs. of $1/2$ normal sea water was placed outside a window where the temperature was 4°C . A similar cylinder was placed in a room at 20°C . To each cylinder was added 17 ccs. of a clay suspension and the cylinders shaken. Paper tags were placed on each cylinder in similar positions.

For about 45 minutes the turbidity of the two cylinders appeared to diminish at about the same rate. At the end of this time the relative rate of flocculation appeared to become slower in the cylinder at 4°C . In 90 minutes the tag on the cylinder at 20° was visible. The tag on the cylinder at 4° was not visible through the suspension for 175 minutes.

J. Application of Results.

Glacial lakes differ from temperate lakes in several important features. Near the ice front at least, they have inverse temperature stratification with the lower part of the lake at a temperature of 4°C . They are fed by glacial streams having a temperature little above 0°C . The deposits in glacial lakes show little or no evidence of wave or current erosion, indicating the lack of important disturbances during sedimentation. The supply of material consists of fine crushed rock; the mechanical analysis of this material shows that it is unsorted. Moreover such fresh ground material is probably to a great extent unflocculated at the time that it reaches the lake. It is generally considered that the glacial lakes contain a low concentration of electrolytes. Under these conditions the sedimentary processes would be undisturbed and the rate of settling of the material would not be influenced to any degree by flocculation.

It has been shown that temperature has a very important influence on the rate of settling of particles. It seems reasonable to assume that in glacial lakes where varves of the diatactic type are formed, ⁽¹⁴⁾ the rate of settling of the particles is a direct function of their size and the temperature of the water. The experimental work has shown that the time of fall of the smaller sized particles is very much increased by low temperatures. Again it has been shown that as the particles decrease in size, retardation increases very rapidly. In a glacial lake this

14. Studies in the Quaternary Varve Sediments in Southern Sweden.

Bull. Com. Geol. de Finlande; N:o 60, p 1 - 164.

Sauramo defines diatactic structure as the effect of sorting of the materials of the varves according to sizes and specific gravity of the

factor would become very important. During the melting season there is a continuous supply of material. The coarser sizes would settle relatively rapidly. The finer sizes would settle very slowly, since the water in the lake would be in the neighborhood of 4°C . This would allow a very definite grading of the material. At the close of the melting season the supply of material would diminish to a relatively small amount, or probably be almost stopped. The result would be that in a short time all of the coarse material would be deposited. The division between the lower and upper parts of the varve would correspond to this change of conditions.

During the winter season the finer material would slowly settle forming the upper part of the varve. The manner of sedimentation of the very fine material during the remainder of the winter season is not so easily understood. In water at 4°C , the fine clay would settle at an extremely slow rate, so slow in fact that it is difficult to understand its complete sedimentation before spring, unless flocculation takes place. The experimental data seem to show that flocculation and subsequent sedimentation take place much more slowly, especially for the finer sizes, in cold than in temperate waters. The stillness of the water during the winter season coupled with the increase in electrolytes and material in suspension due to the formation of the ice would have the effect of

particles, the coarsest at the bottom and the finest at the top.

Symmet structure is the name used to refer to clay deposited under the control of an electrolyte. In this case, the particles, large and small, go down together and form an unsorted mass due to flocculation of the grains.

increasing the rate of flocculation. During the entire melting season there may have been a slow flocculation. It is known that the rate of flocculation increases for increasing numbers of particles per unit volume. As there is an increasing amount of material in suspension in the lake as the season progresses, it is probable that the rate of flocculation would increase towards the close of the melting season.

The maximum salinity permitting the formation of diatactic varves seems to be about $1/50$ that of normal sea water, although flocculation appears at a salinity of $1/90$ that of sea water. With increasing concentrations, the flocculation becomes more rapid as is shown by the decrease in the quantity of unflocculated silt deposited in the bottom layer of the experimental cylinders. Around a concentration of $1/32$ of normal sea water the flocculation and sedimentation of some of the material takes place as rapidly as the sedimentation of the coarser material, so that the coarser material does not appear as an unflocculated deposit but is mixed with this flocculated finer material. Above this concentration the flocculation of the clay takes place in such a manner as to allow the sedimentation of the flocculated coarse material to be fairly complete before the finer material becomes flocculated and deposited. Gally (15) has pointed out that a coarse suspension is more affected by an increase of electrolyte than a fine one. Apparently the coarse material has time to agglomerate and settle before the finer material is sufficiently flocculated to allow rapid sedimentation.

It is evident then, that in the formation of true diatactic varves, flocculation plays little or no part, except possibly in the

15. Gally, Rene, Studies in the Coagulation of Clay,
Kolloidchem. Beihte 21, p. 431 - 489, 1926.

finest part. In the formation of a diatactic varve it is necessary to have material containing at least two different sizes of particles, sedimentation in water of low temperature, a low amount of electrolytes if the material is of such size as to be affected by flocculation and material which is unflocculated at the beginning of the process.

Coarse suspensions, with particles of from 0.03 to 0.1 mms. in diameter are in general indifferent to flocculation and the other influences affecting fine sediments, and settle with a velocity dependent on their size, degree of roundness and the temperature of the water. (16)

When the supply of material contains such sized grains in addition to finer sizes, a type of varve might exist which is diatactic in the coarser portion and symminct in the upper part.

When the supply of material is composed of particles smaller than 0.03 mms. and the concentration of the electrolyte is from about $1/32$ to $1/4$ that of normal sea water, flocculation and sedimentation take place in such a manner as to give the flocculation banding. This phenomenon appears to be one of concentration of electrolyte and size of material and is more or less independent of temperature, at least for the sizes and temperatures used in the experiments. The method of origin of this banding has been explained in a preceding paragraph.

Above a concentration of $1/2$ normal salinity sediments consisting of silts and clays are flocculated too rapidly to allow any banding.

16. Wells, R.C., Flocculation of Colloids.,

Report of the Committee on Sedimentation, April 18, 1923, p. 50 - 52.

These results hold for unflocculated material. The experimental work on partially flocculated clays shows that such material does not form banded deposits. This is probably due to the fact that in such materials the particles are not present in their true sizes, the finer ones especially being agglomerated, and that material once partially flocculated is much more easily flocculated the succeeding times than is unflocculated material.

The contrast in color between the lower and upper bands of a varved deposit is an outstanding feature of such clays. It has been found that quartz when ground in a mortar shows a perceptible darkening as the grinding proceeds to very small sizes. This difference in color for different sized particles is not marked enough to give the contrast that is seen in a varve. Ferric and ferrous sulphides would cause a dark color if they were present in appreciable quantities in the clay. Tests showed a trace of sulphides in the Herb lake material and a small quantity in the Cross lake Clay. When the mechanical analyses were made of this material the different grades were examined. It was found that they varied in color from almost a white for the silt to a dark brown for the fine clay. Tamm ⁽¹⁷⁾ has confirmed the statement, made by many investigators, that there is a large amount of mica in glacial clay. He found that the mica was concentrated in the finer grades. The percentage of alumina and iron is higher in the fine part of the varve. These facts indicate the probability that the dark color in the fine part of the varve is partially due to the mineralogical nature of the material, possibly a concentration of those minerals high in alumina and iron, which frequently are dark colored minerals. The light color in the coarser part of the varve is due to a predominance of quartz and feldspar particles.

17. See reference no.8.

K. Some Conditions Essential for the Formation of Diatactic Varves.

The nature and importance of some of the factors affecting the formation of varves have been determined in the experimental work presented in the preceding pages. Some of the conditions that have been found essential for the formation of diatactic varves are as follows.

1. Unflocculated material of assorted sizes.
2. Sedimentation in water of low temperature. Otherwise there is not sufficient difference in the time of fall of the particles to give the grading that is characteristic of diatactic varves.
3. Periodic supply of material. Varves have been reported by Sayles, (18) in which the lower part of the varve had an alternating series of coarse and fine layers of silt and above this was the finer part of the varve. Banding is not necessarily seasonal when the materials are coarse and consequently sediment rapidly. A daily variation of supply would suffice to give a banding of deposits in shallow water, if the material was coarse. With finer materials and deeper waters a longer period would be required.
4. Low concentration of electrolytes. Since flocculation takes place at a salinity of $1/90$ normal sea water it is doubtful if diatactic varves consisting of fine material could be formed at a much greater salinity than this.

18. Sayles, R.W., Report of Progress of Studies on Seasonal Deposition in Glacial Sediments., Report of the Committee on Sedimentation, April 26, 1924, p. 33 - 39.

SUMMARY.

1. The finer fraction of a varve contains a greater percentage of ferric oxide, alumina and potash, and less lime than the corresponding coarser fraction. The silica content seems variable as does that of the oxides of magnesium and sodium. There is a greater loss by ignition in the coarse fraction, except in the Cross lake sample.
2. There is a definite difference in mechanical composition between the coarse and fine parts of a varve.
3. The evidence indicates a withdrawal of the ice front during the period that the Herb lake sample was being deposited.
4. Temperature has an important effect on the velocity of fall of particles smaller than .5 mm in diameter. As the temperature decreases the velocity of fall of a small particle becomes less, until a minimum is reached at 0°C.
5. As the size of the particle decreases, the retardation by temperature of its velocity of fall becomes much greater.
6. The retardation by temperature of the velocity of fall of small particles is the factor which causes the definite grading seen in varved deposits.
7. Varve like deposits can be reproduced in the laboratory, if unflocculated material is sedimented in fresh water near a temperature of 4°C.
8. Clay suspensions are flocculated in water having a salinity 1/90 that of normal sea water. Around a salinity of 1/50 that of sea water

the flocculation and deposition of the coarse material takes place much more rapidly than that of the fine material. The coarse material is deposited as a more or less uniform layer. The fine material is deposited on top of this as a layer of large floccules. The two layers are fairly definitely divided. The name flocculation banding has been given to this type of deposit. The phenomenon appears to be independent of temperature.

9. Varve deposits cannot be formed in water having a salinity much greater than $1/4$ of sea water.

10. Material that has been flocculated is not likely to be sufficiently deflocculated, by any natural process, to yield diatactic varves.

11. Flocculation, especially of the finer sizes of material, appears to take place more slowly at low temperatures.

12. The experimental data obtained indicate that the following conditions are essential for the formation of diatactic varves.

A. A supply of unflocculated material of assorted sizes. The only readily available material of this nature appears to be the products of glacial erosion.

B. Sedimentation in water of low temperature.

C. A periodic supply of material.

D. A low concentration of electrolytes.

E. Sedimentation in water relatively free from disturbances such as waves or currents.

13. Under certain conditions varves do not necessarily represent a year's deposit.

14. It is suggested that the difference in color between the two bands is partially due to a difference in mineralogical composition.