AN INVESTIGATION OF THE EFFECTS OF SPHERICITY AND ROUNDNESS ON THE PERMEABILITY OF UNCONSOLIDATED SEDIMENTS

Thesis for the Degree of M. S.
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B. T. Sandefur
Major professor

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By

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ABSTRACT

The effect the geometric appearance of the constituent particles of a material has on its permeability has been the subject of emperical conjecture, but never the object of a detailed study. This report describes the methods used and results obtained in determining the influence of sphericity and roundness upon the permeability of eight selected sand samples. Of the six variables most frequently mentioned as having an effect on permeability namely; size, sorting, shape, arrangement or packing, cementation or lithification, and sedimentary fabric, five are believed to have been eliminated by using unconsolidated, sieved samples and a uniform procedure for determining permeability. The sphericity and roundness of each sample was measured and correlated with the laboratory determination of its relative permeability. The results indicate the more spherical the particles the higher the relative permeability; at least within the limits dictated by the range in sphericity and roundness of the samples which were used. Additionally, either extremity in so far as sphericity is concerned, apparently can be modified by abnormal roundness in the opposite direction. Thus a material composed of grains having a "high" sphericity will have a "high" relative permeability only if the roundness of the particles also is correspondingly high.

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11/30/51

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INTRODUCTION

The most important physical properties of sediments are those related to their pore spaces or "interstices". The ability of a rock to contain fluids within its mass (porosity), and more important the ability to allow fluid movement (permeability), either natural or artificially induced, is of the utmost importance in the accumulation, migration, geological and geographical distributation, as well as in the extraction of oil, gas, and ground water.

Moreover, both porosity and permeability vary within wide limits and are subject to constant revision as the normal geologic processes, from sedimentation through lithification and possibly metamorphism, occur. It may be said that any problems concerning porosity and permeability become more complex with the progression of these geologic processes. It would seem apparent then that any attempt to understand thoroughly either porosity or permeability must start with a study of natural, unconsolidated, clastics and not with drill core or even well samples. In this respect the writer is in agreement with Graton and Fraser (1935) who studied the problem extensively from the theoretical viewpoint and whose well known papers were published in the Journal of Geology.

Various authors list different factors as contributing to the sometimes puzzling behavior of sediments insofar as their fluid relationships are concerned. There is general agreement however, that six particle characteristics are among those factors present. Fraser (1935), Pettijohn (1949), Krumbein and Sloss (1951) and LeRoy (1950) indicate the following:

1. Size
2. Shape
3. Sorting
4. Arrangement or packing
5. Cementation or lithification
6. Sedimentary fabric

In addition surface texture, mineralogical composition, (LeRoy 1950), and method of deposition (Fraser 1935) have been mentioned. An effect due to fabric appears only recently in the literature and apparently has received little, if any, investigation. Pettijohn (1949) has recognized the effect fabric may have as evidenced by the following statements from his book:

> "In actual stratified sediments the permeability has been found greater parallel to the bedding than perpendicular to it. Imbrication and other anisotropic fabric patterns are in some way responsible for the vectorial character of the permeability."

Obviously the easiest way to study the effect of any one of these characteristics upon permeability is to conduct research in such manner as to control the effect of the others. The presence of too many variables, in the judgement of the writer, has subtracted from the value and usefulness of many otherwise scholarly achievements.

It is the purpose of this study to determine the effect that one of these particle characteristics, namely shape, may have upon permeability. The method used is believed to offer the best possibility of obtaining objective results.

METHOD OF INVESTIGATION

Eight sands, representing at least three different environments, were used in this study. The names by which they will be referred in this report and the environment and origin of each are as follows:

St. Peter	Marine (Lamar 1928)
Sleeping Bear	Lake Michigan dune
Grand Marais	Lake Superior dune
Mason Esker	Central Michigan glacial
Caseville	Lake Huron-Saginaw Bay beach
Copper Harbor	Lake Superior beach
Detroit Beach	Lake Erie beach
Eagle Harbor	Lake Superior beach

Plate I is a generalized map of Michigan and adjacent areas showing the locations from which the samples were obtained.

As all the sands were unconsolidated any effect on permeability due to cementing material was nullified. Two other variables, size and sorting, were essentially eliminated by sieving. Each sample was placed in the Ro-tap for 10 minutes and only that fraction passing through Tyler sieve 28 (.589 mm.) but retained on sieve 35 (.417 mm.) was used in the final analysis. A small part of each was mounted on slides and retained for the shape analysis.

Of the remaining factors generally accepted as affecting permeability sedimentary fabric is important in laboratory permea-

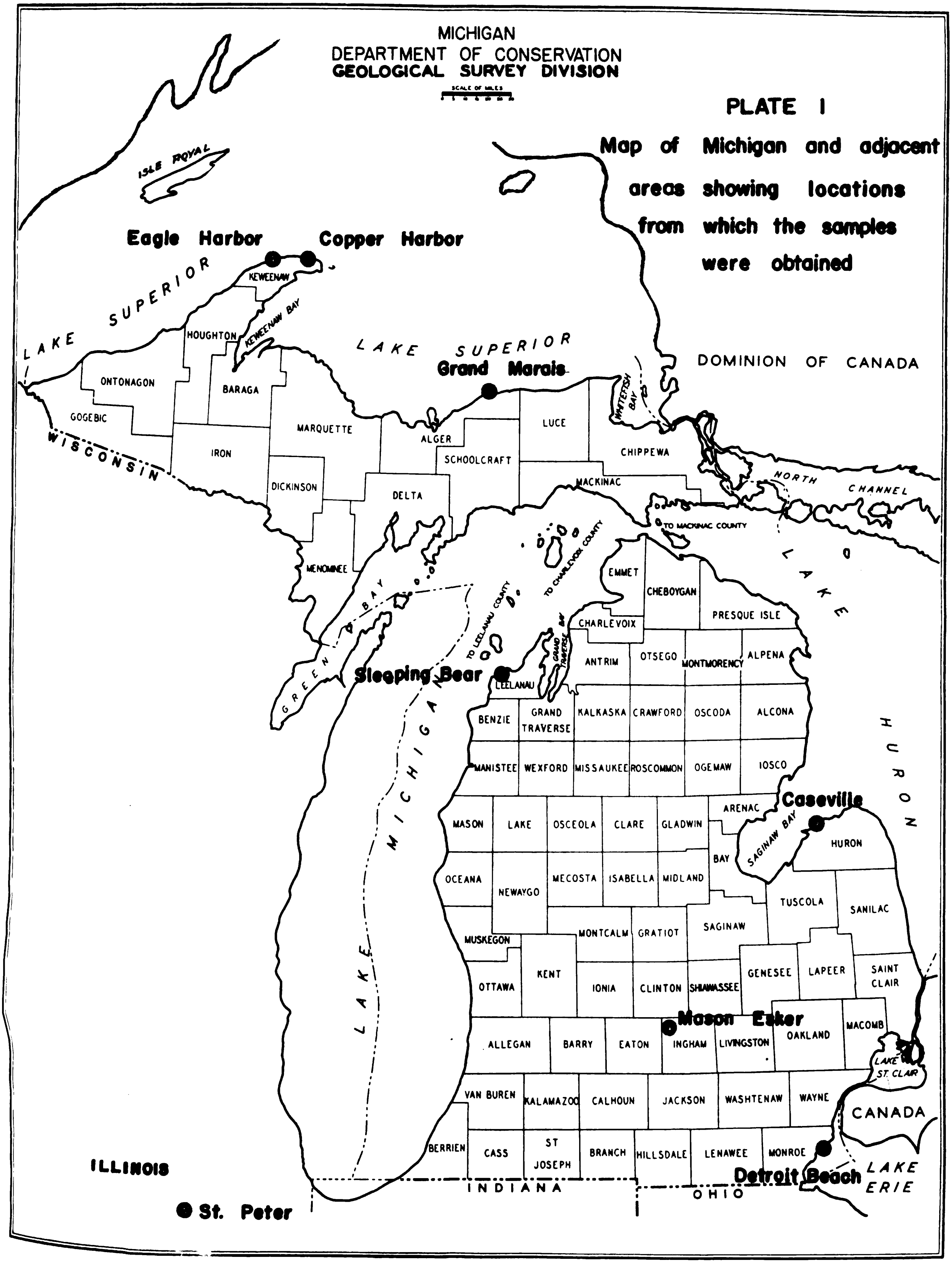

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PLATE I

Map of Michigan and adjacent areas showing locations from which the samples were obtained

bility measurements under certain conditions. A certain amount of "zoning" often takes place in a poorly sorted sediment during a permeability determination; generally in the form of the heavy, coarse material settling while the finer material tends to rise. According to Johnson (1951) this fine particle migration may result in "pore plugging." The result is the formation of several zones, each with different permeability characteristics. The problems involved would be much like those encountered with soil samples, only less obvious. Although it is impossible, by mechanical means at least, to isolate a single grain size, the size range obtainable from sieving is believed so small as to render any effect on permeability due to fabric as negligible.

The two remaining variables; shape and particle arrangement or packing, are not to be discounted. The sands were selected from such locations as might reasonably be expected to give a wide range in shape. The St. Peter sample, particularly sieve size 35, is very "round" (Lamar 1928), while the Copper Harbor sand, locally at least, is generally considered "angular." One might reasonably expect the beach, dune, and esker sands to be intermediate between these two extremes insofar as shape characteristics are concerned.

The variable effect due to grain arrangement or packing, if not controlled, was minimized by adopting a standard procedure as recommended by Johnson (1951). It is explained fully in the section under permeability.

SPHERICITY AND ROUNDNESS

Sphericity and roundness are two components, which combine to produce the geometric aspect of a particle. While perhaps related, they are not synonymous, a fact made clear by Wadell (1932). He recognized a relationship between the surface area and the volume of a particle and realized a sphere has the least surface area of any shaped particle of a given volume. For any particle the ratio s/S may be expressed, where S is the surface area of the particle and s is the surface area of a sphere having the same volume as the particle. For a sphere this ratio will be unity, but for any other shaped particle its value will be less than 1.000. This relationship was given the name sphericity by Wadell (1932). As it is difficult to measure the surface area of any particle, sphericity is often expressed as the ratio between the so-called nominal diameter of a particle and the diameter of the circumscribing sphere. The nominal diameter is the diameter of a sphere having the same volume as the particle while the diameter of the circumscribing sphere usually is the greatest diameter of the particle. To translate this last relationship into planer units for use in measuring projected grains Wadell (1935) has suggested the following formula for determining sphericity:

$$\phi = \frac{d_c}{D_c} \qquad (1)$$

where d_c is the diameter of a circle equal in area to the area of the projected grain (nominal diameter) and D_c is the diameter of the smallest circle which would circumscribe the projected grain.

Wadell's method of sphericity measurement is very time consuming as it is necessary to trace the projected image of the grain before any measurements may be made.

Riley (1941) has proposed a rapid method for determining sphericity, which he has found especially adaptable to particles of sand size. It is called the inscribed circle sphericity and involves the square root of the ratio of the inscribed circle i, and the circumscribed circle D_c as:

$$\phi = \sqrt{\frac{i}{D_c}}$$

Measurements are made with the aid of a concentric circle protractor made to fit the microscope occular. Drawings of the individual grains are not necessary.

Schmitt (1949) combined the best points of both methods and arrived at a scheme, which is both rapid and accurate. After removing the occular and lower nicol of a polarizing microscope the grains were projected with the aid of a camera lucida attached to the barrel of the microscope. The projections were made directly on to a concentric circle protractor, made with black lines on heavy white paper, with which the diameter of the inscribed and circumscribed circles of each grain were easily measured.

The roundness of a particle involves the sharpness or roundness of its corners. According to Wadell (1935) roundness is essentially a planimetric conception, referring to the smooth curvature of the outline of a plane area, projected area, or cross section. It usually is expressed as the ratio between the average roundness of the corners and the radius of the maximum inscribed circle according to the formula:

$$\rho = \frac{\sum\left(\frac{r}{R}\right)}{N} \qquad (3)$$

where r is the radius of a corner, R is the radius of the inscribed circle, and N equals the number of corners measured. The value obtained from measuring a particle of perfect roundness using this formula is 1.000.

This method is readily adapted to a camera lucida projection directly onto a heavy paper concentric circle protractor.

Using Riley's method of sphericity, as modified by Schmitt, and Wadell's method of roundness, measurements were made of the particles found in the sieved fraction (.417 mm. diameter - .589mm. diameter) of each sample. The medium used in the preparation of the glass slides has the trade name "Aroclor." Because of its high index of refraction ($n = 1.66$) it has been found more satisfactory than Canada Balsam for projection methods. It imparts a high relief to quartz, the most frequent mineral in sands. With the aid of a mechanical stage it was easy to devise a system whereby the same grain was not measured twice. A sufficiently large sample was mounted so that only those grains in the center of the field and in sharp focus were considered. Measurements were not confined to quartz particles although it was the most common mineral of each sample.

After measuring 200 grains of the St. Peter sand the average sphericity and roundness were computed for the first 75 grains, the first 150 grains, and the total 200 grains. The results are summarized in the following table.

TABLE I

Sphericity and Roundness of Varying Counts of Sieved St. Peter

Count	Sphericity	Roundness
75	.8688	.7649
150	.8632	.7617
200	.8677	.7681

It is apparent that little, if any, accuracy is to be gained by counting 200 grains rather than 75. It was decided therefore, that the measurement of 100 grains from each sample would result in representative figures for the sample as a whole.

Table II, on the following page, gives the results obtained by measuring the sphericity and roundness of 100 grains from each sample.

TABLE II

Sphericity and Roundness Values of the Sieved Portion of Each Sample

Sample	Sphericity	Roundness
St. Peter	.868	.768
Eagle Harbor	.849	.501
Grand Marais	.832	.620
Sleeping Bear	.828	.532
Mason Esker	.820	.407
Copper Harbor	.819	.307
Detroit Beach	.812	.396
Caseville	.806	.420

PERMEABILITY

The permeability of a material is a measure of its ability to allow fluid movement into and through its mass. Clearly it is related to porosity, especially to the size and arrangement of the interstices. A rock material may be highly porous and either permeable or impermeable, but in no case can it be both non-porous and permeable. Clays actually may be very porous and contain a large volume of fluid for their mass, but the pore spaces and connecting passages are so small that most of the liquid is held by molecular attraction, thus making them essentially impermeable. Such materials as coarse sands, gravels, and certain types of lavas may be less porous than clay, but due to the size and arrangement of the pores be able to transmit large volumes of water. These rocks are said to be highly permeable. A wide range in the permeability of different rock types has been observed. Generally, fine materials such as fine sand, are less permeable than coarse gravels. Coefficients of permeability, expressed in Meinzer's units, ranging from .0002 for a clayey silt to 90,000 for a gravel have been determined in the hydrologic laboratory of the U. S. Geological Survey. Thus the gravel has a capacity for carrying water at a rate about 450,000,000 times that of the clayey silt (Wenzel 1942). A Meinzer unit is defined as the flow in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 per cent at a water temperature of 60°F. It is a unit used in this report and is designated as P_m.

Hagen (1839) and Poiseville (1846) have been given credit for first studying the flow of water through capillary tubes. They found that the rate of flow through capillaries varied directly as the hydraulic gradient of the system. Hagen also investigated the effect of temperature on the viscosity of water, (Tolman 1937). Later Darcy (1856) conducted experiments on sand and verified the results of Hagen and Poiseville, applying the principles to the study of water movement through water bearing materials. He formulated his conclusions into what is known as Darcy's law. For permeability measurement it may be expressed as $Q = PIAt$, in which Q is the volume of flow, P is the permeability coefficient of the material, I is the hydraulic gradient of the system, A is the cross-sectional area of the material, and t is the length of the period of flow.

Subsequent investigation has been carried out to determine the validity of the law under the extremely low hydraulic gradients which occur in nature. The results obtained from the study of the flow of water through sand samples indicate the law applies for heads as low as 2 or 3 inches per mile. Tolman (1937) states that normal ground water gradients seldom exceed 1 per cent, or 53 feet per mile. It is evident that the basis for permeability measurements is well founded.

There are two methods by which the permeability of a water bearing material may be determined with any degree of accuracy. One is a field method, which involves pumping tests and the other is a laboratory method involving determinations, according to the principles of Darcy's law, on undisturbed samples. It is difficult, if not impossible, to secure completely undisturbed samples of rock, particularly unconsolidated rock. The problem is intensified when dealing with subsurface formations. Even the collection of volumetric samples is undesirable as it is doubtful if the original particle arrangement can be reproduced though the original volume may be attained. Furthermore, the lithologic characteristics of many rocks, particularly sediments, change so rapidly within short distances that the permeability of any one sample probably would not approach the permeability of the formation. Reduced to practicality and economics, laboratory permeability measurements may be of doubtful value. The field methods, whereby the combined formational characteristics contribute to the results, are more reliable.

For the collection of basic data, however, laboratory methods are more than adequate; if their limitations are recognized. In this research it was not necessary to arrive at absolute values for the permeability of the various sand samples. Relative values are just as desirable and, as will be shown later, actually involve less chance of error. Consequently, the permeability values in this report are not to be taken as the true permeability of any sample or type of sand; but rather as a value relative to that of the other samples and it is believed, in the correct order of magnitude. This has been accomplished by following a uniform procedure designed to eliminate human error as much as possible.

The apparatus used is pictured on page 16. It is a constant-head, discharging type permeameter designed by Meinzer in 1923. It was devised specifically to measure the rate of flow of water through columns of unconsolidated materials under low heads, such as are found in nature (Wenzel 1942). The glass cylinder is about 20 centimeters high and has an inside diameter of 7 centimeters. A column of sample about 10 centimeters in length is placed within the cylinder and is supported on a perforated disk covered with cheesecloth about midway between the inlet a, and the outlet for the upper pressure gage b. Water from the glass reservoir c is introduced below the sample, under a head which remains essentially constant. It percolates upward through the sample and discharges at d. The difference in head at the top and bottom of the sample is measured by the two pressure gages, e and e'. They indicate respectively, the elevation at which the water is being discharged after passing through the sample and the elevation of the head under which the water is being introduced into the sample from below. Tap water enters the reservoir through a rubber hose f in a volume great enough to maintain an overflow at g, thus insuring a constant head at that point.

As stated in the section under permeability, Darcy's law, when given area and time dimensions and applied to permeability, may be written $Q = PIAt$ where Q is the volume of flow, P the permeability coefficient, I the hydraulic gradient, A the cross-sectional

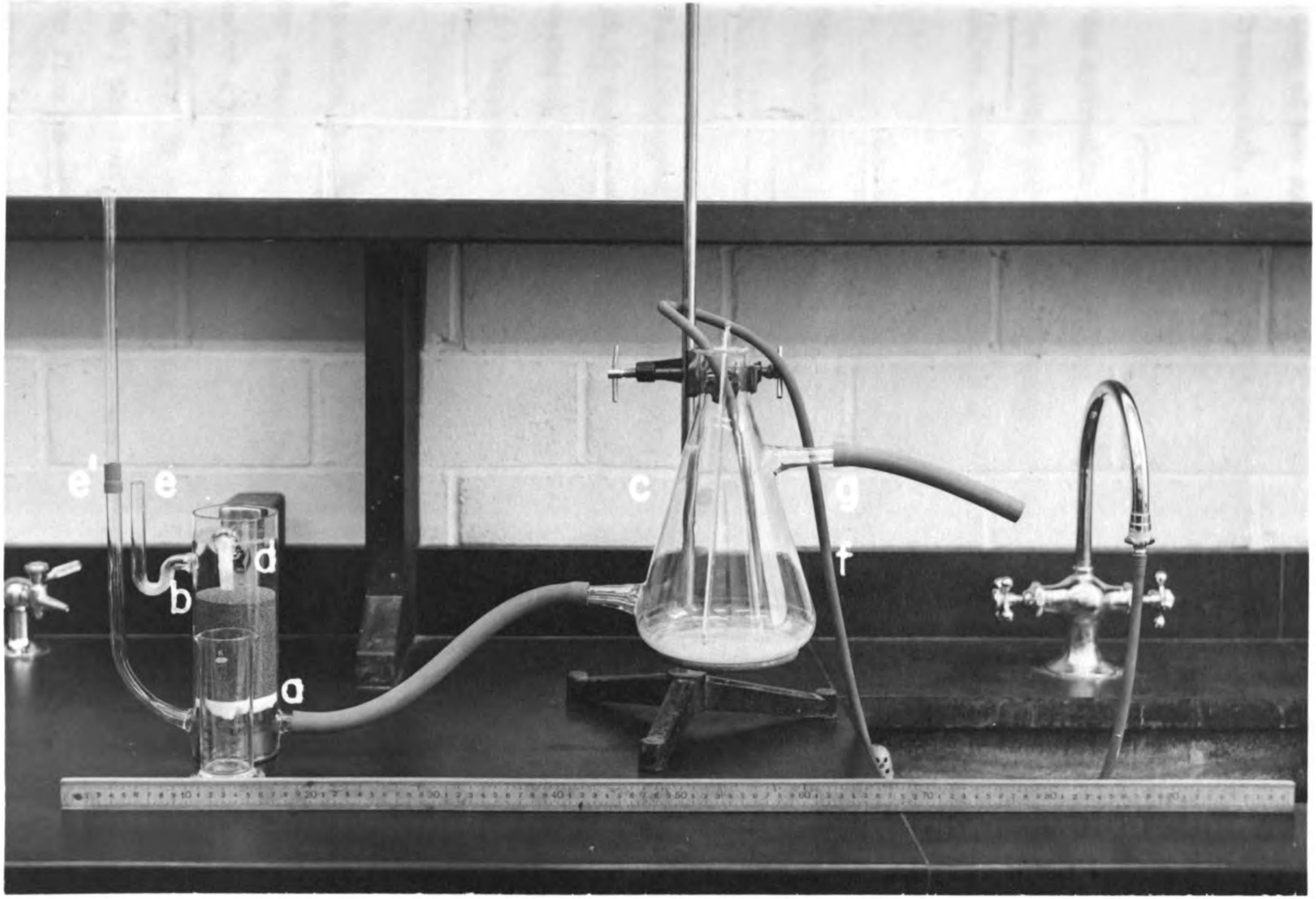


PLATE II A photograph of the apparatus used in the permeability measurements area of the material, and t the length of the period of flow. Transposing, the equation may be written as:

$$P = \frac{Q}{IAt} \tag{4}$$

The hydraulic gradient I, is actually the difference in head at the bottom and top of the sample, as measured by the two pressure gages, divided by the length of the column of material or:

$$I = \frac{h}{l} \tag{5}$$

Substituting (5) in (4) it becomes:

$$P = \frac{Ql}{hAt} \tag{6}$$

The cross-sectional area of the sample using this apparatus is 38.50 square centimeters. The values for Q, l, h, and A are measured in centimeters, and the value t in seconds. Then formula (6) becomes:

$$P = \frac{Ql}{38.50\ ht} \tag{7}$$

in which P is the coefficient of permeability in cubic centimeters per second through a cross-sectional area of 1 square centimeter under a hydraulic gradient of 100 per cent at a water temperature of 60°F. By multiplying equation (7) by the factor 21,200 (Wenzel 1942) the coefficient is expressed in Meinzer units where P_m equals the flow in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 per cent at a water temperature of 60°F. as:

$$P_m = \frac{Ql}{816,200\ ht} \qquad (8)$$

Equations (7) and (8), multiplied by the appropriate temperature conversion factor in Table III, are the ones used in this report.

It was necessary to control as closely as possible the effect packing or particle arrangement would have on the permeability values of the various samples. An attempt was made to do this by using a uniform system of "wet packing" the samples in the percolation cylinder. Four or five millimeters of water was allowed to rise above the cheesecloth covered disk before two or three centimeters of sample was inserted. With the aid of a handle on a rubber stopper this increment was rammed and packed until no further volumetric decrease occurred. Additional fractions of sample were added and packed in the same manner, being kept wet by the capillary action of the water, until the sand column measured ten centimeters in length.

Following the procedure described in the preceding paragraph a sample of the St. Peter was prepared for a trial test. Discharge readings and associated data necessary to calculate the permeability were taken at regular intervals for a period of twenty days. Particular attention was directed to the "megascopic peculiarities" which appeared to influence the test. Within five hours from the beginning of the experiment the water in the reservoir was noticeably contaminated with air, exhibiting a milky color and containing

TABLE III

Factors for converting a permeability coefficient at a given water temperature to a permeability coefficient at a water temperature of 60°F.

Temperature °F.	Factor	Temperature °F.	Factor
55	1.08	66	.92
56	1.06	67	.91
57	1.04	68	.89
58	1.03	69	.88
59	1.01	70	.87
60	1.00	71	.86
61	.99	72	.85
62	.97	73	.84
63	.96	74	.83
64	.95	75	.82
65	.93	76	.81

hundreds of minute air bubbles. This entrapped air caused an occasional bubble to boil through the sample leaving behind a cavity from five to fifteen millimeters in length. The erratic repetition of this "boiling" resulted not only in the rearrangement of the particles, but contributed to a general volumetric increase of the sample. Within eight hours a slight coloration of the white St. Peter sand, near the lower end of the sample, was noted. It was brownish-yellow and may have been iron stain. Since the particular sample of St. Peter used was over 95 per cent quartz, the source of the coloration was due probably to dissolved minerals in the tap water. In about seven days this staining had effected the entire sample and apparently its color was increasing in intensity.

Throughout the test the permeability of the sample decreased. Minor recoveries, as well as short periods of apparent stabilization, occurred within the overall trend. However, no pattern recognizable to the author was observed. When no new peculiarities seemed to be forthcoming the test was discontinued and a sample of the Copper Harbor sand was placed in the permeameter. The same method of "wet packing" was employed and similar observations made throughout a twenty-seven day test. The Copper Harbor sand resembles coffee in appearance, nevertheless iron colored stains were soon evident throughout the sample. Although uniform in chemical composition the Copper Harbor sample contains a greater variety of minerals than the St. Peter sand. It is composed chiefly of basaltic material and the commonly associated basic minerals. The prospect of micro-chemical changes between the dissolved chemicals of the water and the mineral constituents of the sample should not be discounted. Cavities, resulting from released air bubbles, occurred at irregular intervals as in the previous test.

The permeability generally decreased throughout the test. Compared with the St. Peter, it dropped faster to a lower level and when plotted against time its curve tended to be flatter in its lower extremity. Minor fluctuations as well as short intervals of stabilization were observed, but like those of the St. Peter, they did not occur in a definite pattern.

Obviously the method of "wet packing" was unsatisfactory. The recessional curves had no points in common thus making relative permeability determination hazardous. The effect of entrapped air, although undetermined in magnitude, apparently effects the results considerably. Johnson (1951) described the method of packing he employs in the Hydrologic Laboratory of the U. S. Geological Survey at the University of Nebraska. He has designed the "Johnson Compaction Table", which is motor driven and consists essentially of a table on which the percolation cylinder containing the dry sample is clamped. The table is raised one-half inch by means of a cam and allowed to drop once each second, thus packing the sample. The results of considerable research on his part indicate twenty-five drops will give a packing "very similar to natural packing for many materials." He warns against simple jarring, rodding, tamping, or tapping methods of packing due to the presence of the human factor which precludes any possibility of consistency.

Although the "Johnson Compaction Table" was not available a method identical in principle was devised. The percolation cylinder, with ten centimeters of dry sample in place, was raised one and one-half inches and allowed to drop on a book. Twenty-five drops in this manner were given each sample and usually resulted in a ten to twenty per cent reduction in its volume. The uniformity of the operation is believed to have nullified the variable effect packing can have on permeability. Of the six variables listed on page 2 which can effect permeability to an undetermined degree, all have been eliminated except shape. This factor can be measured and in this study will be held responsible for any differences encountered in the permeability of the various samples.

After packing a sample in the permeameter as described the apparatus was started and the exact time of the initial discharge recorded. At each succeeding fifteen minute interval the discharge, water temperature, difference in head at the two ends of the column, and the length of the column were measured and the permeability calculated. The discharge was measured for a five minute period. Readings were continued in this manner for 2 hours and 45 minutes and the results plotted in the form of a time-permeability curve. The curve for each sample is shown on page 23 or 24. The recorded data from which they were drawn is contained in Tables V-XII in the Appendix.

PLATE III

The time - permeability curves of the

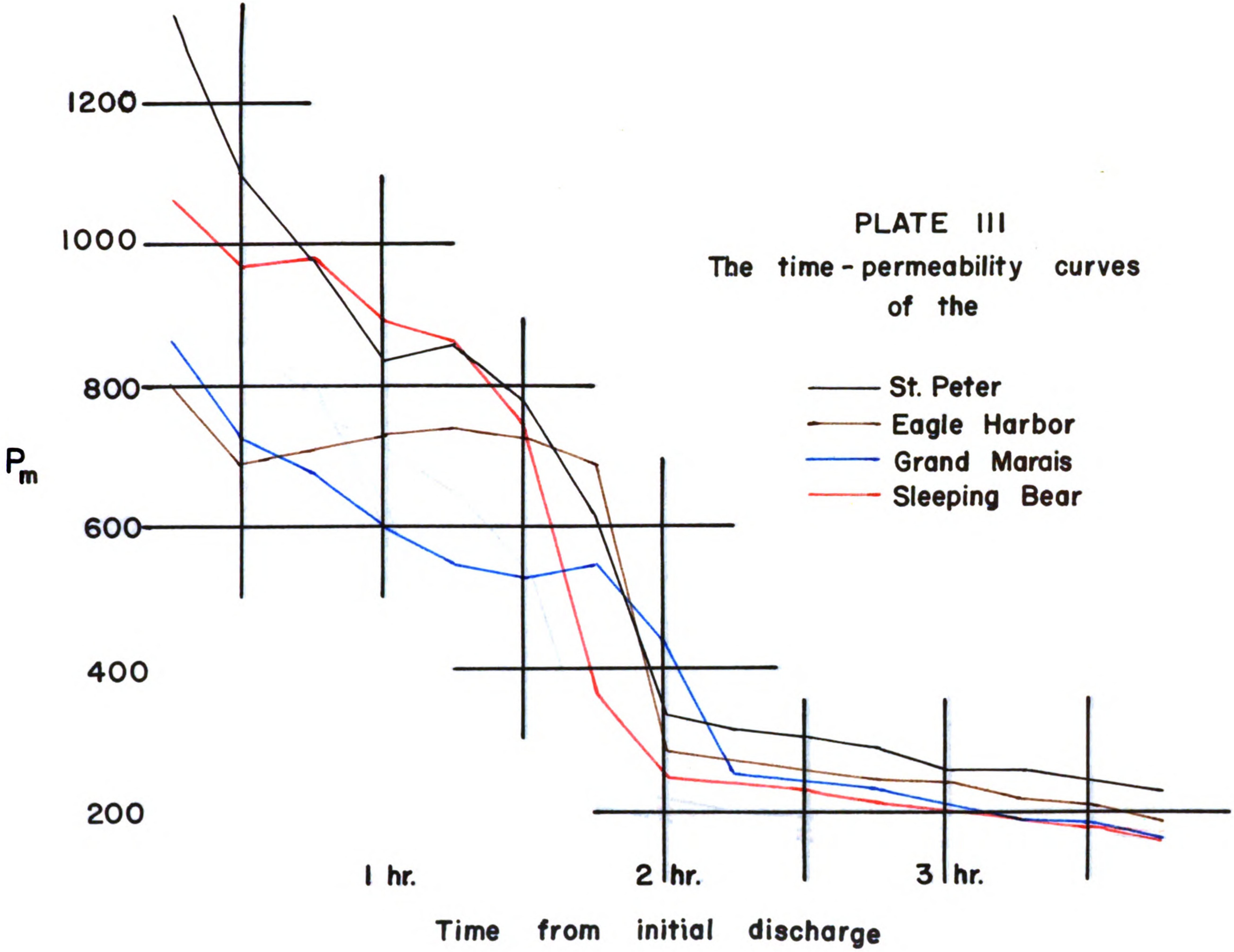
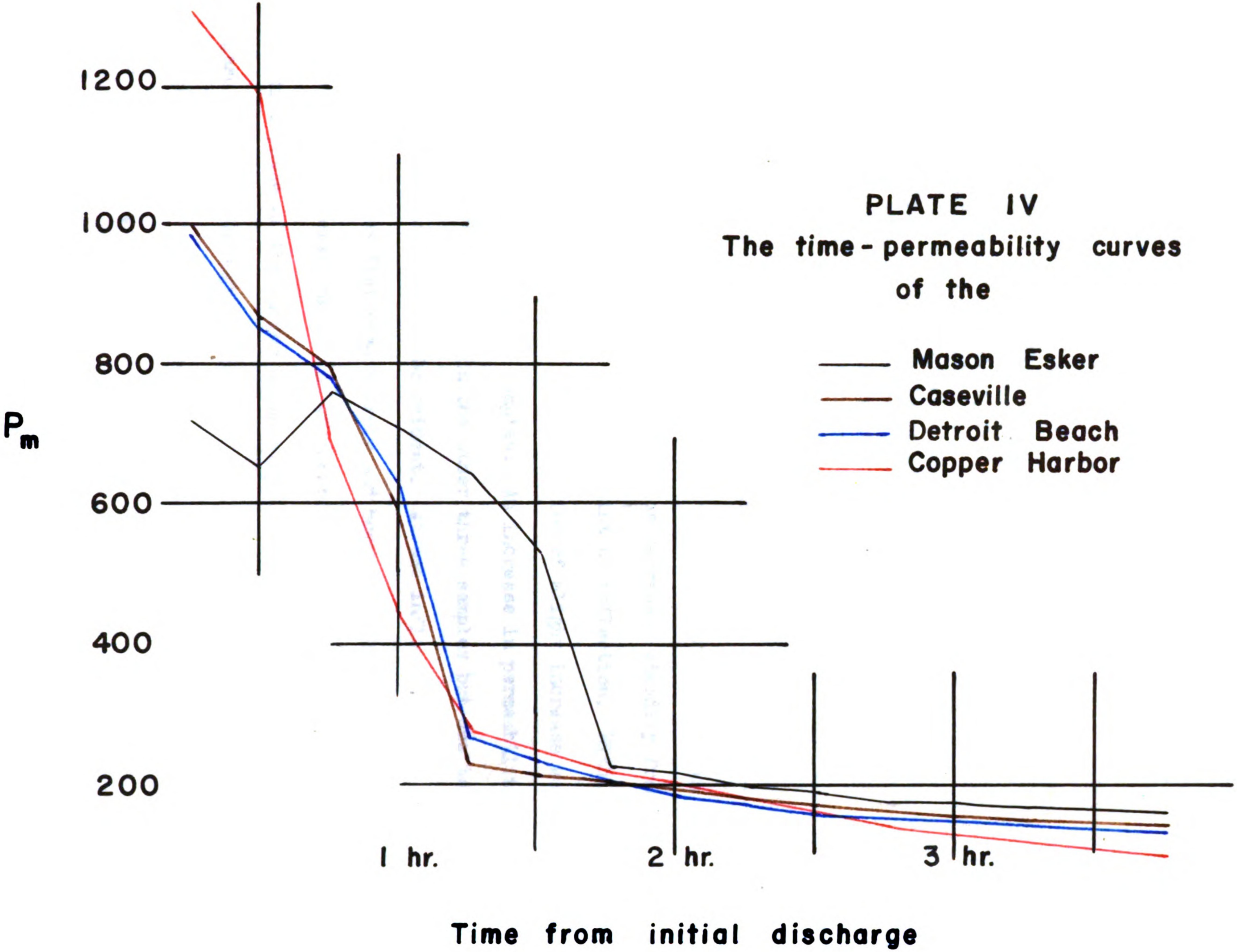


PLATE IV

The time-permeability curves of the



RESULTS

Johnson (1951) describes the behavior of a sample when its permeability is being determined in the following words:

> "If many closely spaced readings are taken, it is usually found that the permeability, using tap water, will have a period of slight increase during the first few days, followed by a short period of relative stabilization. This is then followed by a period of continuously decreasing permeability until finally attaining a minimum value. In addition to this general tendency, it will usually be observed that the permeability is subject to fluctuations during the course of each day."

Although the permeability measurements in this study transgressed a period of hours rather than days a similar sequence in behavior was obvious. All of the samples decreased steadily from an original high value to a distinct point of inflection. Within this initial downward trend a short period of slight increase was noted for five of the eight samples. An increase in permeability may actually have occurred in the other three samples but due to the time unit employed not be evident. At the inflection point all of the curves flattened sharply and became essentially straight lines for the remaining period of record. The irregularity of the initial phase of the curves apparently is due to inherent air and gases escaping through the sample. The conclusion of this is marked by the period of slight increase after which decline continued to the inflection point. The second phase of the curves, that from the inflection point on, represents a period of relative stability. A longer period of record probably would indicate the continuance of the curve as a straight line until the sample particles were completely saturated, after which it would drop sharply to a minimum value of absolute permeability. By this time, however, several tangibles quite possibly could be effecting the results and will be discussed in the section under conclusions.

In order to determine which samples were relatively most permeable the readings from the point of inflection on were averaged. Except for two samples this average resulted in an order identical with the graphic position of the flat portion of the curves as well as the order of decreasing sphericity. A less exact correlation with roundness was probably due to the close relationship which often exists between sphericity and roundness.

Table IV indicates the order of decreasing sphericity, roundness, and permeability, expressed in Meinzer units, for each sample. It will be noted that the samples which are ideally "out of position" are the Copper Harbor and the Caseville. Their positions are reversed from that which would give a perfect direct sphericity-permeability correlation. This may be the result of the extremely low relative value of roundness of the Copper Harbor and the relative high roundness value of the Caseville sands. The Copper Harbor, Caseville, and Eagle Harbor are the only samples which do not have a roundness value corresponding in position to their sphericity value. The apparently important secondary effect of roundness on permeability is shown also in the case of the Eagle Harbor sand. If its roundness value was in a position similar to its sphericity the permeability might be expected to be higher in value and more nearly approach the St. Peter in this respect.

TABLE IV

Order of Decreasing Sphericity, Roundness, and Permeability for each of the Samples.

Sphericity		Permeability		Roundness	
St. Peter	.868	St. Peter	281	St. Peter	.768
Eagle Harbor	.849	Eagle Harbor	241	Grand Marais	.620
Grand Marais	.832	Grand Marais	213	Sleeping Bear	.532
Sleeping Bear	.828	Sleeping Bear	212	Eagle Harbor	.501
Mason Esker	.820	Mason Esker	182	Caseville	.420
Copper Harbor	.819	Caseville	175	Mason Esker	.407
Detroit Beach	.812	Detroit Beach	173	Detroit Beach	.396
Caseville	.806	Copper Harbor	167	Copper Harbor	.307

CONCLUSIONS

Although an apparently close correlation between sphericity and permeability was found, this study should not be considered conclusive. At best it indicates a possible relationship which may exist and which should be substantiated by further study before being fully accepted as fact. However, the results obtained in this research are believed to be an adequate basis for further study.

If possible, even more rigid control should be maintained in any additional work. Although offering no substantiating data, the author feels that the effect of mineral composition and resultant absorptive qualities of the particles may greatly affect permeability. Only distilled water should be used in laboratory measurements of permeability. The total solid content of tap water may be great enough to plug pores, if megascopic in size, or capable of chemical action with the mineral constituents of the sample if in a dissolved state. As pointed out by Johnson (1951) either may contribute to decreasing permeability. A source of filtered water, whereby it has become de-aerated, should be used in any future study. Johnson (1951) listed the effect of entrapped air as a major source of error in laboratory measurements of permeability. A mechanical device such as the "Johnson Compaction Table" mentioned in a previous section should be used for packing the sample, thus eliminating the effect of human error on the results.

The author, surprised to discover the sphericity values of the various samples ranged only from .806 to .868, found the significance of any sphericity difference in the second digit. The fact that all the values were so close in magnitude may be a function of the nearly perfect sorting, which was obtained by sieving. Thus a re-evaluation of the basis for these measurements may be in order perhaps with the idea of determining a standard size grain as the basis for all computations.

RECOMMENDED FUTURE STUDY

If permeability is to be completely understood the writer believes the following problems must be made the subject of future study:

1. The influence of all the variables known to affect permeability must be evaluated individually. This will involve such problems as devising a system whereby laboratory samples may be artificially cemented in order to study the effect of lithification on permeability under controlled conditions.
2. The information gained from studying all the factors known to affect permeability should then be used in an attempt to predict the permeability of laboratory samples.
3. Laboratory discoveries should be applied, whenever possible, to permeability problems encountered in the field.

The ultimate aim of basic permeability research should be the derivation of methods whereby the extraction of our expendable fluid resources will become more efficient.

APPENDIX

APPENDIX

TABLE V

The Recorded Data Used to Compute the Permeability
and Construct the Time-Permeability Curve
of the St. Peter Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	710	8.4	64°	.95	.0626	1325
30	600	8.4	65°	.93	.0517	1100
45	540	8.4	65°	.93	.0466	988
1hr.	465	8.4	66°	.92	.0397	842
15	475	8.4	66°	.92	.0406	860
30	415	8.4	64°	.95	.0366	777
45	335	8.5	64°	.95	.0292	620
2hr.	190	8.6	65°	.93	.0160	340
15	180	8.6	66°	.92	.0150	318
30	174	8.6	67°	.91	.0144	304
45	166	8.6	67°	.91	.0137	290
3hr.	148	8.6	67°	.91	.0122	258
15	144	8.6	64°	.95	.0124	263
30	138	8.6	65°	.93	.0116	246
45	130	8.6	66°	.92	.0108	230

APPENDIX

TABLE VI

The Recorded Data Used to Compute the Permeability and Construct the Time-Permeability Curve of the Eagle Harbor Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	420	8.6	64°	.95	.0380	805
30	360	8.6	64°	.95	.0326	690
45	390	8.7	66°	.92	.0338	715
1hr.	400	8.7	66°	.92	.0347	735
15	405	8.7	66°	.92	.0351	745
30	400	8.7	66°	.92	.0347	735
45	375	8.7	66°	.92	.0325	690
2hr.	160	8.8	66°	.92	.0137	290
15	150	8.8	65°	.93	.0130	275
30	140	8.8	64°	.95	.0124	262
45	130	8.8	64°	.95	.0115	245
3hr.	130	8.8	64°	.95	.0115	245
15	120	8.8	65°	.93	.0104	220
30	115	8.8	66°	.92	.00986	210
45	100	8.5	68°	.89	.00857	185

APPENDIX

TABLE VII

The Recorded Data Used to Compute the Permeability and Construct the Time-Permeability Curve of the Grand Marais Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	520	8.6	70°	.87	.0410	870
30	410	8.6	65°	.93	.0346	733
45	370	8.5	64°	.95	.0322	685
1hr.	335	8.5	65°	.93	.0286	605
15	310	8.5	65°	.93	.0264	560
30	300	8.5	66°	.92	.0253	536
45	305	8.5	65°	.93	.0260	552
2hr.	245	8.5	65°	.93	.0209	443
15	140	8.6	64°	.95	.0121	256
30	135	8.6	64°	.95	.0116	247
45	128	8.6	64°	.95	.0111	235
3hr.	116	8.6	64°	.95	.0100	212
15	106	8.5	65°	.93	.0091	192
30	105	8.5	66°	.92	.0089	188
45	92	8.5	66°	.92	.0078	164

APPENDIX

TABLE VIII

The Recorded Data Used to Compute the Permeability
and Construct the Time-Permeability Curve
of the Sleeping Bear Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	625	8.5	69°	.88	.0505	1070
30	540	8.5	65°	.93	.0461	976
45	530	8.5	63°	.96	.0467	990
1hr.	485	8.5	64°	.95	.0423	896
15	465	8.5	63°	.96	.0410	870
30	420	8.5	66°	.92	.0354	750
45	208	8.5	66°	.92	.0176	372
2hr.	145	8.6	66°	.92	.0121	256
15	140	8.6	67°	.91	.0115	245
30	135	8.7	67°	.91	.0111	233
45	120	8.7	66°	.92	.0099	210
3hr.	115	8.7	64°	.95	.0098	208
15	110	8.9	64°	.95	.0091	193
30	105	8.9	63°	.96	.0086	188
45	95	8.9	63°	.96	.0080	170

APPENDIX

TABLE IX

The Recorded Data Used to Compute the Permeability and Construct the Time-Permeability Curve of the Mason Esker Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	405	8.6	66°	.92	.0338	716
30	385	8.5	66°	.92	.0325	657
45	420	8.5	66°	.92	.0354	750
1hr.	395	8.5	66°	.92	.0333	705
15	365	8.6	66°	.92	.0304	645
30	300	8.6	66°	.92	.0250	530
45	124	8.7	64°	.95	.0105	224
2hr.	120	8.8	64°	.95	.0101	214
15	110	8.8	64°	.95	.0093	196
30	105	8.8	64°	.95	.0089	187
45	98	8.8	65°	.93	.0081	171
3hr.	100	8.8	64°	.95	.0084	171
15	92	8.8	64°	.95	.0078	164
30	90	8.8	64°	.95	.0076	161
45	90	8.8	64°	.95	.0076	161

APPENDIX

TABLE X

The Recorded Data Used to Compute the Permeability and Construct the Time-Permeability Curve of the Caseville Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	550	8.3	71°	.86	.0467	995
30	450	8.3	66°	.92	.0408	865
45	395	8.3	63°	.96	.0375	795
1hr.	300	8.4	64°	.95	.0278	590
15	120	8.4	64°	.95	.0108	230
30	112	8.4	65°	.93	.00991	210
45	108	8.4	66°	.92	.00946	201
2hr.	105	8.4	67°	.91	.00910	193
15	96	8.4	66°	.92	.00841	178
30	88	8.4	64°	.95	.00795	169
45	84	8.4	64°	.95	.00760	161
3hr.	80	8.5	64°	.95	.00715	152
15	80	8.5	65°	.93	.00700	148
30	76	8.5	64°	.95	.00680	144
45	75	8.5	64°	.95	.00670	142

APPENDIX

TABLE XI

The Recorded Data Used to Compute the Permeability and Construct the Time-Permeability Curve of the Detroit Beach Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	570	8.5	68°	.89	.0465	985
30	490	8.5	68°	.89	.0400	850
45	435	8.5	66°	.92	.0367	780
1hr.	355	8.5	67°	.91	.0296	630
15	160	8.6	68°	.89	.0129	265
30	135	8.6	68°	.89	.0109	231
45	118	8.6	68°	.89	.00954	200
2hr.	105	8.6	68°	.89	.00850	180
15	100	8.7	68°	.89	.00796	169
30	90	8.7	68°	.89	.00718	152
45	90	8.7	68°	.89	.00718	152
3hr.	86	8.7	68°	.89	.00686	145
15	85	8.7	68°	.89	.00678	144
30	81	8.7	69°	.88	.00640	135
45	77	8.7	69°	.88	.00606	130

APPENDIX

TABLE XII

The Recorded Data Used to Compute the Permeability
and Construct the Time-Permeability Curve
of the Copper Harbor Sample.

Minutes	Q ml	h cm	t °F	t_f	P	P_m
15	780	8.3	73°	.84	.0615	1305
30	670	8.5	67°	.91	.0560	1185
45	395	8.6	66°	.92	.0329	700
1hr.	255	8.6	67°	.91	.0210	446
15	160	8.6	67°	.91	.0132	280
30	142	8.6	68°	.89	.0115	242
45	126	8.6	68°	.89	.0102	215
2hr.	116	8.6	68°	.89	.00936	198
15	102	8.7	68°	.89	.00814	173
30	92	8.7	68°	.89	.00735	155
45	82	8.7	68°	.89	.00655	139
3hr.	73	8.7	68°	.89	.00583	123
15	67	8.7	68°	.89	.00535	115
30	61	8.7	68°	.89	.00486	103
45	55	8.7	68°	.89	.00450	95

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