6-1-1942

Report of Investigation on the Physical Characteristics of the Oil Sands from the Cut Bank Field, Montana

V. E. Hanes

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ON THE PHYSICAL CHARACTERISTICS OF THE OIL SANDS FROM THE CUT BANK FIELD, MONTANA

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INTRODUCTION

Acknowledgments

This investigation was made possible through the interest and cooperation of the Montana Bureau of Mines and Glacier Production Company who jointly financed the research program. The writer is indebted to Mr. Bird, President of Glacier Production Company, and Dr. F. A. Thomson, President of Montana School of Mines and Director of the Bureau of Mines and Geology, for finances necessary to conduct the research.

This research was a continuation of the program carried out by Dan Feray in 1940-41. The field work and laboratory studies were conducted by the author during the months from August, 1941 to June, 1942.

The writer is especially indebted to Dr. E. S. Perry and Dr. L. L. Sloss, directors of the research, for their interest and everhelpful suggestions. They generously gave their time also to the construction of the permeameter and other equipment necessary to conduct the research. Without their interest and assistance the whole of this work would not have been possible.

Many of the oil companies operating in the cut Bank field contributed cores for study. The author wishes to thank Mr. Erwin Hupp, Mr. James McCourt, and Mr. Edward Scholz of the Glacier Production Company for their assistance in the collection of field data and cores. It is a pleasure to acknowledge the invaluable assistance given to the author by Mr. John E. Blixt of The Texas Company. Mr. T. O'Neil, President of Santa Rita Oil and Gas Company, and Mr. Darling, of the same company, generously supplied the author with cores and maps.

The writer also wishes to take this opportunity to thank the faculty of the Montana School of Mines for their help and suggestions during the course of this investigation.

Purpose of Investigation

The purpose of this research was to study the physical characteristics, mainly, porosity and permeability of the oil sands from the Cut Bank field, Glacier County, Montana. In so doing, a better understanding of the relationship of these physical characteristics to one another and to the pool itself could be obtained.

During the previous year, Mr. Feray[5] made an extensive study of the sedimentary and petrographic aspects of these same oil sands. He was mainly interested in the relationship of the environment and provenance of sedimentation of the Kootenai formation to the type of sediments deposited. In some instances, the author has attempted to combine his results with those of Mr. Feray's in an effort to more fully comprehend the existing conditions in the Cut Bank field.

Some of the problems that have confronted the operating companies in the Cut Bank field are; (1) source of the Kootenai sediments, (2) existing conditions at the time of deposition, (3) source rock of the petroleum, and (4) cause of irregularity of the producing area. The author was more concerned with the fourth problem and concentrated his efforts to the study of the physical characteristics of these sands in order to determine what relationship existed between them and production.

Those familiar with the Cut Bank field realize that conditions exist in parts of the field that prevent some wells from being producers in an otherwise producing area. It is not uncommon to find dry holes completely surrounded by producing wells. This phenomenon is not due entirely to the thinning of the producing sands, although in some instances it may be the deciding factor. The controlling factors must then be porosity and permeability. These two physical characteristics are at least in part related to sorting, shape, roundness, and median diameter of the grains. By conducting a study of the porosity and permeability of cores secured from various wells scattered throughout the field the author has hoped to determine what relationship exists between production and the physical characteristics of the sands.

Porosity and permeability information are valuable when the wells of a pool are declining in production, and when it is necessary to either discontinue operations or to introduce secondary methods of recovery. Although several methods of repressuring are practiced, gas-repressuring and water-flooding are the most common. In order that either of these methods be profitable, it is essential that the oil sands still retain sufficiently large quantities of oil per acre that is removeable with reasonable ease. The proportion of the remaining oil which is subject to recovery by repressuring or water-flooding depends largely upon two factors, namely, permeability of the oil sands as a whole, and the differences in permeability of horizontal layers of the oil sand.

Since the author was not concerned with composition, lithology, texture, and etc. of the Cut Bank oil sands, this information has been omitted from this report. Reference should be made to Feray's report for a detailed account of the above items.

METHODS OF INVESTIGATION

Preliminary Treatment of Samples

Unfortunately, the samples of the Cut Bank sandstone on which porosity and permeability determinations are to be made cannot be selected at random. The purpose of the study must be kept in mind at all times in choosing the samples. Theory imposes no limitation on the size of the sample to be used but it is evident that in order to minimize effects due to local inhomogeneties in the material such as concretions, small shale breaks, and the like, the samples should be of a generous size. The cores may vary in terms of the coarseness of their particles, in their degree of induration, and in their degree of alteration, all of which may affect porosity and permeability. For example, it would not be feasible to choose a sample such as the one pictured on Plate I, A, for permeability determinations. The samples displayed on Plates I and II are typical of the wide variation that may be found in the sands from the Cut Bank field.

Before cutting the cores to the desired size for porosity and permeability determinations, it is necessary to soak them in water or some other liquid which does not effect the cementing material for at least 24 hours. This precaution is taken in order to avoid the fine cutting from being carried into the face of the core by capillary action, thus mudding off the faces and plugging the pores.

It is the common practice in the Cut Bank field to core the sands with a Baker core barrel. The "biscuits" resulting from such a practice are relatively thin, seldom more than one inch in thickness and in most instances less. Because of the desirability for measuring the permeability both parallel and perpendicular to the bedding plane, separate samples were cut in each of these directions and from as closely adjacent portions of the specimen as possible. This necessitated the use of two types of cutting apparatus, namely, a diamond core drill (Plate III), and a diamond-bladed saw (Plate IV).

It was impossible in many instances to cut a cylindrical sample parallel to the bedding plane due to the thinness of the "biscuits". The diamond-bladed saw was used when cylindrical samples cut along the bedding plane were desired. The dimensions of the samples were 1 cm. in width, by 1 cm. in depth by 2 cm. in length. In all cases the samples were cut more than two centimeters in length and reduced to two centimeters by powerful wire-snips. This precaution was taken to prevent the ends of the samples along which air was to travel during permeability measurements from becoming plugged during the cutting action. A mixture of machine oil and kerosene was used to cool and lubricate the blade during the cutting process. On an average the diamond-charged blades will cut about 25 samples.

All the samples on which vertical permeabilities were desired were cut across the bedding plane by the diamond core drill (Plate III). This core drill, which

PLATE I

Core Samples from the Cut Bank Oil Field.

A. Shale streak in Lower Cut Bank sandstone from Santa Rita Fisk No. 1. x 3/4.

B. Lander sandstone from which cylindrical sample has been cut, Santa Rita Lander No. 1. x 3/4.

C. Sunburst sandstone from which cylindrical sample has been cut, Reagan Tribal No. 1. x 3/4.

D. "Salt and Pepper" sandstone, Lower Cut Bank, A. B. Cobb Walburger No. 7. x 3/4.

A

B

C

D

PLATE I.

PLATE II

Core Samples from the Cut Bank Oil Field.

A. Numbers 1 and 2 are cylindrical samples of Upper Cut Bank sandstone showing cross-bedding. Numbers 3 and 4 are also cylindrical samples but from Lower Cut Bank sandstone. All samples are from Glacier Bonnet No. 6. x 3/4.

B. Basal conglomerate with interstices between the larger chert pebbles filled with minute particles, Lower Cut Bank, Glacier Seeba No. 5. x 3/4.

C. Basal conglomerate composed of dark chert pebbles with some pyrite (Py), Lower Cut Bank, A. E. Cobb Walburger No. 7. x 3/4.

D. Core from basal conglomerate composed mostly of pyrite (Py) with some carbonaceous material, Lower Cut Bank, Glacier A. Corrigeus No. 1. x 3/4.

A

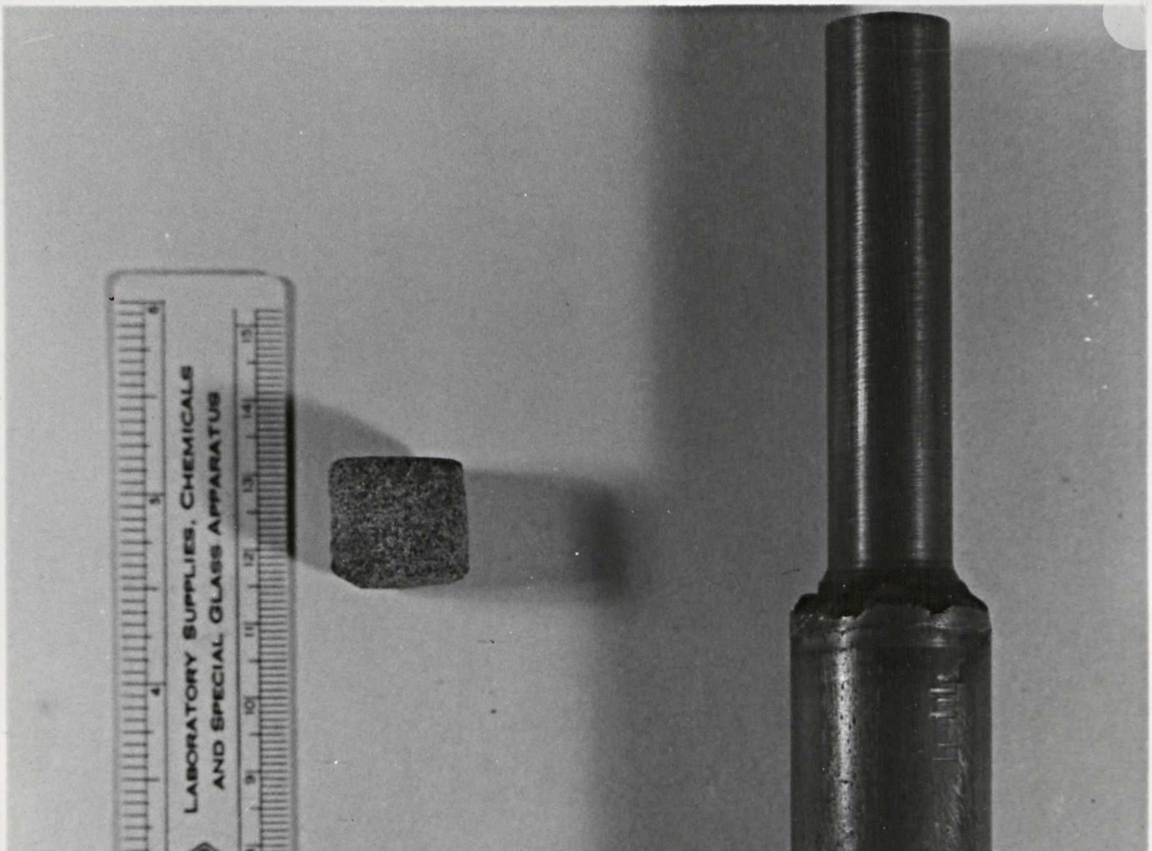
B

C

D

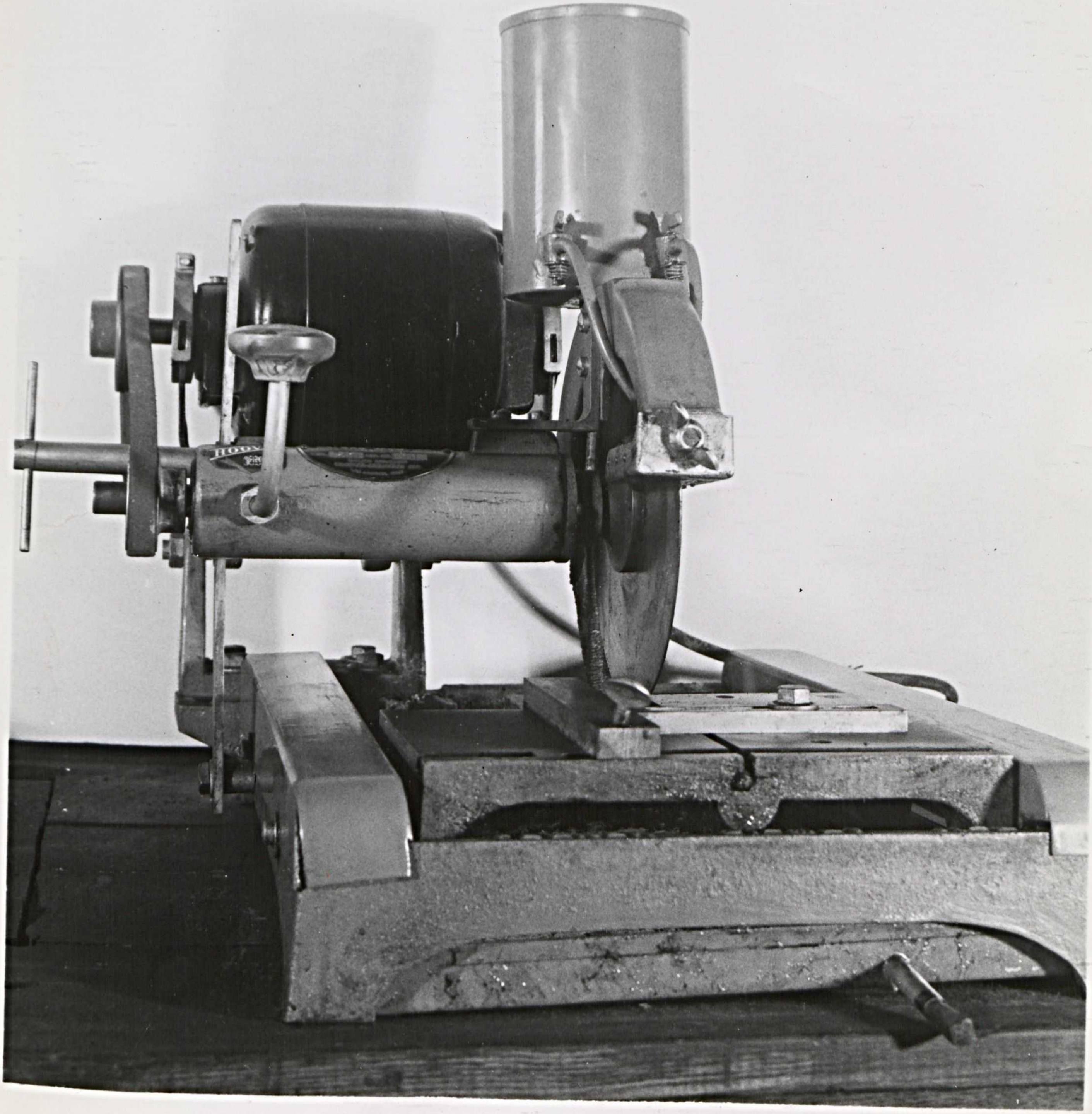
PLATE II

PLATE III



DIAMOND CORE DRILL

PLATE IV



SAW EQUIPPED WITH DIAMOND-CHARGED BLADE

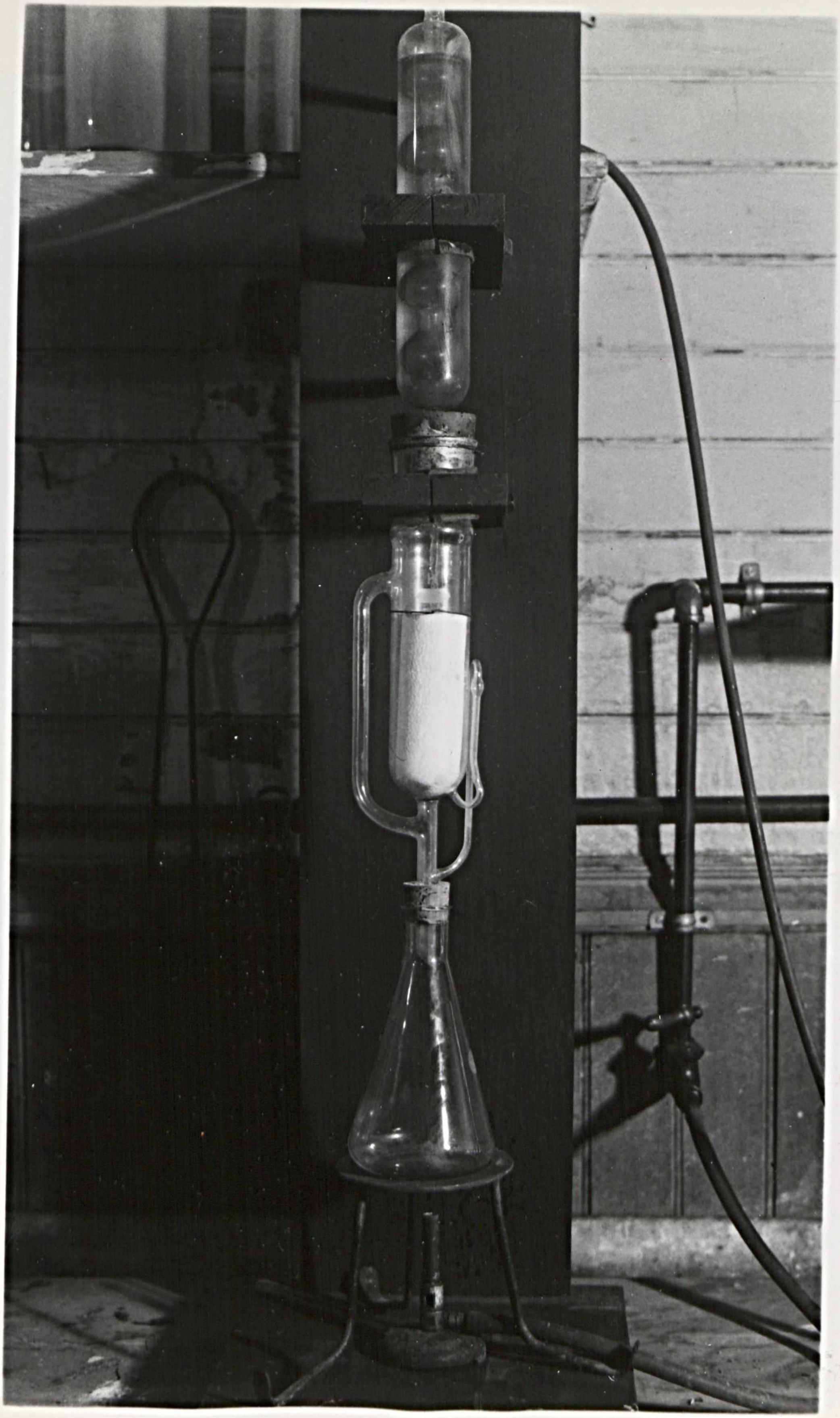
was equipped with a 3 inch core barrel, cut samples about 1.8 cm. in diameter. The core drill was inserted in a large drill-press. The core to be cut was placed in a small pan and immersed in clean water in order that all of the cutting action took place under water. In this case the water acted as the cooling and lubricating agent. It was necessary to replace the dirty water with clean water after each cutting to avoid the cuttings from plugging the pores of the sample. Whenever possible the lengths of the cores were reduced to 1 cm. This method of cutting the samples was found to be more economical than the sawing method.

After the samples were cut from the core it was necessary that they be thoroughly dried. This was accomplished by placing the samples in an oven at 105°C. for several hours. Excess heating of the samples at high temperatures should be avoided since there is a great possibility of decomposition of the cementing material in the pore space. A permeability determination on such a sample may be abnormally high due to a greater communication between pores.

Since many of the samples may contain oil, they must be carefully treated in order to remove, as far as possible, all traces of oily content. One of the most convenient methods for extracting the oil from the samples is by the use of the Soxhlet extractor (Plate V). The samples are carefully marked and placed in an extraction thimble. The extraction thimble is used to prevent small sand grains from clogging the syphon tubes of the extractor. The extraction containing the samples are then inserted in the Soxhlet extractor and treated with carbon tetrachloride for at least 48 hours to remove the oil. The carbon tetrachloride used in the extraction may be used several times depending on the quantity of oil it has dissolved. When it becomes very dark it should be placed in a bottle and saved. The carbon tetrachloride may be purified from time to time by distillation.

The samples are then returned to the oven and heated to 105°C. from four to six hours to drive off all the carbon tetrachloride. They may then be stored in a desiccator until porosity and permeability measurements are to be made.

PLATE V



SOXHLET EXTRACTOR

Permeability

Permeability of a porous medium may be defined as the volume of a fluid of unit viscosity passing through a unit cross-section of the medium in unit time under action of a unit pressure gradient. It is thus a constant determined only by the structure of the medium in question and is entirely independent of the nature of the fluid. It is governed, however, by; (1) grain size, (2) grain shape, (3) porosity, (4) uniformity of grain size, and (5) packing or arrangement of the grains.

As a result of the experiments conducted by Darcy in 1856 on flow characteristics of sand filters, the quantitative theory of the flow of homogeneous fluids through porous media was founded. Darcy's law[13] states that the rate of flow (Q) of water through the filter bed was directly proportional to the area (A) of the sand and to the difference (/ h) between the fluid heads on the inlet and outlet faces of the bed, and inversely proportional to the thickness (L) of the bed, or, expressed analytically, that

$$Q = \frac{c\,A\,/\,h}{L}$$

where c is a constant characteristic of the sand.

When air is used as the penetrating fluid the formula is stated somewhat differently, namely, that

$$k = \frac{V\,u\,L}{T\,A\,P}$$

where k is permeability (darcy), V is the volume of air that passes through the sample (cu. ft.); u is viscosity of the fluid (centipoises); L is the length of the sample in direction of flow (cm.); T is the time required for a volume of air to pass through the sample (seconds); A is the cross-sectional area of the sample (sq. cm.); and P is the pressure gradient across the sample (atmospheres).

The pressure gradient (P) across the system is determined in the following manner:

$$P = \frac{p\,(B + \frac{1}{2}p)}{B}$$

or

$$P = \frac{pB + \frac{1}{2}p^2}{B}$$

or

$$P = p + \frac{p^2}{2B}$$

As previously stated, P is the pressure difference across the system (atmospheres); p is the inlet pressure (atmospheres); B is the barometric pressure or absolute pressure at the outlet; and p + B is the absolute pressure at the inlet. For an absolute c.g.s. system the unit of pressure should be in dynes per square centimeter instead of in atmospheres but this would lead to a small numerical value.

The American Petroleum Institute has adopted a unit of permeability called the "darcy" after the pioneer investigator. Then,

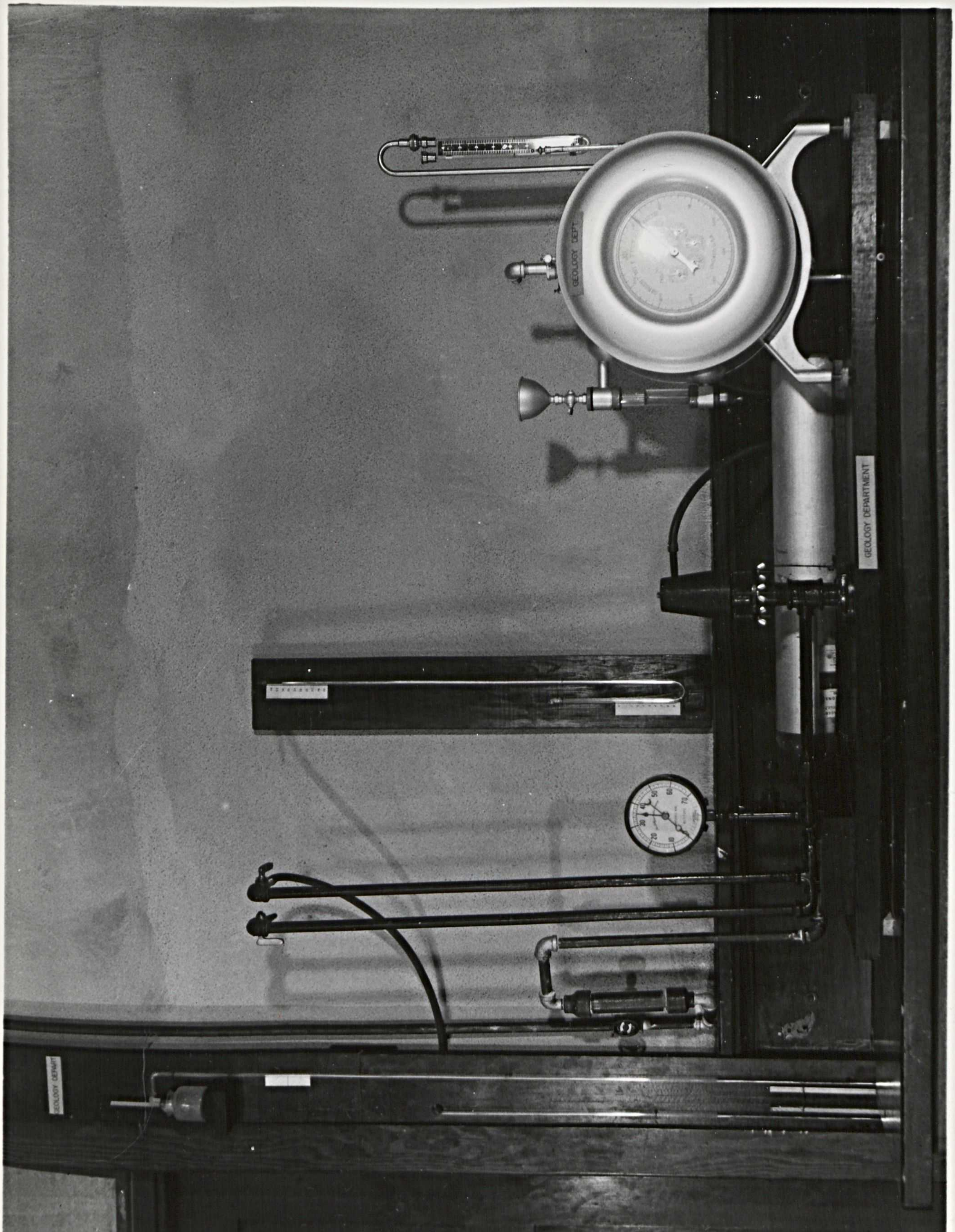
$$k = 1 \text{ darcy} = \frac{1 \text{ c.c./sec.} \times 1 \text{ centipoise} \times 1 \text{ cm.}}{1 \text{ sq. cm.} \times 1 \text{ atmosphere/sq. cm.}}$$

It has become the practice to express the permeability of oil sands in "millidarcys" because it gives a larger number for comparison.

<u>Method of Determining Permeability</u>

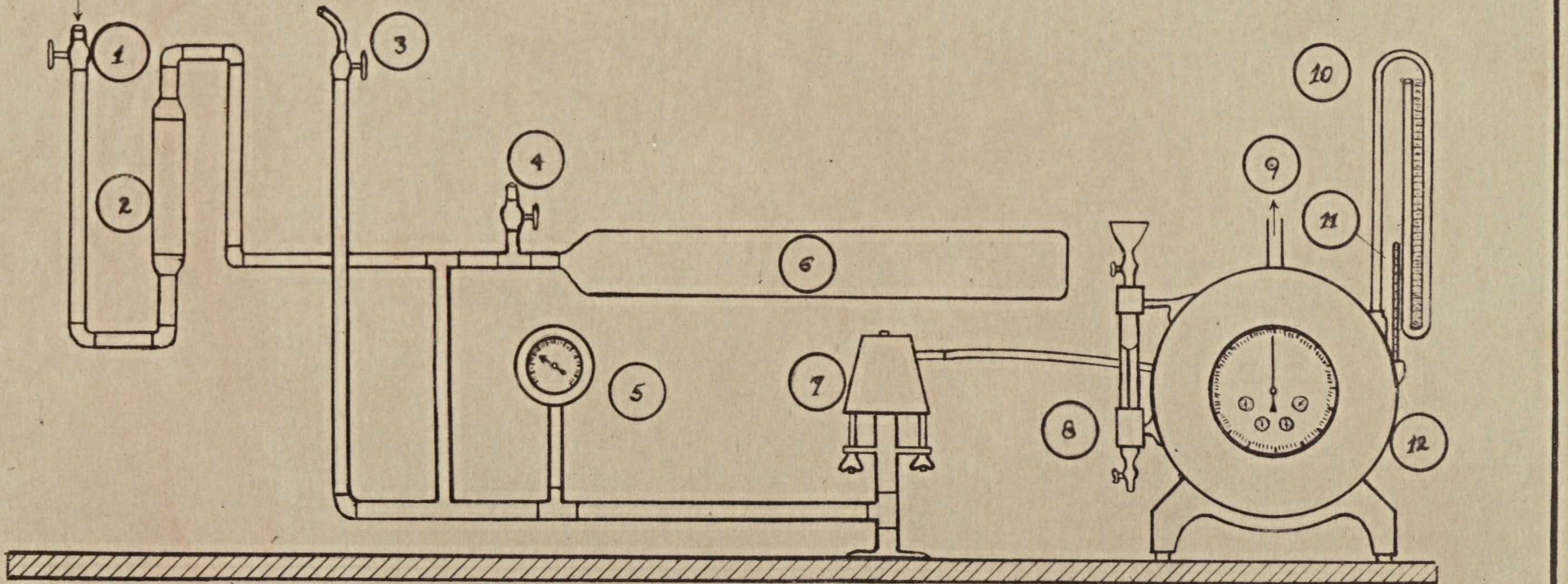
Theoretically, the permeability of a porous medium is a constant determined only by the structure of the medium and is independent of the nature of the homogeneous fluid passing through it. Although gases or liquids may be used to determine the permeability of a porous medium, air was selected because of its many advantages over the other possibilities. According to Muskat[13] the advantages of using gases over fluids are: (1) elimination of the difficulties resulting from plugging the sample by materials carried by the liquids or swelling of the cementing material in a consolidated porous medium; (2) freedom from error due to air trapped within the sample and the necessity for evacuation and filling with liquid under a vacuum; (3) freedom from the danger of disintegrating a con-

PLATE VI



PERMEAMETER

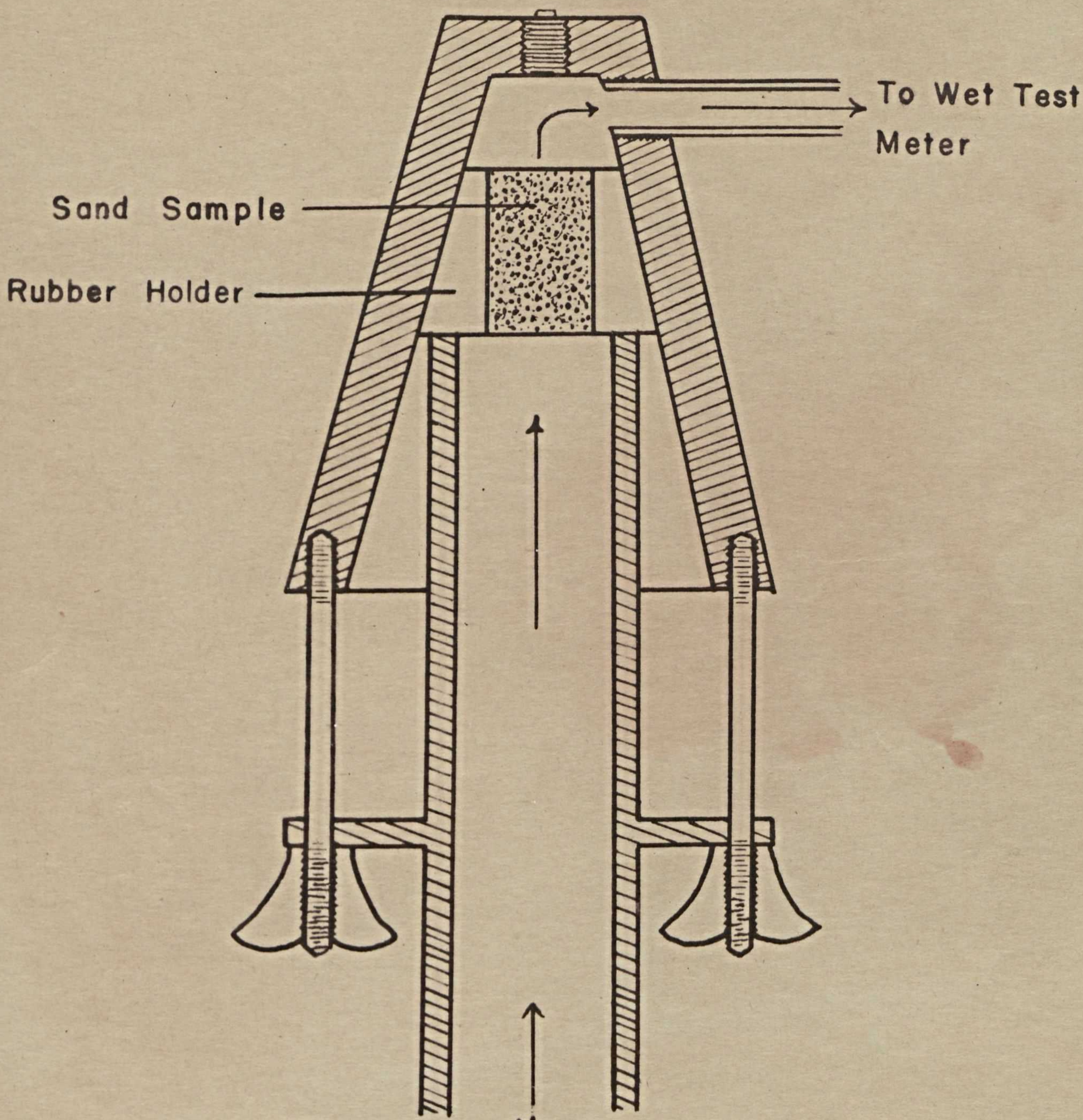
PLATE VII



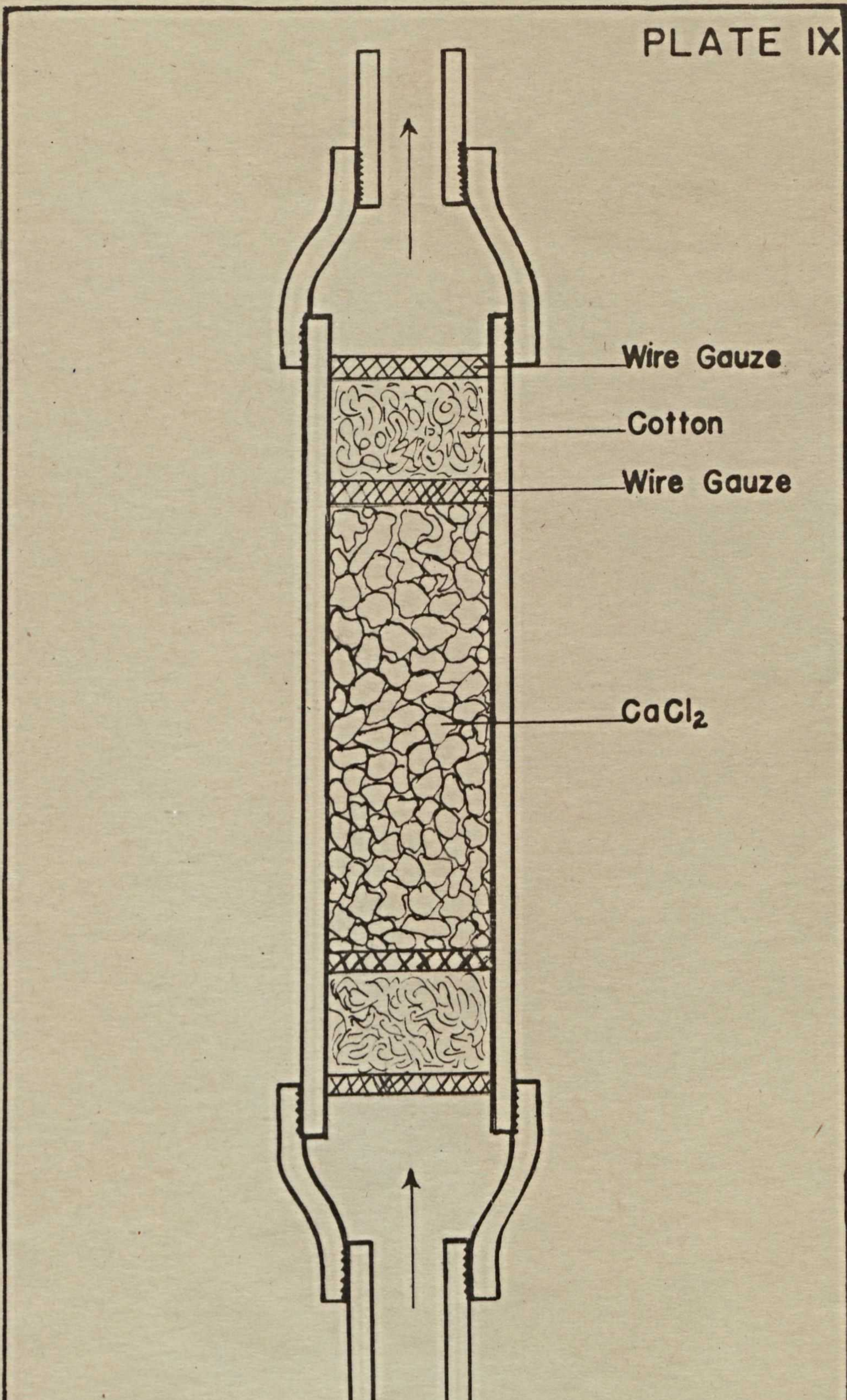
1. Inlet Valve
2. Air Filter
3. Valve to Manometer
4. Release Valve
5. Pressure Gauge
6. Surge Tank
7. Core Holder
8. Water-level Gauge
9. Outlet
10. Manometer
11. Thermometer
12. Wet Test Meter

DIAGRAMMATIC SKETCH OF PERMEAMETER

PLATE VIII



CORE HOLDER



AIR FILTER

LEASE: PERMEABILITY OF THE ________ SAND LOCATION:

WELL NO.: COMPANY:

SAMPLE NUMBER	DEPTH	D DIAMETER (cm)	L LENGTH (cm)	INLET PRESSURE (cm)	BAROMETRIC PRESSURE (cm)	P CORRECTED PRESSURE (cm)	VOLUME (Cu. ft.)	VOLUME (c.c.)	TEMPERATURE °F.	V VOLUME COR. T & P (c.c.)	T TIME (sec.)	K PERMEABILITY (millidarcy)

PLATE X. DATA SHEET FOR PERMEABILITY MEASUREMENTS solidated sample by the loosening of the cementing material; and, (4) the ease of attaining measurable flows without the use of excessive pressures even for very "tight" samples.

The permeameter (Plate VI and VII) was constructed very similarly to those in use in many laboratories over the country for determining the permeability of oil sands. Before the air was allowed to pass through the apparatus it was pre-filtered and dried by passing through a calcium chloride tube (Plate IX). This precaution was taken to remove any water vapor, oily vapors, or foreign particles that may be present in the air.

The cores, either cylindrical or rectangular, were mounted in rubber stoppers (No. 9) which had holes cut in them to exactly fit the sample. The rubber stopper containing the core was then inserted into the core-holder (Plate VIII) and held tightly in place with wing-nuts. This was found to be a satisfactory method of holding the samples and in no instance was there leakage of air between the rubber stopper and the core-holder.

However, in the case of rectangular cores it was found that permeability values varied with the core in different positions in the square in the rubber stopper. The permeability of a sample held in one position in the rubber stopper differed from the value obtained when the core was rotated 90°. There is no reason to believe that the permeability should be different since the area penetrated by the air is the same. It is the author's contention that when the core is in one of the positions (highest permeability) leakage between the core and the rubber stopper occurs. It is impossible to cut the samples in all cases so that all the angles are right angles because of the tendency for the sands to crumble near the edges. If the operator believes that leakage is occurring between the core and the stopper he should rotate the core within the stopper until the lowest permeability is obtained, this being the most accurate value.

The volume of air that was conducted through the sample in a given period of time was measured with a wet-test meter. A stop-watch was used to measure the time that was required for this quantity of air to pass through the sample. The wet-test meter was equipped with a thermometer and a monometer to record the temperature and pressure of the volume of air being measured. It is essential that the level of the water within the meter be checked from time to time and quantities added if necessary. Since the meter recorded volume in cubic feet, it was necessary to change this value to cubic centimeters (1 cu. ft. = 28,317 c.c

The only precaution to be particularly observed in the measurements of the rates of flow is that the pressure differentials remain steady during the measurements. The inlet pressure is measured by means of a mercury manometer. Manometers are necessary to obtain satisfactory results during the runs as gauges are not sufficiently accurate. Mercury manometers are not applicable in cases where pressures over 60 lbs./sq. in. were used due to the extreme height that it would have to be constructed. The inlet pressure was kept constantly at 143.4 cm. of Hg or 1.88 atmospheres.

In order to assure a uniform flow of air through the system a surge tank was installed to help counteract any fluctuations in pressure. The outlet pressure as measured by the water manometer attached to the meter was negligible. This being the case, a barometer was constructed to record the barometric pressure at the outlet. It was necessary that barometric readings be recorded before every sample was run.

The vapor pressure of the water in the meter must be corrected for in measuring the volume of gas that has passed through the sample. At 22°C. (72°F.) the vapor pressure of distilled water is 17.5 millimeters. This value must be subtracted from the barometric pressure. The quantity of air that has passed through the sample must then be corrected to standard conditions of temperature and pressu

Plate X is the type of flow sheet that was used during the experiment. All data vital to permeability determination may be recorded on this form as soon as they are noted. By the use of a slide-rule the permeability of a sample may be quickly determined by substituting the data into darcy's formula.

Porosity Measurements

The same samples that were used to determine permeability were used to measure the effective porosity. These samples needed no other preliminary treatment since they were leached of their petroleum before permeability measurements were made. Permeability measurements were conducted first on the samples because the pores of the sands become plugged with mercury during porosity measurements.

The porosity of a rock is the percentage of pore space in the total volume of the rock, that is, the space not occupied by solid mineral matter. The pores of a substance may be isolated from one another, or they may be intercommunicating. In the latter sense it is referred to as available pore space or effective porosity in contradistinction to "total pore space" or total porosity. Total pore space includes all interstices or voids whether connecting or not and is larger than the limiting value of the effective pore space. If all the grains of a mass of sand are spherical, are of uniform size, and are touching one another, the maximum porosity (cubical arrangement of grains) possible in 47.64 per cent, and the minimum (rhombohedral arrangement of grains) is 29.95 per cent. Under these conditions, the size of the grains has no effect on the total pore space, provided the grains are arranged in the same way.

According to Twenhofel[28], the porosity of a sediment is governed by; (1) uniformity of grain size, (2) shape of the grains, (3) method of deposition and manner of packing of the sediments, and (4) compaction during the after deposition.

All methods for porosity measurements require the separate determination of bulk volume of the specimen. During the course of this research the Russell volumeter was employed to measure bulk volume. The samples were immersed in a beaker or graduate containing carbon tetrachloride until they were thoroughly saturated, that is, all available pore space was filled with the liquid. While immersed in the liquid, the samples should be agitated or shaken frequently until all air bubbles have ceased to issue.

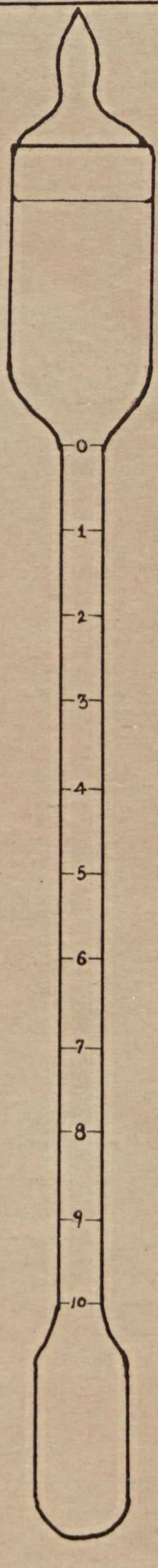
While the samples were being soaked, the volumeter (Plate XI) was mounted on a ring-stand by a clamp. It was then inverted and the level of the carbon tetrachloride noted. The samples were then taken (one at a time) from the beaker and placed in the volumeter. The volumeter was then reinverted and the level of the carbon tetrachloride recorded. The difference in the readings on the volumeter with and without the sand sample was the bulk volume.

Samples that are fractured or cracked should be discarded as a test run on such samples would not be reliable.

On Plate XII is pictured the Washburn-Bunting Pore-Volumeter[26] which was used to determine the pore volume of the sands. The bottom part, A, is of 50 c.c. capacity, and is attached to the upper part, B, by a ground joint lubricated with stopcock grease. Heavy rubber bands are stretched between the glass projecting lugs to hold the two parts together. The stem of A is graduated in 0.05 c.c. divisions from zero at the stopcock to 3.5 c.c. near the bottom. The volumeter should be attached in a vertical position to a ring-stand or some other fairly stationary object and connected from the bottom of A by means of 7 feet of rubber pressure-tubing to a 500 c.c. leveling bottle, which should rest in a movable support also attached to the ring-stand or other objects of support. The procedure is as follows:

1. Fill leveling bottle with mercury and adjust height until meniscus is in bottom part of A.
2. Place sample in A with a short piece of steel piano wire looped over it to prevent the sample from floating upwards when the mercury is introduced.

PLATE XI.



RUSSELL VOLUMETER

3. Attach B to A and fasten securely with rubber bands between the lugs.

4. Elevate the bottle until meniscus stands above the level of the stopcock.

5. Close stopcock. The only air in the chamber is now that which occupied the pores of the sample at atmospheric pressure.

6. Lower the bottle until the meniscus stands as in 1, and hold in that position for two or three minutes to permit the reduced pressure in the chamber to draw air out of the sample.

7. Elevate bottle until the menisci in bottle and graduated stem is then at atmospheric pressure. Read the graduated stem at the meniscus level.

8. Open stopcock and repeat 4, 5, 6, and 7 so as to make sure that all air has been removed from the sample. Read the stem again and add this reading to the one obtained in 7.

9. Remove sample from A and substitute therefore a solid piece of glass approximating in size and shape that of the sample. Repeat operation 1 to 7 and record the volume of air found as the instrumental correction to be subtracted from the reading obtained with the sample to give the pore volume of the sample. This instrumental correction is made necessary because of air absorped on the glass surfaces.

By knowing the bulk volume and the available pore spaces of the sample, the percentage effective porosity was determined by substituting the values into the following formula:

$$\text{Per Cent Effective Porosity} = \frac{\text{Pore Volume}}{\text{Bulk Volume}} \times 100$$

__Acid Treatment__

The cores from the Curran No. 5 were treated with acid in an effort to determine if acidization would increase either porosity or permeability. Other investigators have reported notable increases in the permeability of oil sands after acidization. Permeability measurements were made on the cores from the Curran No. 5 before and after acid treatment. These values were recorded for comparison with the values obtained after acid treatment (Table 2).

Because adequate equipment was not available for detailed coreacidizing experiments, a large number of cores could not be treated. The samples were placed in rubber stoppers as though permeability determinations were to be made. The rubber stopper containing the sample was then placed in a funnel attached to a common laboratory suction filter. The vacuum created by water sucking air from the filter-flask forced the rubber stopper tightly against the funnel. The acid was then added to the funnel until the stopper containing the core was completely covered. Approximately 500 c.c. of acid was forced through the core in this manner. It required about 24 to 36 hours to complete this operation. The cores were then thoroughly washed in distilled water to remove any traces of remaining acid and dried in an oven at 105°C. for several hours. Permeability measurements were then made on these samples.

The acid used in the experiment was a 15 per cent solution of hydrochloric acid to which had been added a small amount of wetting-agent. Many of the common agents used to reduce surface tension of an acid solution are unstable. Care must be taken in selecting one which will cause an acid to froth when shaken vigorously.

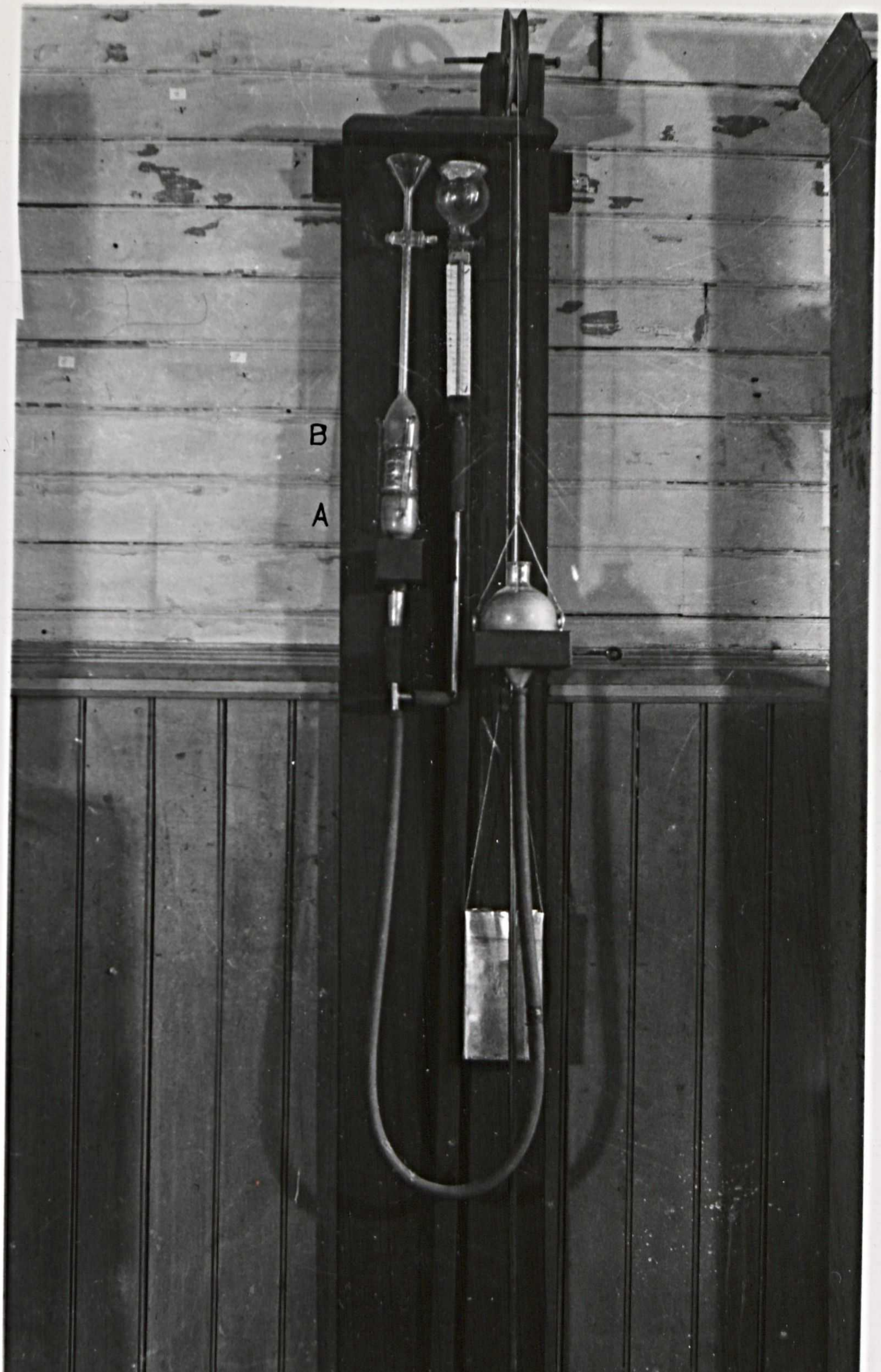
Reference should be made to the article by Fitzgerald, James, and Austin[7] for greater details of the chemicals and apparatus needed to study the effects on oil sands by acidization.

RESULTS OF STUDY

Results of Permeability and Porosity Studies

In general, no relation exists or is to be expected between porosity and permeability, it is evident that any alteration of a given material which produces

PLATE XII



WASHBURN-BUNTING PORE-VOLUMETER

a decrease in porosity must necessarily result in a decreased permeability. For the reduction in porosity of a given material implies a decrease in size of the pores and hence an even greater percentage change in permeability. Aggregates may, however, be porous without being permeable, as in the case of sealed pores. Likewise, two substances may have equal porosities but very different permeabilities as in the case of clay and gravel. Any post depositional alteration in a clastic sediment, whether by composition or cementation, will result in a marked decrease in permeability. Changes in porosity in such cases are due to cementation, and likewise changes in permeability are to be accounted for by the same process.

In Plates XIV, XV, and XVI the relationship between porosity and permeability are diagrammatically shown for different wells in the field. In Plate XIII these sections are located showing their relationship to the producing area of the Cut Bank field. As previously stated, there is no quantitative relationship between porosity and permeability. The author has not meant to imply a quantitative relationship, but merely a comparison of porosity and permeability. That is, to show that in most instances where there is an increase in porosity there is a corresponding increase in permeability.

The above statements do not hold for porosity and permeability measurements on samples from the basal conglomerates of the Kootenai formation. The permeability of this type of sediment should be almost negligible as the voids between the chert pebbles are completely filled with fine particles. During the cutting process a large amount of the material comprising the interstices between the larger chert pebbles is washed from the sample. Therefore, measurements of porosity and permeability on such samples are greatly increased, and do not represent true values.

As shown by these cross-sections there are certain depths that have persistantly high permeabilities, and it is natural to assume that it is from these depths that the greatest production of oil is derived. In general, wells with higher permeabilities have higher production. Reference should be made to Table 1 for a detailed comparison of the permeabilities and porosities of wells from which measurements were made.

Plates XVII and XVIII show the ranges of porosity and permeability. In most instances where the porosity is less than 10 per cent the permeability is negligible. In comparing the two graphs, it is evident that samples cut parallel to the bedding planes, although their porosities are the same. It seems reasonable to assume that orienting those samples in which the elongated axis of the grains are oriented in the direction in which air is to flow will have higher permeabilities than samples cut in any other direction because in this position the grains offer the least resistance to the passage of air.

Plate XIX presents graphically the relationship of permeability, porosity, sorting, and median diameter of samples from the Walburger No. 7. In general, as the coefficient of sorting increases the horizontal permeability and porosity increase. As the median diameter of the sand grains becomes larger the permeability decreases and vice versa.

Acid Treatment

According to Feray[5], the minerals found in the Cut Bank sandstones and conglomerates consist of quartz, chert, tourmaline, zircon, leuxcoxene; barite, calcite, pyrite, black opaques (magnetite or chromite), kaolinite, iron carbonate, and a green mineral that may be glauconite. Quartz and chert compose more then 90 per cent of the sandstone. Kaolinite, a clay mineral, is a very important fraction of the Cut Bank sandstone. These particles fill or partly fill the interstices between the larger mineral grains. Calcite is also found in the interstices in the Cut Bank sandstone, but only in very small amounts.

the results of the acid treatment (Table 2 and Plate XX) show an average increase in permeability of 7 millidarcys. In all cases there was an increase in permeability, although this increase was greater in some samples than in others.

The porosity changes after acid treatment are not as evident. It was impossible to make porosity measurements on the same sample before acidization because the pores of the sands may become plugged with mercury. This could be avoided only by choosing a fragment closely adjacent to the sample that was cut for porosity and permeability comparison. Porosity measurements could then be run on this fragment, and the results compared with the porosity values obtained after acidization.

It is the author's contention that the increase in permeability as a result of acidization was not due to a reaction between the acid and the constituents of the sand, but due to the removal of minute particles in the pores by the passing solution.

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1

Sample Number	Sand	Lease & Well No.	Per Cent Porosity	Permeability** Vertical	Permeability** Horizontal
40	Lander	Lander No. 1	21.4	259.0	466.0
42	"	"	23.9		1725.0
51	Sunburst	Rasmussen No. 1	14.2	15.5	22.5
52	"	"	15.7	8.5	'*
445	"	Reagan Tr. No. 1	11.4		18.2
446	"	"	17.2		529.0
535	"	Morrison No. 9	16.5		109.0
537	"	"	14.6		9.2
538	"	"	16.7		273.0
539	"	"	15.2		25.0
31	U.C.B.*	Walburger No. 7	15.4		74.3
28	"	"	12.2		12.1
26	"	"	15.0		55.5
25	"	"	14.3		36.5
24	"	"	12.1		4.3
23	"	"	15.6		68.2
21	"	"	16.2		293.0
20	L.C.B.*'	"	18.8		454.0
18	"	"	17.3		156.0
17	"	"	16.9		104.0
16	"	"	15.8		49.8
14	"	"	20.3		297.0
13	"	"	16.2		61.0
11	"	"	17.1		49.5
8	"	"	12.4		48.3
6	"	"	17.7		209.0
A21	U.C.B.	Abraham No. 2	15.8	17.5	
A22	"	"	20.0	24.6	
A23	"	"	13.2	'*	
A24	"	"	10.1	'*	
A25	"	"	15.6	'*	
A26	L.C.B.	"	11.6	'*	
A27	"	"	18.3	'*	
A28	"	"	13.6	10.4	
A29	"	"	13.3	8.0	
A210	"	"	14.7	39.4	
A211	"	"	14.2	8.2	
A212	"	"	17.5	39.6	
A213	"	"	17.6	11.2	
A214	"	"	14.0	7.8	
A215	"	"	12.6	73.2	
A216	"	"	15.2	0.5	
A217	"	"	9.9	0.9	
A218	"	"	12.2	1.0	
A219	"	"	16.4	0.2	
A220	"	"	17.0	11.8	
A221	"	"	17.7	20.2	

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1 — Continued

Sample Number	Sand	Lease & Well No.	Porosity	Permeability** Vertical	Permeability** Horizontal
A222	L.C.B.	Abraham No. 2	16.9	6.5	
A223	"	"	16.0	40.5	
A224	"	"	8.8	0.1	
B31	U.C.B.	Barrington No. 2	15.2	1.1	36.4
B32	"	"	12.5	2.8	9.5
B33	"	"	13.1	0.7	7.3
B34	"	"	15.5	21.8	17.6
B35	L.C.B.	"	11.6	1.2	
B36	"	"	16.4		33.9
B37	"	"	16.0	93.5	575.0
B38	"	"	17.0	154.5	186.8
B39	"	"	13.8	49.3	
B310	"	"	19.0		465.0
B311	"	"	14.4	7.9	541.0
B312	"	"	13.6		69.1
C12	U.C.B.	Bonnet No. 3	13.9	10.9	
C32	"	"	16.1	27.9	
C33	"	"	17.3	11.2	
C34	"	"	16.6	8.2	
C35	L.C.B.	"	19.0	33.1	
C36	"	"	13.8	4.9	
C37	"	"	18.2	6.0	
C38	"	"	20.2	4.1	
C39	"	"	12.6	**	
C310	"	"	15.6	23.6	
C311	"	"	10.3	**	
C312	"	"	15.9	33.2	
C313	"	"	15.0	36.9	
C314	"	"	14.9	21.5	
C315	"	"	10.4	0.9	
	U.C.B.	Bonnet No. 4	12.6	7.7	
C42	"	"	15.2	**	
C43	"	"	12.8	0.8	
C44	"	"	16.3	17.5	
C45	"	"	14.4	0.5	
C46	L.C.B.	"	17.2	51.7	
C47	"	"	16.9	27.7	
C48	"	"	13.8	3.1	
C49	"	"	16.4	56.8	
C410	"	"	13.1	1.9	
C411	"	"	16.5	21.1	
C412	"	"	16.8	33.0	
C413	"	"	15.2	17.1	
C414	"	"	13.1	5.1	
C51	"	Bonnet No. 5	13.6	24.8	
C52	"	"	14.3	6.2	
C53	"	"	14.7	41.5	

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1 — Continued

Sample Number	Sand	Lease & Well No.	Porosity	Permeability**	
				Vertical	Horizontal
C54	L.C.B.	Bonnet No. 5	17.7	26.3	
C55	"	"	14.4	24.1	
C56	"	"	15.8	35.7	
C57	"	"	10.4	**	
C58	"	"	15.2	56.5	
C59	"	"	18.7	1.1	
C510	"	"	15.4	1.5	
C511	"	"	15.0	6.5	
C512	"	"	18.4	15.8	
C513	"	"	18.6	7.6	
C514	"	"	16.1	8.8	
C515	"	"	14.2	2.5	
C516	"	"	16.5	59.4	
C517	"	"	10.1	0.2	
C518	"	"	14.0	30.2	
C519	"	"	18.3	60.4	
C520	"	"	16.8	14.8	
C521	"	"	17.5	8.5	
C522	"	"	17.4	4.8	
C523	"	"	18.0	49.6	
C524	"	"	18.2	123.0	
C61	U.C.B.	Bonnet No. 6	15.9	**	
C62	"	"	14.6	2.6	
C63	"	"	14.8	0.6	
C64	"	"	19.4	4.2	
C65	"	"	21.4	26.6	
C66	"	"	19.4	12.5	
C67	"	"	18.5	37.2	
C68	"	"	18.8	12.5	
C69	"	"	17.9	2.3	
C610	"	"	19.3	57.9	
C611	"	"	19.4	22.1	
C612	"	"	15.4	50.2	
C613	"	"	14.6	1.3	
C614	"	"	13.5	**	
C615	L.C.B.	"	20.0	8.4	
C616	"	"	16.1	1.6	
C617	"	"	17.2	5.0	
C618	"	"	17.3	106.2	
C619	"	"	16.8	9.7	
C620	"	"	23.1	127.1	
C621	"	"	16.9	30.7	
C622	"	"	15.7	17.0	
C623	"	"	18.9	88.0	
C624	"	"	20.0	39.0	
C625	"	"	18.4	126.0	

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1 — Continued

Sample Number	Sand	Lease & Well No.	Porosity	Permeability** Vertical	Permeability** Horizontal
C626	L.C.B.	Bonnet No. 6	21.6	92.8	
C627	"	"	22.5	187.5	
C628	"	"	7.8	0.5	
C71	"	Bonnet No. 7	15.4	0.9	
C72	"	"	20.0	12.1	
C73	"	"	15.6	3.1	
C74	"	"	14.7	†*	
C75	"	"	18.6	73.8	
C76	"	"	17.3	10.4	
C77	"	"	16.5	14.4	
C78	"	"	18.8	157.5	
D31	U.C.B.	Coburn No. 3	18.4	0.2	50.7
D32	"	"	13.2	0.2	53.2
D33	"	"	12.9	0.1	45.5
D34	"	"	16.9	2.6	125.0
D35	L.C.B.	"	16.0	2.3	15.0
D36	"	"	17.5	13.2	35.6
D37	"	"	19.6	15.2	186.7
D38	"	"	19.7	23.8	30.4
D39	"	"	16.5	1.0	151.6
D310	"	"	16.0	3.4	24.1
D311	"	"	15.0	0.4	149.4
D312	"	"	25.0	0.5	13.9
D313	"	"	9.7	0.3	
D314	"	"	8.9	0.7	
D41	U.C.B.	Coburn No. 4	15.9	0.5	
D42	"	"	18.5	62.6	
D43	"	"	14.3	48.3	
D44	L.C.B.	"	15.0	45.0	
D45	"	"	17.9	13.8	
D46	"	"	16.1	8.3	
D47	"	"	15.3	†*	
D48	"	"	20.6	0.6	
D49	"	"	17.7	30.8	
E21	"	Condily No. 2	24.0	84.2	
E22	"	"	13.8	0.3	
E23	"	"	17.8	41.2	
E24	"	"	18.0	162.6	
E25	"	"	18.6	56.9	
E26	"	"	13.7	0.5	
E27	"	"	14.6	3.9	
E28	"	"	12.5	0.4	
F11	"	A. Corriguex No. 1	22.9	34.5	
F12	"	"	26.1	61.1	
F13	"	"	21.8	84.0	
F14	"	"	19.3	15.1	
F15	"	"	18.1	3.0	
F16	"	"	14.9	47.8	

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1 — Continued

Sample Number	Sand	Lease & Well No.	Porosity	Permeability**	
				Vertical	Horizontal
G21	U.C.B.	Eisler No. 2	14.0	3.1	
G22	"	"	17.0	38.9	
G23	"	"	20.0	35.8	
G24	"	"	16.9	16.6	
G25	"	"	16.8	0.8	
G26	"	"	14.4	0.2	
G27	"	"	16.0	2.2	
G28	"	"	12.8	0.5	
G29	"	"	20.0	25.0	
G210	L.C.B.	"	20.4	89.6	
G211	"	"	20.0	39.2	
G212	"	"	12.3	'*	
G213	"	"	17.2	4.1	
G214	"	"	16.0	0.5	
G215	"	"	15.4	0.1	
G216	"	"	14.5	7.2	
I11	U.C.B.	Fed.Land Bk. No. 1	15.3	'*	
I12	"	"	16.8	'*	
I13	"	"	18.4	6.5	
I14	"	"	16.6	'*	
I15	"	"	23.2	2.3	
I16	"	"	16.8	'*	
I17	L.C.B.	"	23.3	19.9	
I18	"	"	16.0	7.7	
I19	"	"	11.7	49.4	
I110	"	"	16.9	18.9	
I111	"	"	24.8	75.5	
I112	"	"	20.0	111.0	
P41	U.C.B.	Simero No. 4	21.2	31.5	
P42	"	"	18.9	9.2	
P43	"	"	13.4	13.6	
P44	L.C.B.	"	18.2	11.1	
P45	"	"	18.7	21.8	
P46	"	"	23.6	31.8	
P47	"	"	18.8	14.1	
P48	"	"	17.1	0.5	
P49	"	"	18.2	12.5	
P410	"	"	14.9	1.0	
P411	"	"	15.3	1.5	
P412	"	"	14.2	0.9	
P413	"	"	14.7	'*	
1	"	Curran No. 5	18.9		115.0
2	"	"	11.5		112.0
3	"	"	25.0		137.0
4	"	"	16.1		82.0
5	"	"	14.8		18.9
6	"	"	14.4		40.4

The Permeability and Porosity of the Cut Bank Oil Sands

Table 1 -- Continued

Sample Number	Sand	Lease & Well No.	Porosity	Permeability**	
				Vertical	Horizontal
7	L.C.B.	Curran No. 5	22.8		210.0
8	"	"	14.1		258.0

** Permeability in millidarcys.
* Upper Cut Bank sandstone.
*' Lower Cut Bank sandstone.
'* Sample impermeable under the conditions of test.

Comparison of Permeability and Porosity of Samples from Curran No. 5
before and after Acid Treatment.

Table 2

Sample Number	Horizontal Permeability			Per Cent Porosity	
	The Texas Company	School of Mines	After Acid Treatment	The Texas Company	After Acid Treatment
1	115.0	72.4	82.0	18.9	20.0
2	112.0	114.1	123.8	11.5	21.0
3	137.0	136.0	146.5	25.0	19.0
4	82.0	96.5	99.0	16.1	18.0
5	18.9	73.0	82.3	14.8	17.5
6	40.4	81.3	89.2	14.4	18.5
7	210.0	141.0	156.0	22.8	19.0
8	258.0	237.0	243.0	14.1	20.5

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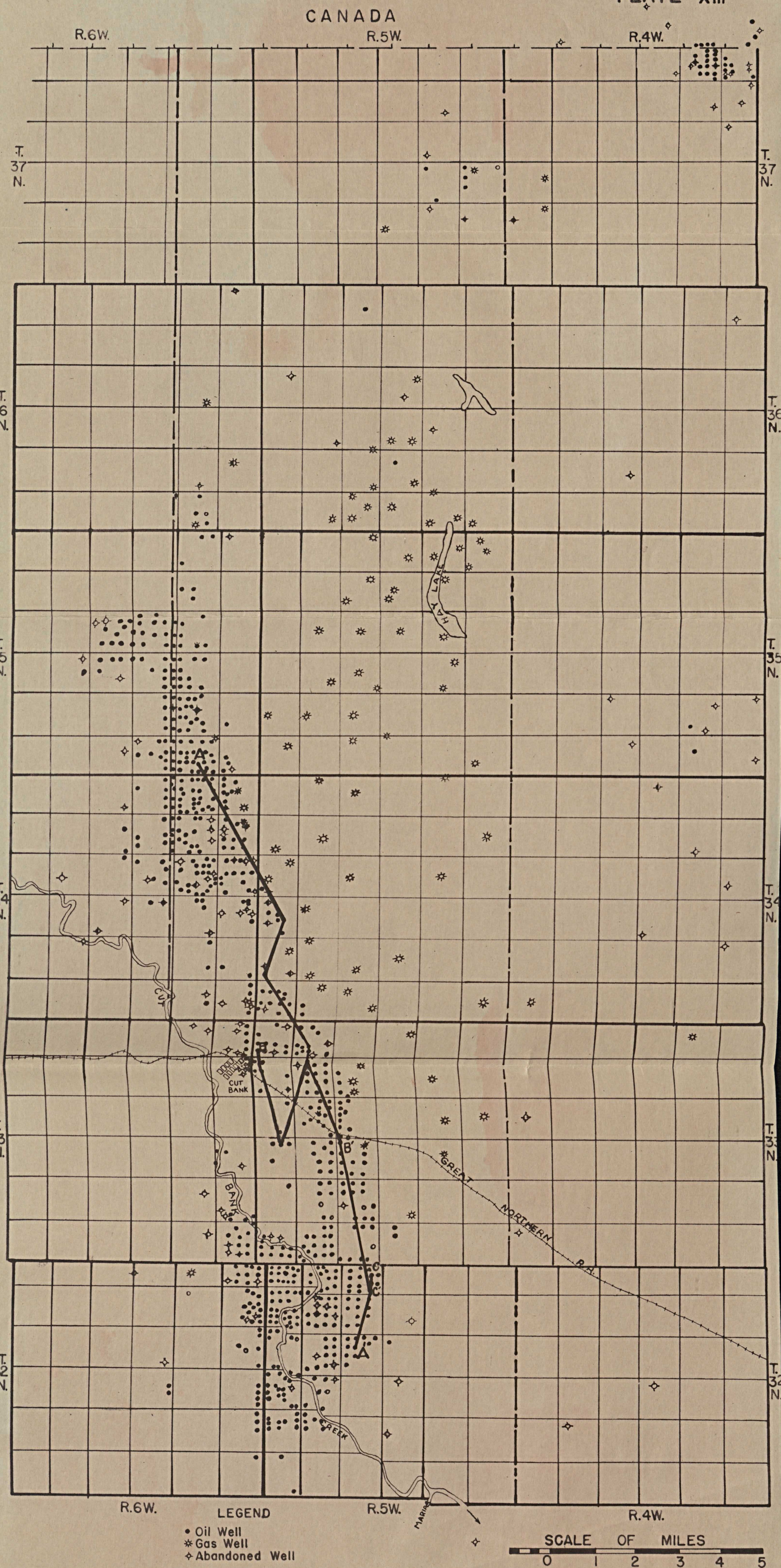
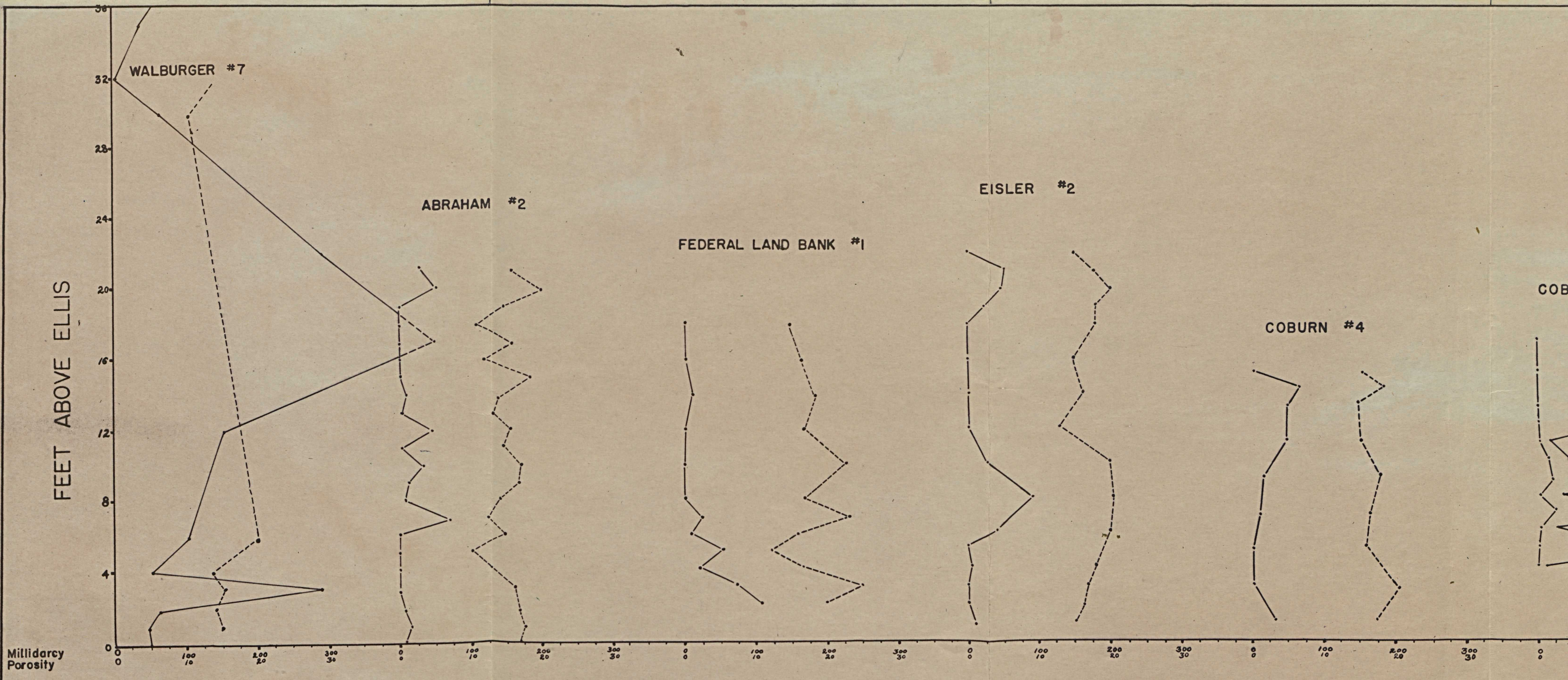
PLATE XIII

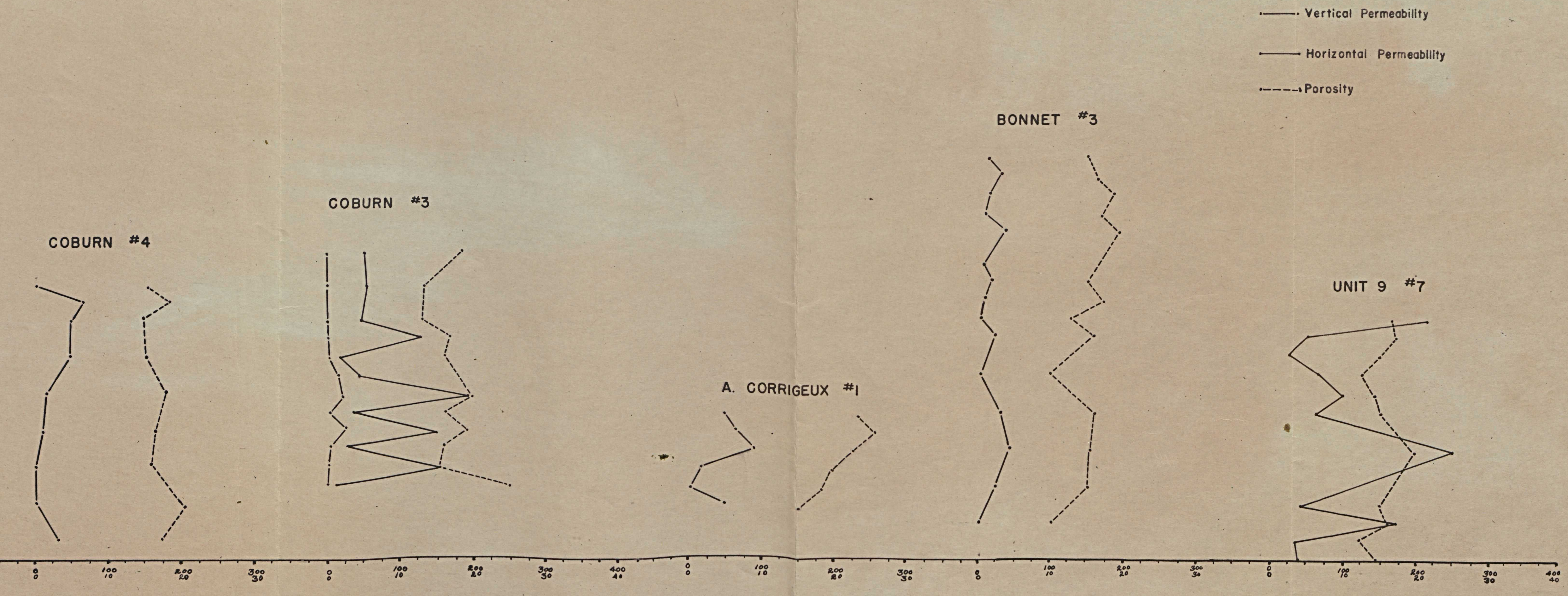


MAP OF THE CUT BANK OIL FIELD SHOWING CROSS-SECTIONS

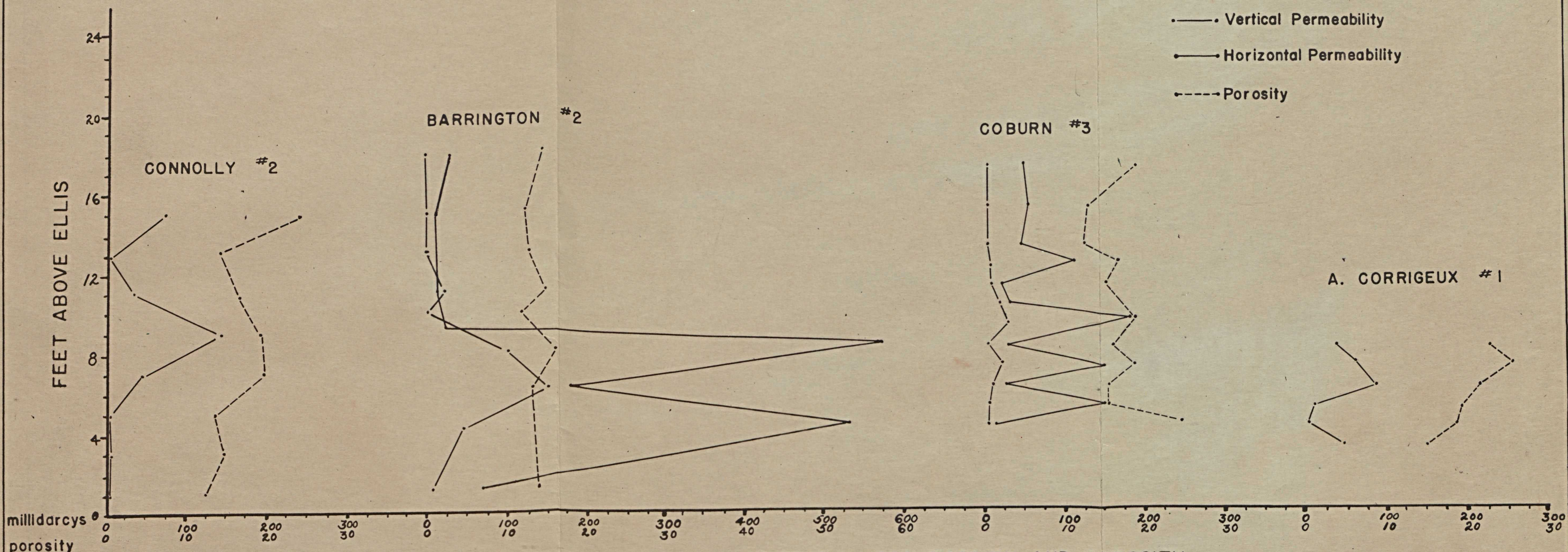


SECTION A-A'. RELATIONSHIP BETWEEN VERTICAL, HORIZO

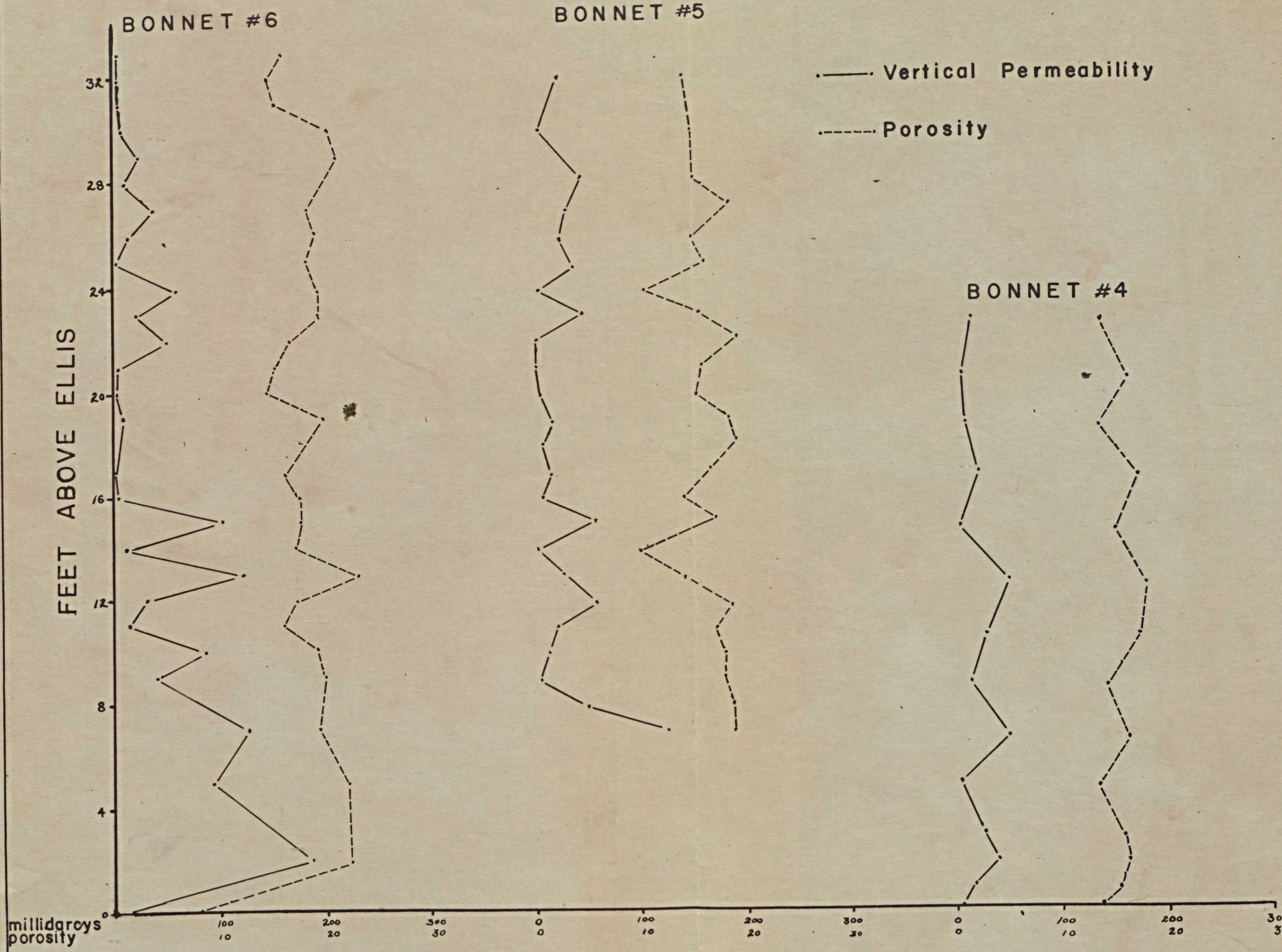
PLATE XIV



ETWEEN VERTICAL, HORIZONTAL PERMEABILITY AND POROSITY



SECTION BB'. RELATIONSHIP BETWEEN VERTICAL, HORIZONTAL PERMEABILITY AND POROSITY



SECTION CC' RELATIONSHIP OF VERTICAL PERMEABILITY AND POROSITY

PLATE XVII

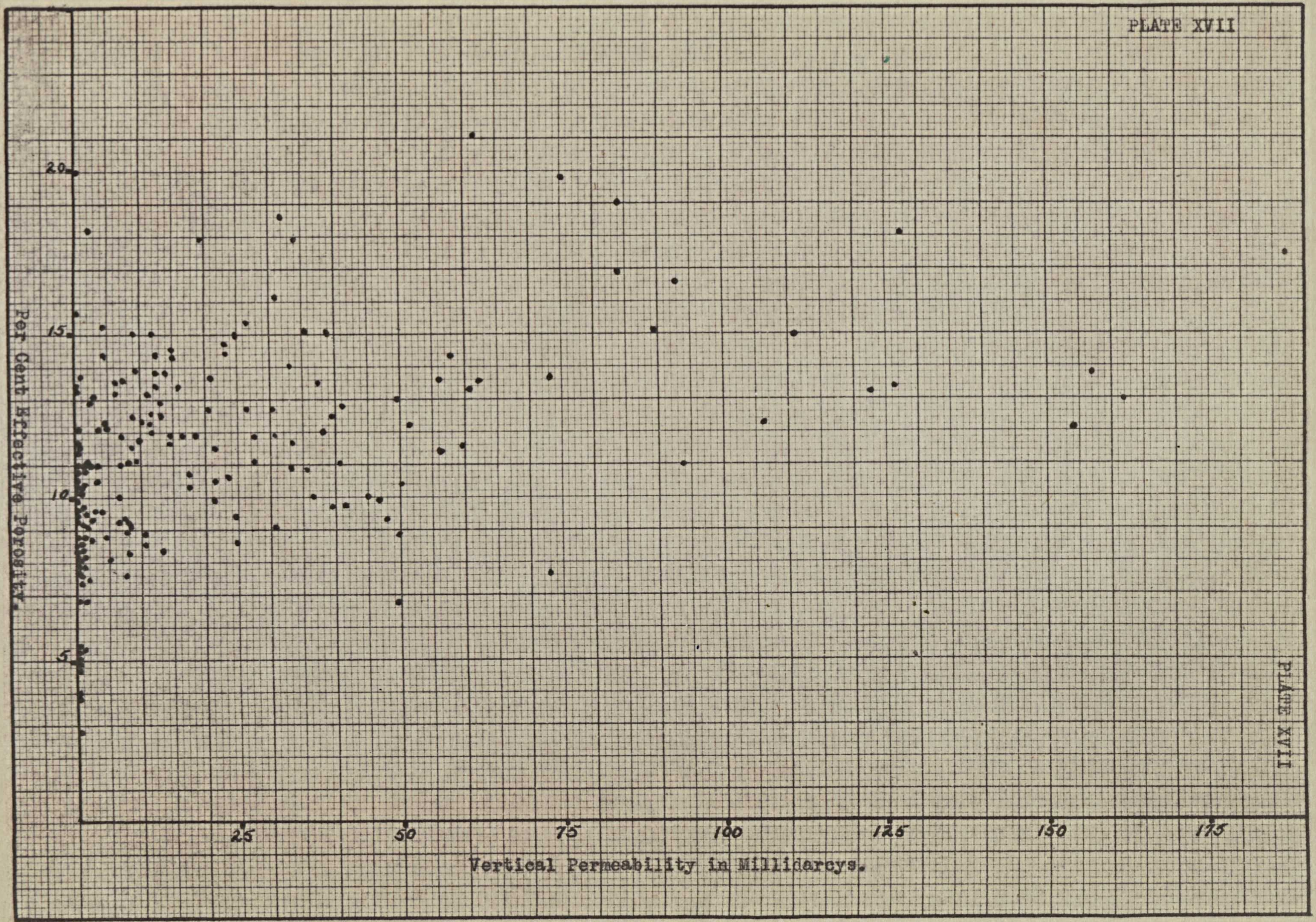


PLATE XVII

GRAPH SHOWING RANGES OF POROSITY AND VERTICAL PERMEABILITY

PLATE XVIII

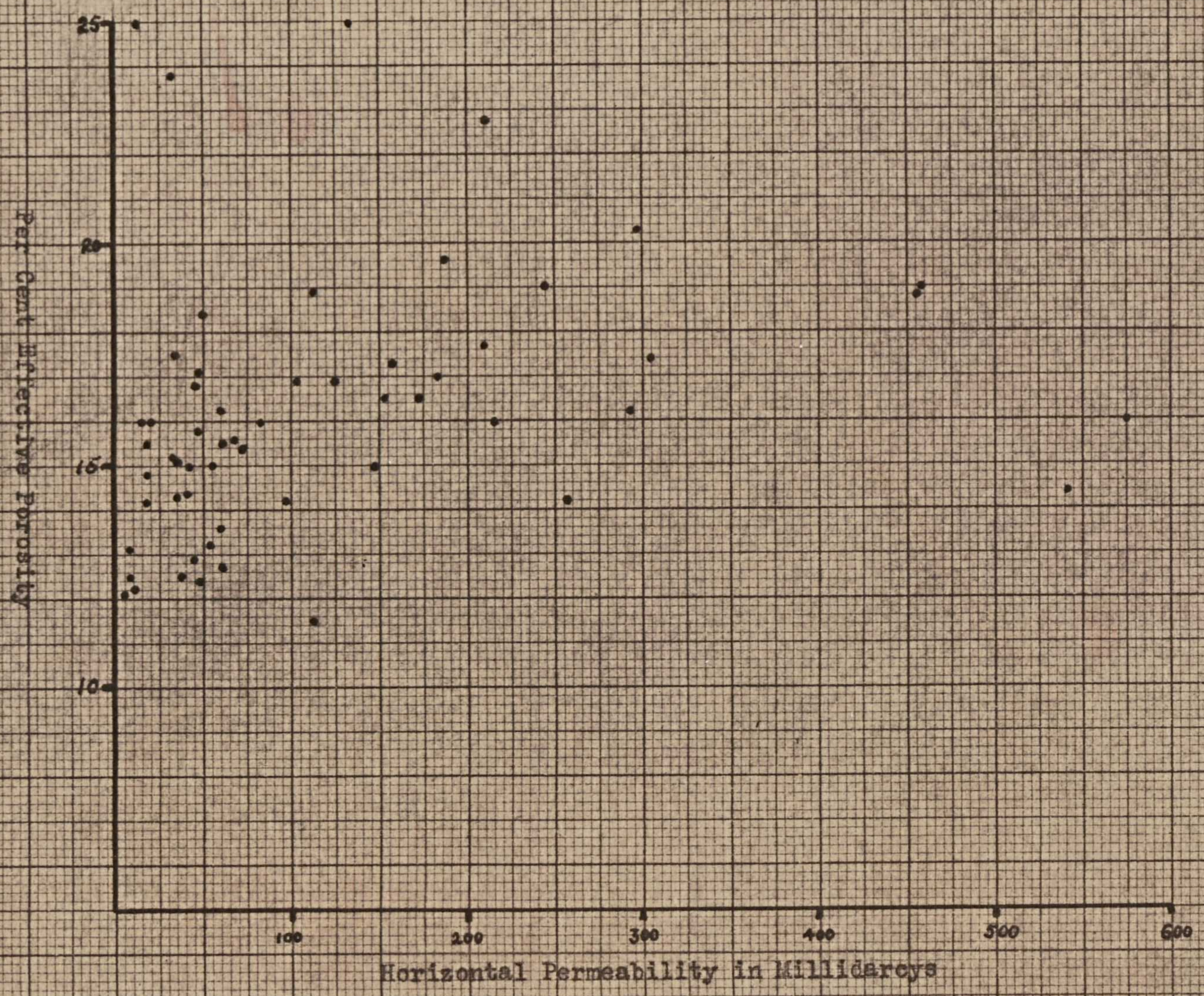


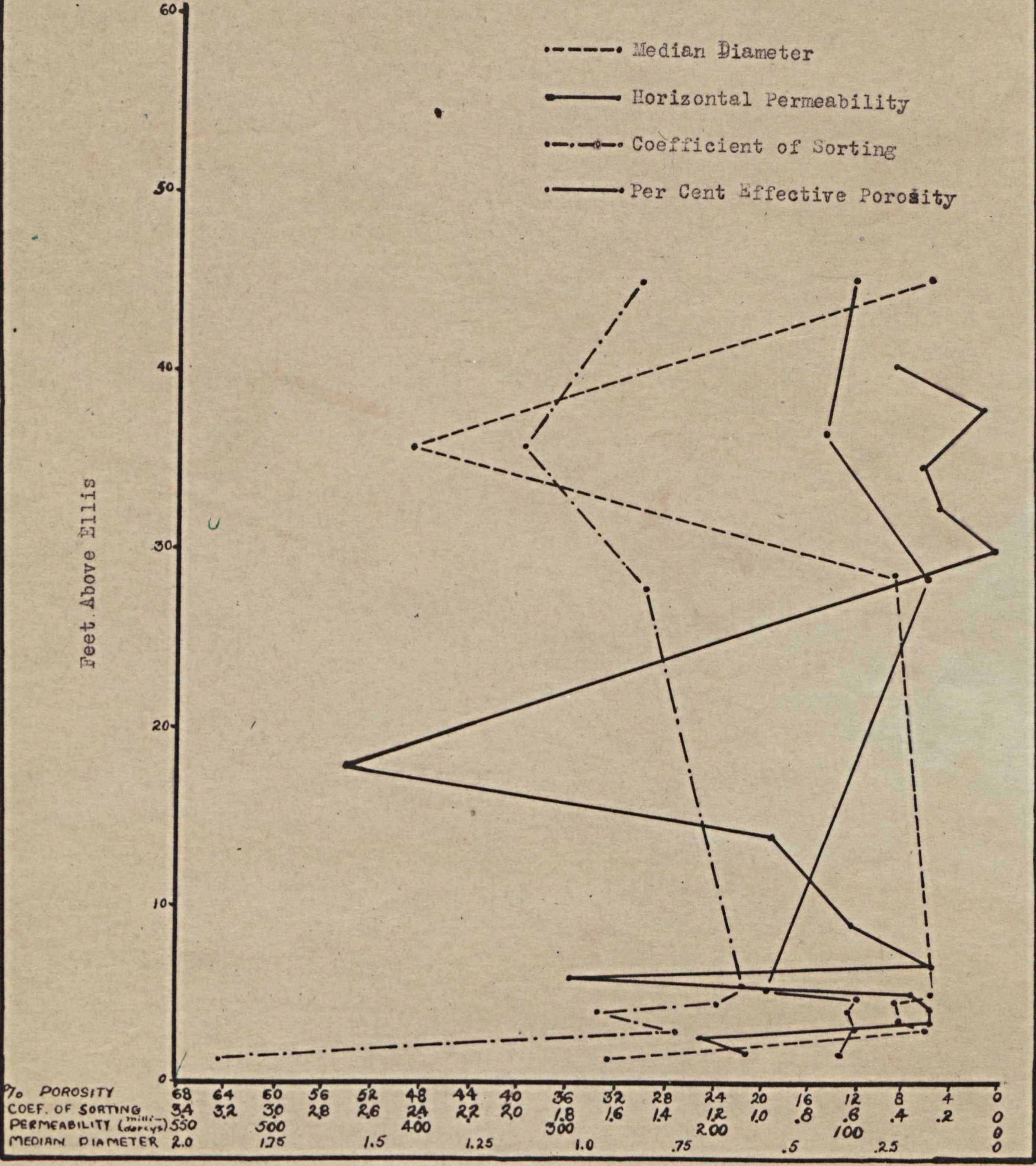
PLATE XVIII

GRAPH SHOWING RANGES OF POROSITY AND HORIZONTAL PERMEABILITY.

PLATE XIX

WALBURGER #7

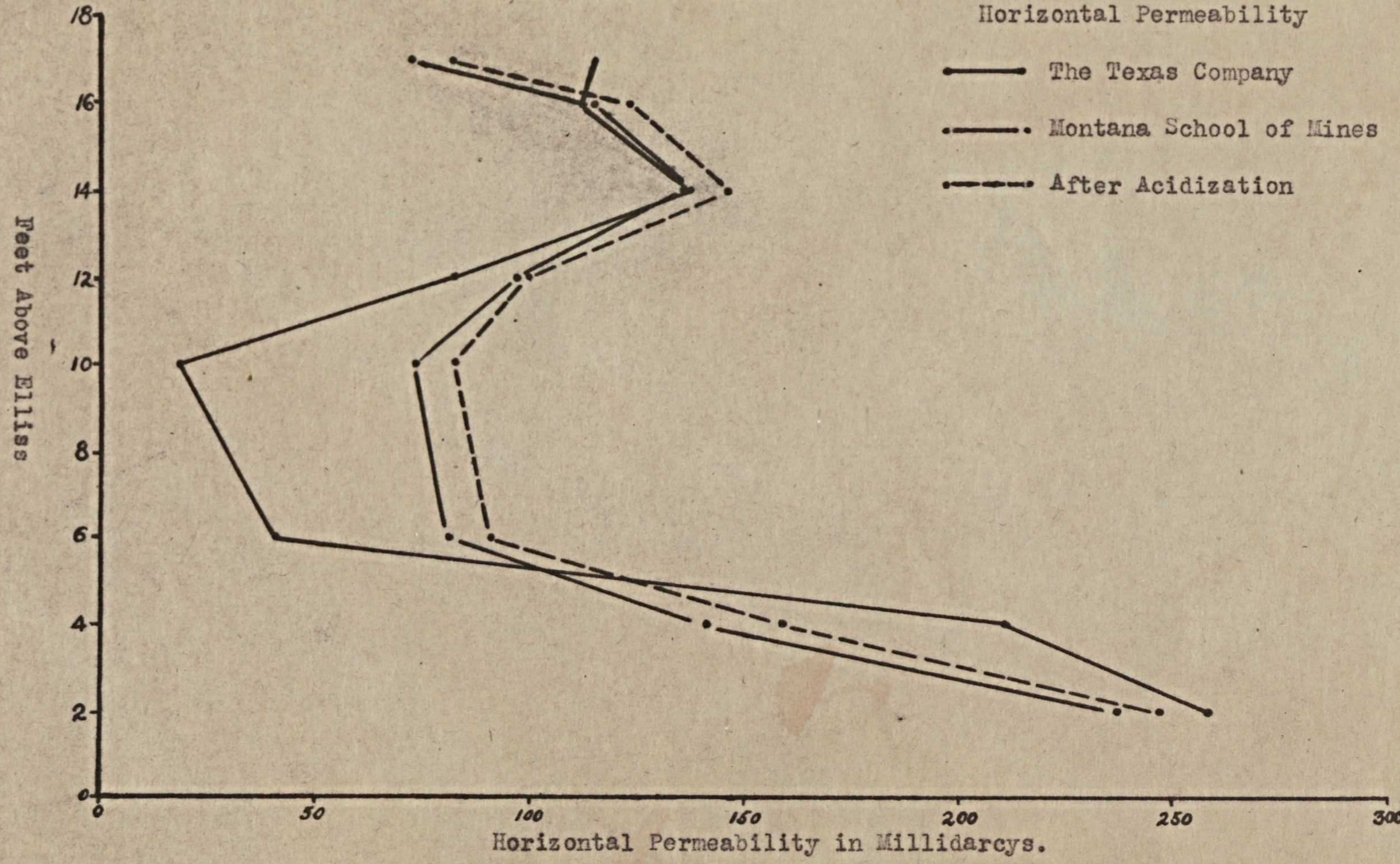
NW SW¼ SE¼ Sec. 35, T.35N., R.6W.



DIAGRAMMATIC RELATIONSHIP OF PERMEABILITY, POROSITY, SORTING, AND MEDIAN DIAMETER

CURRAN #5

C NW$\frac{1}{4}$ SE$\frac{1}{4}$ Sec. 8, T.32N., R.5W.



COMPARISON OF RESULTS OF HORIZONTAL PERMEABILITIES OBTAINED BY THE TEXAS COMPANY AND MONTANA SCHOOL OF MINES

PLATE XX