

A CORRELATION STUDY OF INFILTRATION,
PERMEABILITY, AND PORE SIZE
DISTRIBUTION

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Howard Albert Vollbrecht
1954



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**A Correlation Study of Infiltration, Permeability and
Pore Size Distribution**
presented by

Howard A. Vollbrecht

has been accepted towards fulfillment
of the requirements for
Master of Science degree in **Soil Science**

R. L. Cook

Major professor

Date May 24, 1954

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A CORRELATION STUDY OF INFILTRATION, PERMEABILITY,
AND PORE SIZE DISTRIBUTION

by

Howard Albert Vollbrecht

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Soil Science

1954

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ACKNOWLEDGEMENT

The investigator expresses his sincere thanks to Dr. Earl Erickson, under whose supervision and guidance this study was undertaken.

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INTRODUCTION

The disposition of rainfall and irrigation water has posed a problem to many workers in certain fields of science and engineering. The question is asked, "How fast and at what sustained rate will a soil infiltrate water before surface run-off occurs?"

Estimations of infiltration rates have been made by hydrologic engineers from the analysis of rainfall intensity curves and surface run-off data. The information gained in this manner is satisfactory for certain controlled watershed areas where rainfall intensities and surface run-off measurements can be made. However, a solution to the problem of surface run-off is quite extensive in scope and cannot be easily solved by the soil conservationist or the highway engineer far removed from an area where data is collected and assembled in a hydrograph.

A large volume of data have been obtained from soil core permeability studies. However, the predictions of infiltration rates for a given soil from these data have been subject to question. Therefore, data concerning correlations between infiltration and permeability rates, and pore size distributions would be valuable in planning for irrigation, flood control, drainage, erosion control, and in the construction of highways.

The purpose of this paper is to show what correlation existed between observed infiltration rates, core permeability, and pore size distribution. Soils at twenty-six different sites, including seventeen different soil types found in the lower peninsula of Michigan, were included in this study.

REVIEW OF LITERATURE

The investigation of the processes involved in the infiltration of water into the soil is not new. The investigation of infiltration started as early as 1911 when Green and Ampt (12) made a study on the effect of capillary pull on the downward advance of a moisture front in a column of soil. Investigations of soil-water relationships goes back even farther to the work of King (16) who in 1898 made comprehensive studies on the flow of air and water through a column of soil.

It has been stated that rainfall can enter the soil only as fast as the escape or displacement of an equal volume of soil air (16). If this is the case, the relationship between infiltration and the disposition of soil air becomes quite important. Many investigations have been made of the effect of trapped air on the rate of infiltration. Free and Palmer (11) were interested in determining the importance of air movement in the soil during the infiltration process. They attempted to correlate the interrelationships between air movement, pore size, and infiltration so the results could be applied to field soil under natural rainfall. When they maintained a constant head of water on sands of different texture, they found that in open columns infiltration decreased with depth and time. Infiltration proceeded slowly in the closed columns at first and only increased when entrapped air had sufficient pressure to lift a layer of saturated sand and escape through the top of the column. This was observed to be true only for the columns which contained the finer sand sizes. Free and Palmer felt that retarded infiltration was due

to the small capillaries which were blocked by compressed air and a saturated layer at the top of the soil column which resisted normal air passage. No definite conclusions were drawn but tendencies were noted. Further conclusions were drawn by Free and Palmer when they stated that in undisturbed soils, infiltration was dependent upon the independent interaction of cracks, worm and root holes, degree of aggregation, degree of shrinkage, swelling, number of pores, size and distribution of pores and other factors found in a normal soil.

Musgrave (23), in making infiltration capacity determinations of soils in the field, employed single unbuffered steel rings long enough to reach the "B" or impervious horizon as an infiltrometer, and one thousand cubic centimeter burettes for the maintenance of water heads. With similar apparatus Zwerman (33) found that on Duffield silt loam in four stages of erosion (slight, moderate, severe, and a virgin soil) infiltration rates were unexpectedly high for the moderately eroded soil with lower infiltration rates for the virgin soil next in order. Zwerman reasoned that this unexpected order was due to the impendence of water flow by entrapped air. The air was said to be trapped between particles 2mm and less. An aggregate analysis of the moderately eroded and virgin soils showed that particles greater than 2mm in size were about the same for both. However, at a depth of sixteen inches the moderately eroded soil showed a 38% non-capillary porosity value while the virgin soil showed only 26%. Since the infiltration cylinders were jacked down to the "B" horizon and the moderately eroded soil had more favorable conditions for air permeability as well as water permeability, it showed a much higher infiltration capacity over a seven and one-half hour run. Zwerman felt

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that Musgrave's method gave much higher infiltration values than would be found in natural and artificial rainmaker type infiltrometers.

Lewis and Powers (20) mentioned porosity, chiefly non-capillary, as a factor to be considered in soil infiltration capacity. In addition to non-capillary porosity, the porosity factor is increased by cracks, worm holes, animal burrows, shrinkage, and root channels. In addition, texture and structure were mentioned. They stated that infiltration through soils of a given texture and structure is influenced by colloid content, character of the colloid as to exchangeable bases, pH, $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, character of moisture, wetting and drying effects, swelling of colloids, duration of wetting, and other related effects on organic colloidal material.

Lewis and Powers also discussed the moisture pressure gradients of various kinds that were found to affect the infiltration capacity of a soil. As a unit volume of water entered the soil, conditioned by its physical properties, it became subject to the forces of capillary pull or particle field forces. They stated that to a large extent the pull of capillarity would be determined by the moisture content of the soil horizons at the time of water entry. Among the effects to be considered would be the state of hydration of the soil colloids, the depth of the soil, the permeability of the subsoil or of the soil horizon which is the least permeable. In addition, these investigators mentioned the factors of soil temperature, water temperature and its viscosity, and their influence upon infiltration capacity.

In his study of the surface factors affecting the rate of intake of water by soils, Duley (6) found cultivated and bare soils had a high rate of water run-off and soil erosion. This was especially true when soils

were left smooth by cultivating implements. Making tests on soils ranging from sandy loams to clay loams, Duley used photomicrographic studies of treated soil cross-sections and found that in all cases increased runoff was due to the beating effect of rain drops which formed a thin compact layer of soil. This compact layer was formed by the assortment of small particle sizes from structural disturbances which fitted around larger particles forming a relatively impervious seal.

Workers in the field of soil conservation have contributed to the study of infiltration by indirect methods. By making studies of soil structure and its corresponding permeability characteristics, Uhland and O'Neal (32) have attempted to relate infiltration to soil structure. Although, while not actually performing infiltration tests, these workers have described drainage and irrigation problems mainly in the light of the permeability of the horizons and their interaction for any given soil of known texture, structure, degree of aggregate overlap, and other observable soil characteristics of subsurface horizons. They admitted that the occurrence of natural water passageways were important factors in soil permeability and also agreed that infiltration of water into the surface of the soil was important. However, due to the effect of management and cropping practices, variability in infiltration and permeability of the surface seven inches prohibited significant permeability determinations.

Musgrave (23) used a single unbuffered ring type infiltrometer to conduct a study for determining the infiltration capacity of soils in the field. He attempted to relate infiltration capacity to soil structure insofar as its capacity is related to the structure of the horizon which permits its lowest normal infiltration. While Musgrave's results compared

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favorably with other methods of infiltration measurement, i.e. erosion lysimeters, and Horton's (14) rainfall-runoff curves, it was noted that the variability of the infiltration curve was quite large.

Nelson and Muckenhirn (25) in determining field percolation rates on Wisconsin soils obtained data which agreed with those cited by Zwerman and Musgrave. They found large variations in the amount of water taken into soil columns enclosed by the long steel cylinder type of infiltrometer. They felt this was due to the disturbance of the soil caused by stones and roots being driven down into the soil by the cylinder. They decided that this method was unsatisfactory and settled on the type of apparatus used by Katchinsky (15) and Kohnke (17) as initially designed by Nestrov which consisted of two concentric steel squares, driven to a shallow depth in the surface soil.

Horton (14) stated that infiltration capacity was usually less than transmission capacity because of the related effects of packing and plugging by rainfall on the surface of a soil mass. Transmission of soil water was much more rapid within the soil mass. He believed this to be true because in the process of infiltration soil air must escape from the soil surface as fast as water enters, while percolation is only dependent upon saturated soil. Horton cites the work of King (16) who made calculations of air flow through different grades of sand. King found that air flow was 26.5 times greater than water flow through the same material. Horton did not feel, however, that air would flow as fast when water was flowing into a soil in the opposite direction. He also felt that the determination of infiltration capacities in some instances was actually estimation of transmission capacities. Relative to transmission capacities Horton cited the work of Green and Ampt (12) who were attempting to

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measure the downward advance of a moisture front in a column of soil which was saturated above a moisture front. Horton felt that this determination was a transmission and not an infiltration capacity study. Bodman and Colman (2) with air dry soils maintained a head of water on a soil column for a twenty hour period and found by moisture potential studies that only the surface one to two centimeters of the soil column ever reached the state of pore space saturation.

Probably the most important physical characteristic of the soil profile yet to be considered in a study of infiltration on various soils is the effect of permeability and pore size distribution. Lutz and Leamer (21) studied the relationship between permeability and pore size distribution in three North Carolina subsoils (Iredell, Cecil, and Davidson) each having about the same texture. They found that permeability increased exponentially with particle size and pore size. In addition, they found that permeability increased greatly with the percent increase of pores larger than 0.1mm and suggested a direct relationship might exist between percent increase of pores greater than .05mm but less than 0.1mm. The clay content of these soils was also thought to have some effect upon the decrease in permeability. In order of greatest to least clay content the soils were in order Davidson, Cecil, and Iredell, while in permeability rate their order was reversed. They found that an inverse relationship existed between clay swelling and permeability. The greater the swelling, the lower the permeability. They attributed this to the clogging of smaller pores with swelling water. They also found that in the coarser fractions permeability was found to increase exponentially with an increase in particle size.

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Nelson and Baver (26) showed similar data in regard to the relationship of pore systems and permeability. They found that the disposition of infiltrated water is governed by the nature of the pore space in a given soil profile. These investigators also made a study of percolation rates through cores and found that constant percolation rates were difficult to obtain. They did, however, find a tendency toward characteristic percolation rates and particle size. When working with sand separates, it was noted that as the average size of the particle decreased, the corresponding percolation rate decreased. This is coincident with a decrease in percent non-capillary porosity. It was found that the percolation rate varied directly with volume of pores and inversely with the size of pores.

Baver (1) has stated that the best known direct methods of evaluating soil permeability involve the determination of the infiltration rate in situ and the measuring of percolation rates of cores in the laboratory. Indirect methods must be used to determine the character of soil pore space.

Much work has been done in determining the infiltration capacity of soils primarily from the standpoint of the soil conservationist and the irrigation engineer. Their interest lies in the answer to the question, "How much rain or sprinkler irrigation can be applied to a given area or soil type and for how long a period before the soil becomes saturated and precipitation or irrigation rates exceed infiltration capacities?" The apparatus generally used by these investigators has been the F or FA infiltrometer, of the rainmaker type. This equipment is expensive, has a high operating cost, and is cumbersome.

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Reviewing other methods of infiltration study, Kohnke (17) discusses possible sources of error. In conducting his own study, Kohnke decided to use the concentric square buffer type infiltrometer as proposed by Nestrov, and used later by Katchinsky. He wanted an apparatus that allowed vertical flow, unimpeded lateral flow, and at the same time did not allow air pressures in the soil column to build up to a point where they exceeded natural conditions. Kohnke further explained his viewpoint on trapped soil air during infiltration and pointed out that infiltration rates were much reduced when air pressures greater than atmospheric conditions caused impeded flow of water into the soil. It was for this reason, in addition to others, that he used the concentric steel square principle of Nestrov. The concentric ring infiltrometer used in this study is essentially of the same type used by Lewis (19), Musgrave (23), Katchinsky (15), and Kohnke (17) and has the advantage over the rainmaker type because it is inexpensive, easily set up, and is easily transported.

EXPERIMENTAL PROCEDURES

Field Procedures

Infiltration characteristics in situ. The field laboratory for the measurement of infiltration rates was enclosed in a large tent. (Figure 2 and 3.) The concentric rings were temporarily placed in position in a block "H" (Figure 4) pattern to assure adequate and consistent spacing. After the design and spacing patterns were determined the vegetation was removed with a minimum of soil disturbance. If the soil was thought to have a subsurface horizon impervious enough to impede water flow, a trench as shown in Figure 4 was dug to the surface of the impervious horizon. Rings were placed on these prepared surfaces and driven into the soil to a depth of one to two inches depending upon the micro-topography of the site. This was accomplished by means of a heavy sliding weight on a rod welded perpendicular to a steel plate so designed to hold the rings in place while being driven.

A total of fifteen sets of concentric rings was set up at each soil site. Ten ring sets were used for surface determinations and five ring sets were located on the subsurface for infiltration determinations.

After the rings were in place, a small buffer plate was placed in the inner ring and burettes essentially of the same type used by Stauffer (31) were placed directly over the inner ring. The set up of the burettes, infiltrometer rings, and water cans is shown in Figures 2 and 4.

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Prior to zero time, the two and one-half gallon cans and the burettes were filled with water. The head of water was maintained at the desired depth (two inches) by adjusting the height of the burette and can above the soil surface. Air displacement of water automatically maintained the head of water at the two inch depth. At zero time the stopcock on each burette was opened and the water cans were inverted on the outer, larger rings.

Readings were taken every ten minutes for the first hour, every fifteen minutes for the next three hours, and every half hour for the remaining three hours in the seven hour run. Two runs were made on each site. The initial or dry run was made the first day with the soil in the moisture condition that it was found. On the second day a wet run was made. A minimum of twelve hours was allowed to elapse between runs.

Just prior to the time the initial run was started, moisture samples were taken of each of the horizons in the profile. The samples were placed in standard type moisture cans. Lids were taped on with masking tape.

In addition, air and soil temperatures, temperature of the water, and evaporation readings were recorded at the beginning and at the end of each seven hour run.

At each site the profile was studied carefully. The texture, structure, and color of each horizon was observed and recorded. Core samples of each horizon were taken, using the methods of Uhland and O'Neal (32) and care was taken to have the soil at approximately field capacity before sampling. The numbered cores were placed in pint containers and transferred to the laboratory.

Definition of terms. Various investigators (14), (33) have reported that some confusion exists in the use and definition of the term infiltration capacity. In order to meet on common ground in this matter, this thesis will follow the concepts of Horton (14) and his definition of this term.

Horton states that infiltration capacity is the maximum rate at which a given soil in a given condition can absorb rain as it falls. Horton further states that infiltration capacity varies with time and as a soil continues to absorb moisture, each soil reaches a minimum infiltration capacity.

The term, initial dry infiltration, will apply to the maximum infiltration capacity of a soil at the start of the dry run.

The term, initial wet infiltration, will apply to the maximum infiltration capacity of a soil at the start of the wet run.

Measurements for these two values were taken as the average rate of flow, in inches of water, during the first hour of a seven hour run.

The term, minimum infiltration capacity, is used to describe the rate of flow of water through the soil profile after a dry seven hour run was made on the soil, followed twelve to eighteen hours later by a wet run. The measurement was taken as the flow of water in inches per hour based upon the average rate of flow from the fifth to the seventh hour of the wet run. At that time a constant rate of flow had been established.

Laboratory Procedures

Upon arrival in the laboratory the core samples were trimmed and fitted with a filter paper and cheesecloth base to prevent soil loss

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during laboratory manipulations. Approximate field moisture determinations were made by weighing the prepared cores. The cores were then placed in deep pans of distilled water for a period of one to two days, or until saturated. They were then weighed.

Pore size distribution determinations were obtained from weight loss measurements which were made after equilibrium was established on tension tables similar to those used by Leamer and Shaw (18). The tables were set at 0.01, 0.02, 0.03, 0.04, and 0.06 atmospheres of water tension. The tension tables were contained in an upright steel cabinet which reduced evaporation losses from the cores.

The cores were taken from the 0.06 atmosphere tension table and placed on porous ceramic plates in pressure cookers of the type described by Richards (28). In the apparatus the cores were subjected to tensions of one-third, one-half, and one atmosphere, respectively.

Permeability determinations were made by the method described by Uhland and O'Neal (32). A one inch aluminum ring was taped to the core cylinder with masking tape. The surface of the soil core was protected from excessive turbulence by means of a small filter paper. The cores were then resaturated and water was added in 100 milliliter increments. Permeability was determined from the amount of water percolating through the core in a two hour period and was reported as inches of water per hour.

When permeability determinations were completed, the cores of soil were oven dried at 110 degrees Centigrade for thirty-six hours and weighed. Volume weight and moisture content at the various tensions on an oven dry weight basis were calculated.

The data
form in the App
Laboratory Data

The data obtained from these procedures are contained in tabular form in the Appendix under the section headed, "Basic Field and Laboratory Data."

Statistical Procedures

The procedures followed for all statistical determinations in this thesis were described by Dixon and Massey (5). Data contained in Tables III and IV are the correlation coefficients between the factors thought to influence infiltration and permeability in soils.

Dixon and Massey (5) stated that in a sampling of any population believed to be normal and involving two variables, a test of the independence of corresponding values may be ascertained. This is to say, if these variables as points in a plane have little or no relation to each other, the correlation coefficients will approach or be equal to zero. If the variables are in some manner related, certain minimal values, based on $N-2$ degrees of freedom and percentiles of significance, will show the probability percentiles for the minimum chance of independence in this population. Correlation coefficients which exceed the minimal values in any particular case show a probability of significance toward dependence, or correlation. However, in a sampling of some populations involving two variables which are independent, it is possible to find a series of points, if the data are plotted in two dimensions, which show a significance of correlation at various percentage levels. The test of the validity of the correlation, or an indication of significance, is to show that the correlation coefficient is greater than three standard deviations of the correlation coefficient obtained.

Calculations were made to determine the validity of extreme values found in raw permeability and infiltration data for each soil site. An opinion on the statistical significance of these extreme values was obtained and it was decided that values which exceeded three times the

standard deviation from the mean value, positively, or negatively, would be discarded.

It was noted that only the extremely high values could be discarded on this basis. This was not true for the very low values since three standard deviations from the mean in almost every case allowed zero rates of flow. In addition, it was felt that the range of values obtained in this manner was not too wide when the variability of soil is considered in the light of past investigation and when wide coefficients of variation found in this study are noted.

RESULTS AND DISCUSSION

Variability Analysis

It has been noted by some investigators (10), (26) that constant rates of flow in core permeability studies are difficult to obtain. Replicate infiltrometers have also been found to give a range of rates which are mainly due to soil variability in addition to other variables. Lewis and Powers (20) mention several factors which may limit constant infiltration measurements. They are (1) the pressure effect of different hydraulic heads, (2) depth of moisture penetration, and (3) textural differences in a soil column. As infiltration of water proceeds, differential swelling of the colloids probably due partially to the initial soil variability tends to increase the variability between replicates.

A statistical analysis of individual variability was made of core permeabilities and infiltration rates on a sampling group taken from the twenty-six sites. The sampling group contains three soil types, Fox sandy loam, Hillsdale sandy loam, and Miami silt loam. The Fox sandy loam was replicated to see if there were trends toward constant relationships between the same soil type located in different areas of the state.

The data reported in Tables I and II show that wide variations were commonplace. However, certain trends were found to exist for the sampling group. For instance, as shown in Table I, the average readings

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of minimum infiltration showed the highest range of variability. It was felt that whatever the cause for wide variability in minimum infiltration flow rates, the same processes affected the permeability of saturated cores.

The initial wet infiltration variations were usually less variable than were the measurements for the initial dry infiltration rates. This is not strange since certain variable factors present in a dry soil approach equilibrium in a saturated soil.

The permeability data show wide variation also which, from past investigations (26), was not surprising. However, variations in the measurements for minimum infiltration capacity were also wide and of the same order.

Surface Soil Correlations

Certain of the physical properties of soils seem to be related to the moisture characteristics which a soil may exhibit. The factors of pore size, pore size distribution, continuity of pores, and moisture content of the soil, may have some effect upon the rate of infiltration and permeability. Several of those factors which might be related to each other were selected and tested for a correlation study. Their correlations will be considered individually in the discussion to follow.

Minimum infiltration capacity and permeability. There is a very high significance of correlation for minimum infiltration capacity and permeability. The correlation coefficient is 0.88 ± 0.047 . The reason for this high correlation may be explained by stating that both methods of water flow measurement are of the same type, that is, measuring rates of water flow through soils in a saturated or very wet state. It is be-

lieved that the saturation of cores prior to permeability determinations was approximated by long periods of water flow through a soil profile undergoing an infiltration study. Under these conditions of infiltration, most of the variable properties in a soil body would have reached a state of equilibrium and would give readings related to core permeability.

Figure 5 gives the regression line which appears as a solid line, where $Y = 0.82 X + 0.90$. Examination of this line for the two variables, shows three soils far out of line. The data related to these points were discarded for pertinent reasons.

Sites 7 and 8, Nappanee and Paulding soil series respectively, were very fine textured soils. Due to the dryness of the soils, core sampling was difficult. This probably altered the structure in the soil cores to allow an excessively high permeability rate. Values for Site 3, a Spinks sandy loam, were disregarded for the reason that infiltration rates were obtained on the Spinks soil while the core samples were inadvertently taken from a Hillsdale sandy loam.

An important point to be made at this time is that even though the regression line for the total twenty-six sites is distorted by the poor results from the three previously mentioned soils, the correlation is strong enough to hold the regression line well within significance at the one percent level ($r = 0.59 \pm 0.133$). In addition, if the high correlation of these two variables is considered in the light of the wide variability in the rates of flow for both methods, it must be assumed that the magnitude and direction of the variations are of the same order. The correlation between these two variables has proven to be strong and very highly significant. The correlation is also very close to a straight

line relationship. On the basis of these results it is concluded that if cores of the surface horizon of a given soil are carefully taken at approximately field capacity, the approximate minimum infiltration capacity of a soil can be estimated in the laboratory by saturated permeability determinations

Minimum infiltration capacity and lowest permeable horizon in profile. The correlation coefficient is 0.20 ± 0.196 and is not significant. This is probably due to lateral flow taking place over a horizon which is less permeable than the horizon above it, with flow moving laterally through the more permeable horizon. This also shows a shortcoming in the concentric ring infiltrometer for the measurement of infiltration characteristics of the total soil profile. In defense of the infiltrometer, the buffer compartment prevents lateral flow of water from the inner ring down to the horizon which is impervious. However at this point lateral flow is unimpeded and correlated data for this point are not obtainable.

Minimum infiltration capacity and volume weight. The correlation coefficient is a negative 0.53 ± 0.147 (see Figure 6 for the regression line) and is significant. This is to be expected since as volume weight increases, porosity should decrease, with a corresponding decrease in permeability.

Minimum infiltration and percent pores drained at various tensions. The significant correlations in this group are shown in Table III. Their corresponding regression lines are presented in Figure 7, 8, 9, and 10. The correlations at the 0.01 atmosphere and 0.03 atmosphere tensions were not significant but at higher tensions the correlations improved.

This apparently was where pores were becoming continuous. There was an additional improvement in the correlation when pore sizes 100 and 18 microns in diameter at 0.60 and one-third atmosphere of tension were added to the total volume of pores drained. The addition of pores drained at one atmosphere of tension did not seem to further improve the correlation. The increase and steady correlation, starting at the 0.40 atmosphere tension and continuing through the one atmosphere tension level seems to indicate that the smaller pores influenced the minimum infiltration capacity runs. Schiff (29) working with large pond type infiltrometers, has stated that infiltration rates are directly proportional to the combined depth of the surface water head and the hydrostatic head existing in the soil. The depth of the hydrostatic head is dependent upon the nature of the soil and will not always be constant for a given depth of surface head. Edlefsen and Anderson (8) have stated that hydrostatic pressures in soils are nearly proportional to the depth of water in the soil column. Considering the added depth of the hydrostatic heads that might exist in a soil and the corresponding hydrostatic pressures that could exist, an explanation of the significant values for pore sizes drained at 0.04 atmosphere to one atmosphere of tension might be suggested. Because of the increased pressures it is possible that certain of the smaller soil pores may be forced into functioning as transmitting channels whereas under relatively lower surface heads this would not be the case.

Minimum infiltration capacity and percent total pore space. The correlation coefficient 0.60 ± 0.131 (see Figure 11 for the regression line) is significant at the one percent level. The relatively low cor-

relation is an indication of the dependence of infiltration upon a wide distribution of medium to small sized continuous pores rather than on a few large pores.

Permeability and percent total pore space. The correlation coefficient is 0.72 ± 0.098 (see Figure 12 for the regression line) and is significant. The correlation for these two variables for most soils should be consistently high. If there is a relationship between an increase in total porosity with a corresponding increase in the total percent of non-capillary pores, the rates of flow should be proportional to the percent of non-capillary pores. Usually permeability determinations are conducted under relatively low hydrostatic pressures and the rate of flow would be governed to some extent by the larger, continuous, non-capillary pores.

Permeability and volume of pores drained at various tensions. For the significant correlations see Table III. Their corresponding regression lines are shown in Figures 13, 14, 15, and 16. It will be noted that the correlation between permeability and the volume of pores drained seems to lie only in the larger range of pores. The correlation was most significant when the volume of pores drained was considered for the 0.03 atmosphere tension level. This may be an indication of the fact that permeability under low hydraulic heads of water can only take place through the larger continuous pore systems. The improvement of the correlation at 0.03 atmospheres of tension shows that this pore size (200 microns in diameter) is connected in some way with the formation of continuous channels for water flow. The lower correlation for pore sizes involved in the 0.01 atmosphere (600 microns in diameter) tension, seem to indicate some loss of pore continuity. Correlation may

also be lost due to the fact that when pores approach the smaller sizes, even though they may be continuous, they do not contribute greatly toward permeability.

Permeability and volume weight. The correlation coefficient is negative 0.75 ± 0.089 (see Figure 17 for the regression line) and is highly significant. The high correlation was to be expected for the same reasons as were previously mentioned for a comparison of minimum infiltration capacity and volume weight.

Initial dry infiltration capacity and permeability. The correlation coefficient is 0.63 ± 0.023 (see Figure 18 for regression line) and is significant. This correlation was somewhat dependent upon the initial moisture content of the soil at the start of the infiltration run. When a soil is relatively dry, the initial volume of water carried down through the large pores and cracks is large. However, with time, the larger pores and cracks diminish in size and the rate of water flow diminishes. Therefore when comparisons are made between a soil which is saturated, and a soil which is becoming saturated, the correlation may not necessarily be high.

Initial dry infiltration capacity and initial air space. The correlation coefficient is 0.72 ± 0.105 (see Figure 19 for regression line) and is highly significant. This relationship was expected to be high. Dependent on the moisture content of soil pores, infiltration can be expected to be proportionate to the many factors influencing flow rates as mentioned by Lewis and Powers (20). Among those mentioned are moisture content of pores, degree of colloid swelling, size of pores and their distribution, number of soil cracks and their distribution, and other factors.

Initial wet infiltration capacity and permeability. The correlation coefficient is 0.43 ± 0.166 , is not significant, and is a considerably lower value than was expected. It was assumed that when a soil had been subjected to conditions of saturation for a period of nineteen hours or more the change in pore sizes and pore size distribution, brought about by colloid swelling, should have reached an approximate equilibrium. It is apparent that equilibrium was not established in the surface soil horizons to the extent that they existed later during the infiltration run. Lack of established equilibria probably can be attributed to the differential rates of colloid swelling, sand lenses, and other associated factors which occurred in the different soil sites and types tested in this study.

There is also the possibility that since the soil column was subjected to conditions of saturated water flow, sufficient time was not allowed for complete gravitational drainage of the non-capillaries to field capacity levels. Therefore, continuous soil pore systems might still have contained sufficient water to cause the existence of water columns under tension. These columns may have existed as varying boundaries with variable tensions as suggested by Edlefsen and Anderson (8). When the infiltrating water met those boundaries, the rate of intake of water was increased or decreased according to the variability of the region in which infiltration was taking place.

Summary of Surface Soil Correlations

It has been shown that for surface soils, definite relationships existed between certain types of field infiltration determinations and the permeability of soil cores. In this connection it was demonstrated

that infiltration after the fifth hour on a given soil, closely approximated the permeability of the soil profile. While individual values varied rather widely, the end result seemed to indicate a straight line relationship that results in values which are highly significant at the one percent level. In addition, the correlation is sufficiently high to compensate for values which are out of line by as much as three standard deviations from the mean correlation value. In addition, initial dry infiltration rates were highly correlated with initial air space. Another significant correlation existed between initial dry infiltration rates and permeability which in turn may be interrelated to the initial pore space. These significant correlations were to be expected since infiltration of any type is dependent upon the state of hydration of the soil body.

Still other interrelationships were found through significant correlations between infiltration, permeability, corresponding volume weight, and continuity of the surface soil pore systems.

The importance of soil pore continuity is discussed by Nelson and Baver (26). They conducted tests on prepared soil columns to try out the concepts of Haines (13) on the cellular configuration of soil pore space. In agreement with the concepts of Haines, Nelson and Baver found that soil pores may be non-functional due to a lack of continuity. They demonstrated this fact by showing that large pores may be connected to each other by small pores which effectively blocked the large pore column by forming constrictions or "necks". They further showed that a constriction so located, renders the large pore column only as effective, for functioning in permeability and infiltration, as the diameter of the pore size causing the constriction.

Evidence is presented in data from Table III to show that minimum infiltration rates were not solely dependent upon the larger pores of a soil in situ, as is the case for permeability in soil cores, but were related to a distribution of pores ranging from large to very small with special emphasis being placed on the continuity of the pore within the individual size groups. An additional factor, hydrostatic pressures, acting upon the smaller continuous pore systems, was also suggested to explain the distribution of correlations between minimum infiltration and the variety of pore size groups found in surface soils.

Subsoil Correlations

The study of the behavior of the distribution, size, continuity, and moisture content of subsoil pore systems was thought to be related to the relatively consistent patterns established by surface infiltration curves for various soils under various conditions. An indication of similarity or dissimilarity in these patterns would be of great assistance in explaining and predicting the soil-moisture relationships of soils as they pertain to the disposition of natural or artificially applied surface moisture. A series of quantities identical to those chosen for study of the surface soils were selected and tested for a similar correlation study of the subsoils.

Minimum infiltration capacity and permeability. The correlation coefficient is 0.81 ± 0.095 , which is highly significant as indicated by the regression line in Figure 20. A similar type of comparison was made in the previous correlation between minimum infiltration capacity and permeability of the surface soils. It should be noted that the correlation might have been higher. In most cases the subsoils were

moist at the start of infiltration determinations, consequently pore size and pore distribution should have reached an equilibrium at an earlier time in the infiltration run. In addition, because of less plant and animal activity and soil disturbances caused by man, the size of pores in the subsoil are smaller and tend to be more uniform. Also, the degree of colloid swelling should be less and not affect pore size and the distribution of pores as much as was the case for the surface soils where a greater variety of pore size was found.

Minimum infiltration capacity and lowest permeable horizon in profile. The correlation coefficient is 0.32 ± 0.249 . There is no significance of correlation between these variables. The reasons for this lack of correlation are essentially the same as those previously discussed for the surface soil.

Minimum infiltration capacity and volume weight. The correlation coefficient is -0.17 ± 0.269 . The correlation is negative, which is to be expected, but it is non-significant. The lack of correlation is probably due to the fact that volume weights increased and the rates of flow decreased out of proportion to the apparent decrease in pore volume. It may be noted that the total pore space of the subsoil decreased slightly (see Table V, Basic Field and Laboratory Data). In addition, the large pores (600 to 200 microns in diameter) 0.01 to 0.03 atmospheres tensions contribute approximately nine percent to the total pore space of the subsoil, thus aiding in the maintenance of a relatively high total pore space.

The fact that these large pores are non-functional, as is shown by lack of correlation with minimum infiltration, indicates that they

may be partially responsible for very low correlation between minimum infiltration capacity and volume weight. Other reasons for lack of correlation may be found in the limited capacity of the small soil pores for infiltration when time is a factor and the unmeasurable flow of water through checks and cracks associated with soil structure.

Minimum infiltration and percent pores drained at various tensions.

The correlation coefficients for these two variables are given in Table IV. Their corresponding regression lines are presented in Figures 21, 22, 23, and 24. The significance of correlations for the range of pores drained at 0.04 atmospheres of tension and greater was very high. The fact that correlations were not significant for the larger sized pore (600 to 200 microns in diameter) at 0.01 and 0.03 atmospheres of tension indicates that they were probably discontinuous. On the other hand the smaller pores sizes did, according to the correlation coefficients, contribute to infiltration and showed a degree of continuity. Here again as in the surface soils, the effect of hydrostatic heads of water may have had some part in causing the smaller sized pores to function.

Minimum infiltration capacity and percent total pore space. The correlation coefficient is 0.29 ± 0.254 , which is not significant. The fact that the total pore space does not correlate with infiltration supports the statements concerning the presence of large pore systems in the soil body which do not function as non-capillaries. This is evidenced by the fact that the average decrease in percent total pore space is approximately seven percent, while the average decrease in water flow in inches per hour amounts to 4.4 inches per hour. For ap-

proximate purposes of comparison, minimum infiltration rates of flow may be expressed in terms of the percent of pores required per inch of water flow per hour. For the surface soil, it took seven percent of the total pore space to percolate one inch of water per hour. For the subsoil, it took twenty-five percent of the total pore space to percolate one inch of water per hour. Apparently the eighteen percent difference in pore space lost to percolation is found in the large pores or cracks which are not continuous and do not contribute to infiltration to a great extent.

Permeability and percent total pore space. The correlation coefficient is 0.66 ± 0.156 . (See Figure 25 for the regression line.) This correlation is significant; however the relative significance is moderate. The moderate significance of correlation in this case can be explained by stating that permeability must be more directly related to the percentage volume of continuous pores and the function of cracks and checks associated with soil structure than to total pore space. In this instance water flow through cores appeared to be mainly dependent upon the continuous pore system of the core. However, the fact that the correlation is not higher indicates some additional flow was taking place through other channels.

Permeability and percent pores drained at various tensions. The correlation coefficients for these two variables are presented in Table IV. Regression lines for the corresponding significant correlations can be seen in Figures 26, 27, 28, 29, and 30. The relationship here is essentially the same as discussed for minimum infiltration capacity rates and percent of pores drained at different tensions for

the subsoils. It is to be noted again that the percent of pores drained at higher tensions and reduced permeabilities have very high correlation coefficients. Such close relationships show that continuity as well as size, plays an important role in permeability. Lack of correlation was noted in only one case, pores drained at 0.01 atmospheres of tension, indicating again that the pore size was not continuous and therefore did not contribute to permeability.

Permeability and volume weight. The correlation coefficient is -0.23 ± 0.263 . There is no significance of correlation, and the correlation is negative. These relationships would be expected based upon the data presented thus far. Consistent with this lack of correlation, it should be noted that the correlation between minimum infiltration capacity and volume weight was not significant.

Initial dry infiltration capacity and initial air space. The correlation coefficient is -0.08 ± 0.271 . There is no significance of correlation. The lack of correlation can be related to the fact that when initial infiltration rates are low, the lack of correlation is not to be found in a consideration of the initial volume of air space to be filled with water. The error probably lies in the fact that the volume of the larger pores (approximately nine percent) of the subsoil contribute to an estimate of the initial moisture content of the soil pore system. However, such pores do not contribute to infiltration because of their discontinuity. Therefore, flow rates would be disproportionate again due to non-functioning large pores.

Initial dry infiltration capacity and permeability. The correlation coefficient is 0.81 ± 0.095 . (See Figure 31 for the regression

1

line.) There is a high significance of correlation. Permeability in this case again is probably dependent upon the ability of the smaller continuous pores in the soil to act as transmission channels through a relatively impervious soil. This is consistent with previous discussions.

Initial wet infiltration capacity and permeability. The correlation coefficient is 0.85 ± 0.077 . (See Figure 32 for the regression line.) There is a very high significance of correlation. The situation for this correlation is the same as previously discussed for initial wet infiltration capacity and permeability in surface soils. The degree and extent to which factors influencing infiltration and permeability have acted upon the soil body with its pores and cracks, determines its response to further tests of relative rates of water flow. In the case of subsurface soils, if the pore volume of the smaller pores is reduced by swelling then as is indicated by the high correlation, the infiltration and permeability rates are proportionately reduced.

Summary of Subsoil Correlations

It should be noted that while the number of significant correlations for the surface soil were many, significant correlations for the subsoil were not so frequent. It was noted that this loss of correlation was primarily due to the relatively moderate loss of total pore space with a corresponding increase in volume weight, while permeability and infiltration rates did not decrease proportionately. Most of these cases can be explained by noting that in infiltration and permeability, the continuity of small pore sizes did not always produce a significant correlation. Therefore, some of the distortion of the correlation was due to the flow of water through channels other than the pores. This

flow may have been through cracks and checks associated with soil structure. The lack of correlation between permeability and volume weight illustrates this point.

It was noted that a high correlation existed between minimum infiltration and subsoil permeability. The high correlation between these two variables as opposed to the lack of correlation between permeability, minimum infiltration, and their corresponding volume weights, was thought to arise from the fact that approximately the same type of disturbance of soil structural cracks and pores occurs when preparing cores for permeability determinations and the preparation of subsoil trenches in infiltration studies.

Initial dry and initial wet infiltration, as compared with permeability, had a very high significance of correlation. This close association was probably due to the fact that as in minimum infiltration and permeability correlations, the soils are not too far from a saturated state. Thus flow rates in the subsoil for initial dry, initial wet and minimum infiltration, approximate each other with respect to permeability rates of flow. Evidence is shown of the fact that when comparisons were made between infiltration, permeability and their corresponding pore size distribution, the relatively high correlations involved a wider range of pore sizes which included the very small sizes. Such a close relationship indicates that while the total pore space in the subsoil was less, the continuity of the pores was much increased over the pore systems in the surface soils.

Regression Line Predictions

It was felt that since certain of the correlations in this study were very high, regression lines with the necessary conversion factors could be employed to predict such quantities as the minimum infiltration capacity of a soil from given information on core permeability determinations, or other data which might result in the valuable saving of time.

The regression lines and associated data were submitted to a statistical test to determine the coefficients of the regression lines with regard to predicting the above mentioned quantities. In many cases, the distribution of points about the regression line is wide, thus leading to a high standard error of estimate or a wide margin for predicting purposes. However, certain correlations were found that showed a narrow distribution of points about the regression line. The best of these correlations was selected to test its value in prediction determinations.

The coefficient of the regression line for the best correlation was calculated in order to find the band of normality for predicting purposes. The best correlation coefficient in this study existed between the two variables, minimum infiltration and permeability of the Ap horizon where $r = 0.88 \pm 0.047$. In a comparison of these two variables, Figure 5 shows the limits of the band of normality into which sixty-eight percent of all estimates will fall. The equation for the expression of this association is $Y = 0.82X + 0.90 \pm 2.1$, showing that for any given permeability the corresponding unknown minimum infiltration capacity can be estimated to within 2.1 inches per hour of its actual flow rate.

CONCLUSIONS

The relation between infiltration, permeability, and pore size distribution has been presented in this thesis by means of correlation studies. An attempt was made to make the correlation study complete within the limits of time allowed for a study of only those essential and related variables thought to pertain to soil infiltration rates and permeability determinations. The results of this study seem to point toward certain relationships, listed below, which may be of value as an aid to further research in projects similar to this study.

1. There is a significant relationship between minimum infiltration capacity and permeability rates for a given soil horizon.
2. If cores are taken at the proper moisture content and carefully treated, it is possible to predict, within certain limits, the minimum infiltration capacity of a soil.
3. Permeability and infiltration are directly affected by the extent of continuity and total percent of pores in the soil body.
4. Pores in the size range, 600 to 200 microns in diameter, are more often than not, discontinuous.
5. The infiltrometer, as used in this study, will not supply infiltration data beyond the least permeable horizon in the profile.

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APPENDIX

TABLE I
STATISTICAL ANALYSIS OF INFILTRATION DATA

Site No.	Soil Type	Infiltration	Av. In./hr.	* Standard Deviation	** Coefficient of Variation
9	Fox Sandy Loam Surface	Initial Dry	6.3	.78	12.34
		Initial Wet	3.9	.33	8.38
		Minimum	2.7	2.56	94.81
	Subsurface	Initial Dry	6.6	2.25	34.09
		Initial Wet	3.6	.56	15.46
		Minimum	1.8	.96	53.21
10	Fox Sandy Loam Surface	Initial Dry	9.0	2.84	31.55
		Initial Wet	6.0	1.88	31.33
		Minimum	3.7	1.89	51.08
	Subsurface	Initial Dry	9.0	3.55	39.44
		Initial Wet	5.0	.52	10.44
		Minimum	1.9	.96	50.47
15	Fox Sandy Loam Surface	Initial Dry	14.2	3.68	25.91
		Initial Wet	7.4	2.32	31.35
		Minimum	8.8	3.65	41.47
	Subsurface	Initial Dry	7.3	1.83	25.06
		Initial Wet	3.7	.50	13.37
		Minimum	2.0	.58	28.90
17	Miami Silt Loam Surface	Initial Dry	14.1	6.14	43.54
		Initial Wet	4.7	1.60	34.04
		Minimum	3.6	1.27	35.27
	Subsurface	Initial Dry	3.0	.29	9.6
		Initial Wet	1.4	.29	20.57
		Minimum	.3	.15	50.66
23	Hillsdale Sandy Loam Surface	Initial Dry	8.6	1.92	22.32
		Initial Wet	6.4	1.77	27.65
		Minimum	8.1	4.16	51.32
	Subsurface	Initial Dry	3.5	.37	10.48
		Initial Wet	2.3	.21	9.21
		Minimum	.4	.14	35.25

* in inches per hour

** in percent

TABLE II
STATISTICAL ANALYSIS OF PERMEABILITY DATA

Site No.	Soil Type	Average ml/min.	Average In./hr.	* Standard Deviation	** Coefficient of Variation
9	Fox Sandy Loam				
	Ap	3.50	1.79	1.55	44.15
	B ₁ ***	2.00	1.02	1.19	59.50
	B ₂	4.60	2.30	1.77	38.47
	B ₃	15.60	7.90	8.47	54.22
10	Fox Sandy Loam				
	Ap	2.60	1.33	.87	33.57
	B ₁	1.55	.79	.57	49.20
	B ₂ ***	4.39	2.23	1.93	43.96
	B ₃	30.00	15.30	8.22	27.39
15	Fox Sandy Loam				
	Ap	7.79	3.97	2.40	30.80
	A ₂	4.00	2.04	0.74	18.50
	A ₃	2.52	1.28	1.14	45.23
	B ₁ ***	2.90	1.48	.69	23.79
17	Miami Silt Loam				
	Ap	3.84	1.95	1.28	33.68
	A ₂	1.30	.66	.57	44.88
	A ₃	.40	.20	.28	71.89
	B ₂₁ ***	.77	.39	.37	49.79
	B ₂₂	.28	.14	.10	36.36
	B ₃	.29	.15	.07	24.82
23	Hillsdale Sandy Loam				
	Ap	5.50	2.80	1.52	27.62
	Ap	1.60	.81	.82	51.31
	A ₂	.32	.16	.11	34.37
	B ₂₁ ***	.26	.13	.13	48.46
	B ₂₂	.17	.86	.05	28.23
	B ₃	.25	.151	.101	39.60
	B ₃	.36	.181	.131	36.94
	C	.20	.101	.07	32.75

* in milliliters per minute

** in percent

*** subsoil infiltration capacities were made on this horizon

TABLE III
SURFACE CORRELATION DATA

Figure	Variables	r	σ_r
5	Minimum Infiltration and Permeability	.88*	$\pm$.047
	Minimum Infiltration and Lowest Permeable Horizon in Profile	.20	$\pm$.196
6	Minimum Infiltration and Volume Weight	-.53*	$\pm$.147
	Minimum Infiltration and Percent Pores Drained at		
	0.01 Atms. Tension	.25	$\pm$.191
	0.03 Atms. Tension	.47	$\pm$.159
7	0.04 Atms. Tension	.50*	$\pm$.153
8	0.06 Atms. Tension	.58*	$\pm$.148
9	0.33 Atms. Tension	.58*	$\pm$.135
10	1.00 Atms. Tension	.55*	$\pm$.142
11	Minimum Infiltration and Percent Total Pore Space	.60*	$\pm$.131
12	Permeability and Percent Total Pore Space	.72*	$\pm$.098
	Permeability and Percent Pores Drained at		
13	0.01 Atms. Tension	.53*	$\pm$.147
14	0.03 Atms. Tension	.67*	$\pm$.112
15	0.04 Atms. Tension	.62*	$\pm$.125
16	0.06 Atms. Tension	.57*	$\pm$.138
	0.33 Atms. Tension	.38	$\pm$.175
	1.00 Atms. Tension	.33	$\pm$.182
17	Permeability and Volume Weight	-.75*	$\pm$.089
18	Initial Dry Infiltration and Permeability	.63*	$\pm$.123
	Initial Wet Infiltration and Permeability	.43	$\pm$.166
19	Initial Dry Infiltration and Initial Air Space	.72*	$\pm$.105

* Significant of the 1% level

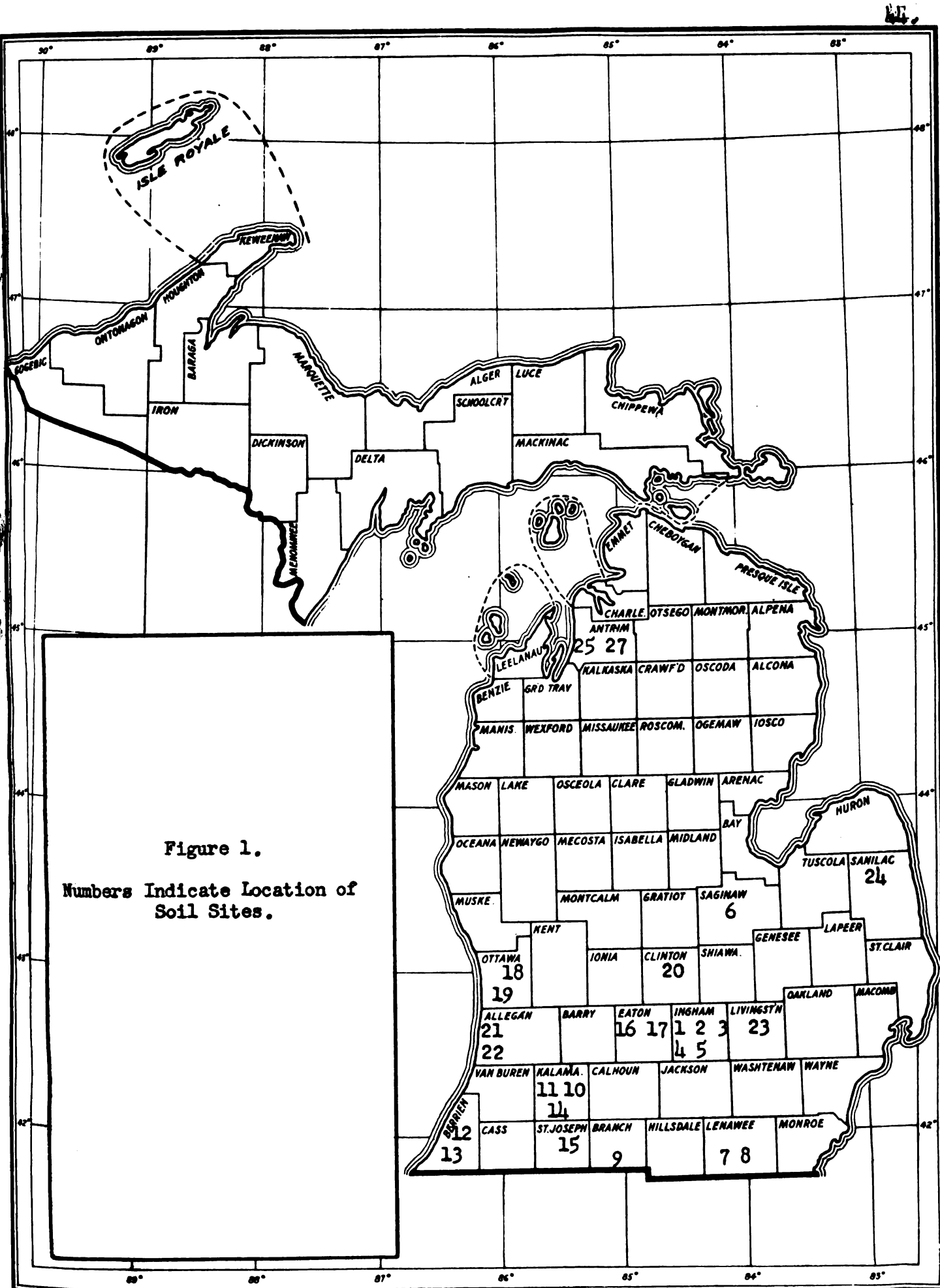
TABLE IV
SUBSURFACE CORRELATION DATA

Figure	Variables	r	σ_r
20	Minimum Infiltration and Permeability	.81*	$\pm$.093
	Minimum Infiltration and Lowest Permeable Horizon in Profile	.32	$\pm$.249
	Minimum Infiltration and Volume Weight	-.17	$\pm$.269
	Minimum Infiltration and Percent Pores Drained at		
	0.01 Atms. Tension	.09	$\pm$.275
	0.03 Atms. Tension	.43	$\pm$.226
21	0.04 Atms. Tension	.81*	$\pm$.095
22	0.06 Atms. Tension	.86*	$\pm$.072
23	0.33 Atms. Tension	.77*	$\pm$.113
24	1.00 Atms. Tension	.78*	$\pm$.108
	Minimum Infiltration and Percent Total Pore Space	.29	$\pm$.254
25	Permeability and Percent Total Pore Space	.66*	$\pm$.156
	Permeability and Percent Pores Drained at		
	0.01 Atms. Tension	.22	$\pm$.264
26	0.03 Atms. Tension	.67*	$\pm$.149
27	0.04 Atms. Tension	.84*	$\pm$.082
28	0.06 Atms. Tension	.81*	$\pm$.095
29	0.33 Atms. Tension	.76*	$\pm$.117
30	1.00 Atms. Tension	.79*	$\pm$.104
	Permeability and Volume Weight	-.23	$\pm$.263
	Initial Dry Infiltration and Initial Air Space	-.08	$\pm$.271
31	Initial Dry Infiltration and Permeability	.81*	$\pm$.095
32	Initial Wet Infiltration and Permeability	.85*	$\pm$.077

* Significant at the 1% level

TABLE V
AVERAGE VALUES FOR BASIC FIELD AND LABORATORY DATA

<u>Surface</u>	
Initial Air Space (%)	28.00
Initial Dry Infiltration (in./hr.)	15.14
Initial Wet Infiltration (in./hr.)	10.60
Minimum Wet Infiltration (in./hr.)	5.85
Permeability	6.71
Volume Weight (gms/cc)	1.35
Total Pore Space (%)	45.04
Percent Pores Drained at	
0.01 Atms.	4.00
0.03 Atms.	8.00
0.04 Atms.	11.00
0.06 Atms.	14.00
0.33 Atms.	18.00
1.00 Atms.	21.00
<u>Subsoil</u>	
Initial Air Space (%)	20.00
Initial Dry Infiltration (in./hr.)	6.86
Initial Wet Infiltration (in./hr.)	4.11
Minimum Wet Infiltration (in./hr.)	1.46
Permeability	2.02
Volume Weight (gms/cc)	1.56
Total Pore Space (%)	38.20
Percent Pores Drained at	
0.01 Atms.	2.80
0.03 Atms.	6.06
0.04 Atms.	7.60
0.06 Atms.	9.40
0.33 Atms.	12.93
1.00 Atms.	14.46
Minimum Permeability of Profile (in./hr.)	2.00



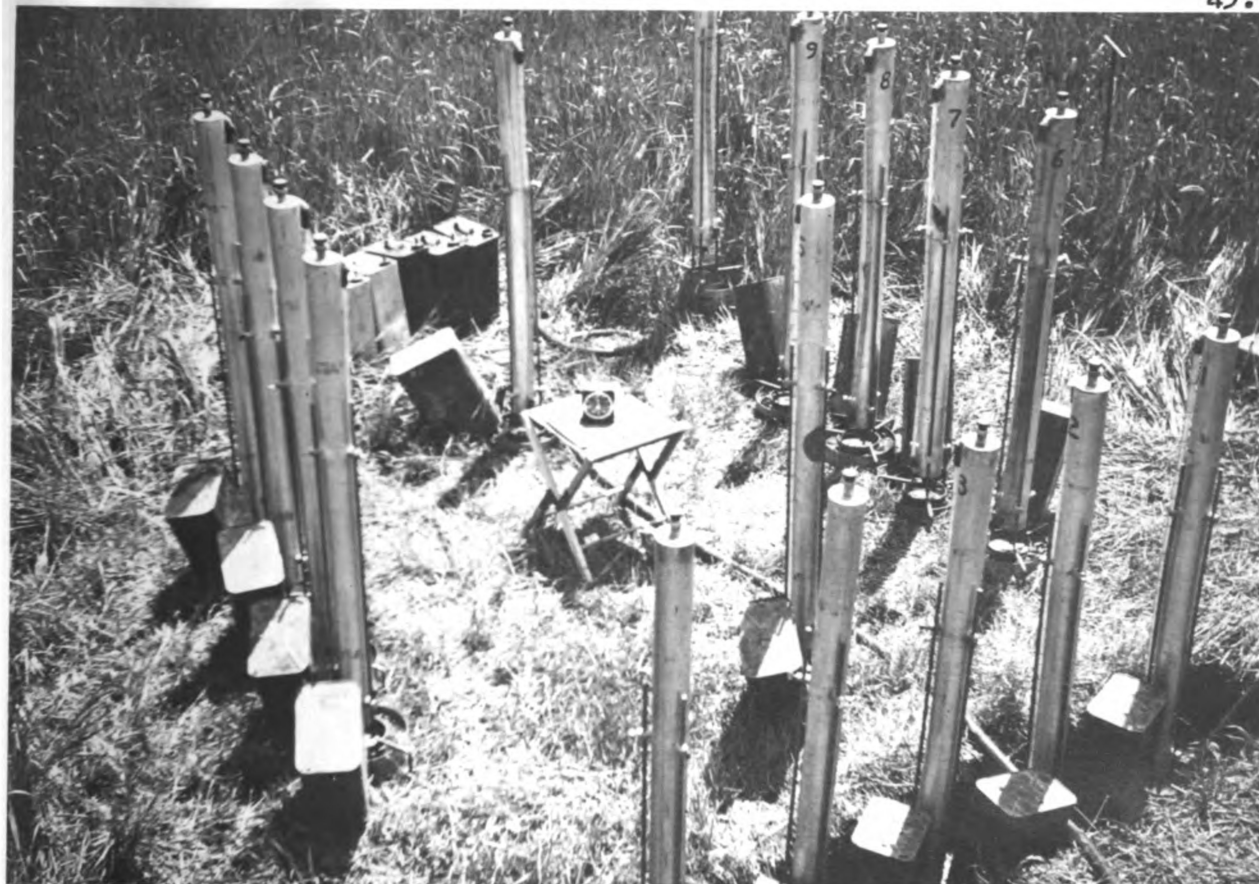
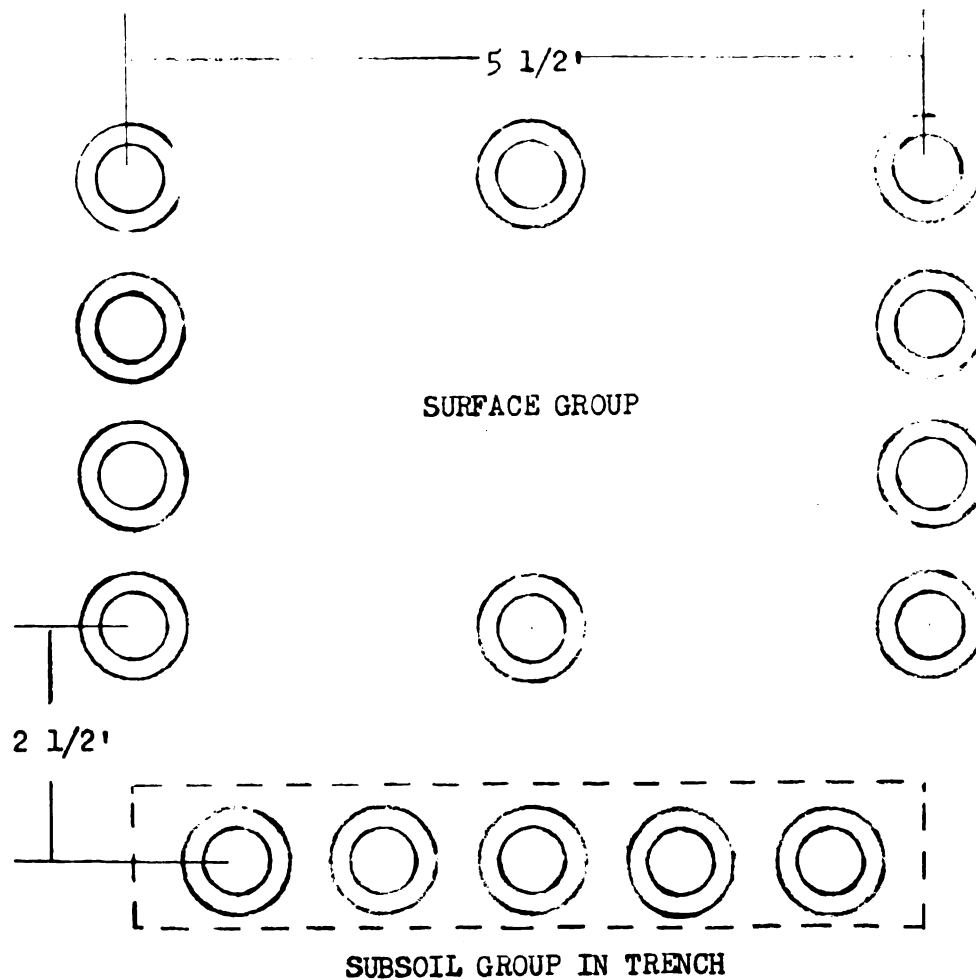


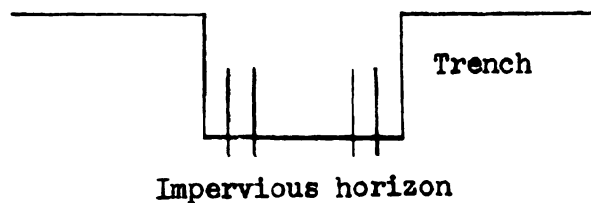
Figure 2. Photograph showing infiltrometer apparatus set up and in operation on a soil site in Southern Michigan.



Figure 3. Typical set up of apparatus and tent.



a. Arrangement of individual infiltrimeters, using 5 and 9 inch rings.



b. Cross section of the subsoil group.

Figure 4. The arrangement used for the infiltrimeters, (a.) showing general set up, (b.) a cross section showing the infiltrimeter on an impervious horizon.

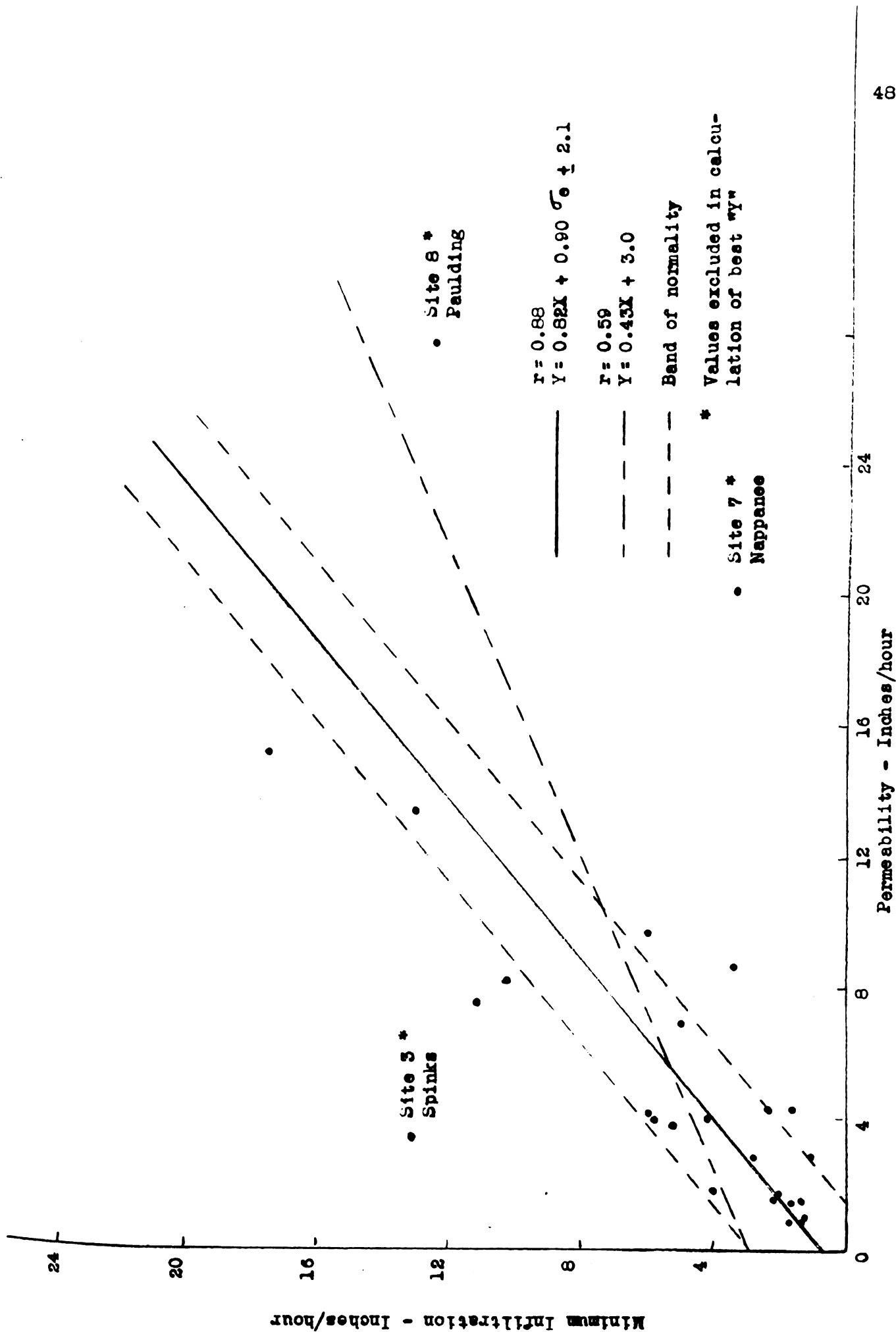


Figure 5. Permeability vs. minimum infiltration of Ap horizon with regression line.

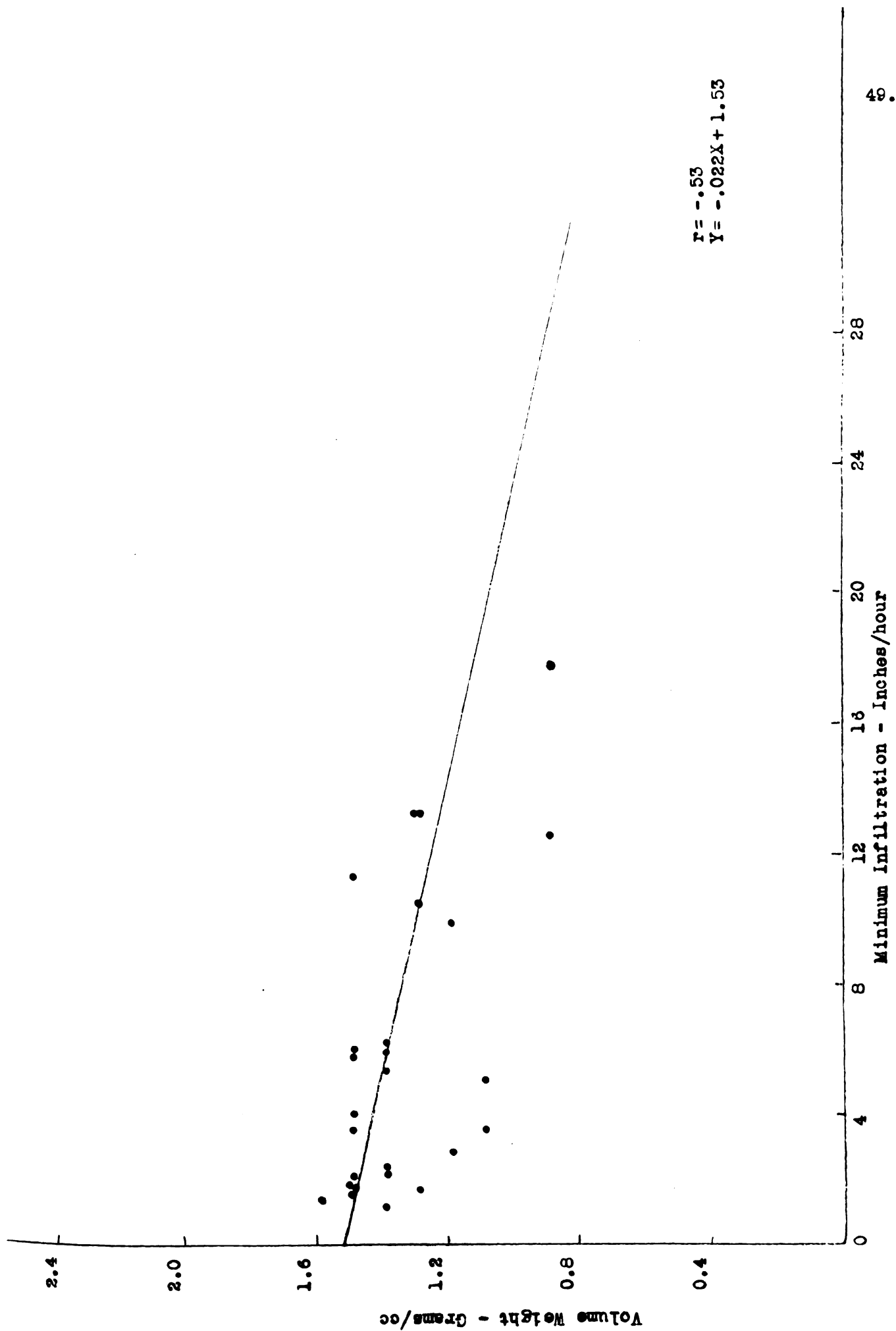


Figure 6. Minimum infiltration vs. volume weight of Ap horizon with regression line.

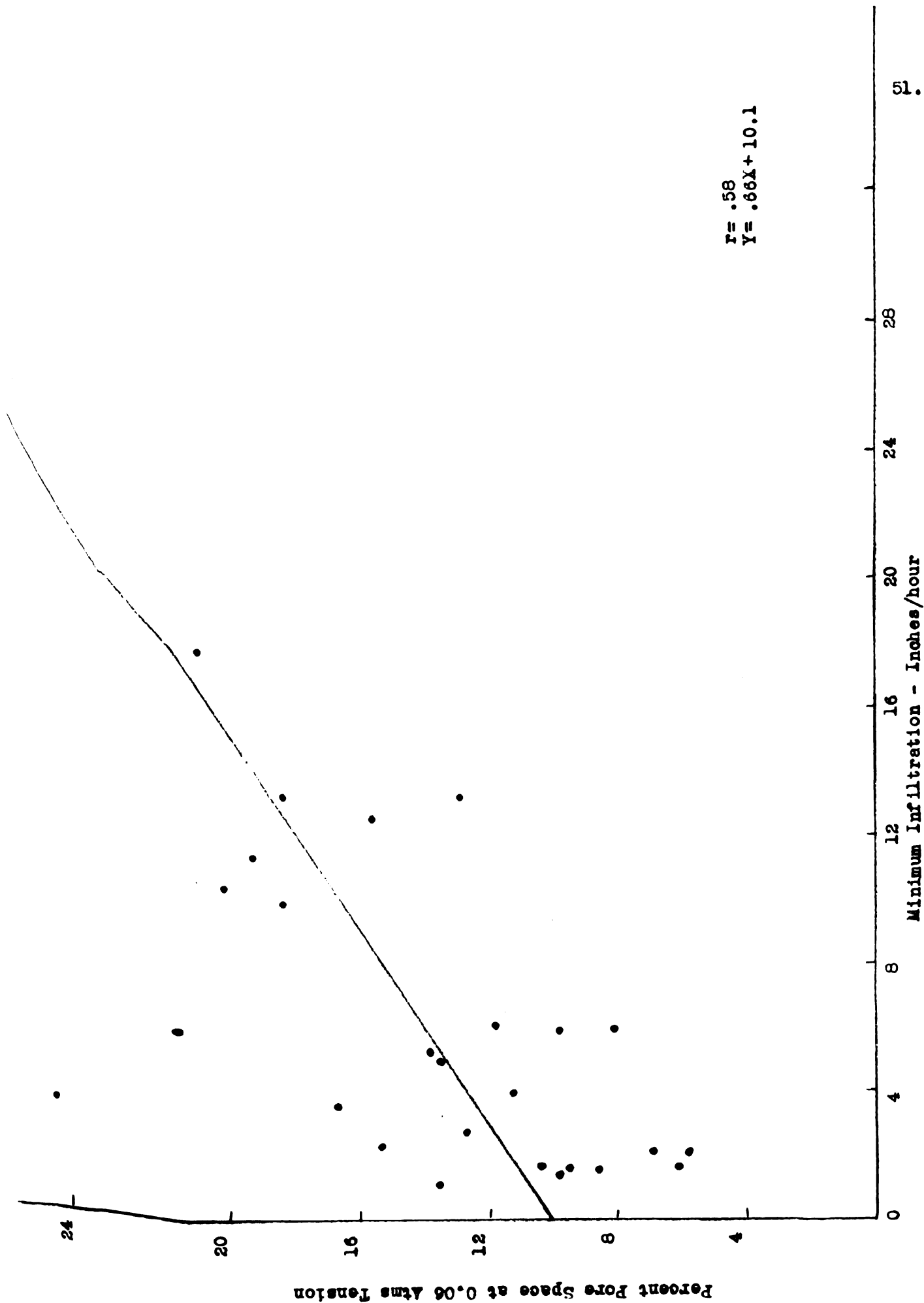


Figure 8. Minimum infiltration of Ap horizon vs. percent pore space at 0.06 Atms tension with regression line.

51.

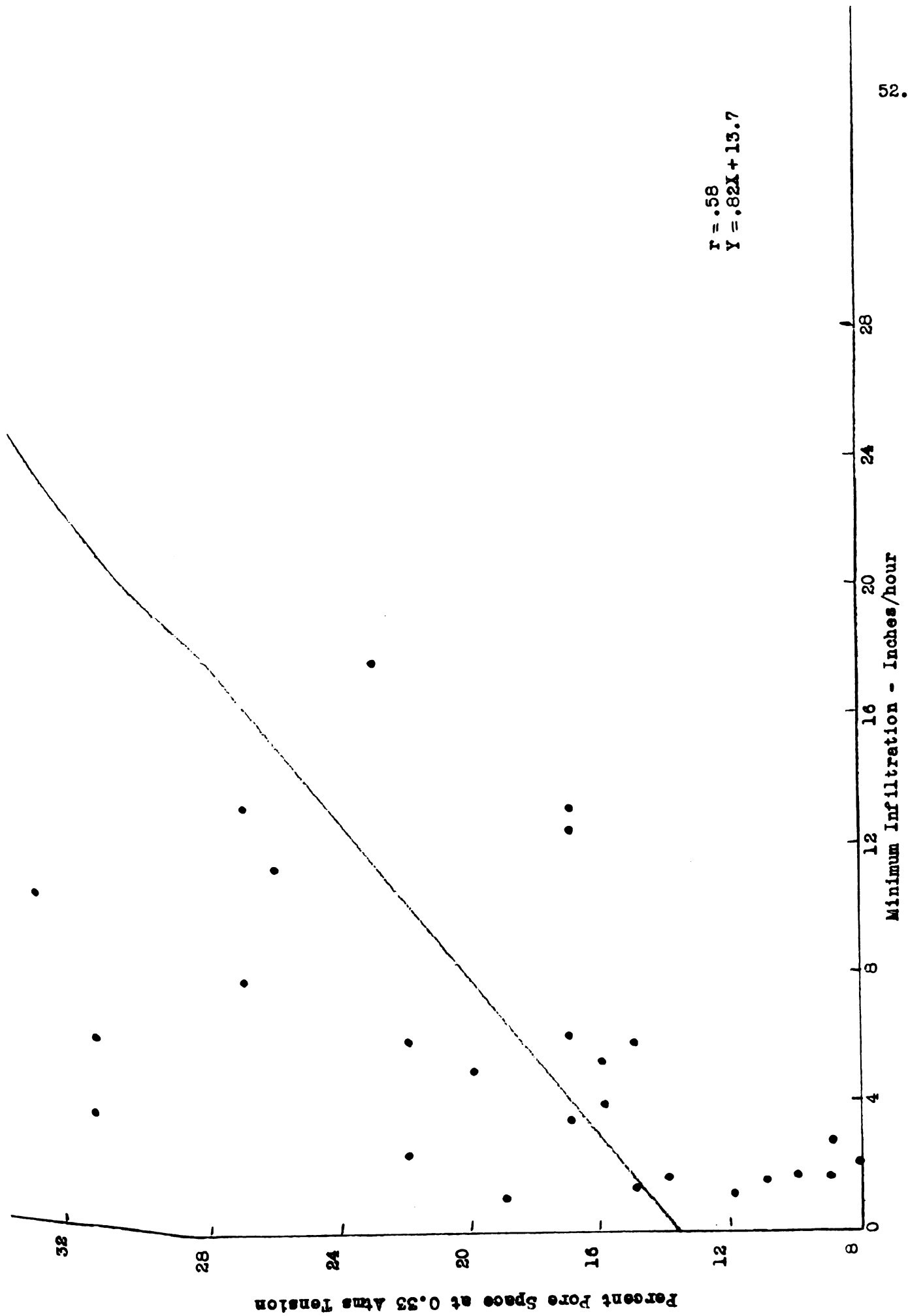


Figure 9. Minimum infiltration of Ap horizon vs. percent pore space at 0.33 Atmos tension with regression line.

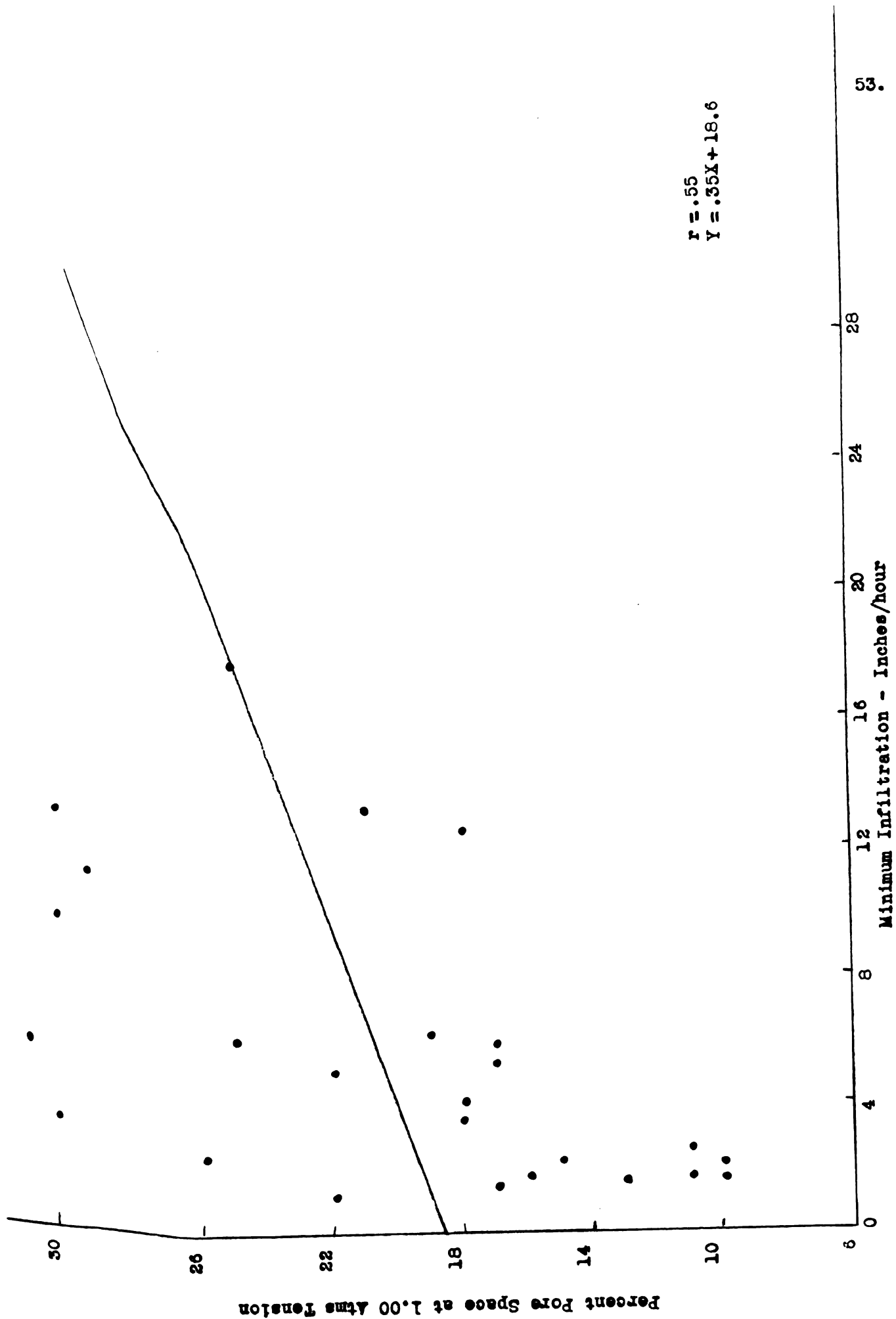


Figure 10. Minimum infiltration of Ap horizon vs. percent pore space at 1.00 Atms tension with regression line.

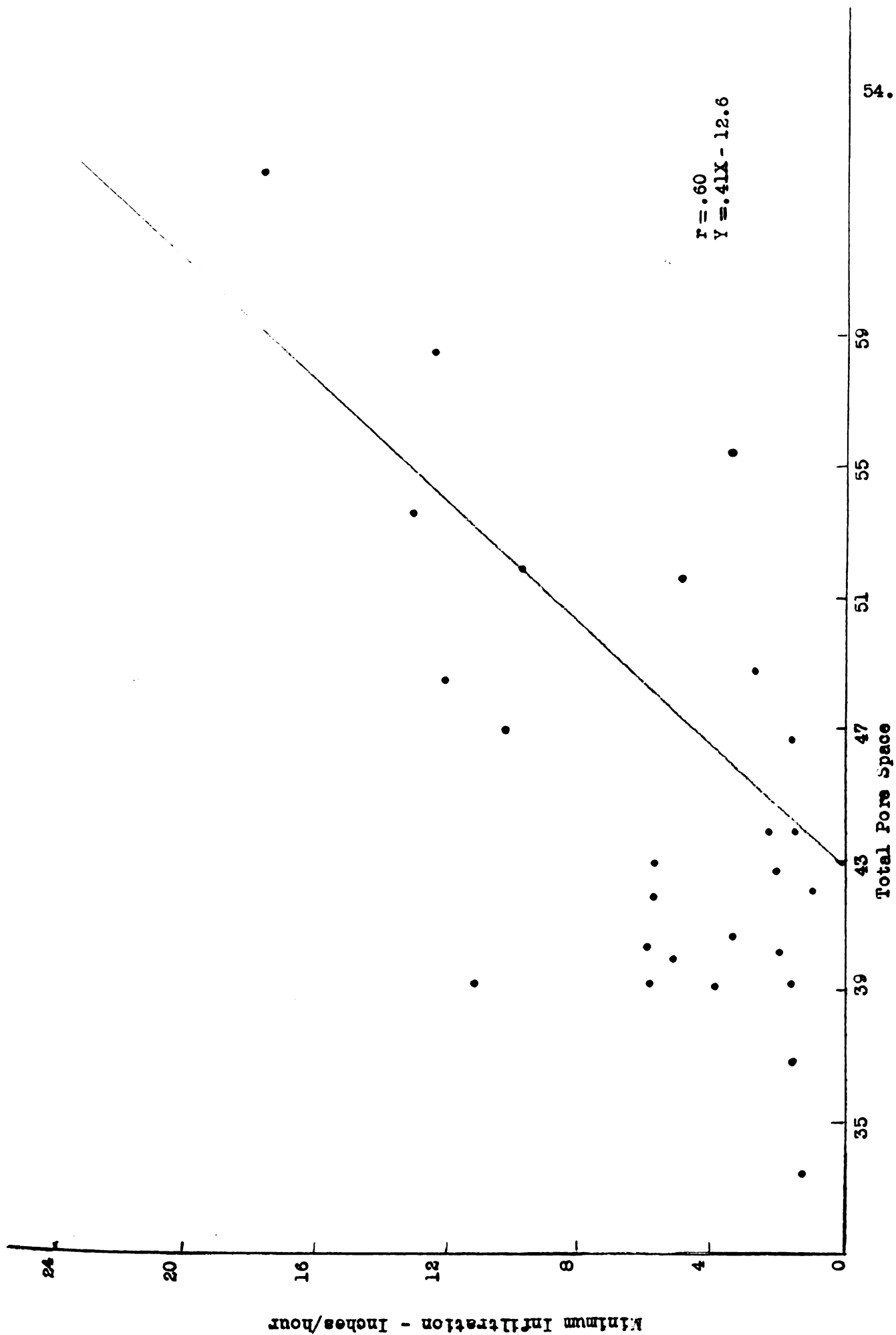


Figure 11. Total pore space vs. minimum infiltration of Ap horizon with regression line.

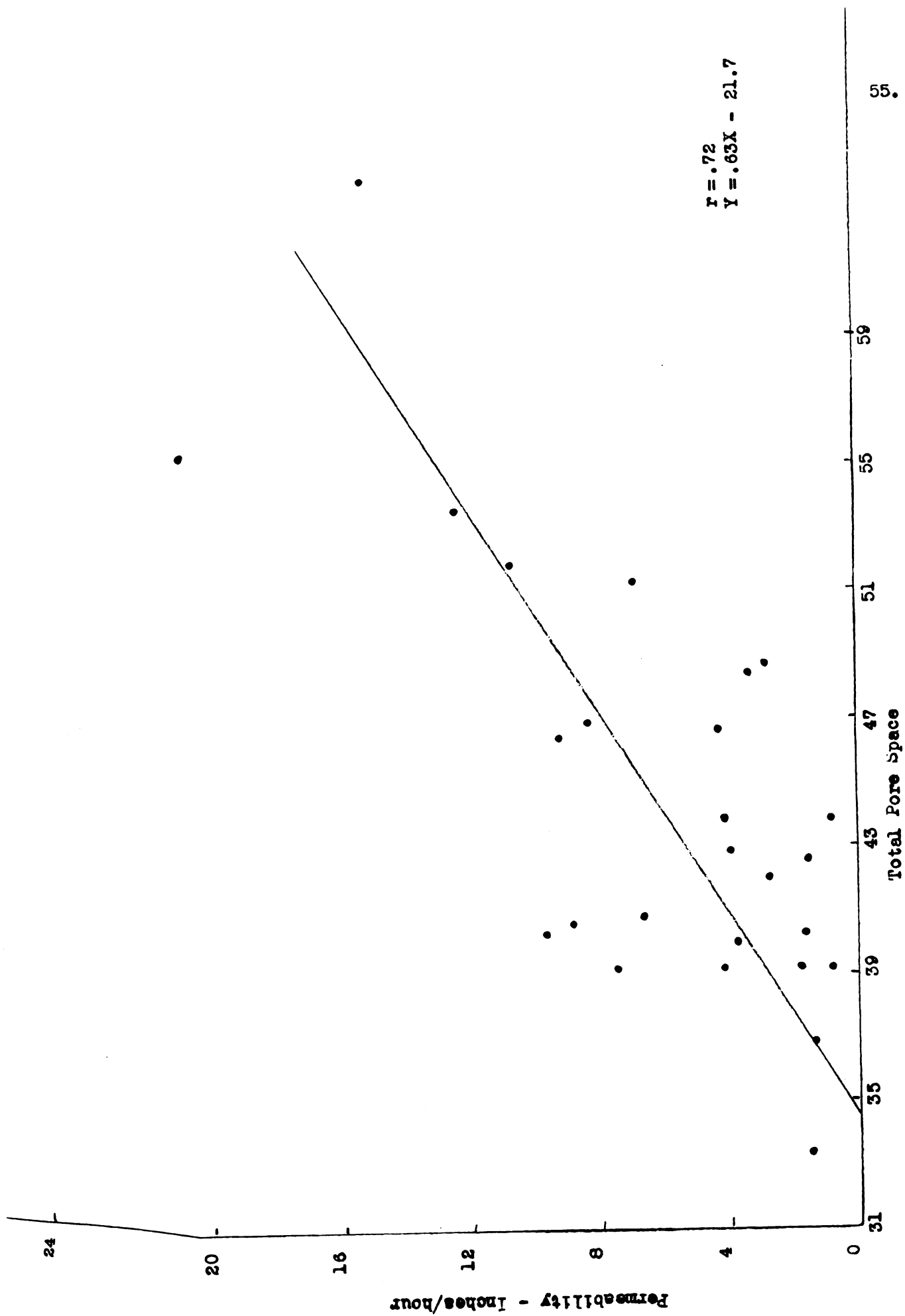


Figure 12. Total pore space vs. permeability of Ap horizon with regression line.

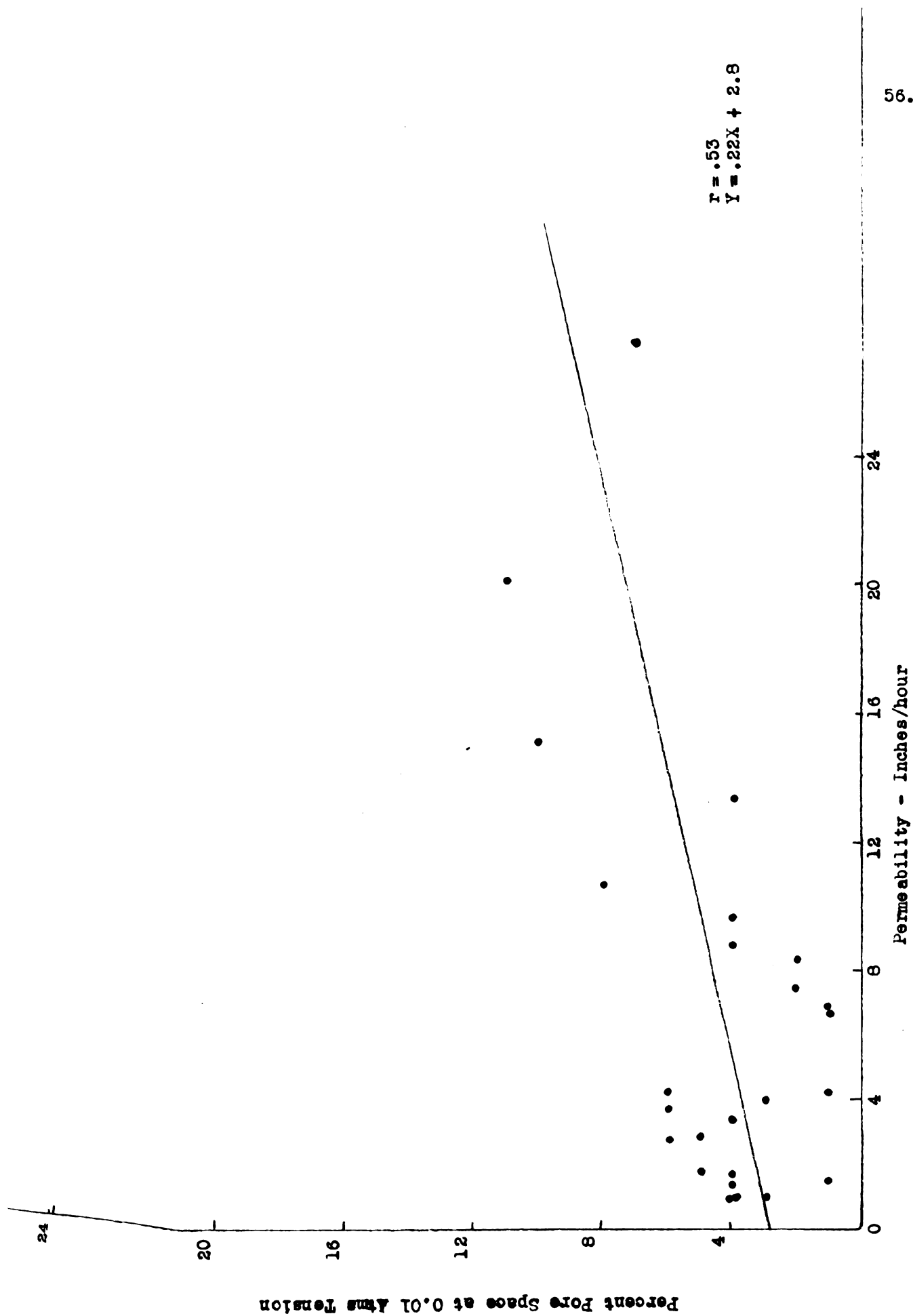


Figure 13. Permeability - Δp horizon vs. percent pore space at 0.01 Atms tension with regression line.

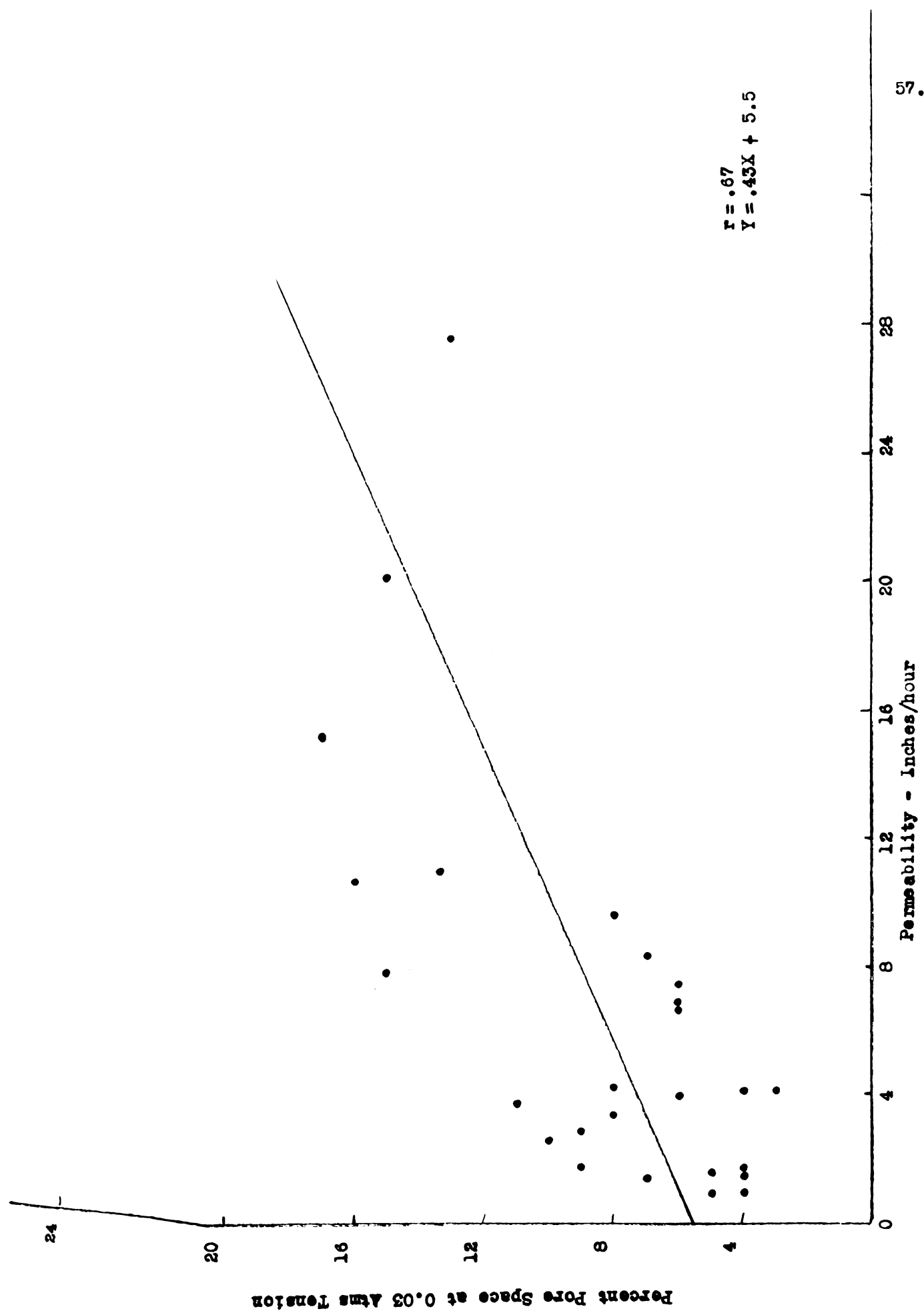


Figure 14. Permeability - Ap horizon vs. percent pore space at 0.03 Atmos tension with regression line.

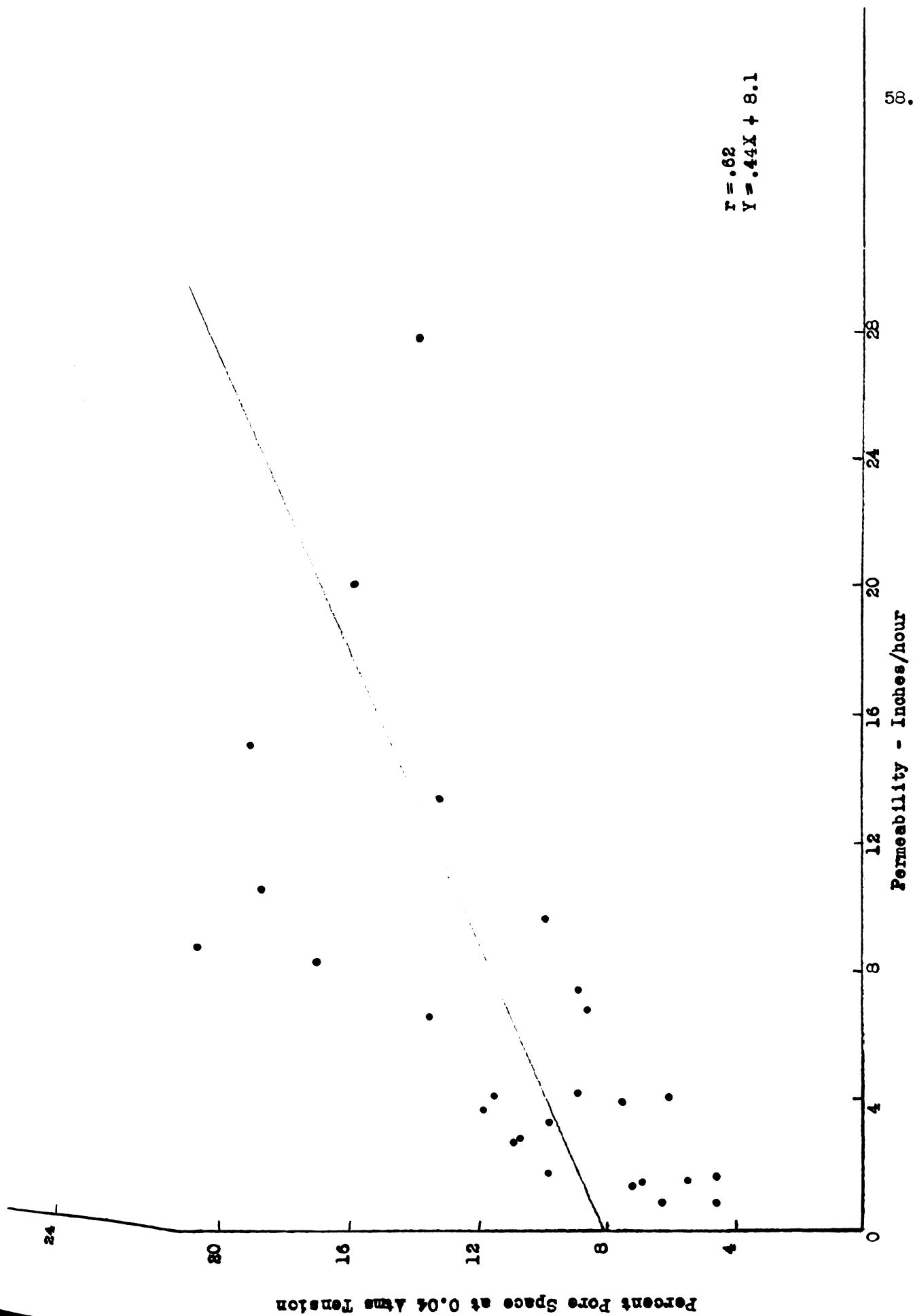


Figure 15. Permeability - Ap horizon vs. percent pore space at 0.04 Atms tension with regression line.

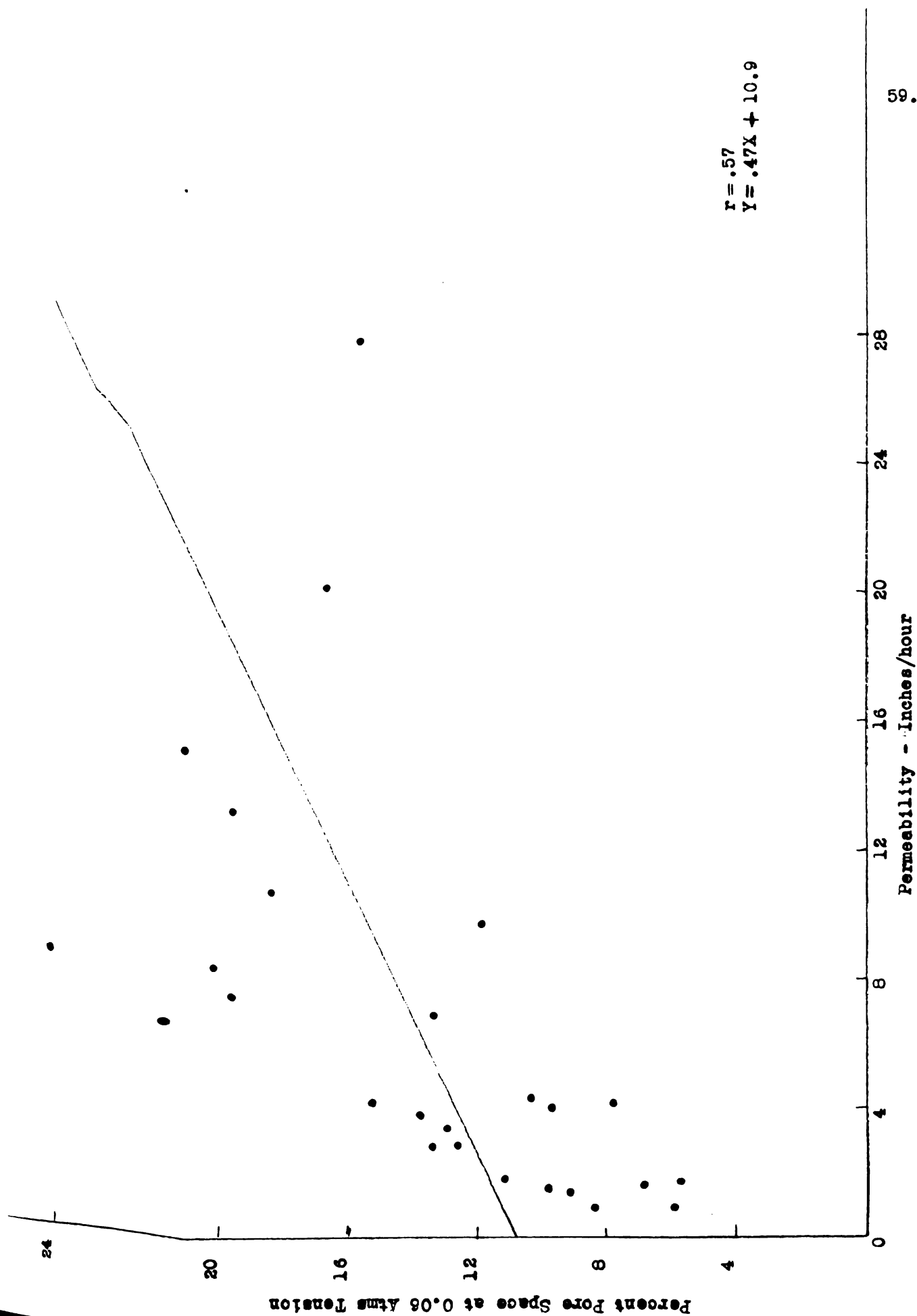


Figure 16. Permeability - Ap horizon vs. percent pore space at 0.06 Atms tension with regression line.

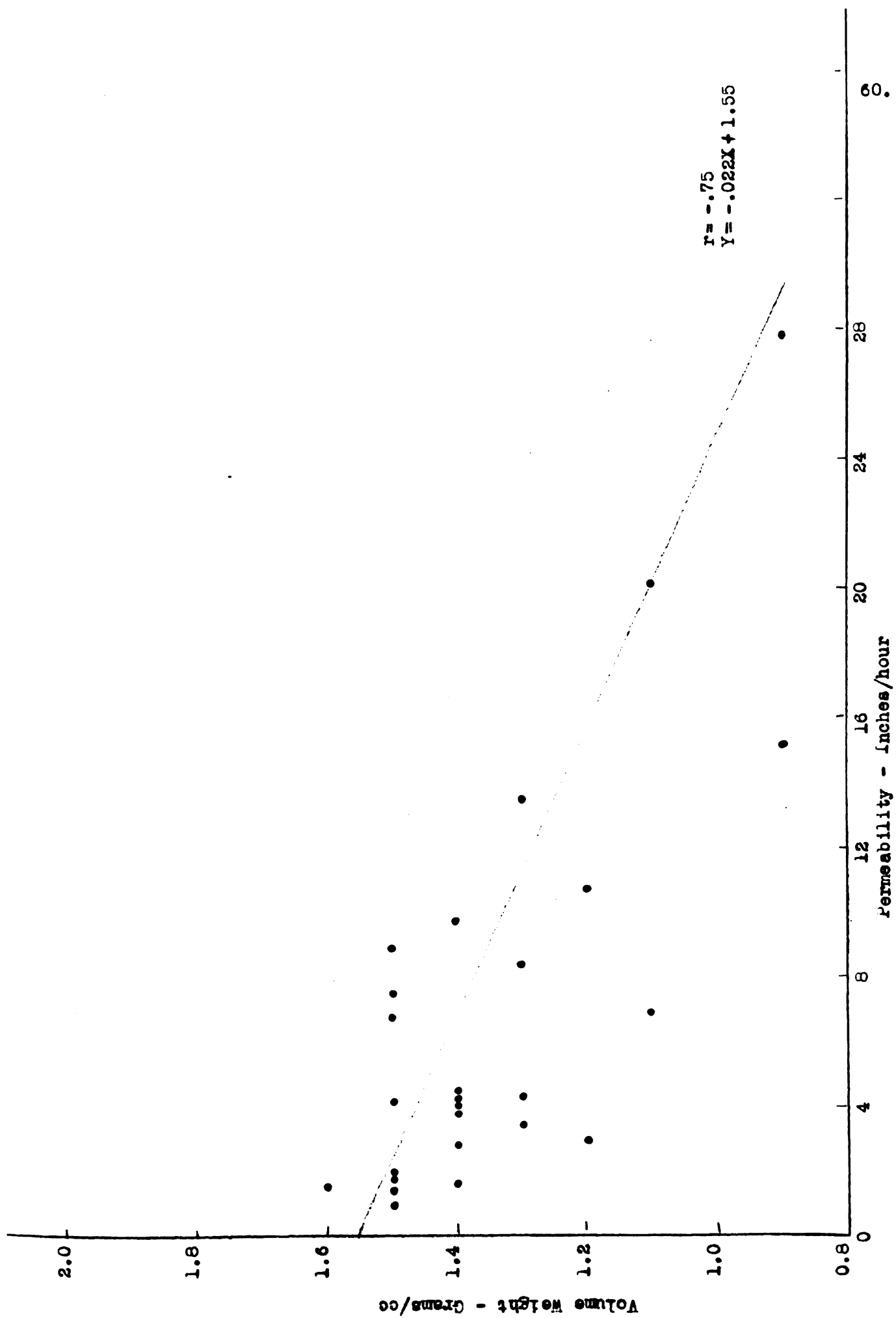


Figure 17. Permeability of ap horizon vs. volume weight with regression line.

11

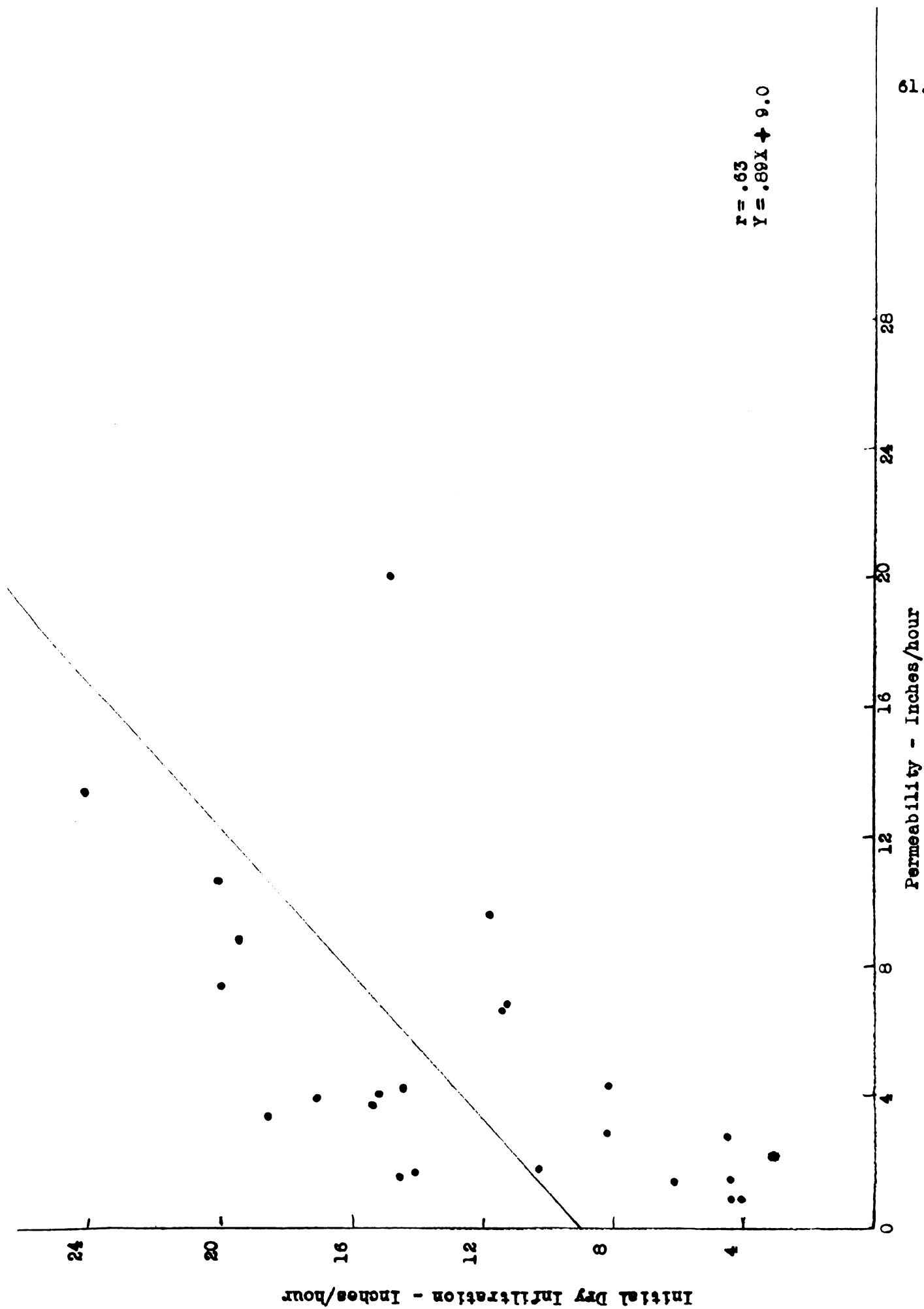


Figure 18. Permeability vs. initial dry infiltration of Ap horizon with regression line.

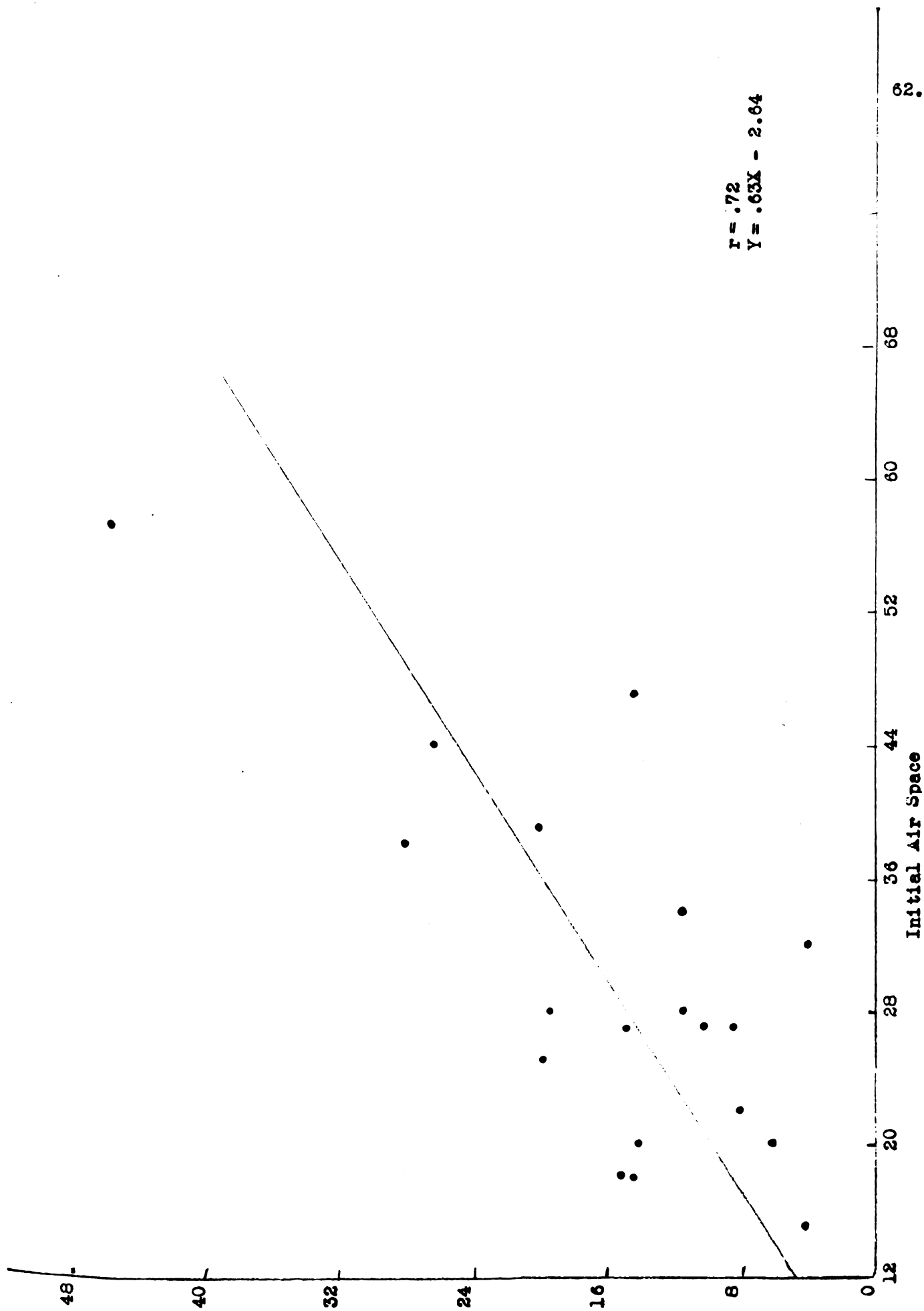


Figure 19. Initial air space vs. Initial dry infiltration of Ap horizon with regression line.

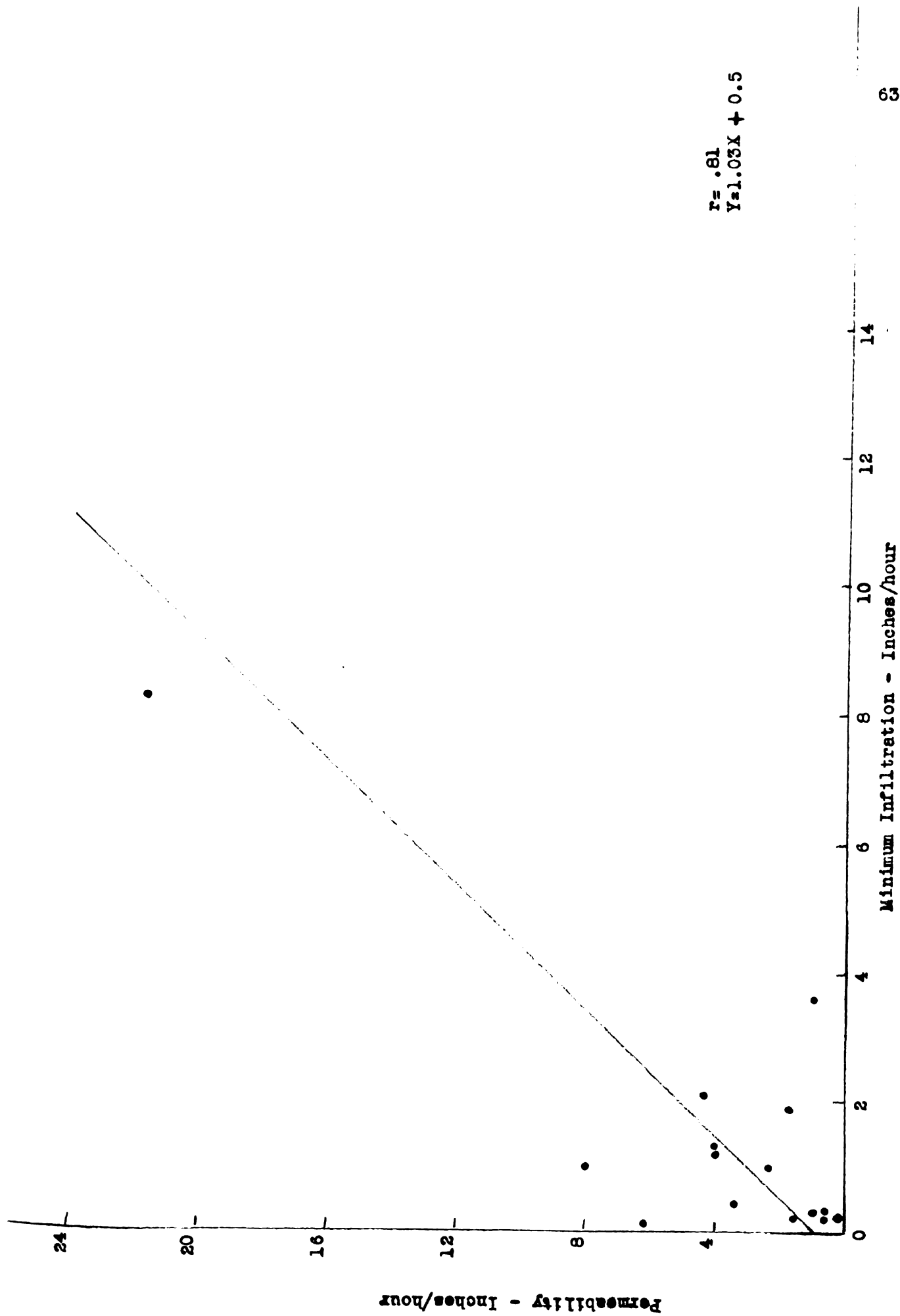


Figure 20. Minimum infiltration vs. permeability of subsoil with regression line.

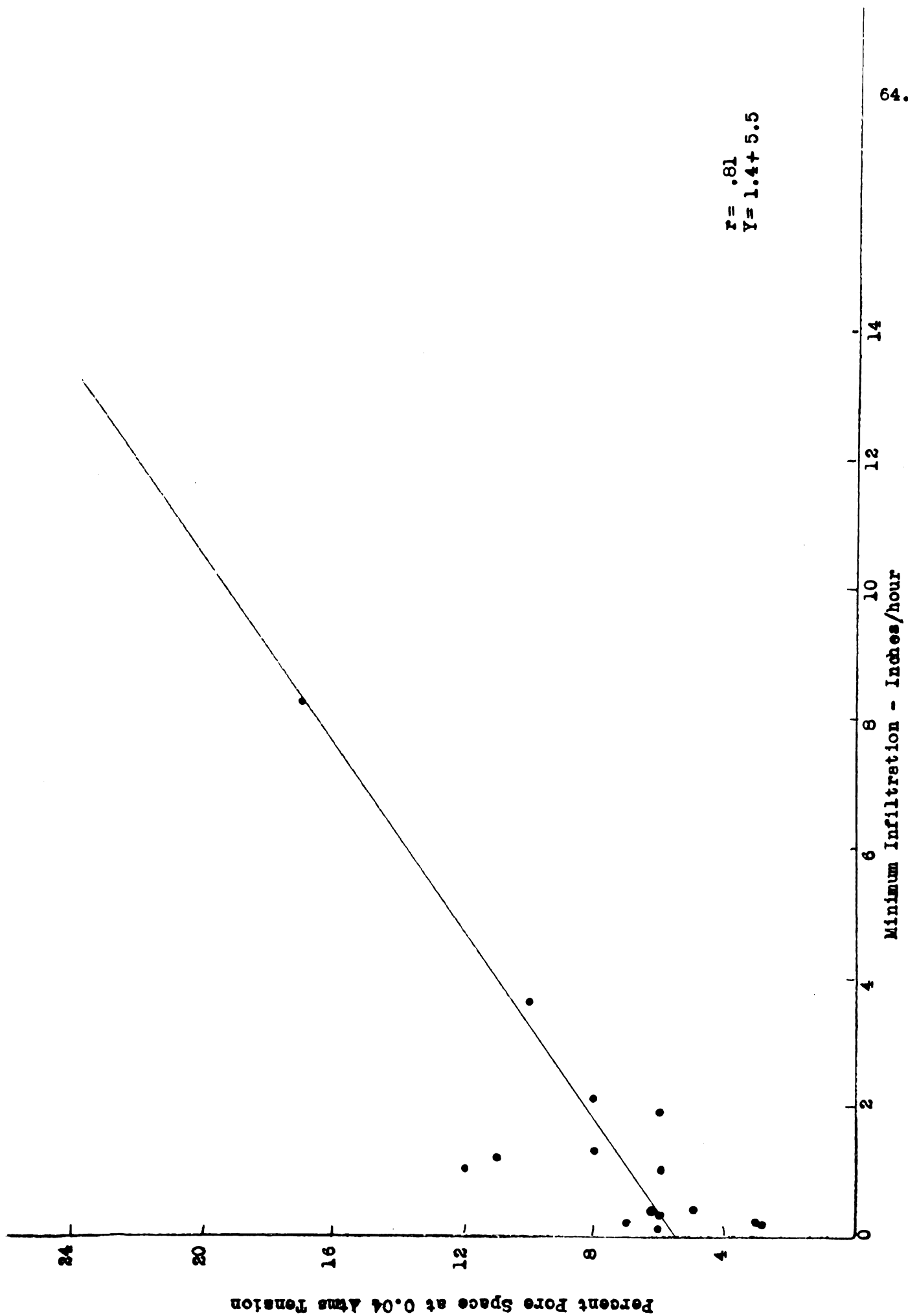


Figure 21. Minimum infiltration of subsoil vs. percent pore space at 0.04 Atmos tension with regression line.

11

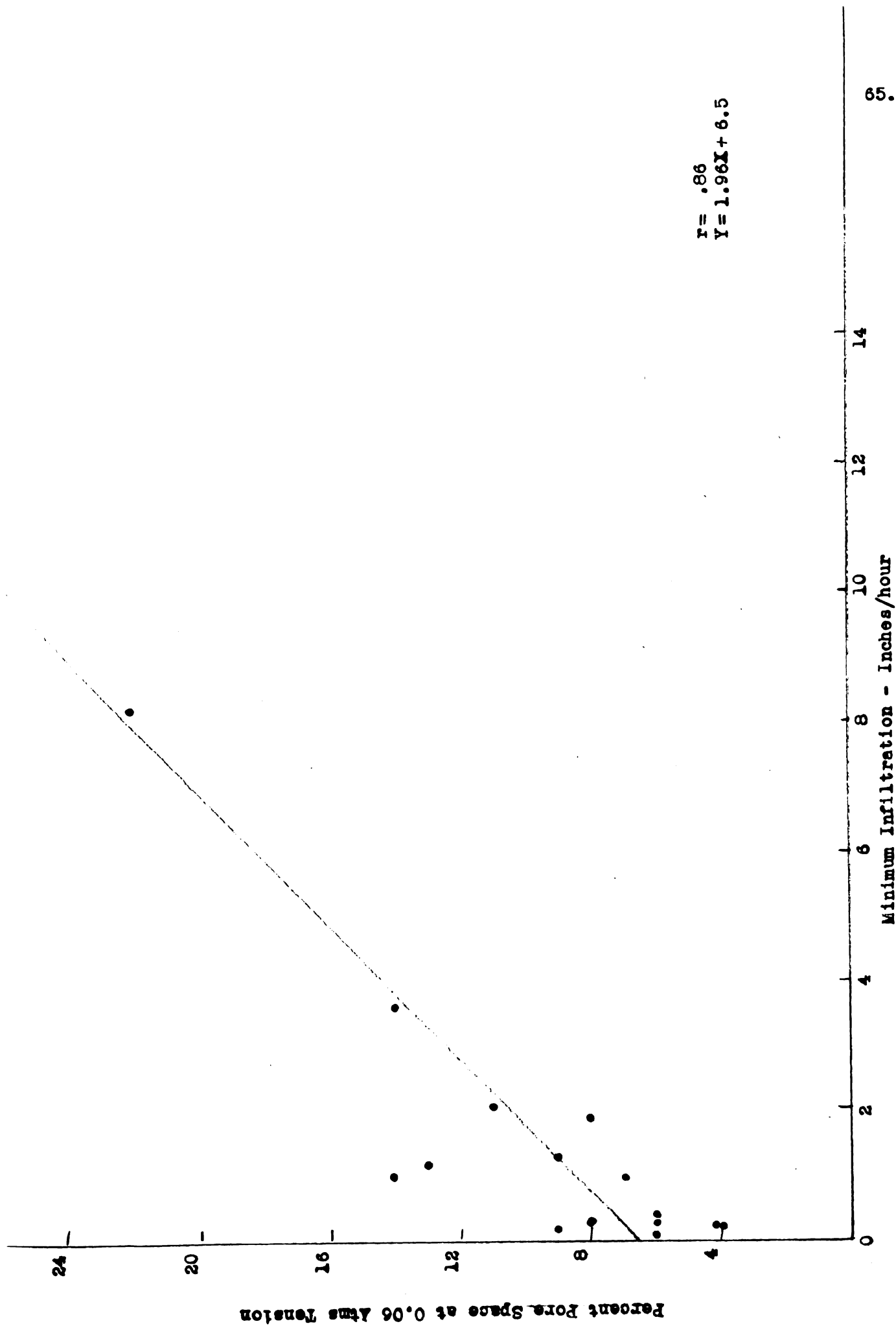


Figure 22. Minimum infiltration of subsoil vs. percent pore space at 0.06 Atmos tension with regression line.

1

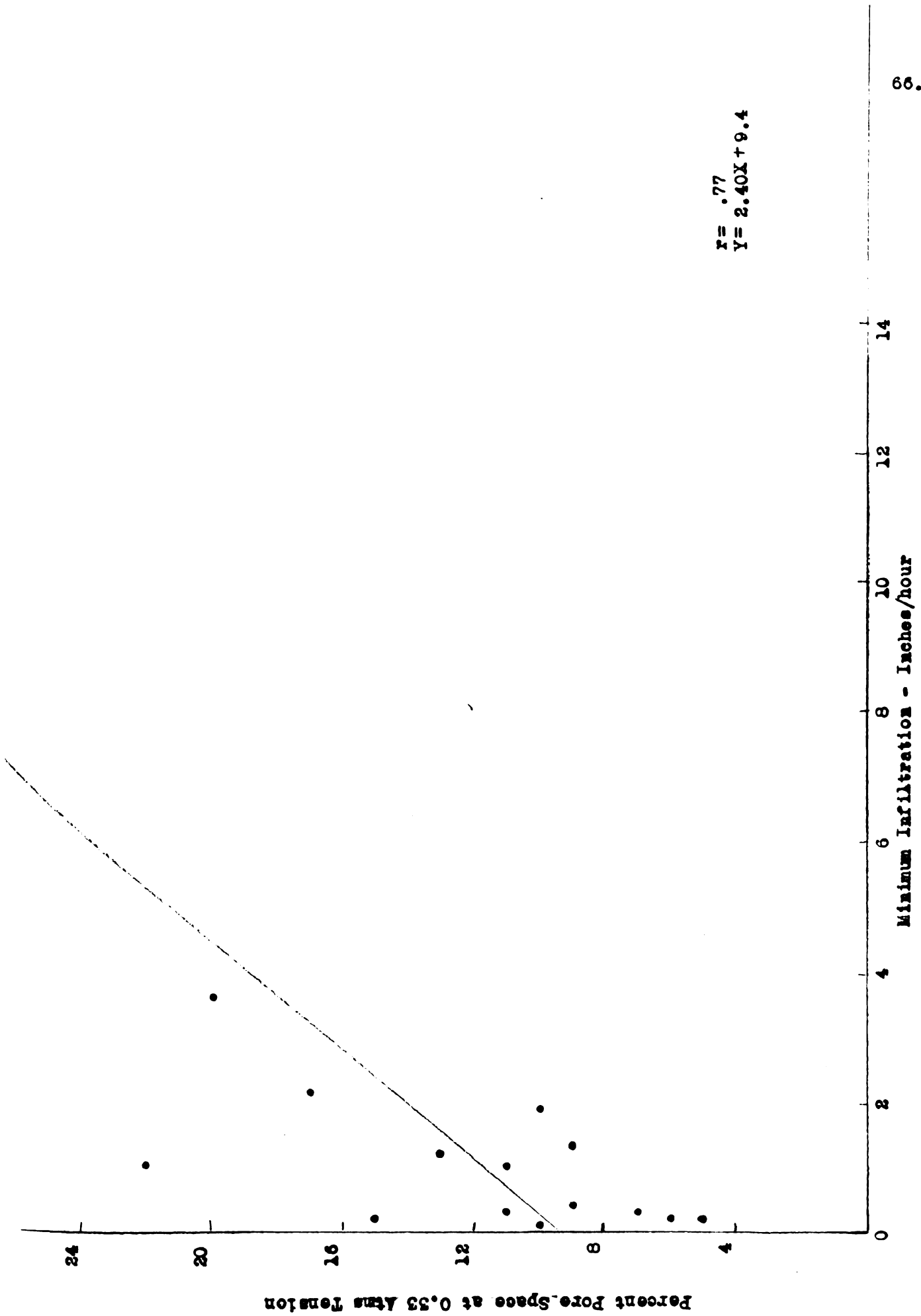
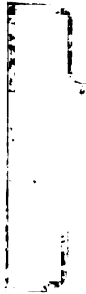


Figure 23. Minimum infiltration of subsoil vs. percent pore space at 0.33 Atms tension with regression line.



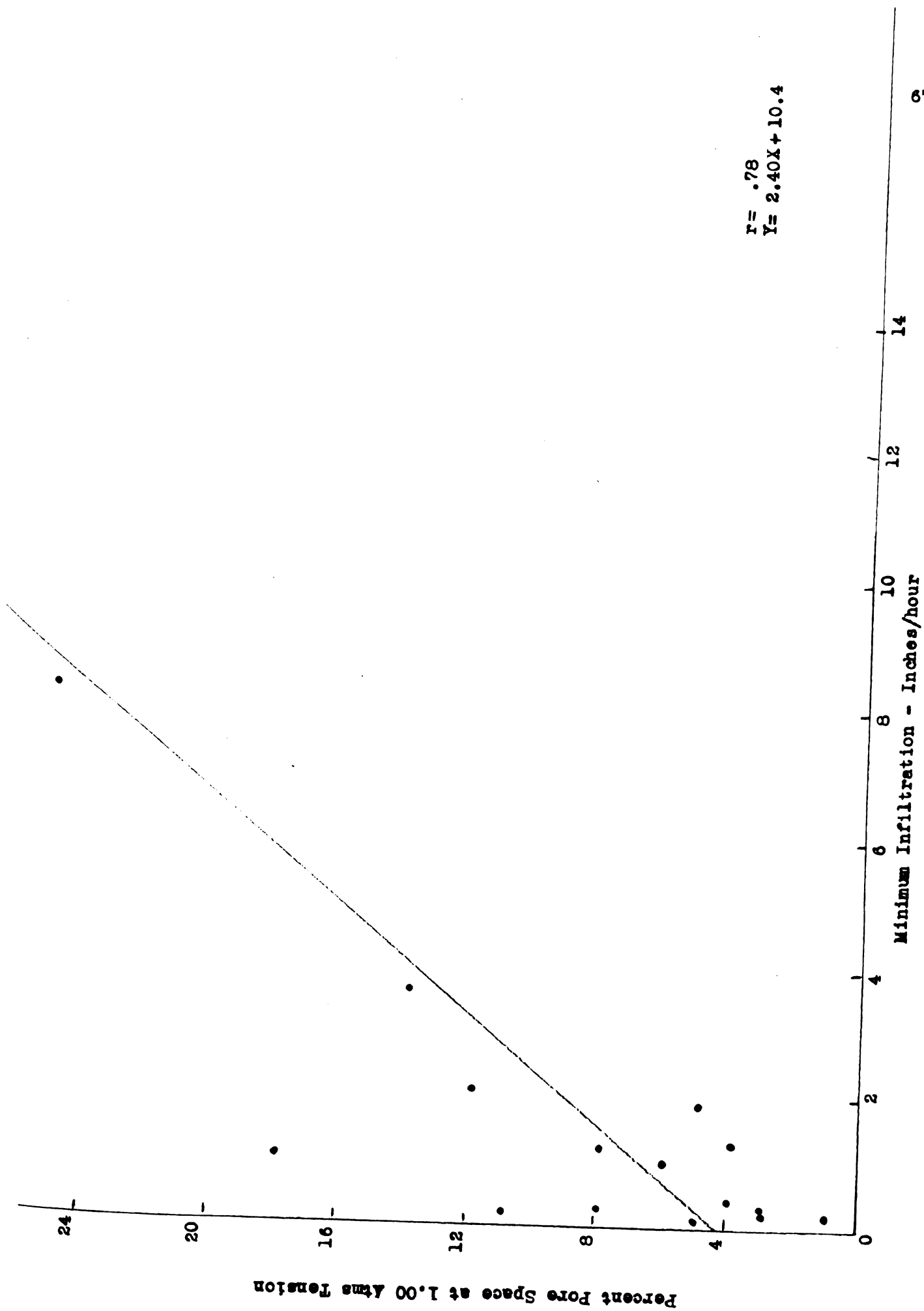


Figure 24. Minimum infiltration of subsoil vs. percent pore space at 1.00 Atmos tension with regression line.

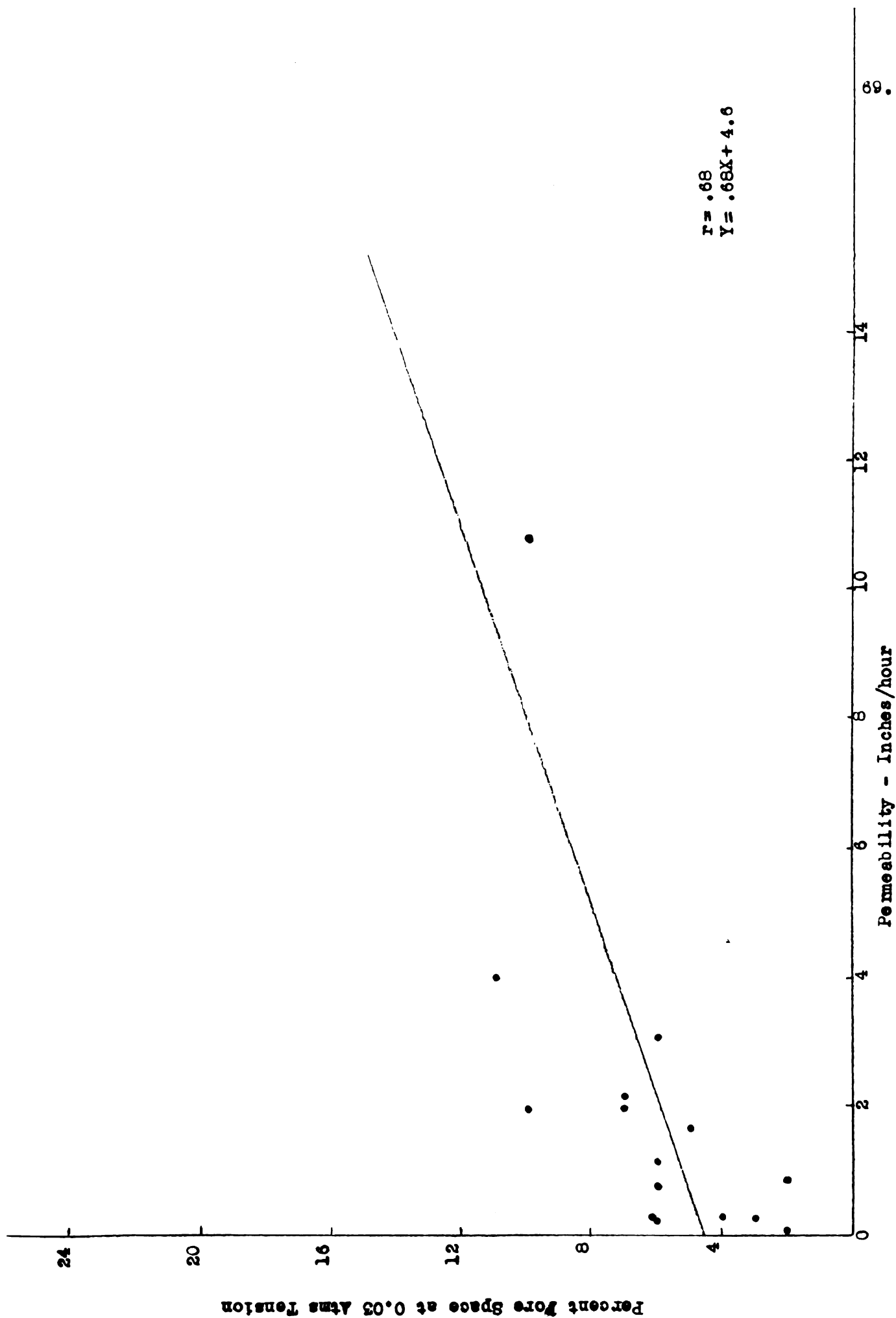


Figure 26. Permeability of subsoil vs. percent pore space at 0.03 Atmos tension with regression line.

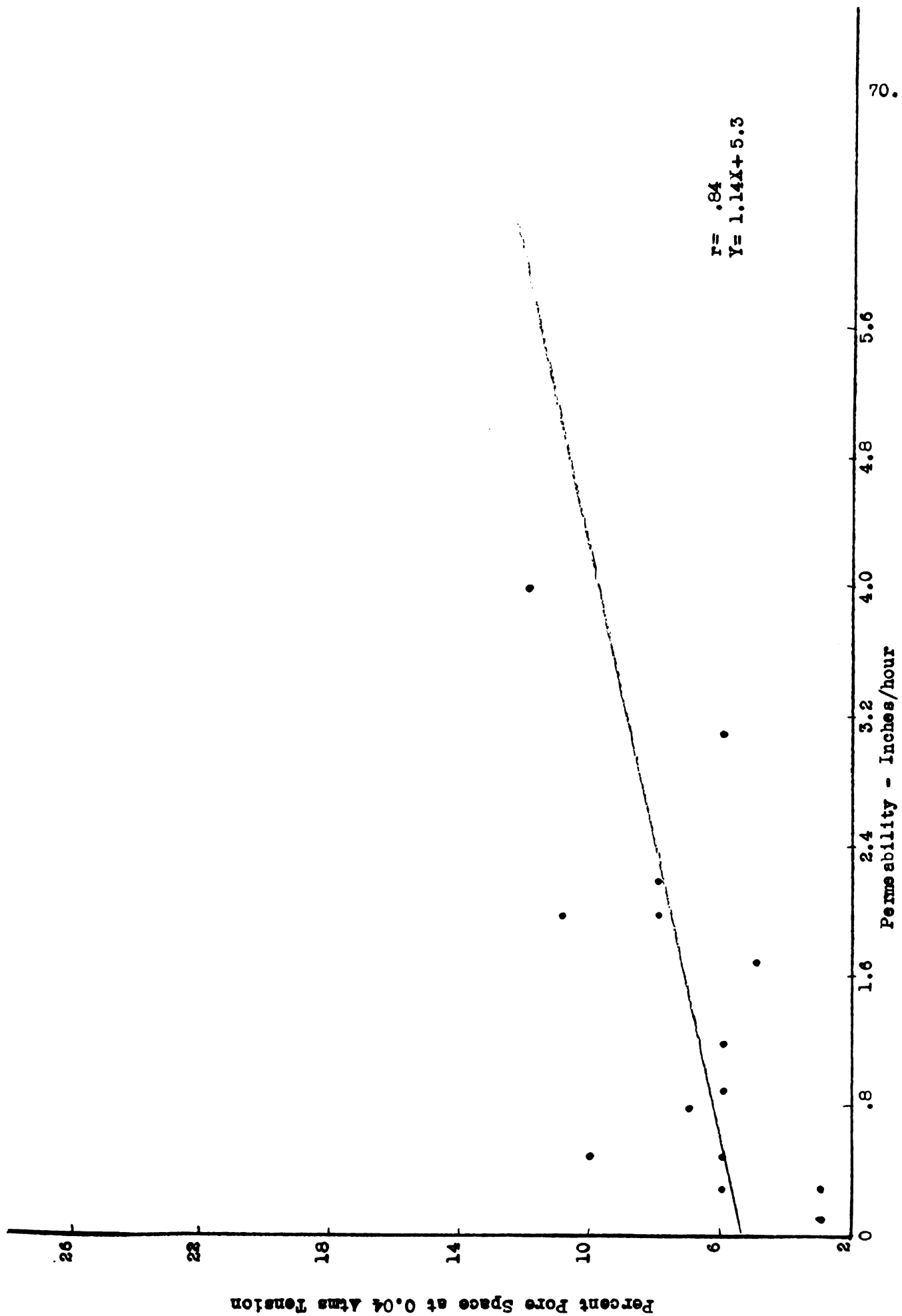


Figure 27. Permeability of subsoil vs. percent pore space at 0.04 Atms tension with regression line.

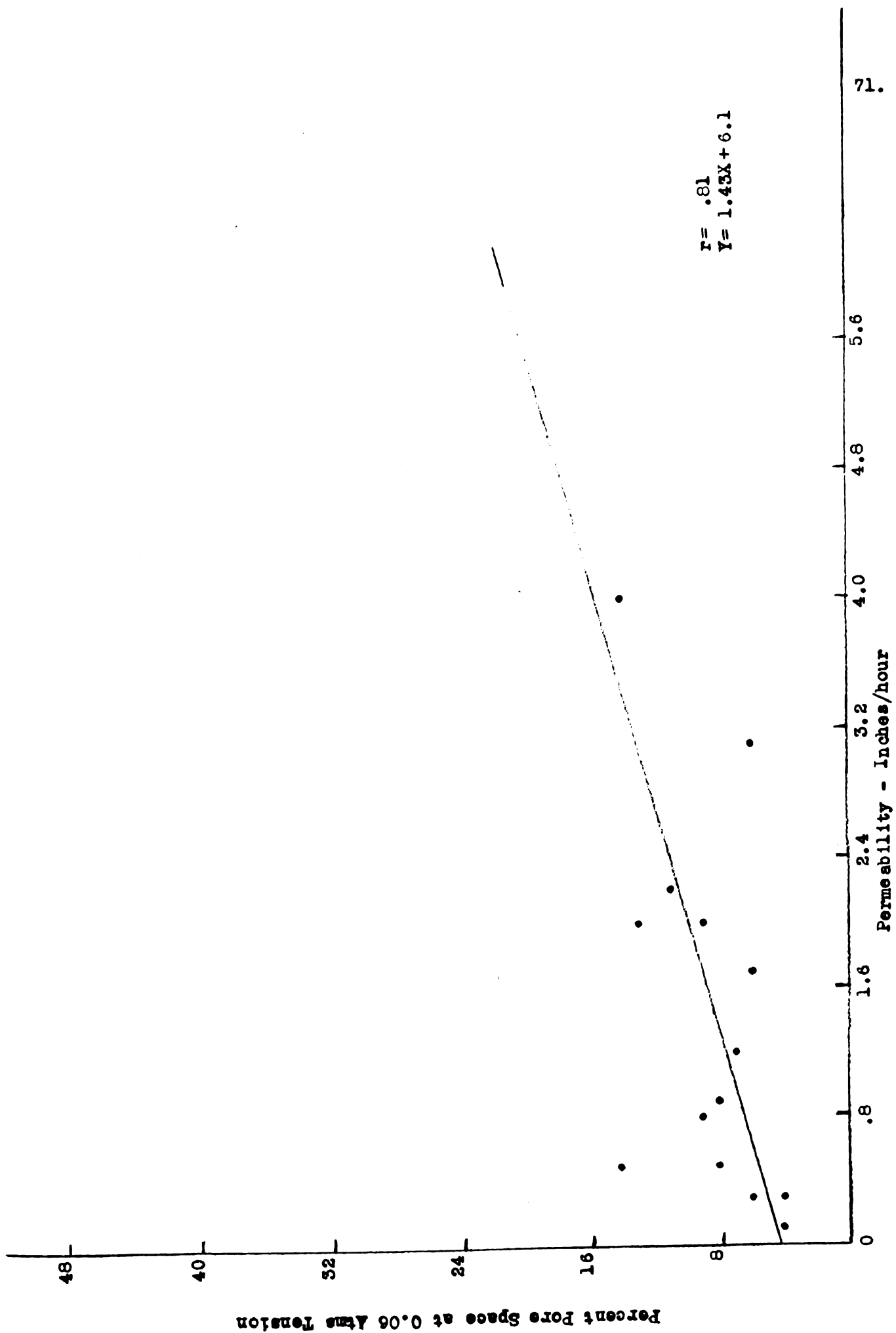
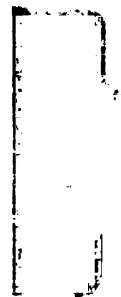


Figure 28. Permeability of subsoil vs. percent pore space at 0.06 Atmos tension with regression line.



11

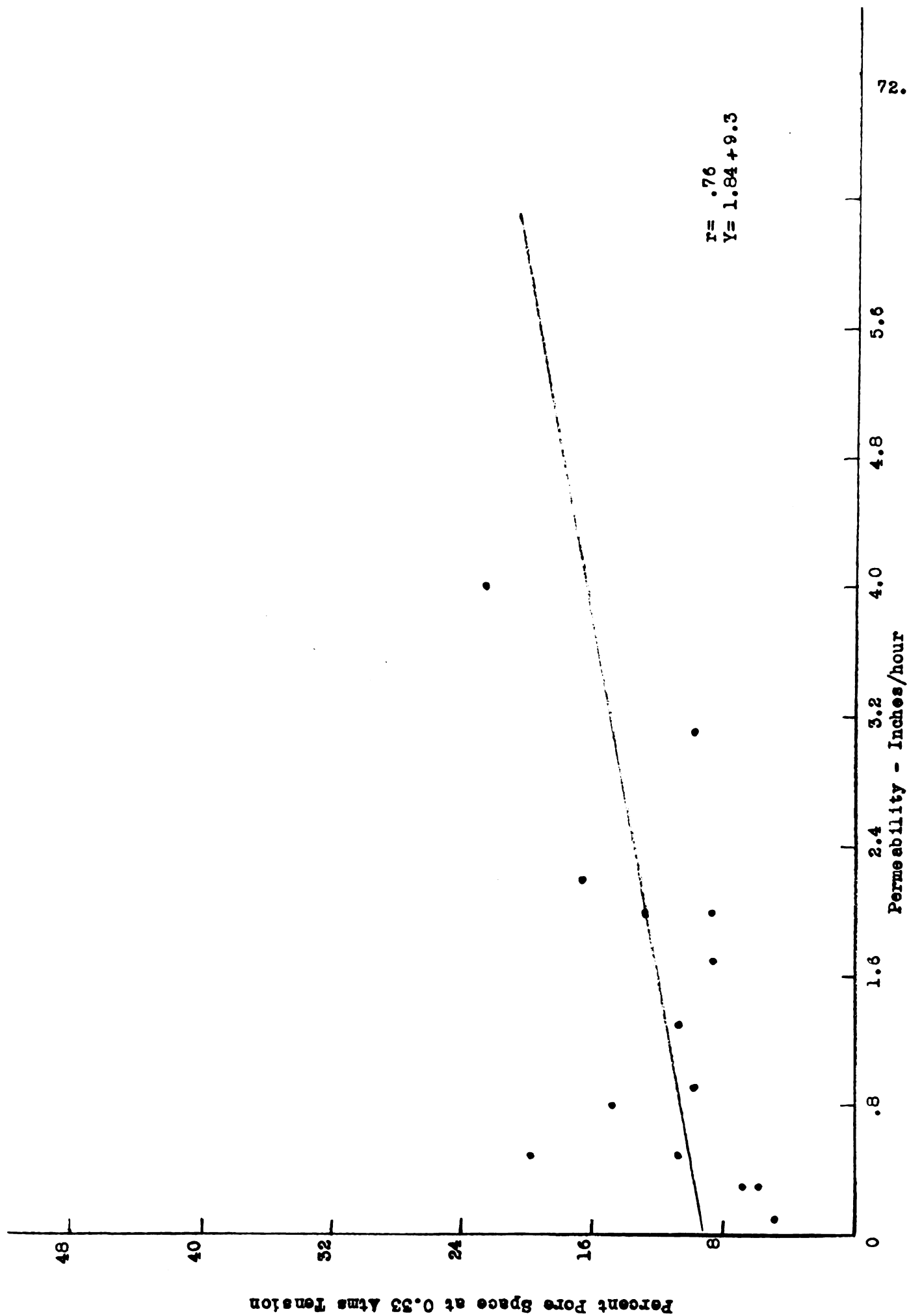


Figure 29. Permeability of subsoil vs. percent pore space at 0.33 Atms tension with regression line.

11

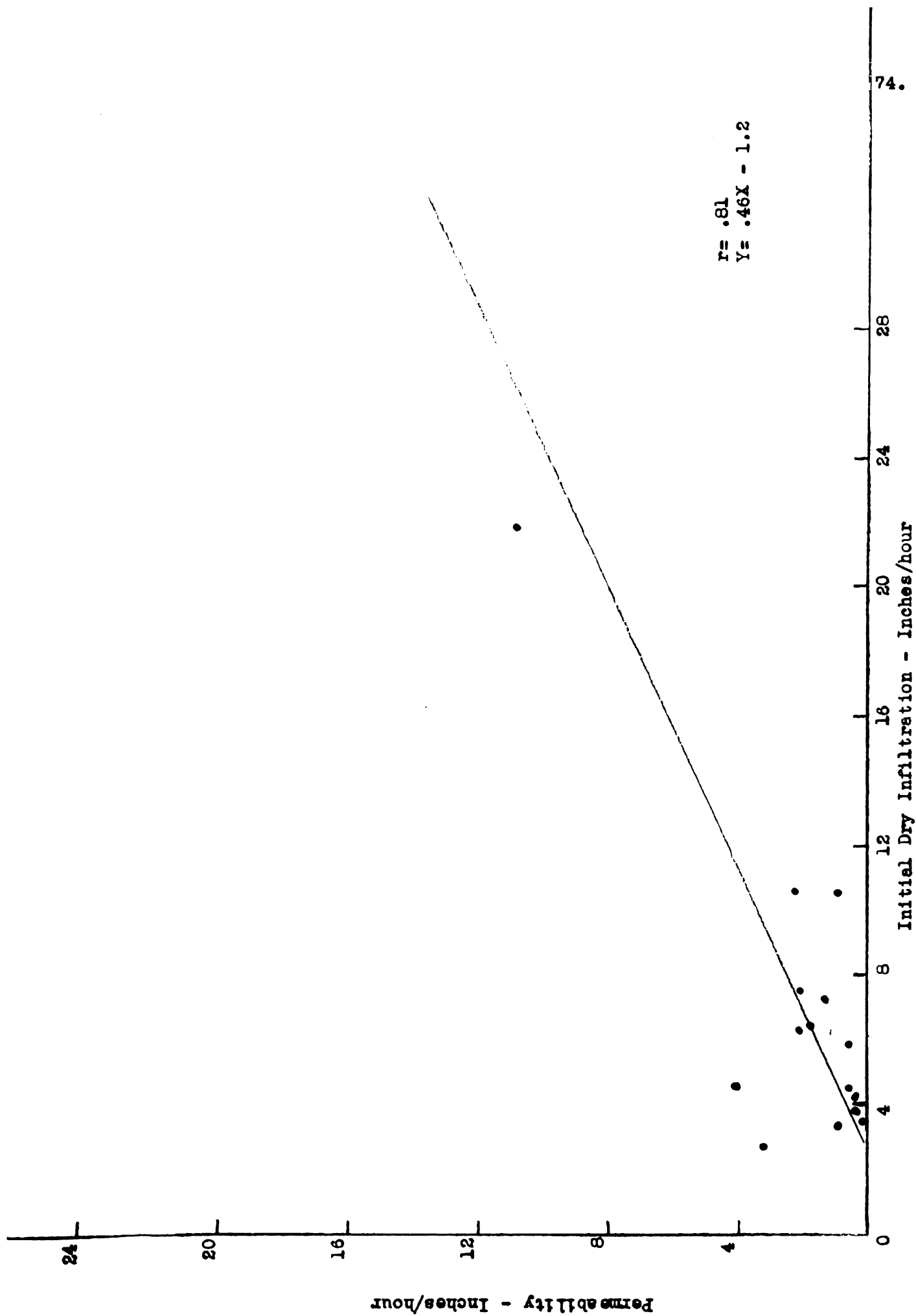


Figure 31. Initial dry infiltration vs. permeability of subsoil with regression line.

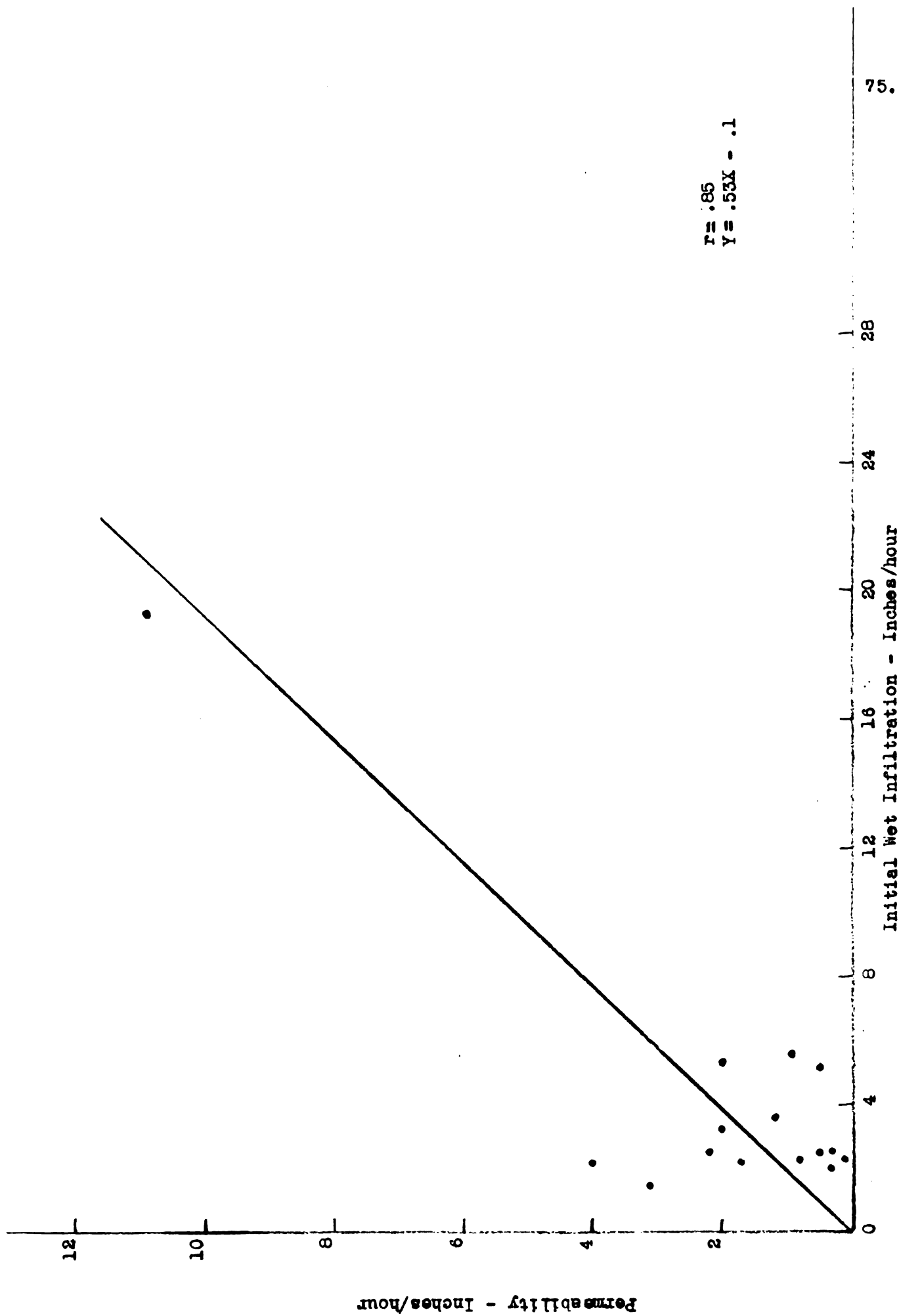


Figure 32. Initial wet infiltration vs. permeability of subsoil with regression line.

BASIC FIELD AND LABORATORY DATA

	Soil Type			
	Berrien Loamy Sand	Granby Loamy Sand	Hillsdale Sandy Loamy	Miami Sandy Loam
Site Number	1	2	3	4
Sample Number	1	6	11	18
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	-	-	-	-
Infiltration				
Initial Dry	24.1	11.3	18.6	4.5
Initial Wet	13.2	6.6	23.5	3.3
Minimum Wet	13.2	5.0	13.2	1.1
Permeability	13.4	6.9	3.4	2.8
Volume Weight (gms/cc)	1.3	1.1	1.3	1.4
Total Pore Space, %	54	52	48	42
Percent Pores Drained at				
0.01 Atms.	4	1	4	6
0.03 Atms.	11	6	8	10
0.04 Atms.	13	9	10	11
0.06 Atms.	20	14	13	14
0.33 Atms.	27	20	17	19
1.00 Atms.	30	22	21	22
Horizon	B ₁₁	B _{2g}	B ₂₁	B ₂₁
Sample Number	2	8	13	21
Initial Air Space, %	-	-	-	-
Infiltration				
Initial Dry	-	-	-	-
Initial Wet	-	-	-	-
Minimum Wet	-	-	-	-
Permeability	-	-	-	-
Volume Weight (gms/cc)	-	-	-	-
Total Pore Space, %	-	-	-	-
Per Cent Pores Drained at				
0.01 Atms.	-	-	-	-
0.03 Atms.	-	-	-	-
0.04 Atms.	-	-	-	-
0.06 Atms.	-	-	-	-
0.33 Atms.	-	-	-	-
1.00 Atms.	-	-	-	-
Lowest Permeability of Profile	.92	2.10	.13	.14

Note: Infiltration and permeability values are given in inches per hour.

BASIC FIELD AND LABORATORY DATA

77.

	Soil Type			
	Brookston Sandy Loam	Sims Clay Loam	Nappanee Silt Loam	Hoytville Clay Loam
Site Number	5	6	7	8
Sample Number	24	30	35	40
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	—	55	47	44
Infiltration				
Initial Dry	17.1	45.8	14.9	26.7
Initial Wet	17.9	27.0	5.5	20.1
Minimum Wet	5.9	17.7	3.5	3.5
Permeability	4.0	15.1	20.1	27.6
Volume Weight (gms/cc)	1.4	.9	1.1	.9
Total Pore Space, %	43	64	55	58
Per Cent Pores Drained at				
0.01 Atms.	3	10	11	7
0.03 Atms.	6	17	15	13
0.04 Atms.	8	19	16	14
0.06 Atms.	10	21	17	16
0.33 Atms.	15	23	17	17
1.00 Atms.	17	25	18	18
Horizon	B _{g1}	B _{1g}	B _{2g}	G _{2b}
Sample Number	25	31	37	42
Initial Air Space, %	—	24	20	32
Infiltration				
Initial Dry	10.6	7.5	2.7	6.4
Initial Wet	2.5	5.3	1.5	2.1
Minimum Wet	2.1	1.2	.1	0.4
Permeability	2.2	2.0	3.1	1.7
Volume Weight, (gms/cc)	1.6	1.4	1.5	1.4
Total Pore Space, %	36	47	41	45
Per Cent Pores Drained at				
0.01 Atms.	2	6	4	3
0.03 Atms.	7	10	6	5
0.04 Atms.	8	11	6	5
0.06 Atms.	11	13	6	6
0.33 Atms.	17	13	10	9
1.00 Atms.	18	14	11	10
Lowest Permeability of Profile	.10	2.00	3.10	1.70

Note: Infiltration and permeability values are given in inches per hour.

BASIC FIELD AND LABORATORY DATA

	Soil Type			
	Fox Sandy Loam	Fox Sandy Loam	Warsaw Silt Loam	Spinks Sandy Loam
Site number	9	10	11	12
Sample Number	43	48	54	60
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	15	20	22	25
Infiltration				
Initial Dry	4.4	6.1	8.1	20.0
Initial Wet	3.9	4.4	6.5	19.8
Minimum Wet	1.4	1.7	2.8	11.3
Permeability	1.5	1.4	2.9	7.5
Volume Weight (gms/cc)	1.6	1.5	1.2	1.5
Total Pore Space, %	33	37	49	39
Per Cent Pores Drained at				
0.01 Atms.	1	4	5	2
0.03 Atms.	4	7	9	6
0.04 Atms.	7	7	11	9
0.06 Atms.	10	9	13	20
0.33 Atms.	15	10	11	29
1.00 Atms.	17	10	11	29
Horizon	B ₃	B ₂	B ₁	B ₁
Sample Number	46	50	-	-
Initial Air Space, %	27	22	-	-
Infiltration				
Initial Dry	4.6	6.3	-	-
Initial Wet	2.1	3.1	-	-
Minimum Wet	1.0	1.3	-	-
Permeability	4.0	2.0	-	-
Volume Weight (gms/cc)	1.5	1.6	-	-
Total Pore Space, %	35	37	-	-
Per Cent Pores Drained at				
0.01 Atms.	3	4	-	-
0.03 Atms.	11	7	-	-
0.04 Atms.	12	8	-	-
0.06 Atms.	14	9	-	-
0.33 Atms.	23	9	-	-
1.00 Atms.	24	10	-	-
Lowest Permeability of Profile	.78	.67	.44	5.00

Note: Infiltration and permeability values are given in inches per hour.

	Soil Type			
	Berrien Sandy Loam	Warsaw Silt Loam	Fox Sandy Loam	Conover Silt Loam
Site Number	13	14	15	16
Sample Number	64	68	73	82
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	34	14	18	18
Infiltration				
Initial Dry	11.8	4.4	15.4	14.5
Initial Wet	7.6	3.9	12.3	7.5
Minimum Wet	6.1	1.7	5.3	1.7
Permeability	9.7	1.0	3.8	4.3
Volume Weight (gms/cc)	1.4	1.5	1.4	1.3
Total Pore Space, %	40	39	40	47
Per Cent Pores Drained at				
0.01 Atms.	4	3	6	6
0.03 Atms.	8	4	11	8
0.04 Atms.	10	5	12	9
0.06 Atms.	12	6	14	10
0.33 Atms.	17	9	16	14
1.00 Atms.	19	11	17	16
Horizon	—	B ₂₂	B ₂	B _{2g}
Sample Number	—	70	76	85
Initial Air Space, %	—	17	11	23
Infiltration				
Initial Dry	—	10.6	7.2	3.3
Initial Wet	—	5.5	3.6	2.3
Minimum Wet	—	1.9	1.0	0.2
Permeability	—	.9	1.2	0.8
Volume Weight (gms/cc)	—	1.6	1.7	1.5
Total Pore Space, %	—	32	37	41
Per Cent Pores Drained at				
0.01 Atms.	—	00	3	4
0.03 Atms.	—	2	6	6
0.04 Atms.	—	6	6	7
0.06 Atms.	—	8	7	9
0.33 Atms.	—	10	11	15
1.00 Atms.	—	11	12	17
Lowest Permeability of Profile	4.00	.76	1.00	.12

Note: Infiltration and permeability values are given in inches per hour.

	Soil Type			
	Miami Silt Loam	Newton Loamy Sand	Saugatuck Loamy Sand	Conover Silt Loam
Site Number	17	18	19	20
Sample Number	87	94	99	104
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	20	27	38	18
Infiltration				
Initial Dry	14.1	8.4	28.2	14.5
Initial Wet	5.8	4.6	23.1	4.9
Minimum Wet	2.1	2.4	10.4	2.2
Permeability	1.7	4.2	8.4	1.6
Volume Weight (gms/cc)	1.5	1.4	1.3	1.4
Total Pore Space, %	10	44	47	43
Per Cent Pores Drained at				
0.01 Atms.	4	1	2	4
0.03 Atms.	4	4	7	5
0.04 Atms.	5	12	17	6
0.06 Atms.	6	15	20	7
0.33 Atms.	8	22	33	12
1.00 Atms.	10	26	36	15
Horizon	B ₂₁	G _{a3}	B ₂₂	B _{1g}
Sample Number	90	-	100	106
Initial Air Space, %	22	-	-	11
Infiltration				
Initial Dry	3.8	-	21.8	4.5
Initial Wet	2.0	-	19.2	2.5
Minimum Wet	0.2	-	8.2	0.3
Permeability	0.3	-	10.8	0.5
Volume Weight (gms/cc)	1.6	-	1.2	1.6
Total Pore Space, %	38	-	49	39
Per Cent Pores Drained at				
0.01 Atms.	1	-	3	3
0.03 Atms.	3	-	10	6
0.04 Atms.	3	-	17	6
0.06 Atms.	4	-	22	8
0.33 Atms.	6	-	28	11
1.00 Atms.	9	-	31	14
Lowest Permeability of Profile	12	66	7.50	.18

Note: Infiltration and permeability values are given in inches per hour.

BASIC FIELD AND LABORATORY DATA

	Soil Type			
	Granby Sandy Loam	Berrien Loamy Sand	Hillsdale Sandy Loam	Ubly Silt Loam
Site Number	21	22	23	24
Sample Number	109	114	121	127
Horizon	Ap	Ap	Ap	Ap
Initial Air Space, %	39	27	27	32
Infiltration				
Initial Dry	20.1	15.2	10.3	4.1
Initial Wet	13.3	13.6	8.4	4.8
Minimum Wet	9.9	6.0	4.0	1.6
Permeability	10.7	4.1	1.8	1.0
Volume Weight (gms/cc)	1.2	1.5	1.5	1.5
Total Pore Space, %	52	39	39	44
Per Cent Pores Drained at				
0.01 Atms.	8	1	5	4
0.03 Atms.	16	3	9	5
0.04 Atms.	19	6	10	6
0.06 Atms.	18	8	11	8
0.33 Atms.	27	22	16	11
1.00 Atms.	30	25	18	13
Horizon	B _g	B ₂	B ₂₁	B ₂
Sample Number	111	-	121	128
Initial Air Space, %	20	-	13	19
Infiltration				
Initial Dry	5.9	-	3.5	4.2
Initial Wet	5.2	-	2.3	2.5
Minimum Wet	3.6	-	0.2	0.3
Permeability	0.5	-	0.1	0.3
Volume Weight (gms/cc)	1.7	-	1.8	1.7
Total Pore Space, %	30	-	31	35
Per Cent Pores Drained at				
0.01 Atms.	4	-	1	1
0.03 Atms.	6	-	2	4
0.04 Atms.	10	-	3	6
0.06 Atms.	14	-	4	6
0.33 Atms.	20	-	5	7
1.00 Atms.	20	-	7	9
Lowest Permeability of Profile	.51	2.80	.06	.31

Note: Infiltration and permeability values are given in inches per hour.

BASIC FIELD AND LABORATORY DATA

	Soil Type	
	Kalkaska Loamy Sand	Mancelona Loamy Sand
Site Number	25	27
Sample Number	130	141
Horizon	Ap	Ap
Initial Air Space, %	28	28
Infiltration		
Initial Dry	11.4	19.5
Initial Wet	8.4	5.8
Minimum Wet	5.9	3.5
Permeability	6.7	8.9
Volume Weight (gms/cc)	1.5	1.5
Total Pore Space, %	42	41
Per Cent Pores Drained at		
0.01 Atms.	1	4
0.03 Atms.	6	15
0.04 Atms.	14	21
0.06 Atms.	22	24
0.33 Atms.	29	29
1.00 Atms.	31	30
Horizon	-	-
Sample Number	-	-
Initial Pore Space, %	-	-
Infiltration		
Initial Dry	-	-
Initial Wet	-	-
Minimum Wet	-	-
Permeability	-	-
Volume Weight (gms/cc)	-	-
Total Pore Space, %	-	-
Per Cent Pores Drained at		
0.01 Atms.	-	-
0.03 Atms.	-	-
0.04 Atms.	-	-
0.06 Atms.	-	-
0.33 Atms.	-	-
1.00 Atms.	-	-
Lowest Permeability of Profile	8.00	8.90

Note: Infiltration and permeability values are given in inches per hour.

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