Zeitschrift: Archives des sciences [1948-1980]

Herausgeber: Société de Physique et d'Histoire Naturelle de Genève

Band: 31 (1978)

Heft: 2

Artikel: A testing of permeability estimation techniques in oolitic calcarenites : Ste. Genevieve Limestone (Mississippian), Southern Illinois

Autor: Hiseler, Robert B. / Carozzi, Albert V.

DOI: https://doi.org/10.5169/seals-739417

A TESTING OF PERMEABILITY ESTIMATION TECHNIQUES IN OOLITIC CALCARENITES, STE. GENEVIEVE LIMESTONE (MISSISSIPPIAN), SOUTHERN ILLINOIS

BY

Robert B. HISELER and Albert V. CAROZZI[1]

ABSTRACT

Porosity, grain size, packing, sorting, and particle shape are the most significant variables controlling permeability in unconsolidated porous media. These variables are briefly discussed in a literature review of permeability in unconsolidated porous media and limestones. Porosity appears to be the most significant of these variables in controlling permeability in oolitic calcarenites.

Existing permeability estimation techniques are critically discussed. Teodorovich's method was found to be insufficiently accurate to estimate permeabilities in samples of the Ste. Genevieve Limestone to within approximately ½ order of magnitude of measured values. Permeability values predicted by this technique are generally lower than measured values. Teodorovich's method can only be applied successfully it effective porosity is known, pore size distribution is uniform, and the operator develops sufficient experience to understand the method's often times vague terminology. The Perez-Rosales technique for estimating permeability was not found to be applicable to thin sections of the Ste. Genevieve Limestone. Permeabilities estimated by this technique were much higher than measured permeabilities. However the Perez-Rosales technique for estimating porosity was found to predict effective porosity to $\pm 10\%$ of measured values from thin sections of oolitic calcarenites.

A petrographic technique is proposed to estimate gas permeability in oolitic calcarenites to within ½ an order of magnitude. The technique assumes that permeability is approximately proportional to porosity in oolitic calcarenites which are divided into uniquely defined lithologic categories. Categories are defined by the areal percentage of ooids, pellets, and bioclasts in thin section.

The distribution of calcite cement in oolitic calcarenites of the Ste. Genevieve Limestone is strongly influenced by bioclastic grains. Cement is preferentially localized around bioclastic centers resulting in an irregular cement distribution, which leaves pores and pore throats between centers of cementation relatively well interconnected, thus enhancing permeability. In the absence of bioclastic grains, cement appears to be more homogeneously distributed among pores and pore throats resulting in an increase in tortuosity and a decrease in permeability.

In oolitic calcarenites of the Ste. Genevieve Limestone, vertical permeability is less than horizontal permeability. Bioclastic grains appear to restrict flow in the vertical direction more so than in the horizontal direction.

---

[1] Department of Geology, University of Illinois at Urbana-Champaign, Urbana, Illinois, 61801, U.S.A. This paper is part of a MS thesis completed by R.B.H. under the supervision of A.V.C. and submitted to the Graduate College in May 1977.

Gratitude is expressed to Petróleo Brasileiro S.A. Petrobrás for financial support of the publication costs.

RÉSUMÉ

La porosité, la granulométrie, l'agencement des grains, le triage et la forme des grains sont les variables principales qui contrôlent la perméabilité dans les milieux poreux non-consolidés. Ces variables sont analysées brièvement dans une revue des travaux concernant la perméabilité dans les milieux poreux non-consolidés et dans les calcaires. Pour le contrôle de la perméabilité dans les calcarénites oolithiques, la porosité semble être la variable la plus importante.

Les méthodes courantes d'estimation de la perméabilité sont analysées de façon critique. La méthode de Teodorovich s'est avérée insuffisamment précise pour estimer les perméabilités d'échantillons du Calcaire de Ste. Geneviève avec une précision supérieure à la moitié de l'ordre de grandeur des valeurs mesurées. Les valeurs de perméabilité prédites par cette méthode sont en général inférieures aux valeurs mesurées. La méthode de Teodorovich ne peut être appliquée avec succès que si la porosité effective est connue, la distribution de la dimension des pores uniforme, et si l'opérateur acquiert une expérience suffisante pour comprendre la terminologie souvent vague de cette méthode. D'autre part la méthode d'estimation de la perméabilité de Perez-Rosales n'est pas applicable aux coupes minces du Calcaire de Ste. Geneviève, les valeurs de perméabilité prédites par cette méthode étant beaucoup plus hautes que les valeurs mesurées. Cependant, la méthode d'estimation de la porosité de Perez-Rosales s'est révélée capable de prédire la porosité effective avec une précision de ±10% des valeurs mesurées dans les coupes minces de calcarénites oolithiques.

Une méthode pétrographique est proposée qui estime la perméabilité gaz de calcarénites oolithiques avec une précision supérieure à la moitié de l'ordre de grandeur. Cette méthode considère que la perméabilité est approximativement proportionnelle à la porosité dans les calcarénites oolithiques divisées en catégories lithologiques distinctes. Ces catégories sont définies par le pourcentage des oolithes, pellets et grains bioclastiques basé sur la surface de la coupe mince.

La distribution du ciment calcitique dans les calcarénites oolithiques du Calcaire de Ste. Geneviève est profondément influencée par les grains bioclastiques. Le ciment est développé de préférence autour de centres bioclastiques. Cette distribution irrégulière laisse entre les centres de cimentation les pores et les étranglements *(pore throats)* relativement bien connectés ce qui augmente la perméabilité. En l'absence de grains bioclastiques, le ciment apparaît distribué de façon plus homogène parmi les pores et les étranglements *(pore throats)*, produisant une augmentation de la tortuosité et une diminution de la perméabilité.

Dans les calcarénites oolithiques du Calcaire de Ste. Geneviève, la perméabilité verticale est plus faible que la perméabilité horizontale. Les grains bioclastiques semblent réduire la circulation plus fortement dans le sens vertical que dans le sens horizontal.

INTRODUCTION

Approximately 50-60% of the world's petroleum is produced from carbonate reservoirs. If carbonate reservoirs are to be exploited to their ultimate potential, it is imperative to gain a thorough understanding of their petrophysical properties and develop the ability to measure and describe them.

Porosity and permeability are two such properties studied in this paper. Variables which control these parameters are discussed, together with a review of theoretical equations and petrographic techniques which are used to estimate porosity and permeability. Finally, a petrographic technique is proposed to estimate intergranular porosity and permeability in oolitic calcarenites. This petrographic technique is especially valuable for samples which are impregnated with drilling mud, fractured, or small and irregularly shaped. Porosity and permeability in such samples cannot be measured satisfactorily using a conventional permeameter.

PREVIOUS WORK

Definition of Permeability

Permeability, or the ability of porous media to transmit a fluid without impairment of the structure of the medium, is a concept studied in several fields of science including Earth Science, Engineering, Chemistry and Physics. The vast amount of literature concerning permeability attests to the importance and complexity of the subject. The theory of laminar flow through homogeneous porous media is based on Darcy's classical experiments (Darcy, 1858) on the vertical flow of water through filter sands. Darcy found that flow of water is directly proportional to the hydraulic gradient. This relationship is expressed in Equation 1 and is known as Darcy's Law. Q is the total volume of the fluid passing through a porous

$$Q = KA\,\frac{(h_1 - h_2)}{L} \tag{1}$$

medium in a unit time, A is the area of the porous medium normal to the flow direction, h_1 is the head at the entrance of the porous medium, h_2 is the head at the discharge end of the porous medium, L is the length of the porous medium parallel to the flow direction, and the quantity $(h_1 - h_2/L)$ is the hydraulic gradient. K is a constant of proportionality with units of length per time, and is commonly referred to as the "coefficient of permeability" or the "hydraulic conductivity".

Hubbert (1940) demonstrated the relationship given in Equation 2 in which Darcy's coefficient of permeability is a property of both the porous

$$K = \frac{\rho g k}{\mu} \tag{2}$$

medium and the fluid. ρ is the fluid density, μ is the fluid viscosity, g is the acceleration of gravity, and k is termed "permeability", "intrinsic permeability" or "specific permeability" and has units of length squared. Specific permeability, k, is independent of the properties of the fluid and, therefore, is more useful in describing porous media than Darcy's coefficient of permeability. In this work, "permeability" will refer to k, as defined by Hubbert (1940), and is measured in millidarcys (md) which is one-thousandth of a darcy. One darcy equals $9.87 \times 10^{-12}\,cm^2$ (Scheidegger, 1960) and is equivalent to the passage of one cubic centimeter of fluid of one centipoise viscosity flowing in one second under a pressure differential of one atmosphere through an area of cross section of one square centimeter and length of one centimeter.

Definition of Porosity

In this study, a pore is defined as any void volume within porous media. A pore interconnection, or pore throat, is defined as any constricted opening connecting larger pores in porous media. The "total porosity" of a porous medium is defined as the ratio of the void volume to the bulk volume (V_p/V_b). In this work, this ratio will be stated in percent. "Effective porosity" is defined as the ratio of the interconnected void volume to the bulk volume. In this work, "effective porosity" will be simply referred to as "porosity" which is less than or equal to total porosity.

Important Variables Controlling Permeability in Unconsolidated Porous Media

Hundreds of scientists in different fields have studied the physical variables of porous media which control permeability. From the literature, there appears to be almost as many variables as there are types of porous media. The most significant variables in unconsolidated sediments are porosity, grain size, packing, sorting and particle shape.

Porosity

Several investigators (Table 1) have determined that permeability is proportional to porosity, ϕ, raised to a power n, in unconsolidated granular porous media composed of synthetic spheres or sand. It is obvious from the large variation in n (~ 1 to 6) that k must be dependent on parameters other than simply porosity.

TABLE 1

Porosity Versus Permeability Relations in Unconsolidated Porous Media

Author	Expression for k
Slichter (1897)	$k \propto \phi^{3.3}$
Fair and Hatch (1933)	$k \propto \frac{\phi^3}{(1-\phi)^2}$
Mavis and Wilsey (1937)	$k \propto \phi^5$ to ϕ^6
Franzini (1951)	$k \propto \frac{\phi^3}{(1-\phi)^2}$

Grain Size

Hubbert (1940), in a series of experiments, demonstrated that:

$$k = c\,d^2 \tag{3}$$

where c is a dimensionless constant describing particle shape, and d is the mean particle diameter of the porous medium. Equation 3 assumes that the mean particle diameter approximates the mean pore size; a condition not necessarily true for all porous media.

Packing

Graton and Fraser (1935) give a pertinent theoretical discussion of the packing of spheres. They systematically describe different packing arrangements from "loosest" cubic packing to "tightest" rhombohedral packing. As packing arrangements become tighter, pore geometry becomes much more complex, implying that fluid flow paths must become extremely irregular. The irregularity of the fluid flow path is commonly referred to as "tortuosity", T, and is usually defined by Equation 4 (Scheidegger, 1960). L_f is the average length travelled by a fluid particle and L_m is

$$T = \frac{L_f}{L_m} \tag{4}$$

the length of the porous medium. Frictional resistance to fluid flow increases with increasing tortuosity. Coogan and Manus (1975) argue that tighter packing arrangements increase tortuosity and, therefore, decrease permeability. Coogan and Manus (1975) review methods which estimate the degree of compaction of limestones on the basis of grain to grain relationships after having reached quantitative estimates of packing in the uncompacted state. However, no attempt is made to experimentally relate either packing measures, or tortuosity differences, to measured permeability values.

Sorting

Extremely poor sorting obviously decreases permeability, as very small spheres will partially fill voids between larger spheres. However, Coogan and Manus (1975) conclude from an extensive literature review that mixtures of spheres of moderate grain size variation (for example fine to coarse grained sand) do not pack into a geometrically ordered system. These mixtures have relatively unpredictable pore geometries and porosity values. Thus, there is no predictable relation between permeability, moderate changes of sorting, and tortuosity.

Particle Shape

Particle shape (including overall geometry and angularity) is sometimes cited (Maiklem, 1968) as affecting permeability. However, this variable cannot be simply quantified for complicated or unknown shapes. Most investigators attempt to incorporate particle shape considerations into tortuosity measures or some other proportionality constant which will be discussed below.

Mathematical Models Used to Predict Permeabilities

Several investigators have undertaken the task of uniting the variables of porosity, grain size, packing, sorting and particle shape into a single relation to predict permeability. The common approach to this problem is to develop a microscopic flow model of the porous medium in question. Scheidegger (1960) gives a pertinent review of microscopic flow models. Typically, pores and pore throats are modeled by theoretical capillary tubes of corresponding "diameters". These tubes are mathematically cut into short segments. The segments are then systematically or randomly rearranged (also mathematically). Large diameter segments model pores, whereas interconnecting smaller diameter segments model pore throats (Scheidegger, 1960; Wyllie and Gardner, 1958).

The Kozeny Equation (Scheidegger, 1960) is one of the most widely

$$k = \frac{c\,\phi^3}{S^2} \tag{5}$$

accepted equations of this type used to predict permeability in unconsolidated sediments. It is derived using a capillary tube model. Equation 5 includes the above mentioned variables in the following ways. ϕ is porosity, c is a dimensionless particle shape factor which commonly varies between 0.4 and 1.5 (Scheidegger, 1960). These values cannot be rigorously derived. S is specific surface, which is defined as the ratio of the internal surface area (of the pores) to the bulk volume of the media and, thus, has units of $(1/(\text{length})^2)$. S generally reflects changes in grain size, packing, sorting and grain roughness. However, since Equation 5 is mathematically derived using capillary tubes, S is only rigorously applicable to porous media composed of capillary tubes.

Permeability in Carbonate Rocks

Up to this point, the discussion has been restricted to granular porous media composed of unconsolidated, relatively uniform, simply shaped monomineralic particles. As one makes the transition from simple theoretical porous media to real carbonate rocks, the number of variables controlling permeability increases by an order of magnitude. The resulting permeability relations become extremely complex.

Constituents

The majority of carbonate rock constituents fall into the categories of grains, *in situ* framework building organisms, micrite matrix and sparite cement. These constituents seldom resemble smooth spheres of uniform size, but are often irregularly shaped and of variable internal crystallinity. The calcite in ancient limestones is composed almost entirely of the low magnesium calcite variety, but the percentage of dolomite present is variable.

Solution and Precipitation of Calcite Cement

Precipitation of calcite cement is partially controlled by rock grains and/or framework. Coogan and Manus (1975) found that angular particles are commonly cemented faster than rounded grains due to increased surface area. Shearman (1976, pp. 128-129) found that:

> In limestones where echinoderm fragments are mixed with polycrystalline grains it is not unusual to find that the volume of first phase calcite overgrowth around the echinoderm fragments is far greater than that of the calcite that comprises the selvedges of cement around the other grains. The monocrystalline echinoderm fragments were clearly able to scavenge the calcium and carbonate ions at a faster rate than calcite crystals could nucleate on the surface of the other grains. The net result of this competitive cementation is that where a given amount of calcium carbonate is available for cement, it is not uniformly distributed. The bulk of the cement is deposited as overgrowths around echinoderm debris, and only thin selvedges of cement form around other grains. In the throat passage between grains, the reduction in width of the selvedges of cement, does not reduce the cross-sectional area so drastically, so that permeability is less impaired.

This irregular distribution of cement is also found in ancient (Paleozoic) carbonates. Murray (1960), in a petrographic study of 17 North American petroleum reservoirs, found that "calcite cement appears to be especially common where particles are monocrystalline, such as crinoid fragments". Calcite precipitation occurs preferentially around relatively large monocrystalline grains since these grains have lower free energies (Bathurst, 1971).

This work is not concerned with the time of origin of the irregular distribution of cement, namely, whether or not the distribution is an arrested stage of primary cementation or represents a solution residue from enhanced porosity in formerly less porous carbonates. This work merely points out the existence of this distribution of cement. However, experimental enhancement of permo-porosity in tight carbonates has been recently achieved with a strong fabric selectivity (Donath, Carozzi, Fruth and Rich, 1976, 1977).

Other Diagenetic Processes

Wardlaw (1976) reported that as porosity reduction proceeds in dolomites, composed of rhombohedral crystals, pore geometries change from more complicated polyhedral pores, to lesser complicated tetrahedral pores, to least complicated sheet pores. Wardlaw claims this precipitation of cement in stages is controlled by free energy differences of the various crystal sizes and pore shapes.

Howard and David (1936) stated that is is possible for solution and precipitation to occur as long as aqueous solutions are present in porous limestones. These processes may result in no net gain or less in porosity, but may change permeability by the precipitation of cement in pore throats.

Coogan and Manus (1975) determined that the process of compaction changes the primary packing arrangements in oolites. When compaction is combined with pressure solution and deformation, the resulting pore geometries no longer resemble those of Graton and Fraser (1935).

Sarkisyan *et al.* (1973) state that formation of solution cavities, fractures and stylolites considerably improves porosity and permeability in carbonate rocks. Secondary mineralization, such as sulfatization, calcitization and silicification, can have both positive and negative effects on reservoir rocks, in relation to these features. On one hand, secondary mineralization adversely affects reservoir rocks, on a small scale, by filling and sealing pores, cavities and fractures. On the other hand, secondary mineralization can improve the reservoir flow capacity by creating larger scale heterogeneous textures such as fractures and solution cavities.

Conclusions

Variables affecting permeability in carbonate rocks are briefly outlined in Table 2. With the present state of the art, our understanding of carbonate rocks is not comprehensive enough to quantify all the variables which control development, size and geometrical arrangements of carbonate pore systems. Until these pore systems can be fully understood in quantitative terms, mathematical models cannot be rigorously developed to predict permeability.

Classification Systems Used to Estimate Permeability in Carbonate Rocks

In an attempt to avoid the complexities of studying each of the variables associated with pores, grains and framework, cement, matrix, and diagenesis, classification systems have been proposed in the literature which roughly estimate permeability.

Archie (1952)

Archie (1952) proposed a crude classification based on matrix texture and the "character" of the pore structure visible in hand specimen and under the binocular microscope (10-15 power). Three types of matrix are given, compact crystalline, chalky and granular. Pore character is subdivided according to pore size and visible porosity.

Archie classified some carbonate rocks, as examples, into these lithologic categories and plotted total porosity against permeability. From these data permeability can be estimated to within one order of magnitude [1], if the exact total porosity is known, or to within two orders of magnitude if total porosity can only be estimated to within 5%.

[1] "Order of magnitude" in this work is equivalent to one log cycle.

TABLE 2

Outline of Variables Affecting Permeability in Carbonate Rocks

I. Pores
   A. Volume Percent
      1) effective porosity
      2) total porosity
   B. Character
      1) size
      2) shape
      3) roughness
   C. Pore Throats
      1) abundance
      2) size
      3) size distribution
      4) shape

II. Grains and Framework
   A. Size
   B. Shape
   C. Roughness
   D. Sorting
   E. Composition
   F. Volume Percent
   G. Packing
   H. Internal Crystallinity
   I. Intragranular Porosity

III. Matrix
   A. Volume Percent
   B. Chemical Composition
   C. Particle Size
   D. Particle Shape
   E. Distribution

IV. Diagenesis [1]
   A. Cementation
      1) volume percent
      2) crystal size
      3) crystal shape
      4) distribution
      5) solution
      6) precipitation
   B. Compaction
   C. Pressure Solution
   D. Deformation
   E. Secondary Mineralization
   F. Fracturing

Robinson (1966)

Robinson (1966) classified carbonates according to lithology, visual characteristics (texture), pore size distribution (determined by mercury injection) and total porosity. Lithology is subdivided into: 1) partly dolomitized limestone, 2) dolomite, 3) limestones (including bioclastic, oolitic, algal and "fine matrix"), and 4) dense limestone and dolomite (completely cemented).

Robinson gave only one "measured" (to within an order of magnitude) permeability value for each category. Therefore, it is impossible to evaluate the actual limits of error of this method for estimating permeability. Robinson classified permeability into 4 groups: less than 1 md, 1-10 md, 10-100 md, and greater than 100 md. From this classification it is apparent that permeability, at best, can only be estimated to within one order of magnitude.

[1] Diagenetic processes may be repeated in successive cycles during diagenesis.

Jodry (1972)

Jodry (1972) modified Archie's classification system by including capillary pressure curves with each classification category. Jodry stated that permeability can vary widely for any given porosity in any category. This classification system has the same shortcomings as Archie's system, being much too general.

Conclusions

In theory, rocks of similar lithology will have similar pore systems (Archie, 1952). Thus, permeability will be proportional to porosity as other variables are held constant. This theory breaks down in practice since the above mentioned classification systems force several carbonate lithologies into relatively few categories. The classification schemes mentioned above estimate permeability from porosity only to within one or two orders of magnitude.

Teodorovich's Method for Estimating Permeability

Aschenbrenner and Chilingar (1960) popularized Teodorovich's method for estimating permeability in thin section. Teodorovich classified sediment pore systems in four general ways: 1) pore system geometry and distribution, termed "pore-space type" (Aschenbrenner and Chilingar, 1960), 2) effective porosity, 3) pore size, and 4) pore elongation. Each of these four categories is further subdivided in four corresponding tables (Tables 3, 4, 5 and 6). Each of these subdivisions is assigned an empirically derived numerical coefficient. A pore system is first classified according to Tables 3, 4, 5 and 6. Then the four corresponding numerical coefficients, A, B, C and D, respectively, are multiplied together (Equation 6).

$$k_{\mathrm{Teod}} = A \times B \times C \times D \tag{6}$$

The resulting value, k_{Teod}, is the permeability, measured in millidarcys, md, predicted from Teodorovich's method. Teodorovich's method is critically discussed below.

Perez-Rosales' Technique for Estimation of Permeability and Porosity

Permeability

Perez-Rosales (1969) developed a technique to estimate porosity and permeability in homogeneous, isotropic porous media. The technique utilizes a two dimensional cross section of the medium and a grid composed of perpendicular intersecting lines. Points of the grid where lines intersect are termed "nodes". The grid, of known dimensions, is positioned on a cross section of the porous medium to be studied. The number of nodes, n, falling inside pores is recorded. Intersections between the lines of the grid and pore boundaries are termed "cuts". The number of cuts, c, is

TABLE 3

Empirical Coefficient A for Pore-Space Type
(From Aschenbrenner, B. C. and G. V. Chilingar, 1960, *Bull. Amer. Assoc. Petrol. Geologists*, *44*, p. 1422).

Pore Space Type [1]	Characteristic of Subtype (As Seen in Thin Sections)	Empirical Coefficient *A*
I	With very narrow conveying canals (avg. diameter ≈ 0.01 mm), usually not visible in thin section under the petrographic microscope using normal range of magnification	2
	With rare relatively wide canals (avg. diameter ≈ 0.02 mm) visible in thin sections	3
	With few relatively wide canals, visible in thin section	8
	With many relatively wide canals, visible in thin section, or with few wide canals (avg. diameter ⩾ 0.04 mm)	16
	With abundant wide canals or few to many very wide conveying canals	32
II	With poor porosity, the pores being relatively homogeneous in size and distribution	8
	With good porosity and (or) porosity ranging from poor to good:	
	pores being of different size	16-32
	pores being vuggy and irregular in outline	32-64
III	With very poor porosity inside the conveying canals	6
	With poor porosity inside the conveying canals	12
	Conveying canals finely porous	24
IV	With interconnected pore space between rhombohedral grains	10
	With interconnected pore space between subangular-subrounded grains	20
	With interconnected pore space between rounded to well rounded grains	30

[1] Pore Space Types I, II, III, IV do *not* correspond to Rock Types I, II, III of this paper.

TABLE 4

Empirical Coefficient B for Porosity
(From Aschenbrenner, B. C. and G. V. Chilingar, 1960, *Bull. Amer. Assoc. Petrol. Geologists*, *44*, p. 1422.)

Effective Porosity		Empirical Coefficient *B*
Descriptive Term	Limits in Per Cent	
Very porous	> 25	25-30
Porous	15-25	17
Moderately porous	10-15	10
Pores abundant	5-10	2-5
Pores present	2-5	0.5-1.0
Some pores present	< 2	0

TABLE 5

Empirical Coefficient C for Pore Size
(From Aschenbrenner, B. C. and G. V. Chilingar, 1960, *Bull. Amer. Assoc. Petrol. Geologists*, *44*, p. 1422.)

Descriptive Term	Maximum Size of Pore (mm)	Empirical Coefficient *C*
Large vugs	> 2.00	16
Medium to large vugs	0.50-2.00	4
Medium pores	0.25-1.00	2
Fine to medium pores	0.10-0.50	1
Very fine to fine pores	0.05-0.25	0.5
Very fine pores	0.01-0.10	0.25
Pinpoint to very fine pores	< 0.10 and in part < 0.01	0.125
Mostly pinpoint porosity	< 0.03 and in part < 0.01	0.0625

TABLE 6

Empirical Coefficient D for Pore Shape
(From Aschenbrenner, B. C. and G. V. Chilingar, 1960, *Bull. Amer. Assoc. Petrol. Geologists*, *44*, p. 1423.)

Descriptive Term	Empirical Coefficient *D*
More or less isometric pores	1
Elongate pores	2
Very elongate pores or pores arranged in bands with emanating conveying canals	4

also recorded. Perez-Rosales has rewritten the Kozeny Equation (Equation 5) in terms of nodes, cuts and the total length of the grid lines as Equation 7.

$$k_{\text{Perez}} = \frac{C L^2 n^3}{4 N^3 c m^2} \tag{7}$$

C is a constant of proportionality equivalent to the shape factor in Equation 5. L is the summation of all the lengths of the lines composing the grid, m is the number of times the medium cross section is magnified with respect to the grid, and N is the total number of nodes in the grid. The quantity (n/N) is equivalent to total porosity, whereas the quantity $(2\,c\,m/L)$ is equivalent to specific surface. k_{Perez} has the units of L^2.

Porosity

Total porosity is determined by the Perez-Rosales technique using Equation 8. The Perez-Rosales technique does not distinguish between

$$\phi_{\text{Perez}} = \frac{n}{N} \tag{8}$$

interconnected and non-interconnected pore space. A critical evaluation of the Perez-Rosales technique for estimating permeability and porosity is given below.

MATERIALS STUDIED

Statement of the Problem

The variables which control permeability in carbonate rocks are not well understood, either qualitatively or quantitatively. The purpose of this study is to increase the understanding of permeability by studying one group of carbonate rocks in detail.

Selection of Samples to be Studied

Limestone samples studied in this paper were selected from 101 core samples from 15 wells obtained from the Illinois State Geological Survey. All wells are located in Clay, Richland and Wayne Counties in southeastern Illinois (Figure 1). Well cores are located stratigraphically using corresponding well logs produced by the Pure Oil Co. All samples are from the Ste. Genevieve Limestone (Mississippian) (Short, 1962), and most are in the Fredonia Limestone Member (Ayer, 1970; Graf and Lamar, 1950; Rao and Carozzi, 1970). Samples are composed largely of oolitic, bioclastic and pelletoidal calcarenites.

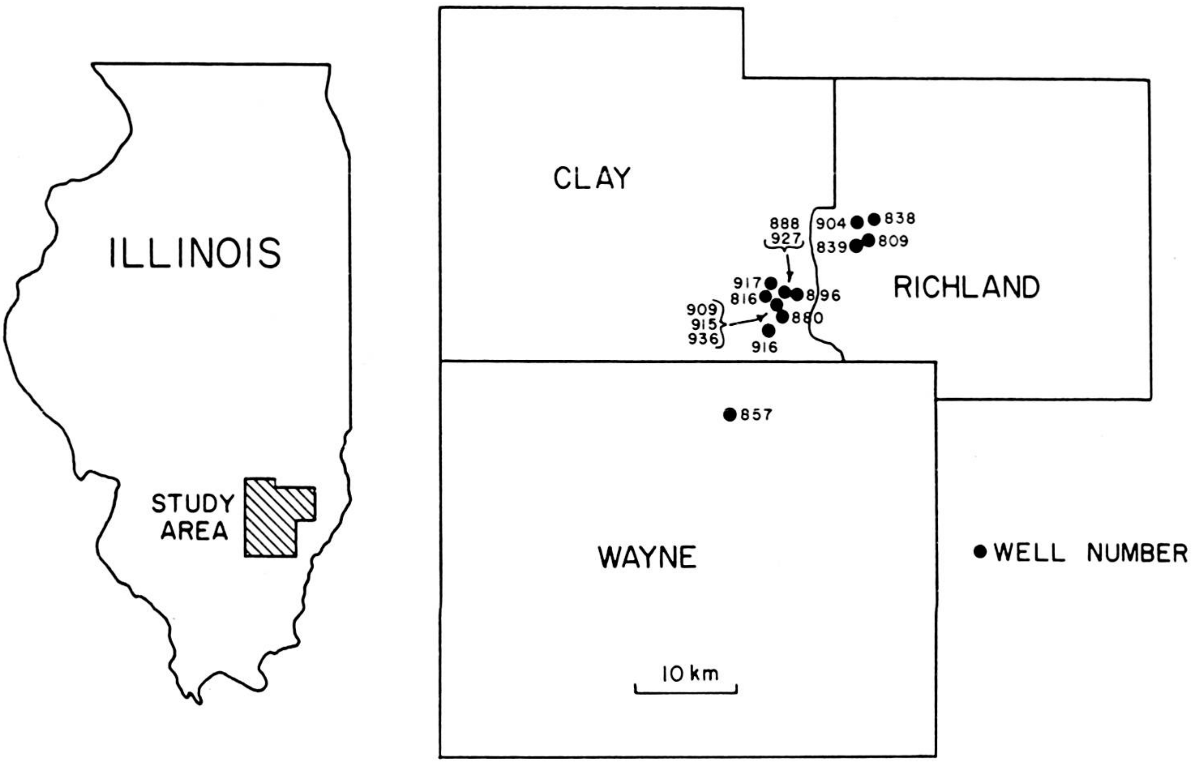


FIG. 1. — Location map of studied area.

These samples where chosen for the following reasons. They are taken from well cores, hence, show no effects of recent surface weathering. The samples are from established petroleum reservoirs and, therefore, have added economic interest. The predominant grains are ooids and pellets which are relatively simple in shape and similar in size.

METHODS OF STUDY OF PERMEABILITY AND POROSITY

Measurement of Permeability and Porosity

Permeability

Permeability was measured using cubes, 2 cm on an edge, cut from the previously mentioned well cores immediately adjacent to the point of thin sectioning. These cubes were washed and then dried for at least 16 hours in a humidity controlled oven at approximately 60° C. Samples which contained fractures, stylolites or excessive drilling mud in thin section were not used in the analysis of permeability.

Permeability was measured in three orthogonal directions (Figure 2): 1) k_m was measured normal to the thin section (thin sections were cut perpendicular to bedding), through the two cube faces parallel to the corresponding thin section, 2) k_{my} was measured in the horizontal plane at right angles to k_m, 3) k_{mz} is the vertical permeability, measured parallel to the thin section and at right angles to both k_m and k_{my}.

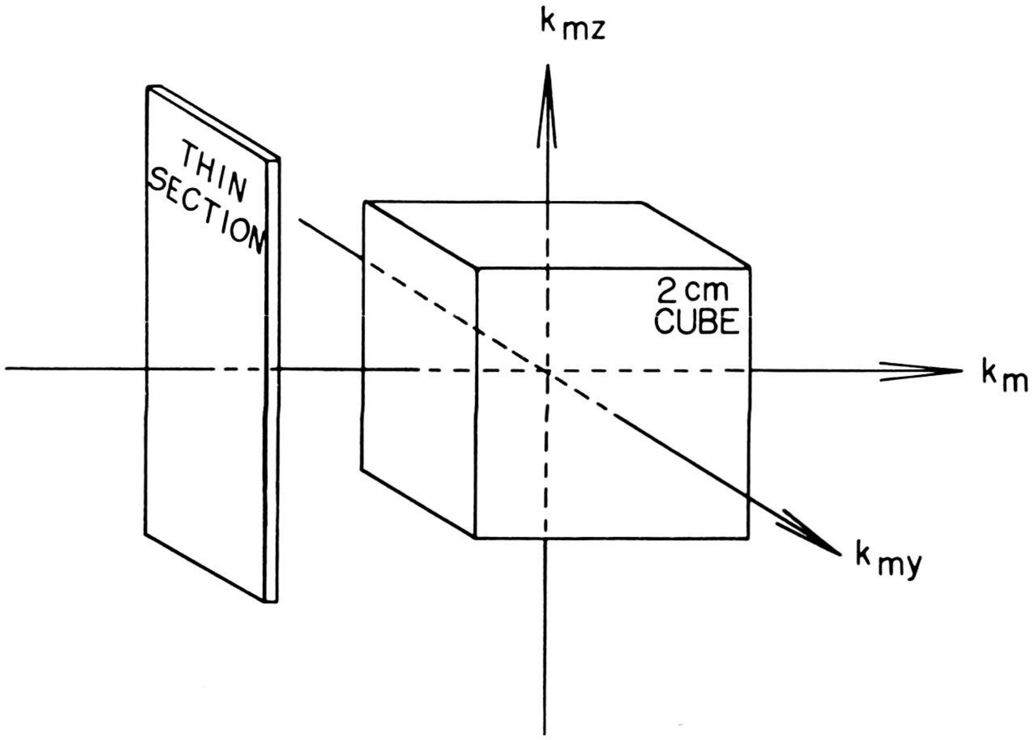


FIG. 2. — Directions of permeability measurement

The permeameter used to measure permeability is described in API Report 40, 1960, pp. 34-36. Nitrogen gas is passed through the sample. The pressure drop across the cube is measured using mercury and water manometers. Permeability is determined using Darcy's Law.

Nitrogen gas permeability, k_m, is not equal to liquid permeability, k_{liq}, since the flow of gas through small pores is not laminar. This difference in flow is termed "gas slippage" or "Klinkenburg Effect", after the author who first observed it (Core Lab, undated, pp. 21-22). In subsequent testing of Teodorovich's method and the Perez-Rosales technique, gas permeabilities were converted to liquid permeabilities using Figure 3.

The limits of error of the permeameter were determined in two ways. The precision was evaluated using one orifice per sample, and measuring permeability several times. The average precision error was found to be $\pm 0.48\%$ of the measured permeability value, k_m. The accuracy of the permeameter was tested by measuring permeability of samples using more than one orifice per sample. The average error in accuracy was found to be $\pm 3.06\%$ of the measured permeability, k_m.

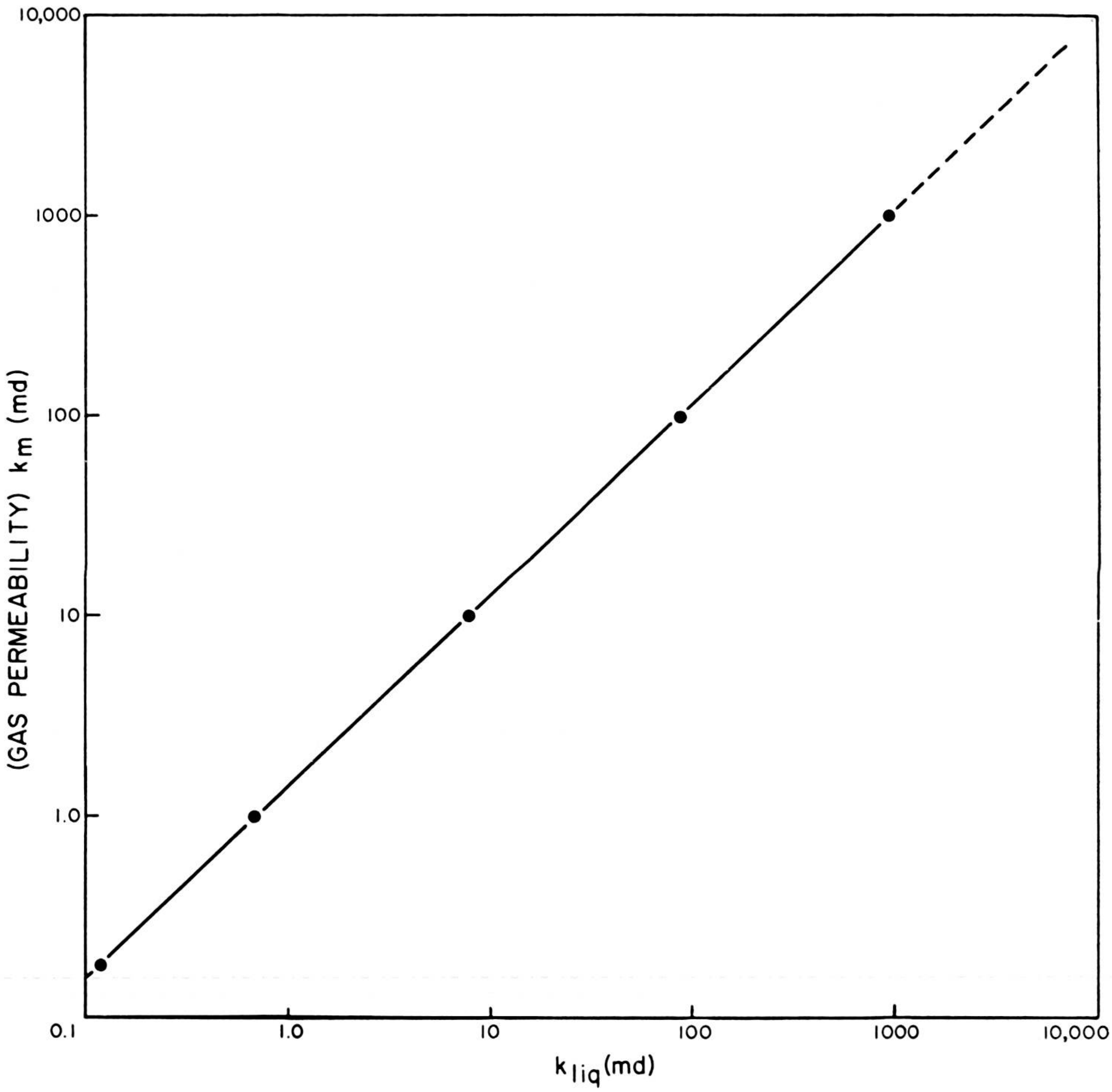


FIG. 3. — Liquid permeability versus gas permeability.

Porosity

Porosity (measured in percent) was determined using Equation 9, where

$$\phi = \frac{V_p}{V_b} \tag{9}$$

V_b is the bulk volume of the sample and V_p is the pore volume. V_b was measured by volumetric displacement of mercury, using a mercury pump. This device is reported to accurately measure bulk volume to ± 0.01 cm^3, and is described in detail in API Report 40, 1960, p. 32. V_p was determined using Equations 10 and 11 and a helium double-cell porosimeter. V_g is the grain

$$V_p = V_b - V_g \tag{10}$$

$$V_g = V_t - V_r \tag{11}$$

volume of the sample, V_t is the total volume of helium needed to fill the porosimeter without the sample, and V_r is the total volume of helium needed to fill the porosimeter with the sample in its cell chamber. The double cell porosimeter consists of two chambers. The sample is placed in one chamber whose helium pressure is adjusted to some known value. The helium in the second chamber is adjusted to some different known pressure. The two chambers are then connected, equalizing the pressures to some final value. Using Boyle's Law, these data are converted to V_t and V_r.

Porosity was measured with the same cubes used to measure permeability. The porosimeter was calibrated using a solid steel plug. The average precision error of the porosimeter was determined to be $\pm 3.97\%$ of the measurement or $\pm 0.56\%$ porosity.

Thin Section Preparation

Thin sections were prepared from 7.5 cm diameter well cores, approximately perpendicular to bedding. Thin section chips were impregnated with a blue epoxy resin to emphasize pore spaces.

Petrographic Study

In subsequent testing of the Perez-Rosales technique, an 11 by 11 line grid (containing 121 nodes) was placed in the ocular of a petrographic microscope. A scale was placed on a thin section to measure the length of the grid lines as they appeared on the thin section. In this way all magnification factors are avoided since both the grid and the thin section are magnified equally, so that $m = 1$. The measured porosity, ϕ_m, was substituted in place of the quantity (n/N) in an attempt to improve accuracy in testing the Perez-Rosales technique for estimating permeability.

The percentage of bioclasts was determined by using the above mentioned grid as a point counting device. 726 points were counted on each thin section. In this study, a "bioclast" is defined as a single fossil fragment. Only those bioclasts larger than approximately 0.4 mm in the longest dimension, were counted. Bioclasts with single, often discontinuous thin oolitic coatings (superficial oolites), and meeting the preceding size requirements, were also counted.

Computer Techniques

Statistical analysis was expedited with the use of the digital computer facilities of the University of Illinois, Urbana. The SOUPAC statistical subroutine *CORRELATION* (SOUPAC, 1974) was used in conjunction with an IBM 360/75 computer to analyze raw porosity and permeability measurements, and petrographic data, encoded onto punched cards (Appendix 1). Output from *CORRELATION* includes means, standard deviations, covariances and linear regression correlation coefficients for the input data.

CRITICAL EVALUATION OF PRESENT PETROGRAPHIC TECHNIQUES USED TO ESTIMATE PERMEABILITY AND POROSITY

Teodorovich's Method

There are several problems in applying Teodorovich's method to carbonate rocks. Descriptions of pore space in the four published tables are poorly defined, both quantitatively and qualitatively. The terms in Table 3 such as "rare", "few", "many", "poor", "good", and "finely porous", are used with no accompanying numerical or descriptive definitions. Table 3 refers to "conveying canals" and their "diameters". The term conveying canal is also not defined, but the term "diameter" implies that conveying canals are cylindrical pore interconnections. Aschenbrenner and Archauer (1960) define conveying canal as "a passage whose average width is rather uniform over its entire length and whose length to width ratio is greater than 10". Wardlaw (1976) found that pores and pore interconnections in dolomites are often sheet-like in shape. If conveying canals are cylindrical, it is unlikely that the 2 dimensional plane of a thin section would lie parallel to, and intersect the axis of, a cylindrical tube. Therefore, the relative size, frequency and geometric arrangement of conveying canals is difficult to study in a 2 dimensional thin section. This work suggests that most linear passages, or so called canals, are sheet-like in geometry and not tubes. The simple example of a high energy calcarenite with an interstitial cavity filling sparite cement shows that the pores are most likely to be sheet-like in geometry, being directed by the contacts of crystal faces and not tubes. It is further noted that under the conventional polarizing microscope, optical resolution is essentially lost in pores smaller than about 0.03 mm. It is difficult to detect a 0.01 mm "diameter" "conveying canal" at all, let alone measure its width to ± 0.01 mm.

Coefficient *A* is determined by placing the pore system in question into one of the 13 pore-space types in Table 3. This assumes only one type of pore structure is present in the pore system, and that the type of pore structure in the sample is present among those 13 listed.

The numerical coefficient *A* varies by a factor of 2 (i.e., 8-16) between each subdivision in Table 3. Aschenbrenner and Chilingar (1960) give no discussion of possible intermediate numerical coefficients compromising between two classification boundary extremes. This ambiguity could result in an error, in coefficient *A*, by as much as a factor of 2 or $\pm 200\%$. Considerable experience is necessary to choose the proper coefficient *A*.

Coefficient *B* is determined from Table 4 using the effective porosity of the pore system. The effective porosity must be known before Teodorovich's method can be applied. In Figure 4 the median effective porosity value for each porosity category in Table 4 is plotted against the corresponding median coefficient *B* value. The irregular changes in slope of this plot indicate a lack of systematic relationship between porosity and coefficient *B*. This makes interpolation difficult when attempting to select a numerical value for coefficient *B* from a known or estimated effective porosity value. This ambiguity suggests that coefficient *B* is likely to be in error by ±5-10%.

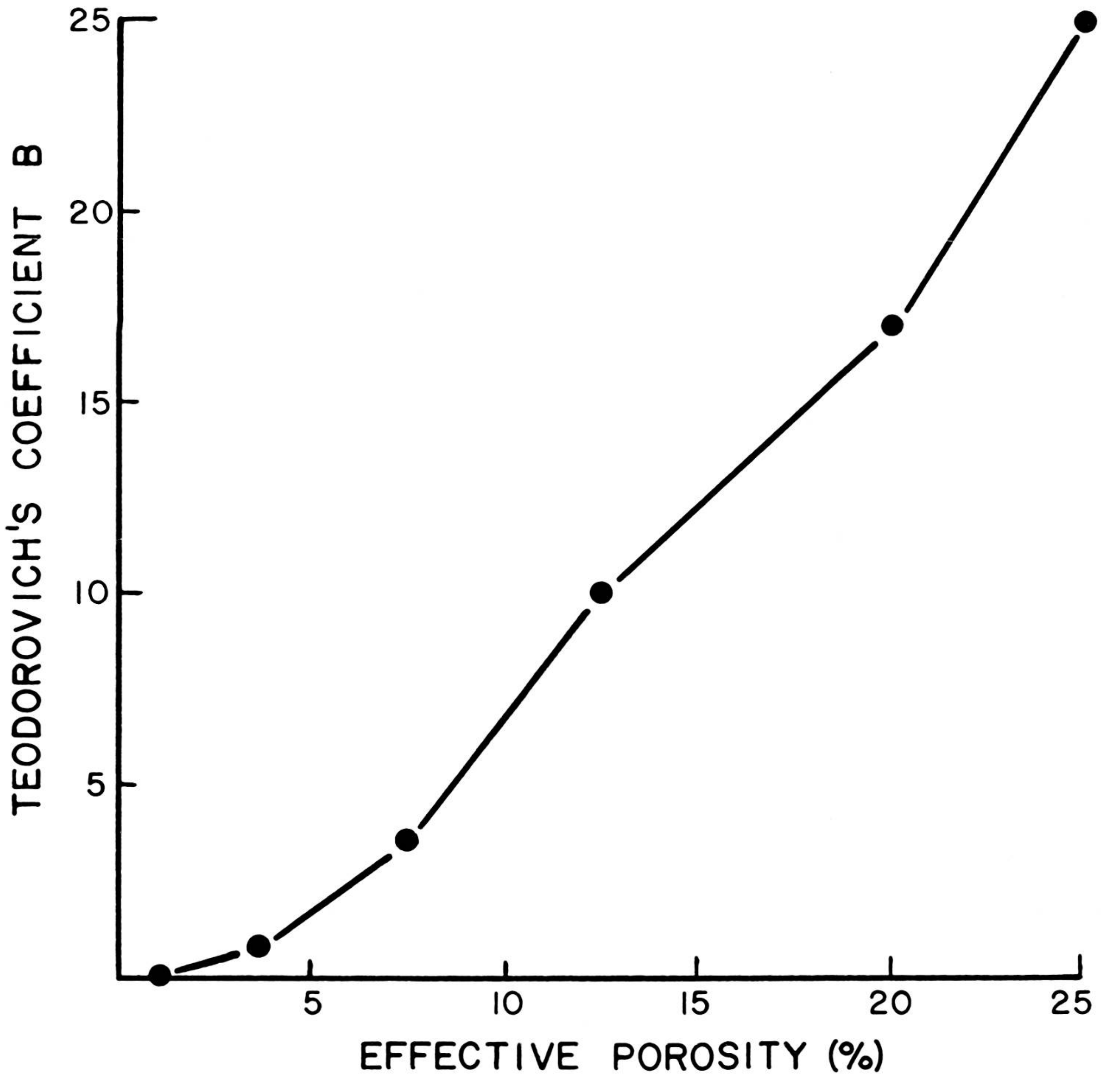


FIG. 4. — Effective porosity versus Teodorovich's Coefficient *B*.

Coefficient *C* is determined using the maximum pore size present in a given pore system. This procedure gives no consideration to the pore size distribution, which can lead to large errors in certain lithologies. For example, sample 816 A (Appendix 2) is a bioclastic calcisiltite with about 10% moldic porosity formed by the solution of bioclasts. About ½ of these moldic pores are greater than 0.25 mm in size. The

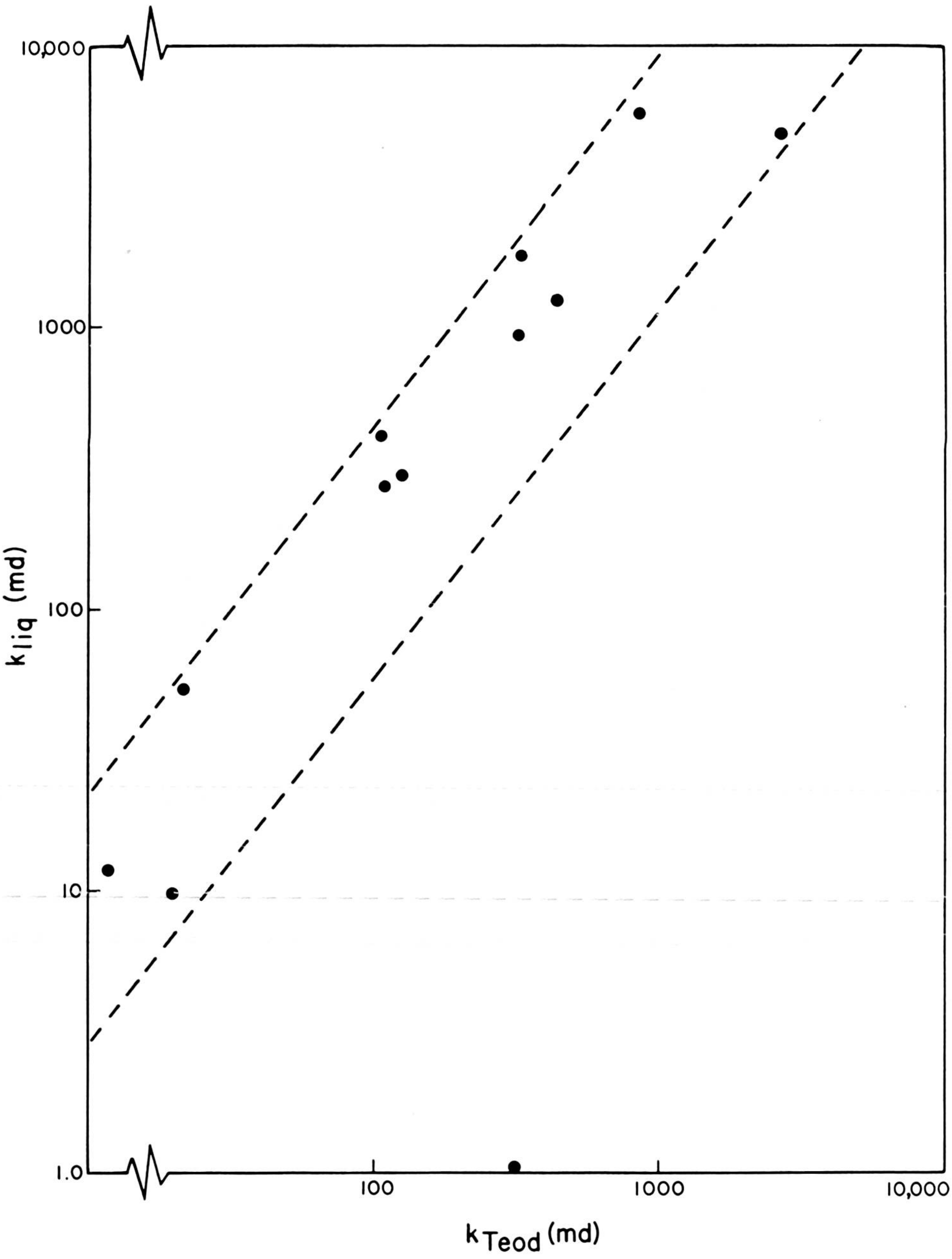


FIG. 5. — Permeability predicted by Teodorovich's Method versus measured permeability.

permeability in this pore system is 1 md, and appears to be dominated by silt-sized pores, probably because the moldic porosity is not well interconnected. Coefficient C is greater than 2 orders of magnitude too high for this rock.

Coefficient D is determined from Table 6, based on the general pore shape or elongation. Terminology is vague as in Table 3. "Elongate" and "more or less" are not defined. In choosing coefficient D between 1 and 4, $\pm 25\%$ error could easily be introduced.

From the previous discussion, it appears that considerable errors can be introduced into each coefficient. Success of the method is only possible it effective porosity is known, pore size distribution is uniform, by chance all errors cancel one another out, and the investigator develops sufficient experience to understand the vague terminology employed in Tables 3, 4, 5 and 6. Aschenbrenner and Chilingar (1960) present data that suggest Teodorovich's method predicts permeability to within $\pm 10\%$ of measured values. The authors tested Teodorovich's method on 12 samples of the Ste. Genevieve Limestone. Data from this study are listed in Appendix 2. Permeability values predicted by Teodorovich's method are plotted against measured permeabilities in Figure 5 (raw data given in Appendix 2). Permeability values predicted by Teodorovich's method are generally lower than measured values. The average error in Teodorovich's method (excluding sample 816 A) is $\pm 59\%$. The authors conclude that Teodorovich's method is insufficiently accurate to predict permeability of samples of the Ste. Genevieve Limestone to within ½ an order of magnitude.

Perez-Rosales' Technique

The Perez-Rosales technique as described above estimates permeability and porosity utilizing a two dimensional cross section of a porous medium and a grid.

Permeability

Upon substituting appropriate values in Equation (7), it was found

$$k_{\text{Perez}} = \frac{C L^2 n^3}{4 N^3 c m^2} \tag{7}$$

that permeabilities predicted by the Perez-Rosales technique were unreasonably high (Appendix 3 and Figure 6). C is assumed to range approximately between 0.4 and 1.4 (Scheidegger, 1960), but no values were given by Perez-Rosales (1969). Twelve samples of the Ste. Genevieve Limestone with measured permeabilities ranging between 1 and 6,000 md had calculated permeabilities ranging between 23,000 and 280,000 md. Even if an appropriate constant is used for C to lower k_{Perez} values to an appropriate order of magnitude, scatter in the observed data plotted in Figure 6 is approximately equivalent to an error of ± 0.5 order of magnitude.

One major problem in applying this technique to carbonate rocks is that pore structure is often highly irregular. Pores are frequently lined internally by minute

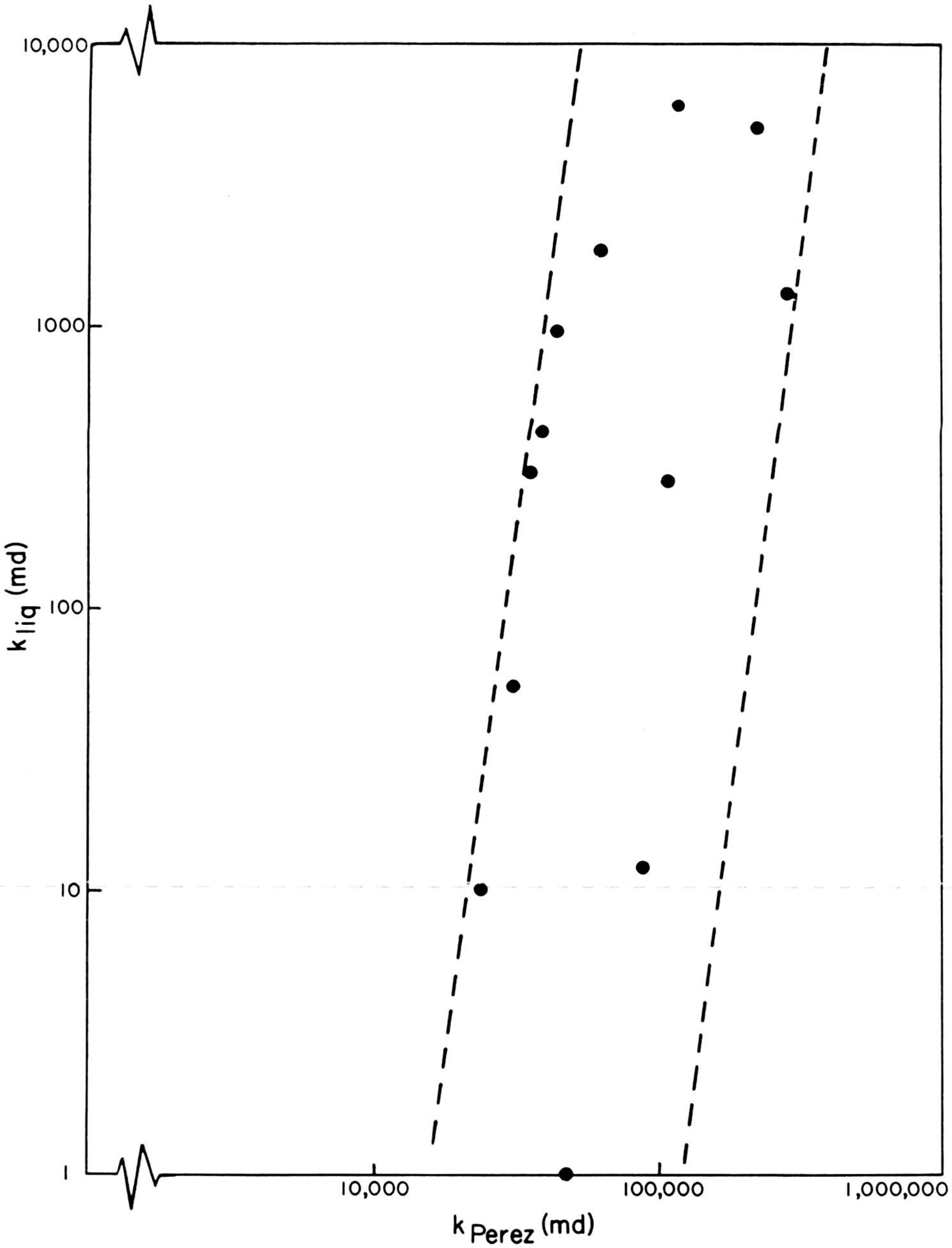


FIG. 6. — Permeability predicted by the Perez-Rosales Technique versus measured permeability

calcite crystals. If a grid line tangentially traverses along the inside of a small pore boundary, it is difficult to resolve the grid line-pore perimeter intersections, and thus determine c.

The Perez-Rosales technique does not differentiate between interconnected and non-interconnected pore space. Thus, the method is limited to porous media in which all pore space is interconnected. The method is also theoretically restricted to homogeneous, isotropic material. Since carbonate rocks seldom meet these criteria, it is concluded that the Perez-Rosales technique for estimation of permeability is generally not applicable to carbonate rocks.

Porosity

The Perez-Rosales technique for estimation of porosity was found to be very useful in samples of the Ste. Genevieve Limestone with grain size larger than approximately 0.03 mm. Data used to test the Perez-Rosales technique for porosity estimation are listed in Appendix 4 and plotted in Figure 7. Theoretically, the technique determines total porosity, since it does not differentiate between interconnected and non-interconnected pore space. However, in samples of the Ste. Genevieve Limestone, it appears that the difference between total and effective porosity is canceled out by the fact that pores of less than 0.02 mm in diameter cannot be resolved under the microscope, and thus, are not accounted for when determining n. It is concluded that total porosity as determined by the Perez-Rosales technique is a good approximation of effective porosity in samples of the Ste. Genevieve Limestone, with an average error of $\pm 10\%$ of the porosity value.

PERMEABILITY AND POROSITY IN OOLITIC CALCARENITES

Introduction

From the previous text it is obvious that no petrographic method exists which can predict permeability in limestone to within ½ an order of magnitude of its measured value. As stated in the literature review, variables which control permeability in limestones are thought to be too complex to be described mathematically from petrographic data. However, if limestones are classified completely according to lithology and texture, it is conceivable that most of the variables controlling permeability will be held constant. This is because rocks of uniquely defined lithology and texture will theoretically be composed of similar pore geometry (Archie, 1952). Under this assumption, for any given pore geometry, permeability is proportional to porosity.

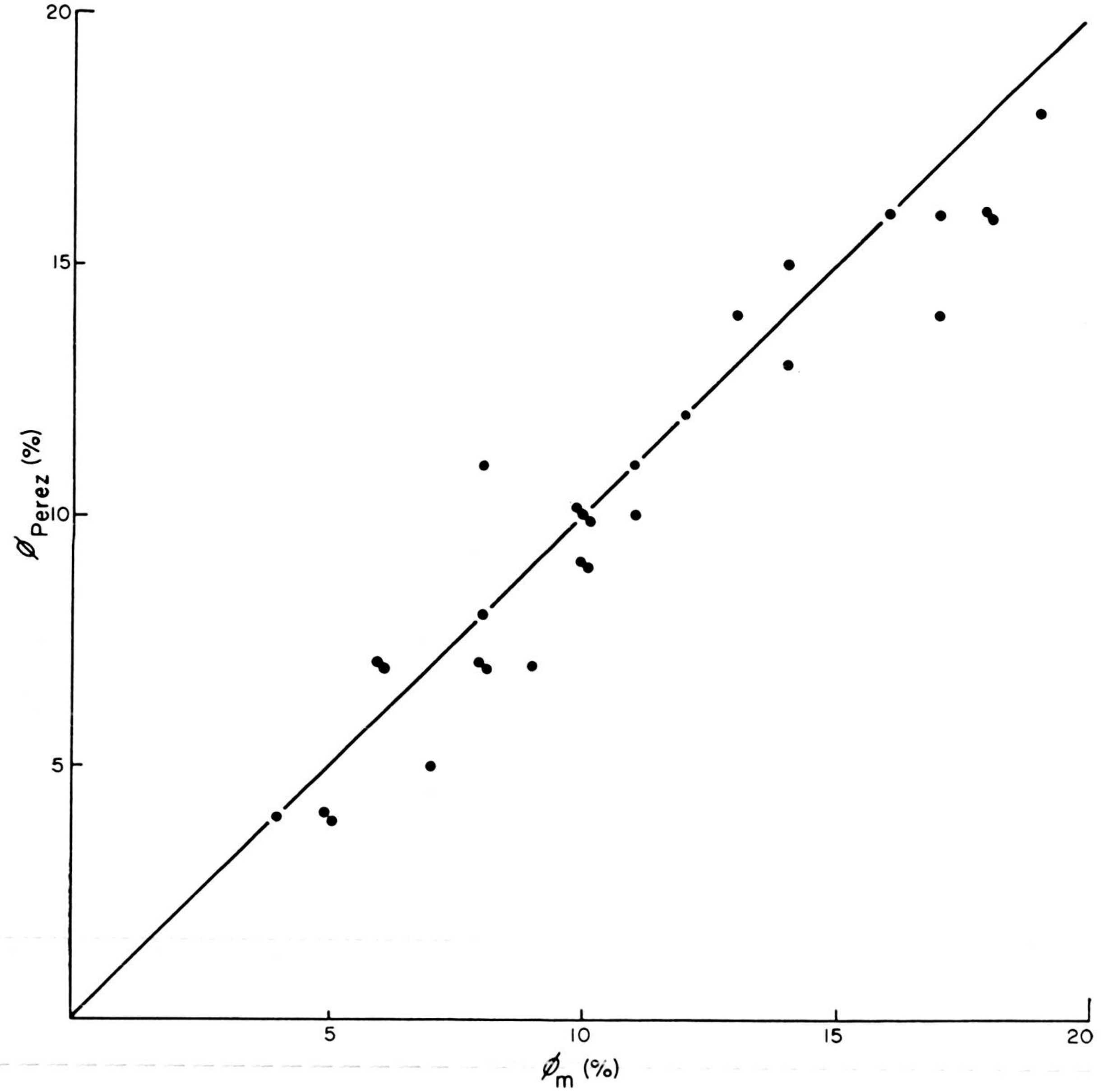


FIG. 7. — Measured effective porosity versus porosity estimated by the Perez-Rosales Technique.

Experimental Observations

To test if permeability is proportional to porosity for a given pore geometry, 69 oolitic calcarenites with predominantly fabric selective porosity (Choquette and Pray, 1970) were studied with respect to porosity, permeability and selected lithologic variables. Log (ϕ_m) versus log (k_m) is plotted in Figure 8. For any given value of log (ϕ_m), log (k_m) varies by as much as ± 0.6 or within 1.2 orders of magnitude. To reduce this variation, the samples are divided into three categories based on the areal percentage [1] of bioclasts and pellets in thin section. These categories are as follows:

[1] "Percent" bioclasts, as determined by the Perez-Rosales technique, is the ratio of the thin section area composed of bioclasts to the total thin section area, times 100%. Total thin section area includes pore space, grains, matrix and cement. For example, a rock composed entirely of bioclasts, cement and pore space, whose primary interparticle porosity was 50%, is composed of 50% bioclasts regardless of the present state of cementation (assuming no compaction).

Type I	Greater than 18% pellets Less than 10% bioclasts Remaining grains predominantly ooids	Oolitic pelletoidal calcarenites and pelletoidal calcarenites with or without minor [1] bioclasts
Type II	Greater than 3% bioclasts Less than 18% pellets Remaining grains predominantly ooids	Bioclastic oolitic calcarenites, oolitic bioclastic calcarenites, and oolitic calcarenites with minor [2] bioclasts
Type III	Less than 18% pellets Less than 3% bioclasts Remaining grains predominantly ooids	Relatively pure oolitic calcarenites

It was found that samples of oolitic calcarenite containing greater than 18% pellets have the highest permeabilities for a given porosity (Type I). Samples containing less than 18% pellets, and greater than 3% bioclasts, have intermediate permeabilities for any given porosity value (Type II). Samples containing less than 18% pellets, and less than 3% bioclasts, have the lowest permeabilities for a given porosity value (Type III). After the samples were divided into these three categories, for any given value of log (ϕ_m), log (k_m) varies by less than ± 0.25, or within ½ an order of magnitude.

Most of the residual variation around the three regression lines in Figure 8 is thought to be due to inaccuracies in measuring ϕ_m. For example, the average precision error in measuring ϕ_m was found to be approximately $\pm 0.56\%$ porosity. In Figure 8, at $\phi_m = 5.0$, this average error in ϕ_m produces an error in log (k_m) of ± 0.2. This error decreases at higher values of ϕ_m, and there appears to be a corresponding decrease in the regression line scatter at higher ϕ_m values.

To facilitate the following discussion, the regression lines for Types I, II and III rocks, in Figure 8, are drawn schematically as frequency distributions for each rock type, in Figure 9. The width of the frequency plots represents the relative number of samples, for each rock type, at a given porosity value. The "mean permeability" of a rock type is the average of all its permeability measurements. Note that "mean permeability" and "permeability for a given porosity" are independent quantities. A rock type may have relatively high mean permeability, but also lower values of permeability for given values of porosity, if compared to another rock type. For example, Type III rocks have a higher mean permeability than Type I rocks. However, for a given value of porosity, Type III rocks have lower permeability (Figures 8 and 9).

Of the three rock types drawn in Figures 8 and 9, Type I rocks appear to be most permeable for any given porosity value, followed by Type II and Type III rocks, respectively. Since both Type I and II rocks generally contain more than 3% bioclasts, it is suggested that the presence of bioclasts increases permeability at any given porosity value. To test this assumption, the percentage increase in permeability from the log (ϕ_m) versus log (k_m) regression line for pure oolites, Type III, is plotted

[1] "minor", here, is defined as 3-10%.

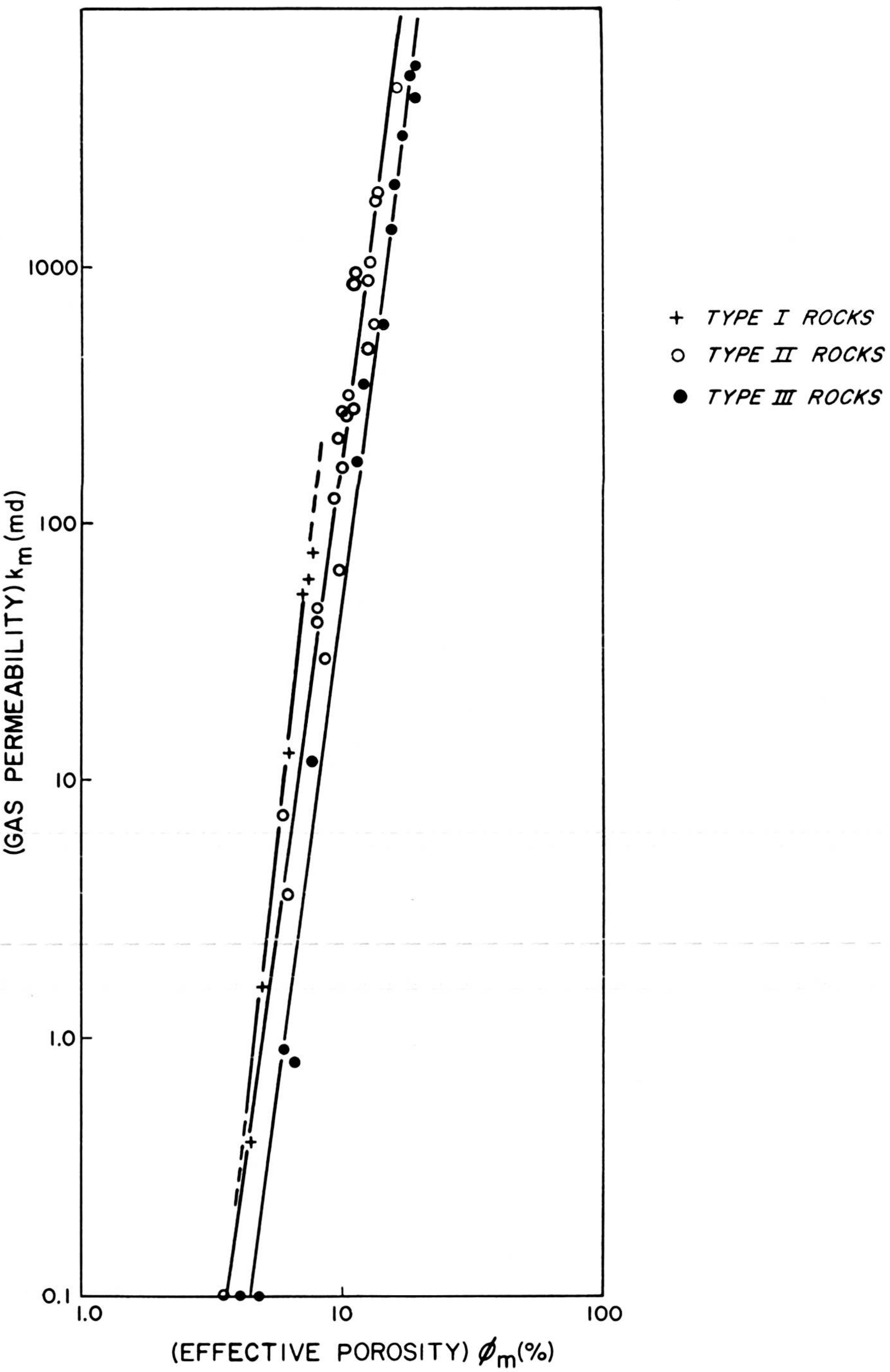


FIG. 8. — Effective porosity versus gas permeability.

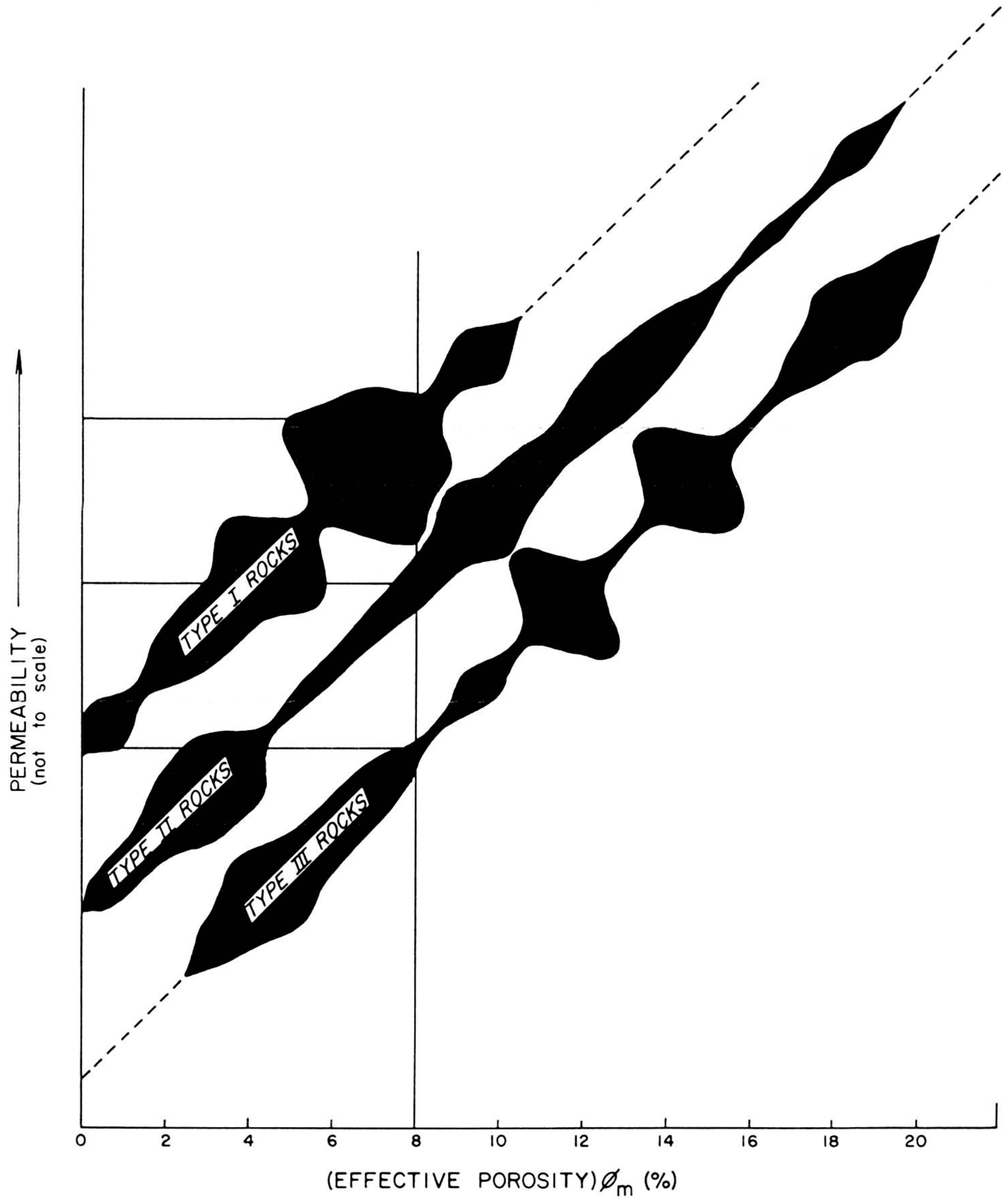


FIG. 9. — Frequency distributions of Rock Types I, II and III drawn schematically on porosity and permeability axes.

against the percentage of bioclasts (Figure 10). A weak correlation exists between the percentage increase in log (k_m) and the percentage of bioclasts. In other words, the permeability generally increases, for any given porosity value, as the percentage of bioclasts increases (Figure 9).

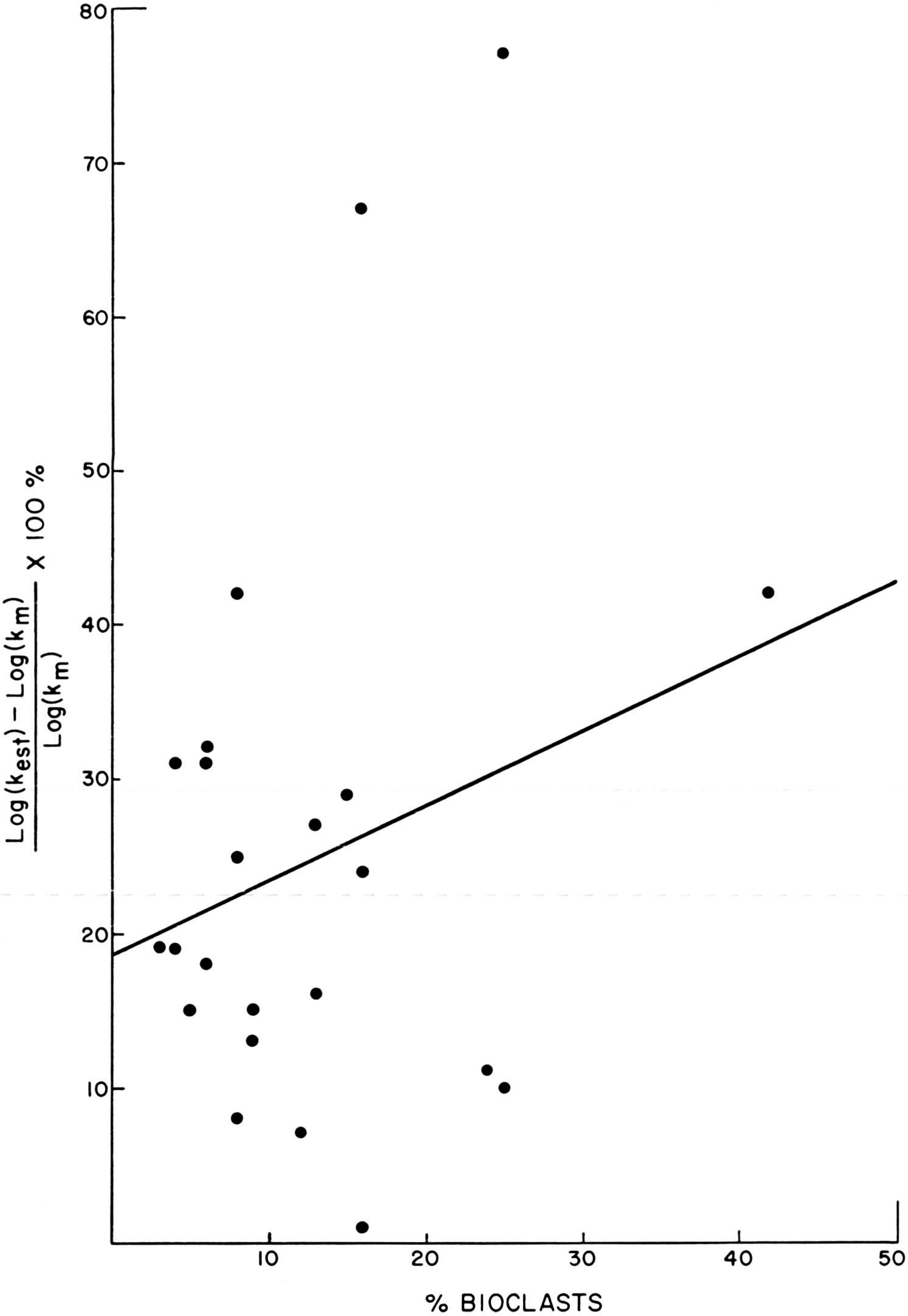


FIG. 10. — Percent bioclasts versus percent increase in permeability relative to permeability estimated by the regression line for Type III Rocks (k_{est}).

Although the presence of bioclasts appears to increase permeability fory an given porosity level, in general, Types I and II rocks have significantly lower mean porosity and permeability than Type III rocks. Type III rocks have the highest mean porosity and permeability, followed by Type II and Type I rocks, respectively (Figure 9, Appendices 5 and 6).

To further investigate the relationships between the presence of bioclasts, porosity and permeability, the percentages of bioclasts present was plotted against porosity (Figure 11) and permeability (Figure 12). A weak negative correlation exists between both the percentage of bioclasts and porosity; and the percentage of bioclasts and permeability. This implies that as the percentage of bioclasts increases, porosity generally decreases, as does permeability.

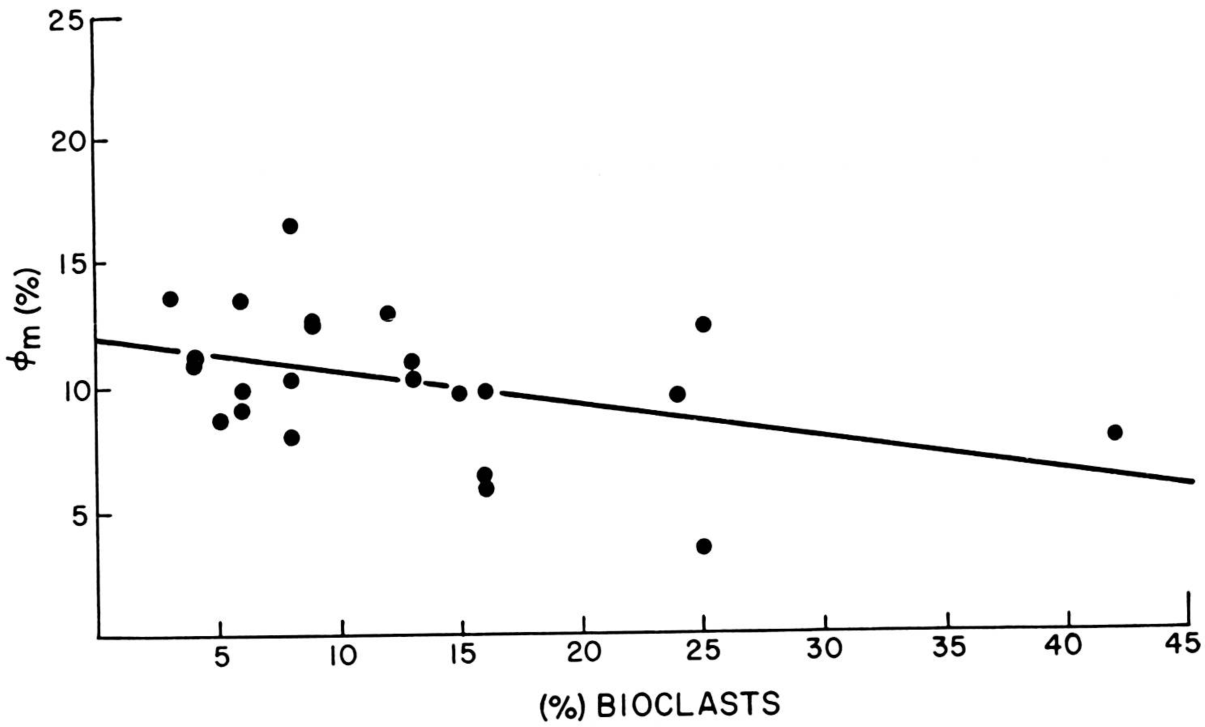


FIG. 11. — Percent bioclasts versus effective porosity.

Permeability, in 90% of the oolitic calcarenites studied, varied by less than 20% between the horizontal directions k_m and k_{my}. However, permeability variations are much more substantial between the vertical and horizontal directions (Greenkorn *et al.*, 1964; Potter and Mast, 1963). Vertical permeability, k_{mz}, averages only 50% of the horizontal permeability (k_m). In only two cases is the vertical permeability greater than the horizontal permeability, k_m, and in these two cases, horizontal permeability (k_{my}), measured orthogonally to k_m, is greater than the vertical permeability. Permeability variations between k_m and k_{mz} appear to be greater for Type I and Type II rocks than for relatively pure oolites.

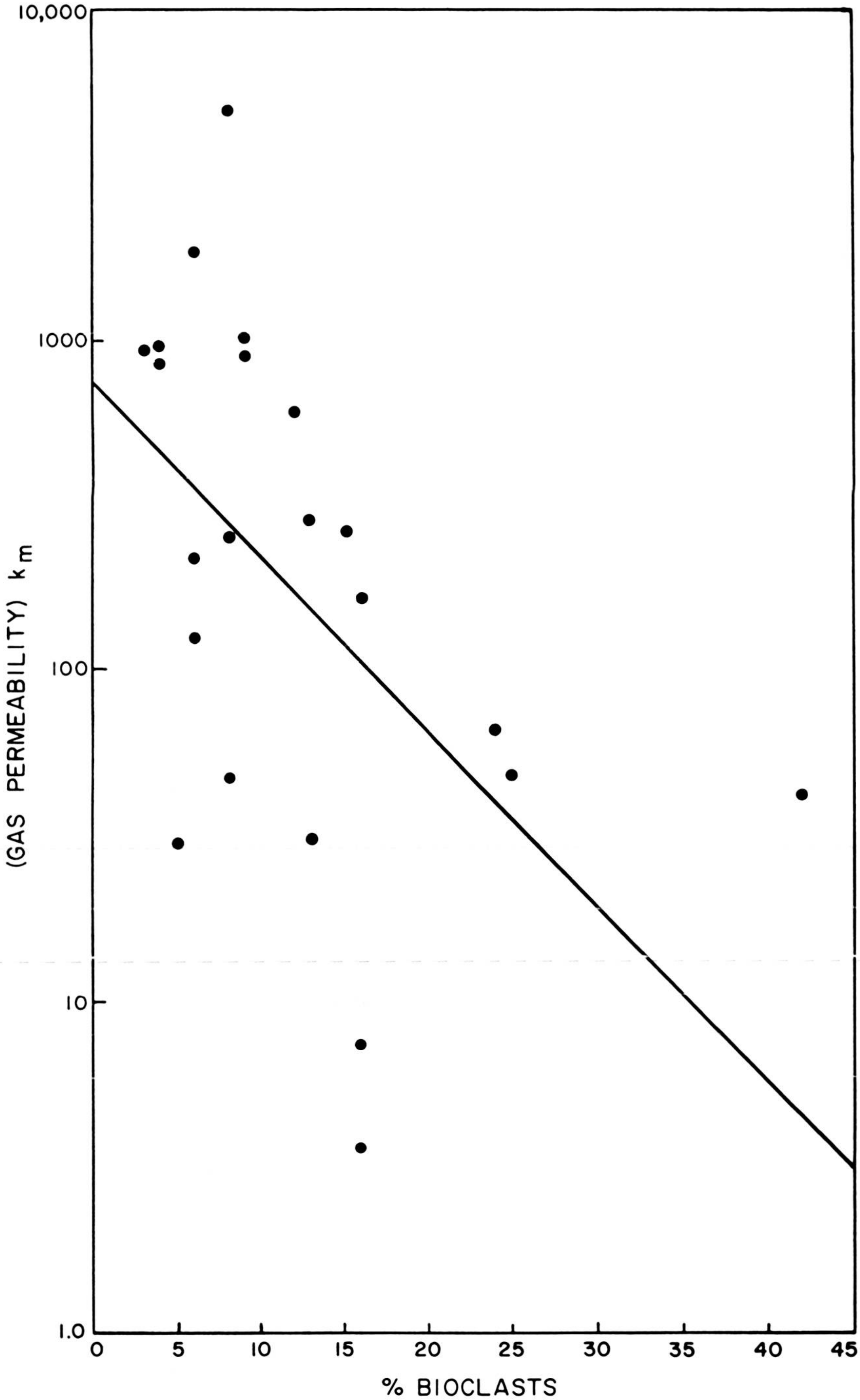


FIG. 12. — Percent bioclasts versus gas permeability.

Discussion of Observations

To account for these observations, it is proposed that permeability is controlled by the distribution of calcite cement. This distribution is at least partially controlled by rock composition (Plate 1, C and D). It is postulated that coarse grained bioclastic material provides nucleation sites for calcite cement which are preferred over the nucleation sites provided by either ooids or pellets. Consequently, porosity and permeability decrease with increasing bioclastic content.

Bioclastic nucleation sites are preferred due to free energy differences produced by differences in crystal size. Therefore, calcite cement will be found preferentially around bioclasts, regardless of the time of its precipitation (primary or secondary). These free energy differences could also control solution, so that calcite cement might preferentially dissolve in the reverse order in which it was precipitated. Thus, the irregular distribution of cement found in the reservoir rocks studied is not necessarily dependent on whether or not porosity is a result of incomplete cementation or secondary solution.

In theory, pellets would form the least favorable sites for nucleation of calcite cement, since they are composed of the finest micritic material. In Type I rocks, then, bioclastic nucleation sites are preferred over pellets. This can be observed in thin section (Plate 1, A) where cement is generally coarsely crystalline, and drusy calcite lining pores bounded by pellets is rare. For this reason, pores are generally smooth in Type I rocks (Plate 1, B). Calcite cement is thought to be localized at scattered points throughout the rock, leaving intermediately positioned pores with less cement, and therefore, are left relatively well interconnected. Note that cement is likely to nucleate in three directions from a bioclastic center. The nucleating bioclast may not lie in the plane of the thin section. Therefore, a bioclast is not expected to be observed in every patch of cement. Furthermore, it is not suggested that every patch of cement must have nucleated around a bioclast, only that bioclastic nucleation sites are preferred.

The preferential nucleation of cement, combined with the relatively smooth pore walls of Type I rocks, is thought to be responsible for their relatively high permeability for a given porosity value. Low mean porosity and permeability are thought to be the result of compaction, pressure solution, grain interpenetration and cementation (Plate 1, A). The Type I rocks studied here generally contain more than 3% crinoid fragments, which enhances cementation.

Type II rocks (Plate 1, C) have intermediate permeability for any given porosity value as compared to Type I and Type III rocks (Figures 8 and 9). Ooids most likely compete as cement nucleation sites more so than pellets, but bioclasts are thought to be preferred. Thus, cement is likely to be more homogeneously distributed than in Type III rocks. It is thought that if cement tends to be localized around scattered bioclastic centers, there is less cement left over to occlude pore throats between centers of cementation. Type II rocks are thought to have lower mean porosity and permeability than Type III rocks since cement is found preferentially around bioclastic material.

Type III rocks, relatively pure oolites, are thought to be the least permeable for any given porosity value (Figures 8 and 9). Cement is likely to be more homogeneously distributed throughout these rocks than in Type I or Type II rocks. A homogeneous distribution of drusy cement could conceivably choke off pore throats at random, increasing tortuosity (Plate 1, F and G). Type III rocks studied here have relatively high mean porosity and permeability, since they contain few bioclasts. Thus, holding all other variables constant, cement will occur preferentially in the surrounding bioclastic units.

Sarkisyan *et al.* (1973, p. 1305) lend support to the observation that bioclastic rocks are more permeable, at a given porosity, than non-bioclastic rocks by saying:

> " *Bioclastic carbonates, with small amounts of cement,*
> *and without any appreciable amounts of secondary minerals,*
> *form the best carbonate reservoir rocks*".

Horizontal permeability is likely to be greater than vertical permeability due to primary depositional fabric. Grains are likely to preferentially orient their long axes parallel to the horizontal in response to gravity. Flow is easiest parallel to a grain's long axis (Aschenbrenner and Chilingar, 1960). This theory is supported by the fact that bioclastic rocks have greater permeability differences between their vertical and horizontal flow directions than relatively pure oolites. Since many bioclasts, such as bivalves, are platy or elongate in shape, they tend to inhibit flow in the vertical direction.

CONCLUSIONS

At present, no procedure exists to exactly predict permeability in carbonate rocks from other related parameters. The variables which control permeability in carbonate rocks are not completely understood. They cannot be described exactly, either qualitatively or quantitatively. In an attempt to limit the number of variables involved, classification systems have been developed to relate permeability to simplified parameters, such as porosity and lithology. Classification systems used to estimate permeability such as Archie (1952), Teodorovich's method (Aschenbrenner and Chilingar, 1960), Robinson (1966), and Jodry (1972), are plagued with errors between 1 and 2 orders of magnitude because they are much too general to sufficiently limit the number of pore geometries possible in each of their categories.

It is possible to predict gas permeability in oolitic calcarenites, from petrographic data, to within ½ an order of magnitude, if the rocks are divided into uniquely defined groups based on lithology and texture. Upon dividing oolitic calcarenites into 3 types, based on the percentages of bioclasts and pellets present, it was found that k_m is approximately proportional to ϕ_m^7 (the slope of the regression line relating log (ϕ_m) to log (k_m) is approximately 7). This relationship is used in conjunction with the Perez-Rosales technique of estimating porosity to predict gas permeability to within approximately ½ an order of magnitude. This apparently large residual error results from small errors in measuring ϕ_m and k_m. Very small errors in measuring the effective porosity are essentially raised to the seventh power when ϕ_m is used to predict permeability. Since it is doubtful that effective porosity can ever be estimated petrographically with errors of less than $\pm 1\%$ porosity, petrographic techniques, which estimate permeability in oolitic calcarenites, initially start with errors of up to ¼ of an order of magnitude.

Oolitic calcarenites with greater than 3% bioclasts, tend to have higher permeability than non-bioclastic samples for any given value of porosity. Yet, Type II rocks have lower mean porosity because they generally have more cement. A working hypothesis is proposed in which bioclasts form preferential nucleation sites for calcite cement, as compared to ooids and pellets. In the reservoir rocks studied, Type II samples generally contained more cement than purely oolitic or pelletoidal rocks. However, when significant porosity is present in Type II rocks, whether by incomplete primary cementation or by secondary solution, calcite cement is preferentially located around scattered bioclastic centers, producing an irregular distribution of cement. This texture leaves passages of clumps of pores and pore throats relatively well interconnected, promoting "regular" flow paths which enhances permeability. In rocks of more homogeneous lithology, cement tends to be more equally distributed among pores and pore throats. This increases tortuosity, since pore throats may be blocked at random producing "irregular" flow paths.

Vertical permeability averages 40-45% of the horizontal permeability in the Type II rocks studied, and about 70% of the horizontal permeability in the relatively pure oolitic calcarenites studied. The presence of bioclasts appears to increase the variation between vertical and horizontal permeability.

The numerical relations between porosity and permeability (measured approximately horizontally), Figure 8, may only apply to oolitic calcarenites of the Ste. Genevieve Limestone with fabric selective porosity. Permeability in rocks of slightly different lithology, texture and diagenetic origin may be controlled by a different set of variables. Therefore, numerical relationships between porosity and permeability are likely to vary from basin to basin.

LIST OF REFERENCES

API (1960). Recommended Practice for Core-Analysis Procedure: *Amer. Petroleum Inst., Report 40, 1st edition*, 55 p.

ARCHIE, G. E. (1952). Classification of Carbonate Reservoir Rocks and Petrophysical Considerations: *Bull. Amer. Assoc. Petroleum Geologists*, v. 36, pp. 278-298.

ASCHENBRENNER, B. C. and C. W. ACHAUER (1960). Minimum Conditions for Migration of Oil in Water-Wet Carbonate Rocks: *Bull. Amer. Assoc. Petroleum Geologists*, v. 44, pp. 235-243.

ASCHENBRENNER, B. C. and G. V. CHILINGAR (1960). Teodorovich's Method for Determining Permeability from Pore-space Characteristics of Carbonate Rocks: *Bull. Amer. Assoc. Petroleum Geologists*, v. 44, pp. 1421-1424.

AYER, N. J., Jr. (1971). Statistical and Petrographic Comparison of Artificially and Naturally Compacted Sediments: *Unpublished Ph. D. Thesis, Univ. of Illinois at Urbana-Champaign*, 92 p.

BATHURST, R. G. (1971). *Carbonate Sediments and Their Diagenesis*: Developments in Sedimentology, No. 12, Elsevier Publishing Co., 658 p.

CHILINGAR, G. V., R. W. MANNON and H. H. RIEKE, eds. (1972). *Oil and Gas Production from Carbonate Rocks*: Elsevier Publishing Co., 408 p.

CHOQUETTE, P. W. and L. C. PRAY (1970). Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates: *Bull. Amer. Assoc. Petroleum Geologists*, v. 54, pp. 207-250.

COOGAN, A. H. and R. W. MANUS (1975). Compaction and Diagenesis of Carbonate Sands: in *Compaction of Coarse-grained Sediments* (G. V. Chilingarian and K. H. Wolf, eds.), Developments in Sedimentology, No. 18A, Elsevier Publishing Co., pp. 79-166.

CORE LAB (undated) Fundamentals of Core Analysis: *Unpublished report*, pp. 21-23.

DARCY, H. (1856). *Les Fontaines Publiques de la Ville de Dijon*: Victor Dalmont, Paris, pp. 590-594.

DOMENICO, P. A. (1972). *Concepts and Models in Groundwater Hydrology*: McGraw-Hill, pp. 149-154.

DONATH, F. A., A. V. CAROZZI, L. S. FRUTH, Jr. and D. W. RICH (1976). Experimental Development of Permoporosity in Carbonate Rocks (abstract): *Bull. Amer. Assoc. Petroleum Geologists*, v. 60, pp. 665-666.

—— (1977). Fabric Selective Permoporosity Experimentally Developed in Carbonate Rocks. (abstract): *Bull. Amer. Assoc. Petroleum Geologists*, v. 61, p. 781.

FAIR, G. W. and L. P. HATCH (1933). Fundamental Factors Governing the Streamline Flow of Water through Sand: *J. Amer. Water Works Assn.*, v. 25, pp. 1551-1563.

FRANZINI, J. B. (1951). Porosity Factor for Case of Laminar Flow Through Granular Media: *Trans. Amer. Geophys. Union*, v. 32, pp. 443-446.

GRAF, D. L. and J. E. LAMAR (1950). Petrology of Fredonia Oolite in Southern Illinois: *Bull. Amer. Assoc. Petroleum Geologists*, v. 34, pp. 2318-2366.

GRATON, L. C. and H. J. FRASER (1935). Systematic Packing of Spheres — with Particular Relation to Porosity and Permeability: *J. Geology*, v. 43, pp. 785-909.

GREENKORN, R. A., C. R. JOHNSON and L. K. SHALLENBERGER (1964). Directional Permeability of Heterogeneous Anisotropic Porous Media: *J. Society of Petroleum Engineers*, v. 4, pp. 124-132.

HARBAUGH, J. W. (1967). Carbonate Oil Reservoir Rocks: in *Carbonate Rocks* (G. V. Chilingar, H. J. Bissell and R. W. Fairbridge, eds.). Developments in Sedimentology, No. 9A, Elsevier Publishing Co., pp. 349-398.

HUBBERT, M. K. (1940). Theory of Ground Water Motion: *J. Geology*, v. 48, pp. 785-944.

JODRY, R. L. (1972). Pore Geometry of Carbonate Rocks (Basic Concepts): in *Oil and Gas Production from Carbonate Rocks* (G. V. Chilingar, R. W. Mannon, H. H. Rieke, eds.) Elsevier Publishing Co., pp. 35-82.

LIPPMAN, S. A. (1971). *Elements of Probability*: Holt, Rinehart and Winston, Inc., pp. 149-186, 226-250.

MAIKLEM, W. R. (1968). Some Hydraulic Properties of Bioclastic Carbonate Grains: *Sedimentology*, v. 10, pp. 101-109.

MAVIS, F. T. and E. F. WILSEY (1937). Filter Sand Permeability Studies: *Engineering News Record*, v. 118, pp. 299-300.

MURRAY, R. C. (1960). Origin of Porosity in Carbonate Rocks: *J. of Sed. Petrology*, v. 30, pp. 59-84.

PEREZ-ROSALES, C. (1969). Simultaneous Determination of Basic Geometrical Characteristics of Porous Media: *J. Society of Petroleum Engineers*, v. 9, pp. 413-416.

POTTER, P. E. and R. F. MAST (1963). Sedimentary Structures, Sand Shape Fabrics, and Permeability, I, II: *J. Geology*, v. 71, pp. 441-470, 548-565.

RAO, C. P. and A. V. CAROZZI (1970). Application of Computer Techniques to the Petrographic Study of Oolitic Environments, Ste. Genevieve Limestone (Mississippian), Southern Illinois: *Archives des Sciences, Genève*, v. 24, pp. 17-55.

ROBINSON, R. B. (1966). Classification of Reservoir Rocks by Surface Texture: *Bull. Amer. Assoc. Petroleum Geologists*, v. 50, pp. 547-559.

SARKISYAN, S. G., M. A. POLITYKINA and G. V. CHILINGARIAN (1973). Effect of Postsedimentation Processes on Carbonate Reservoir Rocks in Volga-Urals Region, USSR: *Bull. Amer. Assoc. Petroleum Geologists*, v. 57, pp. 1305-1313.

SCHEIDEGGER, A. E. (1960). *The Physics of Flow Through Porous Media:* Macmillan Co., pp. 5-22, 89-112.

SHEARMAN, D. J. (1976). In *An Introduction to Sedimentology:* Selley, R., Academic Press, pp. 128-129.

SHORT, N. M. (1962). Ste. Genevieve (Mississippian) Formation at its Type Locality in Missouri: *Bull. Amer. Assoc. Petroleum Geologists*, v. 46, pp. 1912-1934.

SLICHTER, C. S. (1897). Theoretical Investigations of the Motion of Ground Water: *19th Ann. Rep. U.S. Geol. Survey 1897-98*, part 2, pp. 295-380.

SOUPAC (1974). *SOUPAC Program Descriptions:* CSO No. 9, Univ. of Illinois, Urbana-Champaign, PP.V.COR. 1-V.COR. 6.

WARDLAW, N. C. (1976). Pore Geometry of Carbonate Rocks as Revealed by Pore Casts and Capillary Pressure: *Bull. Amer. Assoc. Petroleum Geologists*, v. 60, pp. 245-257.

WYLLIE, M. R. J. and G. H. F. GARDNER (1958). The Generalized Kozeny-Carmen Equation, its Application to Problems of Multiphase Flow in Porous Media, Parts 1 and 2: *World Oil*, v. 146, pp. 121-128, 210-228.

Appendix 1

Raw Data Used in Analysis of Permeability

I. D. No.	Rock Type	ϕ_m (%)	k_m (md)	k_{my} (md)	k_{mz} (md)	% bioclasts	$\log(k_{cal})$ [a]	$\left[\frac{\log(k_m) - \log(k_{cal})^{b}}{\log(k_m)}\right] \times 100\%$
857 A	I	07.5	79.0	76.0	55.0	01		
909 B	I	04.5	00.4	00.8	00.1	04		
915 G	I	06.9	54.0	43.0	09.3	08		
915 I	I	07.3	62.0	57.0	11.0	03		
915 K	I	06.2	13.0	14.0	07.0	04		
927 G	I	04.9	01.6	01.8	01.3	05		
809 A	II	11.2	453.0	452.0	94.0	04	2.140	19
809 B	II	13.0	605.0	588.0	325.0	12	2.587	07
838 F	II	08.0	47.0	56.0	03.0	08	0.975	42
839 B	II	12.8	1024.0	1033.0	246.0	09	2.533	16
839 C	II	10.3	254.0	258.0	115.0	08	1.815	25
839 D	II	09.9	219.0	198.0	49.0	06	1.615	31
857 E	II	07.9	41.0	36.0	18.0	42	0.936	42
896 B	II	10.3	310.0	282.0	30.0	13	1.815	27
904 A	II	12.4	486.0	432.0	127.0	25	2.426	10
904 E	II	11.0	857.0	808.0	231.0	04	2.029	31
915 A	II	06.3	03.6	03.6	01.2	16	0.180	67
915 E	II	13.4	1868.0	1906.0	1557.0	06	2.686	18
915 F	II	09.9	167.0	179.0	96.0	16	1.685	24
916 A	II	09.9	266.0	293.0	85.0	15	1.708	29
916 C	II	09.6	66.0	67.0	17.0	24	1.623	11
916 G	II	05.9	07.4	08.7	01.6	16	−0.034	01
917 B	II	03.5	00.1	00.1	00.0	25	−1.769	77
917 E	II	13.6	1933.0	1973.0	1018.0	03	2.663	19
917 F	II	11.1	286.0	281.0	221.0	13	2.060	16
917 G	II	12.7	897.0	1030.0	992.0	09	2.531	13
927 J	II	8.7	30.0	31.0	15.0	05	1.257	15
936 A	II	16.7	5000.0	5165.0	3309.0	08	3.419	08
936 E	II	09.2	128.0	154.0	95.0	06	1.441	32
809 C	III	04.0	00.1	00.1	00.1	01		
809 D	III	06.5	00.8	00.5	00.3	00		
838 B	III	14.1	600.0	530.0	416.0	01		
838 E	III	11.9	324.0	353.0	345.0	00		
839 A	III	17.1	3262.0	3102.0	1416.0	02		

APPENDIX 1 *(Continued)*

I. D. No.	Rock Type	ϕ_m (%)	k_m (md)	k_{my} (md)	k_{mz} (md)	% bioclasts	$\log(k_{cal})$ [a]	$\left[\frac{\log(k_m) - \log(k_{cal})^b}{\log(k_m)}\right] \times 100\%$
857 B	III	07.7	12.0	11.0	01.8	02		
888 C	III	18.7	4541.0	5245.0	3102.0	02		
888 G	III	04.8	00,1	00.1	00.1	02		
888 I	III	06.0	00.9	00.9	00.6	02		
896 A	III	18.2	5640.0	5117.0	4094.0	02		
904 C	III	15.8	2110.0	2623.0	1357.0	02		
904 D	III	15.6	1400.0	1429.0	942.0	00		
909 C	III	11.3	177.0	176.0	06.2	02		
936 C	III	19.0	6109.0	6363.0	4582.0	02		

$\log(k_{cal})^a$ = gas permeability calculated from the Type I ϕ_m vs. k_m regression line and ϕ_m.

$\left[\frac{\log(k_m) - \log(k_{cal})^b}{\log(k_m)}\right] \times 100\%$ = percentage increase of observed gas permeability over gas permeability calculated from ϕ_m vs. k_m regression line.

Appendix 2

Raw Data Used to Test Teodorovich's Method

I. D. No.	Lithology [a]	Coefficient A Pore-Space Type	Coefficient B ϕ_m	Coefficient C Maximum Pore Size in mm	Coefficient D Pore Elongation	k_{Teod}	k_{liq} [b]	% error [c] $\frac{\lvert(k_{Teod}-k_{liq})\rvert}{k_{liq}}$
809 A	B	18 II	6 11	1.00 0.25	1	108	410	74
816 B	C	10 IV	20 23	0.0625 0.01	1	12	12	0
816 A	C	10 IV	16.5 18.5	2.00 1.0	1	330	1	32900
838 E	O	16 II	8 12	1.00 0.25	1	128	300	57
839 B	B	32 II	10 13	1.00 0.25	1	320	960	67
896 B	B	22 II	5 10	1.00 0.25	1	110	280	61
904 D	O	16 II	13 16	2.00 0.50	1	416	1300	68
915 I	P	16 II	3 7	0.50 0.10	1	24	53	54
915 K	P	16 II	2.5 6	0.50 0.10	1	20	10	50
917 E	B	30 II	11 14	1.00 0.25	1	330	1856	82
936 A	B	48 II	14 17	2.00 0.50	2	2680	5000	46
936 C	O	28 II	16 19	2.00 0.50	1	896	6010	85

[a] Lithology: B = oolitic bioclastic calcarenite; C = calcisiltite; O = oolitic calcarenite; P = pelletoidal oolitic calcarenite.

[b] k_{liq} = liquid permeability after correcting gas permeability for Klinkenburg effect.

[c] Mean % error = 59%, excluding sample #816 A.

APPENDIX 3

Data Used to Test Perez-Rosales' Technique for Estimating Permeability

I. D. No.	Lithology [a]	$n = (\phi_m)(1.21)$ [b]	C	$k_{Perez} = \frac{L^2 n^3}{4N^3 c^2 m^2} [K_1]$ [c] (md)	k_{liq} [d] (md)
809 A	B	13.3	52	38,532	410
816 B	C	27.8	105	86,305	12
816 D	C	18.2	80	47,717	1
838 E	O	14.5	62	35,124	300
839 B	B	15.7	63	43,181	960
896 B	B	12.1	27	107,624	280
904 D	O	19.4	34	279,724	1300
915 I	P	8.5	30	30,220	53
915 K	P	7.3	27	23,633	10
917 E	B	16.9	59	61,410	1856
936 A	B	20.6	42	219,475	5000
936 C	O	23.0	69	113,180	6010

[a] Lithology: B = oolitic bioclastic calcarenite; C = calcisiltite; O = oolitic calcarenite; P = pelletoidal oolitic calcarenite.

[b] ϕ_m = measured effective porosity.

[c] k_{Perez}: N = 121; L = 1.76 cm; $K_1 = \frac{1 \text{ millidarcy}}{9.87 \times 1^{-12} \text{ cm}^2}$.

[d] k_{liq} = measured gas permeability corrected for Klinkenburg Effect.

Appendix 4

Data Used to Test Perez-Rosales' Technique for Estimating Porosity

I. D. No.	ϕm	$\phi_{Perez} = \frac{n}{N} N$[a]	error $\lvert \phi_{Perez} - \phi_m \rvert$	% error $\frac{\lvert \phi_{Perez} - \phi_m \rvert}{\phi_m}$
809 A	11	11	0	0
809 B	08	07	1	12
838 E	12	12	0	0
838 F	08	07	1	12
839 A	17	16	1	6
839 B	13	14	1	8
857 A	08	08	0	0
857 E	08	11	3	40
888 B	18	16	2	11
888 C	19	18	1	5
888 F	09	07	2	22
888 G	05	04	1	20
896 A	18	16	2	11
896 B	10	10	0	0
896 C	10	10	0	0
904 B	14	13	1	7
904 D	16	16	0	0
909 B	05	04	1	20
915 A	06	07	1	17
915 F	10	09	1	10
915 I	07	05	2	29
915 K	06	07	1	17
916 A	10	10	0	0
916 C	10	09	1	10
917 B	04	04	0	0
917 E	14	15	1	7
917 F	11	10	1	9
936 A	17	14	3	18

Average error = $\pm 10.3\%$ of ϕ_m

[a] $N = 1000$.

APPENDIX 5

Data Describing Mean Porosity in Oolitic Calcarenites

Rock Type	Mean ϕ_m	Standard Deviation (% ϕ_m)	Mean ϕ_m difference between rock types	Confidence level of significance	Number of Samples = N
I	5.10	2.58			12
			$\bar{\phi}_{m\,II} - \bar{\phi}_{m\,I} = 3.35\%$	0.99	
II	8.45	4.98			40
			$\bar{\phi}_{m\,III} - \bar{\phi}_{m\,II} = 3.01\%$	0.98	
III	11.46	5.40			17

APPENDIX 6

Data Describing Mean Permeability for Oolitic Calcarenites in Appendix 1

Rock Type	Mean k_m	Standard Deviation (md)	Mean k_m difference between rock types	Confidence level of significance	Number of Samples = N
I	30	33			6
			$\bar{k}_{m\,II} - \bar{k}_{m\,I} = 626$ md	0.93	
II	656	1096			23
			$\bar{k}_{m\,III} - \bar{k}_{m\,II} = 1063$ md	0.97	
III	1719	2229			14

Tests of significance assume k_m and ϕ_m are nearly normally distributed.
Tests of significance given in Lippman, 1971, pp. 149-167.

PLATE 1

A. Type I. Pelletoidal oolitic calcarenite with minor bioclasts. Sparite cement in optical continuity with crinoid fragment. Grain interpenetration common. Nicols crossed.

B. Type I. Enlargement of A. Relatively smooth pore walls typical of Type I rocks. Nicols not crossed.

C. Type II. Oolitic calcarenite with minor bioclasts and cavity filling sparite cement. Sparite cement localized as syntaxial overgrowth around crinoid fragment, in center. Large "ooid", at right, consists of crinoid fragment core and two oolitic coatings. Left center, detrital quartz grain with hexagonal overgrowth partially replacing ooids above and below. Gray outline of quartz grain consists of residual drusy calcite, engulfed by the overgrowth. Nicols crossed.

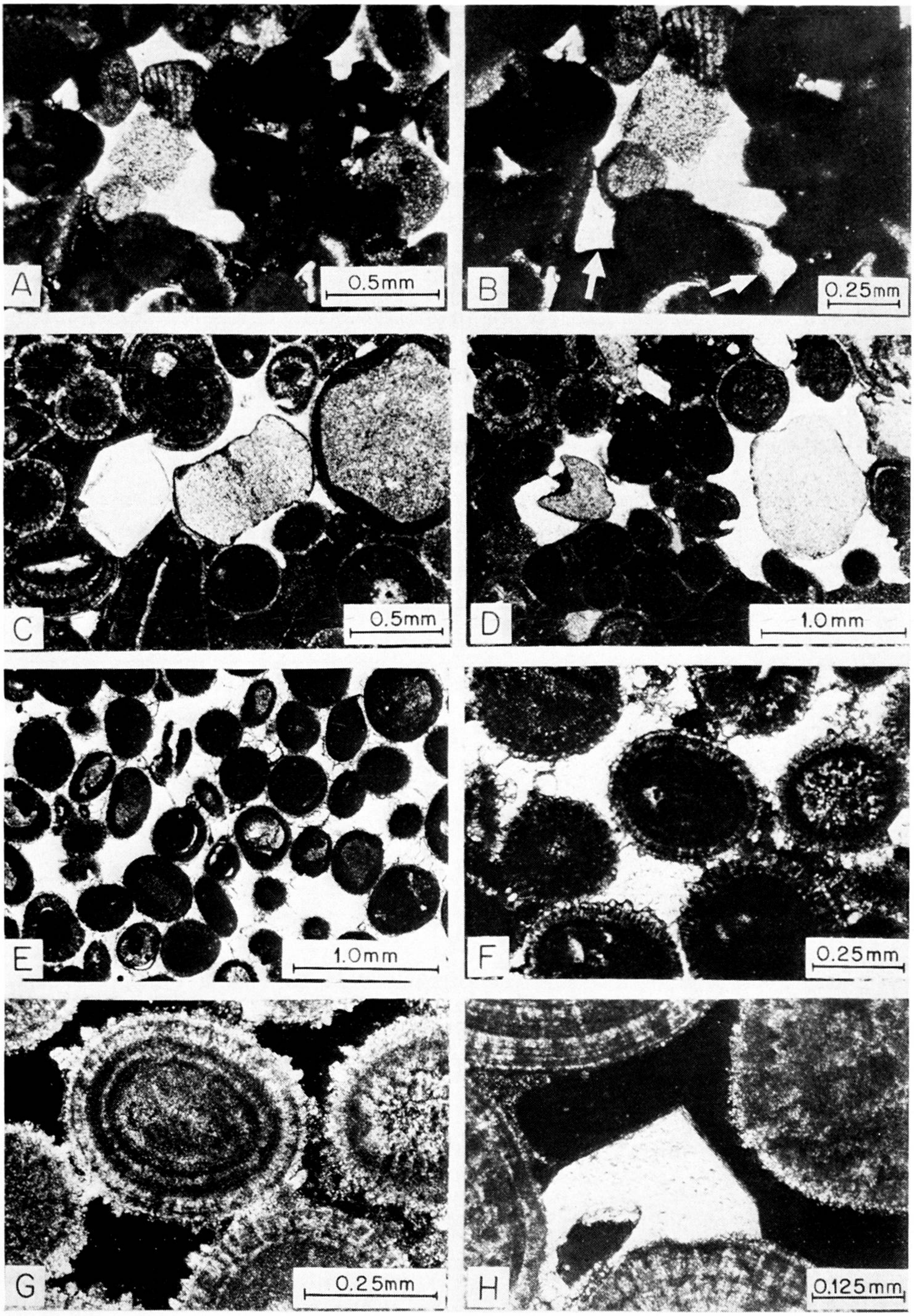
D. Type II. Oolitic calcarenite with minor bioclasts. Syntaxial overgrowths of sparite around crinoid fragments. Nicols crossed.

E. Type III. Relatively pure oolitic calcarenite with cavity filling sparite cement. Nicols not crossed.

F. Type III. Relatively pure oolitic calcarenite with drusy calcite cement. Relatively rough pore walls typical of Type III rocks. Dark interstitial material consists mainly of drilling mud. Right center, authigenic quartz replacing ooid. Nicols not crossed.

G. Type III. Enlargement of D. Drusy calcite blocking "pore throats". Nicols crossed.

H. Type III. Relatively pure oolitic calcarenite with part of a single calcite rhomb blocking pore. This single crystal, surrounding a small quartz grain, appears to dominate pore, inhibiting growth of drusy cement. Nicols crossed.


A
0.5mm
B
0.25mm
C
0.5mm
D
1.0mm
E
1.0mm
F
0.25mm
G
0.25mm
H
0.125mm