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SACLANT ASW RESEARCH CENTRE MEMORANDUM

THE DETERMINATION OF PERMEABILITY IN IN-SITU MARINE-FLOOR SEDIMENTS

by

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This memorandum has been prepared within the SACLANTCEN Underwater Research Division as part of Project 05.

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TABLE OF CONTENTS

List of Figures

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LIST OF SYMBOLS

R_s	Resistivity of fluid-filled matrix (sample)
R_f	Resistivity of pore fluid
F	Formation factor
K	Permeability
M	Hydraulic radius (the ratio of the pore volume to pore surface area)
Ko	Pore-shape factor
K_p	Capillary-shape factor
β	Porosity
d	Grain size
Q	Quantity of transmitted flow in unit time
A	Cross-sectional area
r	Pore radius
ΔP	Pressure difference
μ	Viscosity of fluid
U_p	Velocity of fluid flow in a pipe
U	Velocity of fluid flow over the sample length
L_p	Length of flow path
L_s	Length of sample
r	Radius of sample
ρ	Density
I	Electric current

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THE DETERMINATION OF PERMEABILITY IN IN-SITU MARINE-FLOOR SEDIMENTS

by

Stephen L. Goldsberry*
December 1984

ABSTRACT

A method of evaluating in situ permeability of unconsolidated marine floor sediments has been developed using mathematical manipulation of previously formulated empirical equations. The final equation makes use of various sediment characteristics that can be mathematically described and used to calculate permeability without greatly disturbing the sediment. The formula requires a knowledge of the soil's median grain size, pore shape, porosity, and formation factor (the resistivity of the fluid-saturated porous sediment divided by the resistivity of the fluid itself). Calculated permeabilities came to within 16% or less of those measured for a series of natural sands when a simple coefficient was introduced into the equation for the data available. Original calculated permeabilities were consistently close to five times greater than those measured for the same natural sand samples. The need for a coefficient to adjust calculated permeabilities could possibly be due to sorting effects that were not considered in the derivation; the incorporation of these effects remains an area of future investigation.

*This work was initiated at the SACLANT ASW Research Centre, while Mr S.L. Goldsberry was employed as a Summer Research Assistant under the supervision of Dr M. von Haumeder of the Environmental Acoustics Group, and completed as a thesis for the Master of Science degree in the Faculty of Baylor University, USA.

INTRODUCTION

In recent years scientists from diverse disciplines have found it increasingly important to better understand the nature of the ocean floor. Since the ocean floor can be described as a fluid-filled porous medium, much attention has been directed to research on porous materials.

One of the most advanced models describing sound reflection, conversion, and transmission, through porous materials is the Biot model, proposed in the mid 1950's by M.A. Biot (1956) <1>. The model requires sediment permeability (the measure of the ability of a porous material to transmit fluid flow through its pore space) as the most important material input parameter.

Permeability measurements can take one of two forms: liquid flow measurement or gas flow measurement. The measurement using a liquid is easy since liquids can be considered incompressible — thus allowing volumes to be measured with great precision — and because the outlet pressure can always be considered atmospheric. One disadvantage of liquids in comparison with gases is their higher viscosity, which tends to limit accurate measurement at low permeabilities. Most importantly, however, they are not truly inert, so that any reaction with rock components severely limits the validity of the test <2>.

The measurement of gas flow through a porous medium to determine fluid permeability has the advantages of inertness and low viscosity, which tends to aid in evaluating low permeability samples. However, the compressibility of gas and the conversion from gas flow to fluid flow must be accounted for.

While both of the previously discussed methods for determining permeability appear to be quite accurate when properly performed, their most serious drawback is the inability to measure samples in situ. Most engineering analyses are made in a laboratory on samples from the material in question. However, sampling disturbance in marine environments creates a serious problem in interpreting the results of such tests. Cohesive sediments can be sampled fairly undisturbed with properly designed apparatus, but granular sediments are almost impossible to sample. The effect of sampling can be quite detrimental to permeability (the most easily disturbed of all the properties discussed), for even a slight rearrangement of grains can substantially alter pore network geometries.

Since it is extremely difficult to measure permeability in situ at the ocean bottom, it is necessary to express it in terms of measurable properties of the porous material such as porosity, grain size, pore size, and pore shape.

For this purpose sediment properties must be described mathematically in such a way that they can be used as specific input variables in Biot's model. Furthermore, each variable must be easy to determine using direct measuring techniques.

The primary purpose of the present study was to develop three separate cases of material properties that mathematically describe fluid permeability in unconsolidated sediments: a pore case, a grain case, and an electrical case. On the completion of these three cases, the most appropriate combination of material properties was determined according to ease and accuracy of measurement.

The secondary purpose was to establish how permeability varies with changes in specific material variables and to determine the sensitivity that permeability exhibits to each of these changes. A ranking of the material variables according to the sensitivity of permeability to each variable can be helpful in providing guidance towards future investments both in purchasing and development of measurement equipment.

The study consisted of five phases. First, an extensive literature review was undertaken on the various aspects of flow phenomena through fluid-filled porous media. Second, the numerous sediment parameters used to classify various unconsolidated sediments were reviewed so as to identify the ones applicable to this study. Third, empirical formulae were mathematically developed to relate these parameters to the fluid flow through unconsolidated sediments. Fourth, using the final empirical formula, graphs were drawn to relate permeability to individual sediment variables. Fifth, the sediment variables were ranked according to the sensitivity of permeability to changes in each variable.

1 PREVIOUS WORK

Much work has been done over the past six decades to better understand the relationship between electrical and physical properties of porous materials so as to successfully predict physical characteristics of rocks and sediments by means of direct electrical measurements.

Sundberg (1980) <3> first introduced the simple relation:

$$R_s = F \cdot R_f \quad ,$$

where R_s is the resistivity of the sand when all the pore spaces are filled with a highly conductive pore fluid such as brine, R_f is the resistivity of the fluid alone, and F is the formation factor relating the two.

Archie (1942) <4>, plotting the formation factor against porosity and permeability of consolidated sandstone, noted that the formation factor was a function of the type and character of the formation and varied with the porosity and permeability of the reservoir rock. He also empirically determined an equation that relates the formation factor, F, to the formation porosity, β ,

$$\frac{1}{F} = \beta^m \quad ,$$

where m is an exponent relating F and β .

Winsauer et al (1952) <5> developed the relationship

$$F = \frac{T}{\beta} \quad ,$$

where F is the formation factor, T is the tortuosity, and β is the porosity of the sampled specimen. To make use of such a relationship it was assumed that the electrical tortuosity was equal to the hydraulic tortuosity in the case of fully saturated rocks.

Wyllie and Spangler (1952) <6> pointed out that the use of the resistivity-measuring technique to determine tortuosity is inapplicable to those cases where the matrix of the porous medium is itself an electrical conductor or to cases where no conducting fluid can be found. However, they went on to state that by saturating the rock with a high-conductivity fluid when measuring electrical resistivity, the errors due to the conductivity of the matrix could be rendered negligible. They also postulated that the equality of electrical and hydraulic tortuosity in partially unsaturated porous media may be a less valid assumption than is the corresponding assumption in fully saturated porous media.

Atkins and Smith (1961) <7> presented laboratory test data to show that the value of "m" in Archie's expression $1/F = \beta^m$ was determined by the shape of the particles in the system and they suggested that an equation of the form $1/F = a\,\beta^m$ (where "a" is a factor that varies with the amount of clay and sand in the sample) could be used to describe properties of natural formations containing varying amounts of sand and clay.

More than twenty years after Archie <4> suggested that the formation resistivity factor was interrelated to and dependent on both porosity and permeability, Brace et al (1965) <8> introduced the empirical relation.

$$K = (m^2/Ko)\ (R_f/R_s)^2 \cdot \frac{1}{\beta} \quad ,$$

where K is the permeability, m is the hydraulic radius (a measure of the ratio of pore volume to surface area), Ko is a pore shape factor, R_f is the resistivity of the pore fluid, R_s is the resistivity of the fluid-filled sample, and β is the porosity. The work was done on samples of granite, so the idea of grain size and its relationship to pore size was never discussed.

M.G. Croft (1971) <9> successfully predicted the permeability and transmissivity of two aquifers in North Dakota by use of electric logs and graphs relating permeability to formation factor of similar sediments.

D.H. Griffiths (1976) <10> determined experimentally for the Bunter Sandstone in parts of England that if sandstone resistivity, matrix

conduction factor, and water conductivity could be determined to within 10% using surface resistivity measurements, then the error of determining permeability was not likely to exceed half an order of magnitude.

Jackson, Smith, and Sanford (1978) <11> investigated the relationship between electrical resistivity measurements, porosity, and grain shape for a series of marine sands. They concluded that for such sands the electrical formation-factor/porosity relationship was indeed governed by Archie's Law ($F = \beta^{-m}$), the exponent m being entirely dependent on the shape of the particles, varying from 1.2 for spheres to 1.9 for platey shell fragments.

Jackson, Baria, and McCann (1981) <12> experimentally evaluated a number of marine sands, silts, and clays according to their grain size, formation factor, porosity, and their range of grain sizes (sorting). They concluded that porosity and formation factor are not only dependent on grain size but also on the sorting of the sediment: as the spread of sizes increases in the sediments porosity decreases.

Attenborough (1983) <13> experimentally deduced that for a packing of spheres of diameter d and porosity β, the hydraulic radius is given by:

$$m = \frac{\beta}{(1-\beta)^2} \cdot \frac{d}{6} \quad ,$$

thus eliminating the need for complicated hydraulic radius measurements in sedimentary samples.

Each of these works has greatly enhanced our knowledge of how electrical properties interrelate with physical properties in unconsolidated and semi-consolidated elastic sediments. Such knowledge can be used as a foundation on which to develop new and better methods of determining fluid flow through porous media by combining electrical and physical techniques.

2 APPLICATION OF VARIABLE MATERIAL PROPERTIES OF SEDIMENT

2.1 Flow processes

Permeability is the measure of the ability of a porous material to transmit fluid through its pore space. Darcy's law <14> determines permeability by the flow rate of a given fluid under specific conditions through a porous medium, and can be expressed mathematically as

$$K = \frac{\mu \cdot Q \cdot L_s}{A(P_2 - P_1)} \quad , \qquad \text{(Eq. 1)}$$

where

Q = quantity of transmitted fluid per unit time (L^3/T).

K = permeability (related to sizes, shapes, and interconnection of pores).

A = cross-sectional area at right angles to direction of flow (L^2).

L_s = length along which pressure differential is measured (L).

$P_2 - P_1$ = pressure difference (atmospheres) between two points separated by distance L.

μ = viscosity of fluid (centipoises).

A measure of permeability is the darcy. One darcy is the permeability that allows 1 cm^3/s of fluid having a viscosity of one centipoise to pass through a cross-sectional area of 1 cm^2 under a pressure gradient of one atm/cm^3 (measured at right angles to the surface of the flow).

Thus permeability is a measure of the ease with which a liquid is able to penetrate the porous material. The quantity of fluid allowed to flow through a material depends on the one hand on the experimental conditions chosen, as, for example: the viscosity of the fluid, the driving pressure exerted on the fluid, the length through which the fluid must pass, and the cross-sectional area over which the fluid is allowed to flow. On the other hand it is determined by the micro-structure of the matrix itself. Within the porous material, flow is limited by the size of the grains, which determines the size, shape, and the degree of interconnection of the pore spaces. It is the permeability factor that formally accounts for these material influences.

Material properties such as porosity, pore size, and pore shape are not included explicitly in Darcy's flow equation. Therefore, using the flow equation as a guide and a framework on which to build, the permeability can be described as a function of material properties that can be categorized into physical properties (pore variables and grain variables) and into electrical properties (resistivity).

The main purpose of the following sections is to express permeability explicitly as a function of variable material properties. The three ways to do so, by pore or grain or electrical characteristics, are described in Sects. 2.2, 2.3 and 2.4, respectively.

2.2 Pore Characteristics

The first variable set deals with the characteristics of the pore network found in unconsolidated or semi-consolidated sediments. The actual pore network is three-dimensional and contains pores of various diameters and lengths in some unknown sequence. A complete description of the structure

of the pore network would require a complete knowledge of all sizes and arrangements of the pores. This detailed information may not be available to the researcher; therefore the usual approach consists of extracting the essential features of pore structure by introducing distributions for such single parameters as pore size, pore shape, and others. Since we assume that we are dealing with isometric materials and therefore with symmetric distributions of size and shape parameters, we represent the distributions by their mean values.

The use of pore characteristics for the formulation of permeability is the most direct approach of the three variable sets proposed in this paper. Since fluid flow is entirely by way of pore channels, a quantitative description of the pore network should lead to an accurate set of material properties for the relationship of pore structure to permeability.

Using Poiseuille's equation, the flow in a channel can be described by

$$U_p = \frac{(m^2)}{K_p} \frac{(\Delta P)}{\mu L_p} \quad , \qquad \text{(Eq. 2)}$$

where

U_p = speed of flow in the pipe.

μ = viscosity of the fluid.

ΔP = the pressure difference causing the flow.

L_p = the length of the flow path.

K_p = a capillary-shape factor that varies from 2 for circular cross-sections to 3 for rectangular cross-sections.

m = hydraulic radius, described as the ratio of the volume to area of the "pipe".

Assuming that our porous solid is perforated by a network of pipes and openings of various shapes and with a random pore distribution, any plane through the material exposes a constant fractional void area proportional to porosity <15>.

We further assume that the pore area of the solid can be represented by an effective cross-sectional area, βA, where A is the cross-sectional area of the solid normal to the macroscopic flow and β is the porosity of the material.

The flow path through the solid, L_p, is actually longer than the external length of the porous solid. Therefore, for other than straight capillaries parallel to the flow direction, the ratio L_p/L_s, where L_p represents the actual distance through which the fluid must pass and L_s is the length of the sample, is always greater than one.

The average fluid velocity U_p, within the porous solid, is greater than the approach velocity, U, being measured at the surface of the sample, because the available area for flow is only βA and the distance through which the fluid must pass, L_p, is greater than the apparent path length L_s. Thus,

$$U_p = \frac{U}{\beta} \frac{L_p}{L_s} \quad . \qquad \text{(Eq. 3)}$$

Solving for U we get

$$U = \beta U_p \frac{L_s}{L_p} \quad . \qquad \text{(Eq. 4)}$$

We can write Darcy's law <14> as,

$$U = \frac{Q}{A} = \frac{K}{\mu} \frac{\Delta P}{L_s} \quad . \qquad \text{(Eq. 5)}$$

Substituting $\beta U_p \frac{L_s}{L_p}$ for U leads to

$$\beta U_p \frac{L_s}{L_p} = \frac{K}{\mu} \frac{\Delta P}{L_s} \quad . \qquad \text{(Eq. 6)}$$

Solving for K gives

$$K = \frac{\mu L_s}{\Delta P} \beta U_p \frac{L_s}{L_p} \quad . \qquad \text{(Eq. 7)}$$

By combining Eqs. 7 and 2 we obtain

$$K = \frac{m^2}{K_p} \cdot \beta \cdot \left[\frac{L_s}{L_p}\right]^2 \quad , \qquad \text{(Eq. 8)}$$

which describes permeability solely as a function of the pore network within the porous medium.

L_p represents an idealized ficticious path length through the solid, which would be impossible to obtain directly. Electrical measurements are required for such an indirect measurement and therefore are dealt with in more detail under that heading in Sect. 2.4.

2.3 Grain Characteristics

A second important characteristic of a sediment relative to permeability is its grain size. The size of the constituent grains for a given packing arrangement is directly proportional to the effective pore size. To illustrate the significance of grain size on permeability let us consider two aggregates of uniformly sized spheres, each having identical packing but one made up of large spheres and the other composed of small spheres. If particle size increases while the packing arrangement remains the same, the porosity of the aggregate of spheres remains constant but its permeability increases. This results from the fact that although the fractional volume of pores is the same in both aggregates of spheres, the number of pores among the larger spheres decreases with $1/r$, whereas their diameter increases with r .

The flow through larger pores increases with r^4 :

$$Q = \text{flow} = \pi \cdot \frac{r^4 (P_2 - P_1)}{8 \mu L} .$$

Permeability increases because the sizes of the pores have increased and frictional wall effects are less important in larger pores <16>. Jackson et al <11> confirmed by experiments that grain size indeed had little to do with porosity while noting greatly reduced permeabilities in fine grained samples.

However, this is not the case in most natural sediments. It turns out that porosity generally increases with decreasing grain size, for unconsolidated, uncompacted sediments (Fig. 1) <17>. This phenomenon is due primarily to a distinct change in grain shape as sediment sizes move from sand to clay. The figure shows that only sands can be represented adequately by hard sphere packing models. Sand-sized particles are generally spherical, while clays are more card-like (Fig. 2) <17> and difficult to arrange in a dense packing. This inherent difference in grain shape gives rise to higher porosities in non-compacted clays than in non-compacted sands.

Permeability is influenced by grain shape in much the same way as porosity. The conduction paths are most tortuous (i.e., having greater resistance) in platey, shaley samples than in the more spherical sandy samples at a given porosity <11>. This could be because spherical sand grains, arranged in a more ordered fashion, provide more direct paths through the material than the random distribution provided by the anisometric shaley grains.

In order to derive a set of variables that accurately describes permeability with respect to grain properties, we begin with the assumption

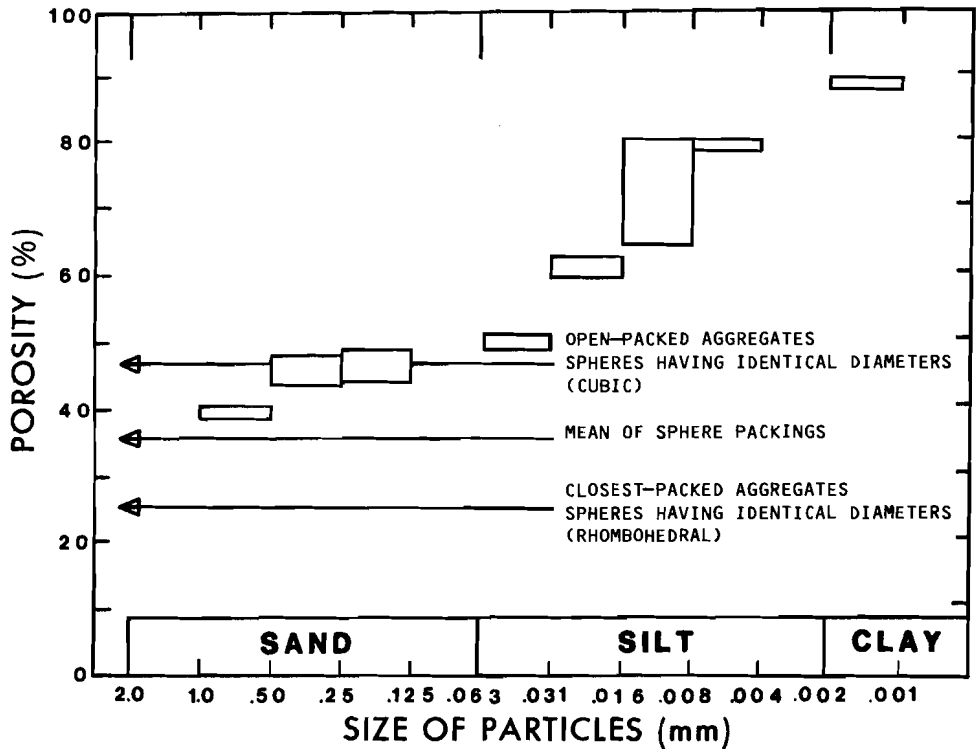

FIG. 1 VARIATION OF POROSITY WITH PARTICLE DIAMETER
After <16>

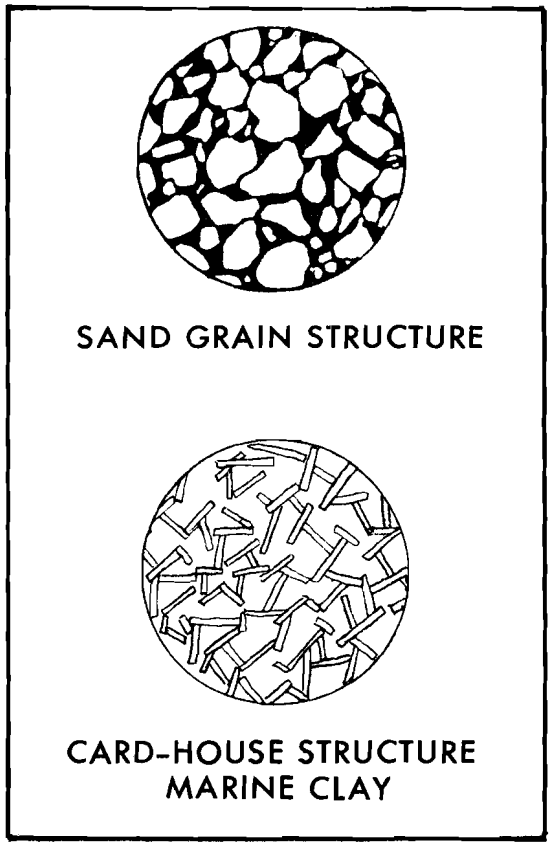

FIG. 2 COMMON SEDIMENT STRUCTURES
After <18>

that definite numerical equivalences exist between pore structure and grain structure. From this assumption we begin with Eq. 8 that describes permeability as a function of pore network variables:

$$K = \frac{m^2}{K_p} \cdot \beta \cdot \left[\frac{L_s}{L_p}\right]^2 .$$

Attenborough <13> experimentally determined that the relationship between hydraulic radius, m, and grain diameter, d, for a packing of identical spheres is given by

$$m = \frac{\beta}{1-\beta} \cdot \frac{d}{6} . \qquad \text{(Eq. 9)}$$

By combining Eqs. 8 and 9 we effectively eliminate the hydraulic radius and obtain

$$K = \frac{\beta^3}{(1-\beta)^2} \cdot \left[\frac{d}{6}\right]^2 \cdot \frac{1}{K_p} \cdot \frac{L_s}{L_p}^{2} . \qquad \text{(Eq. 10)}$$

Our porous solid is said to be an aggregate of grains that is randomly intersected by a network of capillaries through which fluid is directed. The hydraulic tortuosity, T, (a measure of the increase in flow resistance due to the prolonged, real path length) in such a fluid-filled porous medium will be the ratio of the flow length, L_p, to the sample length, L_s, divided by the overall pore volume present in the sample (porosity) <6>. Thus,

$$T = \frac{L_p}{L_s} \beta^{-1} , \qquad \text{(Eq. 11)}$$

and combining Eqs. 10 and 11 we obtain

$$K = \frac{\beta}{(1-\beta)^2} \left[\frac{d}{6}\right]^2 K_p^{-1} T^{-2} . \qquad \text{(Eq. 12)}$$

Equation 12 describes permeability in terms of grain and pore variables. In order to totally eliminate the pore shape variable (K_p) we would have to introduce another shape variable. This would not only make the final derivation more complex but would also aid in making the final equation less precise, for it is easier to describe numerically the two-dimensional

geometric cross-section of a pore space than to assign a value to a three-dimensional grain.

2.4 Electrical Characteristics

Using electrical resistivity as a means of formulating permeability is one of the most recent advances in geotechnological evaluation of seafloor sediments. Here we suggest a method of obtaining permeability (which is difficult to measure) from resistivity (which is easy to measure).

As earlier noted, some of the physical material characteristics needed to determine permeability in unconsolidated marine sediments are rather difficult to measure. In situ measurements with the previously described methods are impossible and sampling techniques often make laboratory evaluations inaccurate. It would be clearly desirable to find a general relationship between permeability and more easily measured property. Electrical resistivity appears to be one such property. Conduction of electricity through porous rock saturated with a conductive pore fluid is by way of ionic conduction (movement of ions through the fluid), assuming that the porous frame material acts as an insulator. Such is the case in marine sediments, due to the highly conductive nature of the saline pore fluid and the highly isolating nature of the rocks.

If the movement of ions through pore fluids is influenced by the same sediment properties that govern the flow of the pore fluids, we might expect permeability and resistivity of a given rock to be related directly. In fact many experiments <11, 18> have given overwhelming evidence of the validity of this assumption. Laboratory experiments <15, 19, 20> have shown a proportionality between the resistivity of the fluid-filled matrix (R_s) and the resistivity of the fluid itself (R_f):

$$R_s = R_f \cdot F \quad . \qquad \text{(Eq. 13)}$$

The constant of proportionality, F , is called the formation factor and is a pure material constant. It expresses the increase in resistivity that is caused by the ions having to follow a more complicated path through the porous network than through a pure fluid.

The formation factor is of a dimensionless magnitude greater than one. It describes the behaviour of the porous medium concerning all transport phenomena. The rate of fluid or ionic transport is proportional to the cross-sectional area of the transport duct and inversely proportional to the length of the duct, provided that the transport takes place in the pore space only, avoiding the solid matrix <18>.

In many cases, such as conductive shaley rocks or when pore fluids are low-conductive fresh waters, large deviations can occur in the expected formation factor proportionality. While these extreme deviations are of significant importance to geologists, who test resistivity of subsurface rock formations without prior knowledge of the composition of the pore fluid, it is of little importance to marine studies. Pore fluids in

marine sediment display a very constant resistivity and changes occur only gradually over extremely large distances. Furthermore, marine saline solutions are extremely conductive and therefore any conduction by way of the solid medium is negligible.

The electrical resistance of such a fluid-filled porous medium, assuming a random pore distribution, is directly proportional to the resistivity of the pore fluid and the L_p/L_s ratio, and inversely proportional to the sample porosity <15>:

$$R_s = R_f \cdot \frac{L_p}{L_s} \cdot \beta^{-1} \quad . \qquad \text{(Eq. 14)}$$

Combining Eqs. 13 and 14 we obtain

$$F = \frac{R_s}{R_f} = \frac{L_p}{L_s} \cdot \beta^{-1} \quad . \qquad \text{(Eq. 15)}$$

Substituting the ratio R_s/R_f into Eq. 8 yields

$$K = \frac{m^2}{K_p} \cdot \left[\frac{R_f}{R_s}\right]^2 \cdot \beta^{-1} \quad , \qquad \text{(Eq. 16)}$$

which can be written <15>, using Eq. 13 as

$$K = \frac{m^2}{K_p} \cdot F^{-2} \cdot \beta^{-1} \quad . \qquad \text{(Eq. 17)}$$

By combining Eqs. 9 and 17 we derive the final equation:

$$K = \frac{\beta}{(1 - \beta)^2} \cdot \left[\frac{d}{6}\right]^2 \cdot K_p^{-1} \cdot F^{-2} \quad . \qquad \text{(Eq. 18)}$$

Because grain and pore variables are both used in Eq. 18 its main advantage over previous equations is that all the variables are readily measurable <u>in situ</u> without substantially altering pore shape geometries.

3 EXPERIMENTAL EVIDENCE

The laboratory data used for verification were collected from the published and unpublished literature to be cited. Although not conclusive, the collected data do give evidence supporting the validity of the equation.

3.1 Glass beads data

An unpublished permeability study <21> of unconsolidated packed glass beads from the US Naval Oceanographic Research and Development Activities Center (NORDA) provided the first useful information. The study consisted of determining permeability and porosity of eleven samples composed of glass beads 0.039 cm in diameter (Table 1). Given these three variables for each of the samples analyzed and assuming a pore shape factor, Ko, of 2.5 it was possible to calculate the formation factor of the various samples (Table 1) using Eq. 18.

$$K = \frac{\beta}{(1 - \beta)^2} \cdot \left[\frac{d}{6}\right]^2 \cdot (K_p)^{-1} \cdot (F)^{-2} \quad .$$

The calculated formation factors fell well within the range given in <11> for glass spheres with porosities between 34% and 38% (Fig. 3).

TABLE 1

PERMEABILITY, POROSITY, AND CALCULATED FORMATION FACTORS FOR DIFFERENT SIZES OF PACKED GLASS BEADS
(Unpublished NORDA data)

BEAD SIZE (cm diam)	PERMEABILITY ($\times 10^{-6}$ cm^2)	POROSITY (%)	FORMATION FACTOR (ratio value)
0.039	1.31	35.6	3.34
0.039	1.10	36.2	3.70
0.039	1.05	35.2	3.76
0.039	1.01	35.7	3.67
0.039	1.09	35.7	3.59
0.039	1.11	36.0	3.76
0.039	1.03	35.2	3.67
0.039	1.06	35.2	3.59
0.039	1.48	35.7	3.12
0.039	1.05	35.2	3.76
0.039	1.30	35.2	3.30

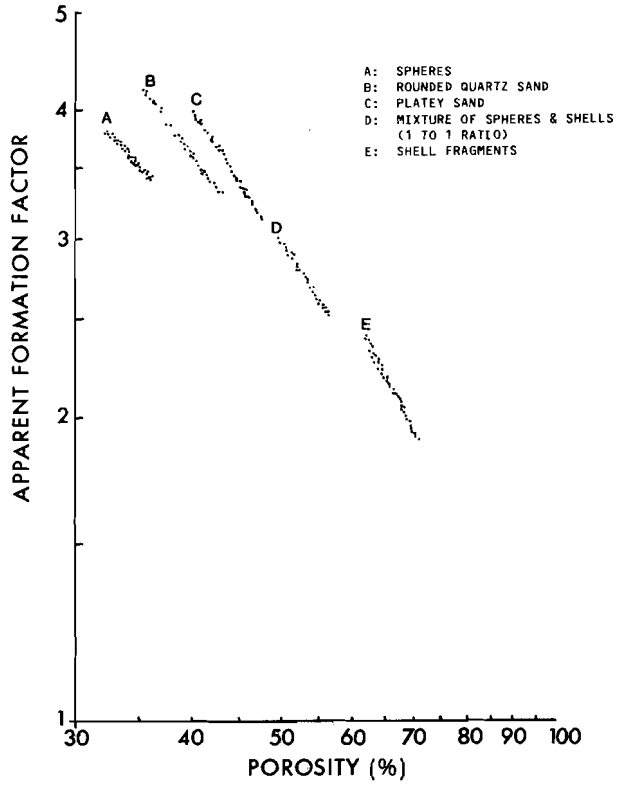

FIG. 3
FORMATION FACTOR VERSUS POROSITY FOR ARTIFICIAL SAMPLES OF DECREASING SPHERICITY. After <11>

3.2 Natural sands data

Croft <9> published the only available data listing porosity, grain size, permeability, and formation factor for a group of sediment samples. The results calculated for permeability were consistently high by a factor of approximately 5 for the eight samples tested (Table 2). As shown in Fig. 4 <22>, the range of permeability of silts to gravels is of 7 orders of magnitude but a factor of 5 should be acceptable in most studies <10>.

Because calculated permeabilities were consistently five times higher than those measured, it was possible to introduce a coefficient of 0.2 into the equation to adjust the calculated permeabilities to within 16% or less of those measured (Table 2). This factor of 0.2 was chosen arbitrarily to fit the limited laboratory data available; it may not be applicable over a wider range of data. However, the use of some correction factor might be needed in a similar fashion for other data.

There are two primary reasons why a coefficient of 0.2 might be needed to adjust the calculated permeabilities so that they might agree more closely with those measured. First, the very process of measuring the resistivity of subsurface features lends itself to a variety of malfunctions and errors. If the process is not done carefully the resulting measurements can be incorrect by a substantial margin. This does not, however, appear to be the case here: the systematic difference between calculated and measured permeabilities indicates a systematic influence.

Report no. changed (Mar 2006): SM-185-UU

TABLE 2

MEASURED, CALCULATED, AND ADJUSTED PERMEABILITIES OF EIGHT SAMPLES OF NATURAL SAND DEPOSITS <9>

GRAIN SIZE (cm diam)	POROSITY (%)	FORMATION FACTOR (ratio value)	PORE SHAPE	MEASURED PERMEABILITY ($cm^2 \times 10^{-7}$)	CALCULATED PERMEABILITY ($cm^2 \times 10^{-7}$)	ADJUSTED PERMEABILITY ($cm^2 \times 10^{-7}$)
0.021	41.5	3.0	2.5	1.14	6.6	1.32
0.025	41.5	3.1	2.5	1.57	8.8	1.76
0.030	41.5	3.25	2.5	2.10	11.0	2.20
0.035	41.5	3.55	2.5	2.70	13.0	2.60
0.045	41.5	3.9	2.5	3.61	18.0	3.60
0.050	41.5	3.93	2.5	4.50	22.0	4.40
0.060	41.5	4.0	2.5	6.21	30.0	6.03
0.089	41.5	4.1	2.5	14.10	63.0	12.60

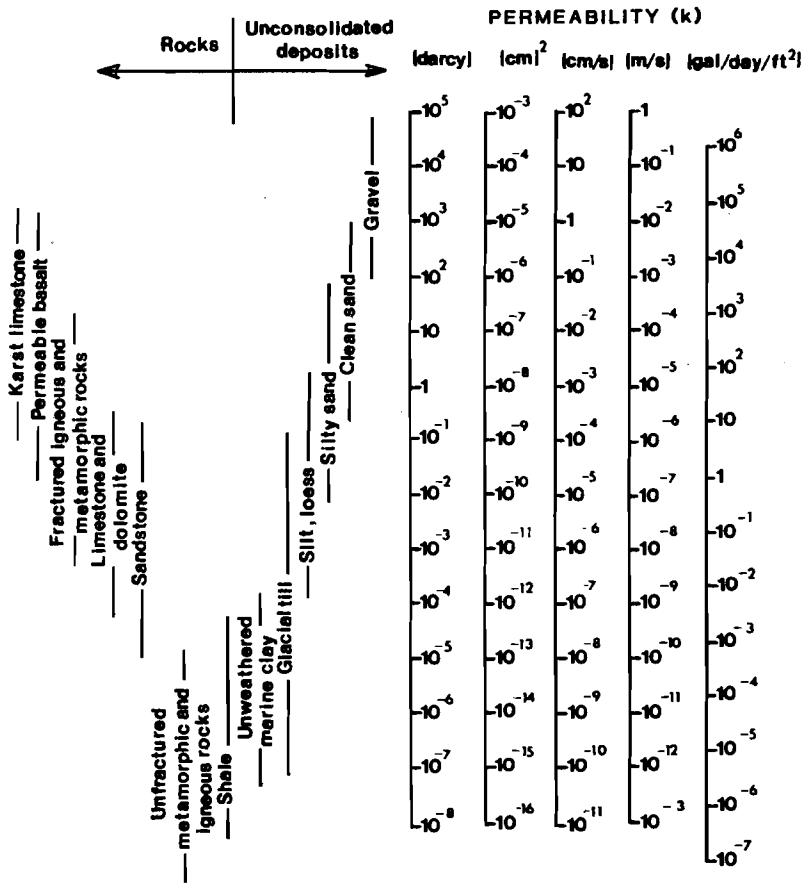

FIG. 4
RANGES OF HYDRAULIC CONDUCTIVITY AND PERMEABILITY
After <10>

Report no. changed (Mar 2006): SM-185-UU

3.3 Sorting data

The second possibility for such a consistent variation in permeability and the need for a correction factor is the idea of grain size distribution, better known as sorting. It seems logical that if there are two grain sizes, the pores between the larger grains will be filled with the smaller grains. It also seems reasonable to believe that averaging these two grain sizes would not give a reliable estimation of the developed pore geometries, for it is primarily the infilling of the small grains between the large grains that is responsible for limiting permeability (Fig. 5).

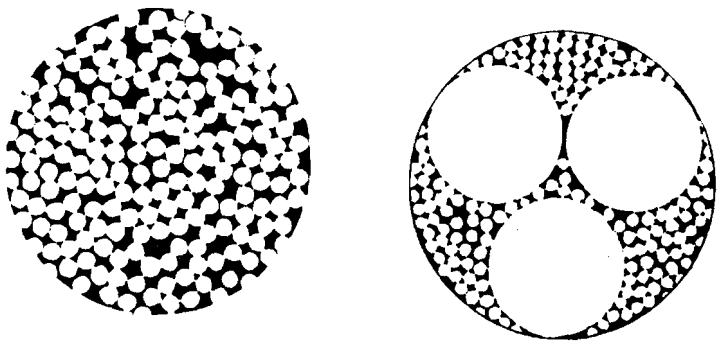

FIG. 5
TWO SEDIMENT SAMPLES OF THE SAME AVERAGE GRAIN SIZE BUT DIFFERENT PERMEABILITIES

Using the median diameter of the grains does not seem to adequately describe grain relationships in sediments that possess more than one distinctive grain size. Beard and Weyl <23> showed that for artificially mixed sands with a common median grain size, permeability decreased by as much as a factor of 30, from extremely well sorted to very poorly sorted sands (Table 3).

TABLE 3

AVERAGE PERMEABILITIES OF ARTIFICIALLY MIXED, WET-PACKED SAND <23>

	AVERAGE PERMEABILITY (darcy)			
	Coarse	Medium	Fine	Very fine
Extremely well sorted	457	119	30	7.4
Very well sorted	458	115	29	7.2
Well sorted	302	76	19	4.7
Moderately sorted	110	28	7.0	2.1
Poorly sorted	45	12	3.7	0.93
Very poorly sorted	14	3.5	0.83	0.21
	1.00	0.50	0.25	0.13
	Median diameter (mm)			

Ward <24> determined permeability values for different mediums and related these values to the geometric standard deviation and mean grain size of the samples. The results revealed that the permeability increased with increasing mean particle diameters and decreased with increasing geometric standard deviation values for the same mean particle diameter.

Masch and Denny <25>, using unconsolidated artifically mixed sand, systematically varied the values of numerous statistical variables, including grain size and grain-size distribution, and evaluated the corresponding permeabilities. Their conclusions concerning grain-size distribution were that it was obvious that the greater the range between the largest and the smallest particles, the greater is the opportunity for interstitial clogging to occur within particle clusters. It follows then that there would be much less flow area and consequently lower permeability values for samples characterized by large deviations in grain size.

To further illustrate the idea of sorting and its effects on permeability, formation factors were calculated for a series of laboratory samples for which permeability, porosity, and median grain size were available (Table 4). Each of the samples was unsorted and exhibited a gaussian-like size distribution similar to that of the Ottawa Sand.

The calculated formation factors were much higher than those of Jackson's <11> when the mean grain size was used in the calculations (Fig. 3). Higher formation factors indicate lower permeabilities. In order to adjust the calculated formation factors so that they fitted well into the experimental range denoted by Jackson it was necessary to decrease the mean grain size from 0.039 cm diameter to 0.026 cm (Table 4). Such an adjustment would also be needed to correct calculated permeabilities, because the presence of smaller grains in the voids between larger grains is primarily responsible for measured permeabilities that are lower than those calculated using the mean grain size.

4 INTERDEPENDENCE OF VARIABLES

The sensitivity that permeability exhibits to each of the previously discussed variables is of primary importance in the development of future sampling techniques, as well as in a better understanding of the role that each variable plays in the determination of fluid flow through porous media.

Through a series of computer-generated plots relating each of the variables (porosity, grain diameter, pore shape, and formation factor) to permeability, each was ranked according to its relative influence on permeability. This was accomplished by varying one variable in the general equation while the others were left constant and plotting the resulting variations in permeability versus the changes in the variable.

Report no. changed (Mar 2006): SM-185-UU

TABLE 4

FORMATION FACTORS CALCULATED FROM AVAILABLE LABORATORY MEASUREMENTS OF PERMEABILITY AND POROSITY

PERMEABILITY ($\times 10^{-6}$ cm^2)	POROSITY (%)	FORMATION FACTOR (MEDIAN GRAIN)	
		Size 0.039 cm	Size 0.026 cm
0.800	0.441	5.46	3.64
0.661	0.432	5.85	3.90
0.761	0.435	5.50	3.67
0.811	0.439	5.39	3.59
1.035	0.466	5.17	3.44
0.951	0.457	5.23	3.50
0.865	0.447	5.34	3.56
1.373	0.492	4.84	3.23
1.282	0.483	4.88	3.25
1.198	0.476	4.95	3.30
1.193	0.474	4.93	3.28
1.051	0.465	5.11	3.41
0.934	0.454	5.25	3.50
0.817	0.444	5.45	3.63
0.732	0.433	5.58	3.72
1.241	0.490	5.06	5.31
1.167	0.478	5.18	3.36
1.074	0.466	5.07	3.38
0.990	0.456	5.13	3.42
0.676	0.433	5.98	3.99
0.761	0.438	5.55	3.70
1.475	0.496	4.73	3.15
1.448	0.490	4.69	3.13
1.372	0.485	4.75	3.16
1.285	0.479	4.82	3.20
1.219	0.472	4.84	3.23
1.198	0.467	4.82	3.21
1.056	0.458	4.99	3.33
0.969	0.452	5.12	3.42
1.418	0.496	4.82	3.22
1.417	0.493	4.78	3.19
1.332	0.487	4.85	3.23
1.242	0.480	4.91	3.28
1.117	0.468	5.00	3.33
1.032	0.463	5.13	3.42
0.979	0.457	5.17	3.45
0.890	0.451	5.33	3.55
0.820	0.445	5.46	3.64
0.765	0.440	5.57	3.71
0.662	0.472	5.76	3.84
0.662	0.418	5.61	3.74
0.760	0.429	5.41	3.61

4.1 Influence of porosity

The equation

$$K = \frac{\beta}{(1 - \beta)^2} \left[\frac{0.005 \text{ cm}^2}{6}\right] (2.5)^{-1} (3.5)^{-2}$$

expresses the variation of permeability with porosity. The mathematical function relating the two is third degree and plots linearly on semi-logarithmic paper, as shown in Fig. 6a. Permeability varies half an order of magnitude (from 0.05×10^{-5} cm^2 to 5.5×10^{-5} cm^2) over a range of porosities from 30% to 53%. This is logical, for as porosity increases void space increases and flow area becomes greater and less restrictive.

4.2 Influence of grain size

Permeability exhibits a marked sensitivity variation over a range of grain sizes from silt to fine gravels (0.001 cm to 0.023 cm diameter), as shown in Fig. 6b. As grain size, d , increases from silt-size particles to gravel-size particles, permeability increases by over two orders of magnitude, from 1×10^{-6} cm^2 for silt to 5×10^{-4} cm^2 for gravels. According to the equation

$$K = \frac{0.4}{(1 - 0.4)^2} \left[\frac{d}{6}\right]^2 (2.5)^{-1} (3.5)^{-2} ,$$

permeability varies by a power of two with changes in grain size. As one might intuitively guess, as grain size increases so do the pore sizes between them, therefore increasing permeability.

4.3 Influence of pore shape

The range over which pore shape is allowed to vary within the equation

$$K = \frac{0.4}{(1 - 0.4)^2} \left[\frac{0.005 \text{ cm}}{6}\right]^2 (K_p)^{-1} (3.5)^{-2}$$

is limited (2.0 for circular pores to 3.0 for rectangular pores) and influences permeability only slightly. As the pore-shape factor increases from 2.0 to 3.0, permeability decreases from 3.1×10^{-5} cm^2 to 2.1×10^{-5} cm^2 (Fig. 6c). Such an inverse relationship seems reasonable, for as pore shapes change from circular (2.0) to rectangular (3.0) they become more restrictive to flow and thus result in lower permeability.

Report no. changed (Mar 2006): SM-185-UU

4.4 Influence of the formation factor

Permeability exhibits an inverse-square relationship to the formation factor, as stated in the equation

$$K = \frac{0.4}{(1 - 0.4)^2} \left[\frac{0.005 \text{ cm}}{6}\right]^2 (2.5)^{-1} (F)^{-2} .$$

As the formation factor increases from 1.5 to 4.0, permeability decreases from 1.5×10^{-4} cm^2 to 2×10^{-5} cm^2 (Fig. 6d). This is because the formation factor is a measure of the resistance that the rock exhibits to electric flow and permeability is the measure of fluid conductivity through the rock.

4.5 Ranking of the variables

Ranking of the discussed variables with respect to their relative influence on permeability is of importance for determining the accuracy with which measurements have to be performed. When developing new and advanced machinery and techniques for sampling, two things should be highly scrutinized. First, the accuracy of the previously adopted methods and second, the sensitivity that permeability exhibits to the sampled variable.

4.5.1 Grain size

The parameter to which permeability exhibits its highest sensitivity is grain size. Permeability varies two and a half orders of magnitude over a grain size range of silt to gravel (Fig. 6b). Accordingly, the accuracy with which grain size is determined is of the utmost importance in the calculation of permeability. Sieve analysis is recommended for proper analysis of bulk samples and is generally accurate to within 2% to 3%, depending on the grain size.

4.5.2 Formation factor

The second most important variable used in the calculation of permeability is the formation factor of the porous medium. As the formation factor varies from 1.5 to 4.0, the permeability varies by approximately one order of magnitude (Fig. 6d). The determination of the formation factor is difficult and complicated and procedures vary drastically from sub-marine measurements to sub-surface measurements.

4.5.3 Porosity

Porosity evaluation is almost as important as the determination of the formation factor for calculating permeability. Permeability varies half an order of magnitude over a porosity range of 30% to 53% (Fig. 6a). The determination of porosity in the laboratory is very precise and the

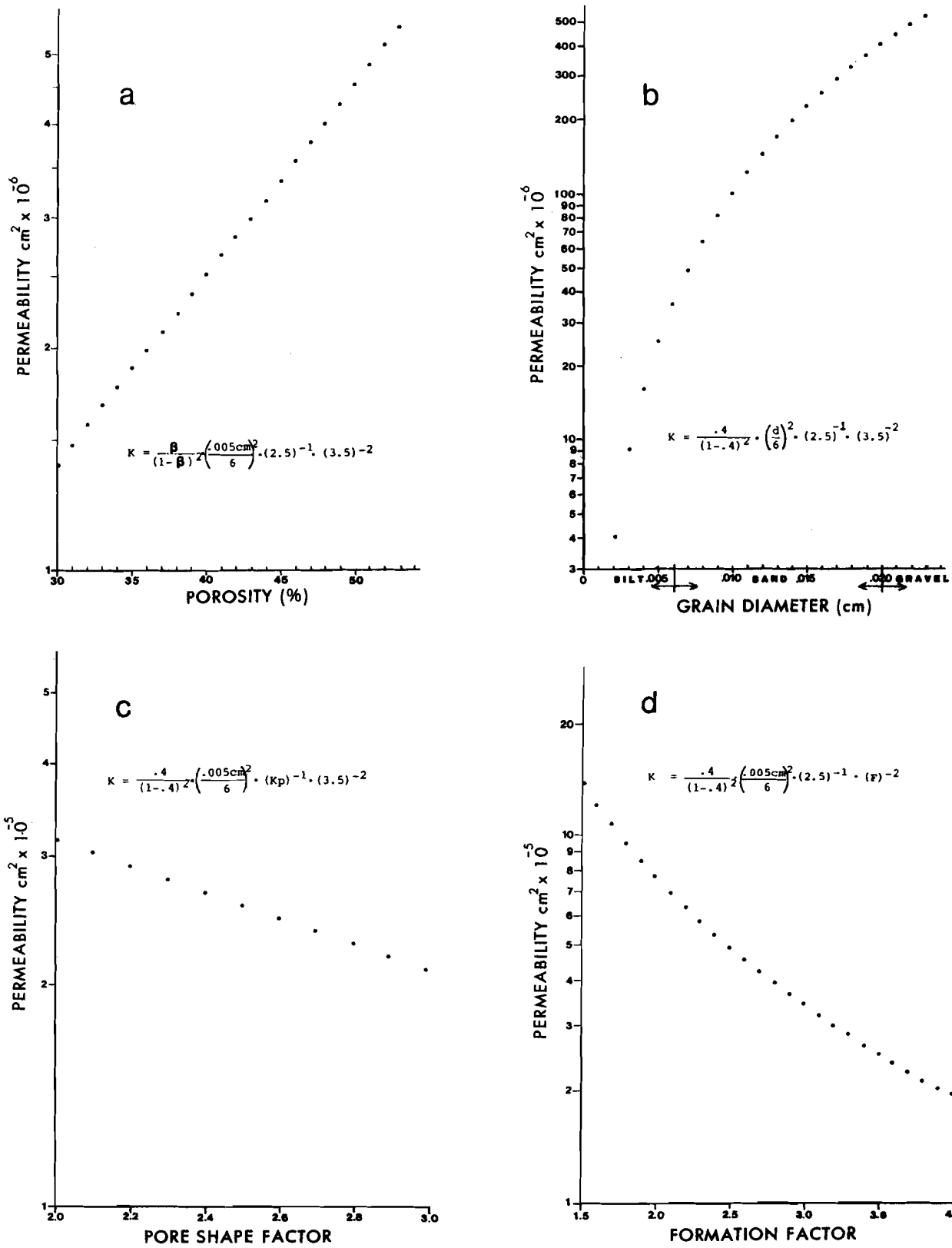

FIG. 6 PERMEABILITY AS A FUNCTIONS OF VARIABLE SEDIMENT PROPERTIES
a) porosity b) grain diameter
c) pore shape d) formation factor

accuracy relatively high; however, determining porosity in situ is much more difficult. The use of Archie's Law $F = \beta^{-m}$ makes use of the formation factor for in situ porosity determinations. For this reason the formation factor is ranked above porosity as the second most important input parameter in the calculation of permeability.

4.5.4 Pore shape

Permeability is least sensitive to changes in pore shape. Over the entire range of pore sizes, permeability varies only one tenth of an order of magnitude (Fig. 6c). Generally, pore shape is evaluated visually by means of photographs taken of in situ sediments.

This is of course partially subjective but it is generally acceptable as a method of determination. However, for most calculations it is reasonable to assume a value of 2.5 for pore shape.

5 DISCUSSION

5.1 Experimental evidence

Two sets of data were used to test the validity of Eq. 18. Although not conclusive, the evidence does seems to support the utility of the equation.

The first line of evidence supporting the equation was the calculation of formation factors for a series of spherical glass bead samples. Formation factors were computed using measured permeabilities, porosities, and grain sizes for each of the samples. The calculated formation factors fit within the range given by Jackson et al <11> for glass spheres of approximately the same porosities. If indeed accurate formation factors can be calculated using measured permeabilities, porosities, and pore shapes, then it would seem reasonable to assume that accurate permeabilities could be calculated using measured formation factors, porosities, and pore shapes.

The second line of evidence makes use of calculated and measured permeabilities for a series of natural sand samples. Permeabilities were calculated for a series of eight natural sands using Eq. 18 and measured values of porosity and grain size. The calculated results were then compared with measured permeabilities for the same samples. The error in the calculated permeabilities was consistently a factor of approximately 5. Such an error might be acceptable, but by introducing a correction factor into the formula the error was reduced to 16% or less for each of the samples used.

The need for a correction factor might possibly stem from a lack of sorting within most natural sediments. As the difference between grain sizes becomes greater in unconsolidated sediments, the possibility of the pores between large grains being filled by smaller particles becomes greater. Poorly sorted rocks possess substantially lower permeabilities than well

sorted rocks, even when the median grain sizes are the same (Table 3). If permeabilities can be substantially different in sediments with identical median grain sizes, then the use of only median grain diameters for sediments that are not well sorted could lead to extraneous calculated permeabilities.

Two methods have been proposed to help make the calculation of permeability more accurate in samples that might not compare well with measured permeabilities. First, the use of a correction factor or coefficient. This method is most useful when measured permeabilities are available as references in determining the factor, as was the case with the data in Table 2. When using measured permeabilities to calibrate calculated permeabilities, it is important to realize that error can arise in measurements as well as in calculations. Therefore, it might be necessary to use several permeability measurements to calibrate the formula to fit a particular area.

When no measured permeabilities are available to compare with calculated permeabilities, the first method cannot be used and the second method is recommended. The second method makes use of the knowledge that the matrix of finer particles dominates the permeability of the material in sediments that are not well sorted. Calculated permeabilities of sediments that are not well sorted tend to be higher than measured permeabilities when the sediment's median grain diameter is used in the formula. Calculated permeabilities using a grain diameter smaller than the sediment's median grain diameter would tend to agree more closely with those measured. To determine the grain size to be used, a knowledge of the sorting would be necessary. For well sorted sediments the grain diameter to be used in the formula would compare closely to the median grain diameter. As sediments become more poorly sorted the grain diameter used in the formula would become progressively smaller than the median grain diameter of the material. An in-depth study of sorting and its effects upon permeability might possibly substantiate these ideas.

5.2 Interdependence of variables

The graphs relating each of the variables to permeability (Fig. 6) illustrated how, and to what degree, permeability was affected by changes in the individual variables. The variables were then ranked according to their relative influence on permeability. It is necessary to understand which variable affects permeability the most, so that efforts can be made to improve the accuracy of its determination.

Permeability is most sensitive to changes in grain size; over a series of grain sizes ranging from silts to small gravels it varied over two orders of magnitude.

The second most important variable is the formation factor: as it varied from 1.5 to 4.0, permeability was found to vary by approximately one order of magnitude.

Porosity, less important than grain size and the formation factor in the calculation of permeability, is nonetheless of primary concern in accurate

determinations. For changes in porosity of from 30% to 53%, permeability varied half an order of magnitude.

Pore shape affected permeability the least among the variables reviewed. Over the entire range of pore shapes (2.0 to 3.0) permeability varies by only one tenth of an order of magnitude.

The ranking of the variables according to their relative influence on permeability was therefore as follows: grain size, formation factor, porosity, and pore shape. It follows that future efforts towards increasing the accuracy of calculated permeabilities should centre primarily around increasing the precision with which grain size is determined (both in sampling techniques and laboratory evaluation). Efforts should also be made to improve techniques and equipment used in determining the formation factors of in situ ocean-floor sediments.

CONCLUSIONS AND RECOMMENDATIONS

- Because the permeability of unconsolidated marine sediments cannot be measured in situ at the ocean bottom, this paper proposes that it be expressed in terms of more easily measurable properties of the porous material, using the following equation:

$$K = \frac{\beta}{(1 - \beta)^2} \left[\frac{d}{6}\right]^2 (K_p)^{-1} (F)^{-2} ,$$

  which relates the permeability (K) to the porosity (β), grain size (d), capillary shape (K_p), and formation factor (F). The accuracy of this equation is acceptable for computer models designed to evaluate sound reflection, conversion, and transmission in fluid-filled porous media, as based on the Biot acoustic model.

- By using the derived empirical formula to calculate permeabilities of in situ marine-floor sediments, errors associated with present sampling techniques can be avoided.

- Published values <9> of porosity, grain size, and formation factor for semi-consolidated sandstone were used to calculate permeability values that could be compared with measured values from the same source <9>. Calculated permeabilities were consistently higher than those measured, by approximately a factor of five. This was primarily due to a variation in grain sizes (sorting) within the rock. A correction factor was introduced that reduced the margin of error between calculated and measured permeabilities to within 16% or less for each of the samples presented.

- Knowledge of the relative sensitivities of permeability to the four sediment variables should assist in the development of more refined sampling equipment. Plotting these variables against permeability indicates that they are of the following order of importance: grain size, formation factor, porosity, and pore shape.

- It is recommended that more laboratory data are needed to help substantiate the validity of the final working equation beyond the range of the experimental data available for the preparation of this paper.

- Further research is needed to establish a mathematical relationship between sorting and permeability that can be incorporated into the equation. Such a relation could take the place of the correction factor introduced to adjust calculated permeabilities to fit more closely with measured permeabilities.

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APPENDIX A

MEASUREMENT AND EVALUATION OF SEDIMENT VARIABLES

To understand the various aspects and multiple facets of sediment relationships requires a knowledge of the methods of measurement and evaluation employed to determine specific values for each of the parameters used in the final working equation. This appendix discusses these for each parameters in turn.

A.1 POROSITY

All methods used to determine porosity consist of measuring two of the three relevant volumes — pore volume (V_{por}), matrix volume (V_{mat}), and total volume (V_{tot}) — and an evaluation using one of the three equations:

$$\beta = \frac{V_{por}}{V_{tot}}$$

$$\beta = 1 - \frac{V_{mat}}{V_{por}}$$

$$\beta = \frac{V_{por}}{V_{por} + V_{mat}}$$

A.1.1 Archimedean method

The Archimedean method is the most commonly used. It consists of three weight (mass) determinations of the rock sample <A.1>.

1) In the dry state with air-filled pore space,

$$mass_1 = \rho_{mat} \cdot V_{mat}$$

2) In the wet state with completely liquid-filled pore space,

$$mass_2 = \rho_{mat} \cdot V_{mat} + \rho_{por} \cdot V_{por}$$

3) In the wet state, submerged in an identical liquid,

$$mass_3 = (\rho_{mat} - \rho_{por}) \cdot V_{mat} ,$$

where

ρ_{mat} = density (kg/m^3) of the material,

ρ_{por} = density of the pore fluid, and

ρ_{tot} = total density of the fluid-filled sample.

From these values we can compute β without knowing the density of the fluid used.

$$\beta = \frac{mass_2 - mass_1}{mass_2 - mass_3} = \frac{\rho_{por} \cdot V_{por}}{\rho_{por} (V_{por} + V_{mat})}$$

Care should be taken to ensure saturation of the sample. A low-viscosity, air-free, well-wetting fluid must be used. The waiting period for full saturation depends on the permeability of the sample. The sample must be evacuated at least to the order of 1 μbar one to two hours before injection of fluid can take place. Then the sample must stand immersed in the wetting liquid from half a day to 14 days to ensure accurate results. The time of immersion can be reduced from days to hours by an applied pressure of approximately 50 μbar. It is quite important that the fluids used for saturation and immersion are identical and inert, in order that no matrix material be disolved in the liquids.

Of the three weight (mass) determinations, the wet state with completely liquid-filled pore space ($mass_2$) is the most difficult to perform accurately. The true state of saturation is very difficult to determine, because when the sample is recovered from the fluid it is covered by an excess film of fluid, and when the fluid is removed, some pore fluid may be expelled as well <A.1>. Therefore it is advisable to repeat the entire measurement procedure several times to ensure the highest degree of accuracy.

A.1.2 Boyle's Law method

The second of the two procedures to determine porosity is the gas porosimetry method using Boyle's Law:

$$pv = \text{constant} .$$

In general, the common principle is to determine the gas volume in a chamber with and without the rock sample by monitoring the pressure during compression or expansion, the volume difference being the matrix volume.

To calculate the porosity, it is necessary to know the total volume or the pore volume. The easiest to measure is the bulk volume. For this measurement the sample is immersed in mercury, which, with its high-surface tension and non-wetting property, does not enter the pores. The bulk volume can thus be determined by the displaced volume of mercury.

Errors can arise with the Boyle's-law method by failing to maintain isothermal conditions during gas compression or expansion. Another source of error is due to an uncertainty in the determination of bulk volume. If the sample has large pores, the mercury often will not adhere smoothly to the surface of the sample and will enter the pores, thereby yielding a low value for the bulk volume.

A.1.3 General errors

The most serious type of error that can occur in the previously described methods results from the redistribution of grains due to sampling movements and laboratory experimentation. Although variations in packing do not affect porosity as adversely as permeability, this is still the largest source of errors in measuring non-cohesive materials.

A.2 GRAIN SIZE

A.2.1 Sieve analysis

Sieve analysis is the most common and unquestionably the best-liked method of grain-size analysis in use today. As a rule, it is not used when the grains are less than 0.005 cm in diameter, at least not for dry sieve methods. The existence of screens that measure particles down to 0.0037 cm diameter implies a possible lower range of sizing but their use is exceptional in routine work and wet sieving is almost always inevitable with such particles.

Casual sieving is commonly carried out by hand, but for routine analysis mechanical shakers are much to be preferred. Sieving is a statistical process; that is, there is always an element of chance as to whether or not a particle will pass through the apertures and therefore there is no definite ending point to sieving analysis. It is therefore necessary to arbitrarily define an ending point by a fixed time or by sieving until particles pass the sieve at a fixed rate per minute. Thus mechanical shakers have the advantage that they can standardize both the time and method of shaking and thus produce more consistent results than hand sieving.

Accuracy of sieving analysis is limited by the tolerances in the weaving of the sieve screen and by the irregularity of particle shape. Fractionation by means of sieves is a function of the maximum breadth and the maximum thickness of the particle; for unless the particles are excessively elongated the length of the particles does not hinder their passage through the sieve apertures.

Milner <A.2> discusses sieve procedures in detail under three main operational categories: hand sieving dry, hand sieving wet, and mechanical

shaking. This reference is recommended as an in-depth description of sieving procedures.

A.2.2 Sedimentation analysis

If the assessed particles are less than 0.005 cm diameter, the sedimentation method of evaluation must be used. Stoke's Law postulates that the rate of fall of a spherical particle bears a direct relationship to its diameter <A.3>. Generally speaking, sedimentation procedures must be classed as indirect, because actual separation of particles into different sized groups is not feasible. Size distribution is assessed by measuring falling particles at a fixed level in a suspension and at successive intervals of time. An in-depth description of sedimentation procedures is also given by Milner <A.2>.

A.3 FORMATION FACTOR

To calculate the formation factor of a given sediment requires two separate electrical measurements. First, the resistivity of the fluid-filled porous medium and second, the resistivity of the pore fluid alone.

A.3.1 Resistivity of the medium

Measuring techniques designed to evaluate the electrical resistivity of ocean-floor sediments have taken several forms over the past years. Some of the first electrical measurements were made in the laboratory, on cores taken from soft clays <A.4>; however, for the purpose of this report, we are interested in in situ determinations.

In general, the technique for determining the in situ resistivity of a fluid-filled porous medium as described by Jackson <A.5> consists of a four-electrode array that passes a direct or low-frequency alternating current of known intensity through two electrodes into the ground, while measuring a potential difference between the other two electrodes. The resistivity of the medium is calculated from the ratio of the potential difference to the current passing, and from a proportionality factor that depends on the geometrical arrangement of the four electrodes.

In the Wenner array, one of the most widely used configurations, the electrodes are in-line and equi-spaced at a, distance a apart. If the two outer electrodes pass a current I, and the two inner ones measure a potential difference ΔV , the resistivity of the medium is given by

$$R = c\, a \frac{\Delta V}{I} \quad ,$$

where the value of c depends on the location of the measuring device. If the resistivity is measured from within the sediment (whole space), the value of c is 4. If the measurement takes place from on top of the sediment (half-space), then the value of c is 2. This resistivity represents a

true value only if the medium is homogeneous, isotropic, and semi-infinite. In heterogenous materials it denotes an apparent resistivity that represents the average of all homogeneous sediments within the assessed area.

One of the earliest devices to determine in situ resistivity was developed at SACLANTCEN in 1969 <A.6>. This was a free-falling probe that penetrated up to 10 m of unconsolidated sediments in order to measure their resistivity.

Recently a flexible, focused, in situ resistivity probe has been designed to lie on the seafloor without penetrating the sediments. Its function is to measure the apparent resistivity of the surperficial sediments without disturbing them <A.5>. The main problem of the device is reducing the water layer between pad and sediment so that current does not escape into the ocean water.

A.3.2 Resistivity of the pore fluid

Pore-fluid resistivity is measured by the same device as that used to measure sediment resistivity. It is assumed to be sufficient to measure the potential difference when the electrodes are surrounded by water as when they are in contact with the sediment. The ratio of the resistivity of the fluid-saturated sediment (R_s) to that of the saturating water (R_f) denotes the formation factor of the sediment:

$$F = \frac{R_s}{R_f} \quad .$$

A.4 PORE SHAPE

Determination of pore shape is by far the most subjective evaluation of all the variables discussed. Direct optical methods, such as the study of micrographs and photographs, are the most common means of estimation. Micrographs are used in laboratory evaluations when the sample is available for close microscopic scrutinization and pore geometries are too small for direct visual observation. Photographs are used when the sediment is still in place and can not be sampled for laboratory observation either because errors would be introduced by sampling techniques or because of an inability to sample the sediment. Evaluation of the methods entail subjective visual observation, which makes the accuracy totally dependent upon the observer. In many cases a median value of 2.5 is assigned and direct evaluation is not employed.

A.5 HYDRAULIC RADIUS

Brace (1977) <A7> describes two previously used methods of determining the hydraulic radius.

Report no. changed (Mar 2006): SM-185-UU

A.5.1 Calculation method

This method, first used by Wyllie and Spangler (1952) <8>, makes use of the well established relation

$$m^{-1} = P_D \cdot \sigma^{-1} , \qquad \text{or } m = \frac{\sigma}{P_D} ,$$

where m is the hydraulic radius, P_D is the pressure that must be applied to a nonwetting phase in order to displace a wetting phase in a fully saturated porous medium, and σ is the interfacial tension between the two phases. The accuracy of this method depends heavily on the uniformity of pore size throughout the sample.

A.5.2 Measurement method

The second method is more direct. The pore geometry is directly assessed with the use of enlarged photomicrographs and estimated values are assigned by eye. Obviously this method is much more subject to human error but it should be noted that values obtained this way agreed closely with those obtained by the calculation method.

A.5.3 Accuracy

The accuracy of the two methods is approximately the same. Brace <A7> gives a range of error of approximately ± 15% of the true value for both the measurement calculation methods.

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Report no. changed (Mar 2006): SM-185-UU

KEYWORDS

PERMEABILITY
SEDIMENTS
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