Journal of Hydrology, 78 (1985) 331—344
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

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A STUDY OF THE HYDROGEOPHYSICAL PROPERTIES OF FISSURED AQUIFERS USING A DOUBLE POROSITY MODEL

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(Received May 24, 1984; revised and accepted December 21, 1984)

ABSTRACT

Tselentis, G.-A., 1985. A study of the hydrogeophysical properties of fissured aquifers using a double porosity model. J. Hydrol., 78: 331—344.

The purpose of this paper is to examine to what extent the hydrogeophysical properties of fissured aquifers can be derived from geophysical logs alone.

To do this a theoretical double porosity model based on a tortuosity-free, parallel conduction path assumption is introduced and is used to establish possible relations between geophysical parameters that can be measured from conventional geophysical formation logs and the hydraulic characteristics of the aquifer.

The relation between the formation's cementation factor and the electrical properties of the water and the solid particles of the formation is investigated and the results are applied for three different types of geologies.

Finally an expression for assessing the aquifers hydraulic conductivity from parameters measured from geophysical formation logs is derived.

INTRODUCTION

Over the past decade there has been a growing interest concerning the relationship between the hydraulic conductivity of aquifers and some parameters measured from geophysical logs.

A usual approach to this problem was to try to establish a relation between formation factor, porosity and hydraulic conductivity. The first results, obtained from the oil industry during the study of brine-saturated formations (Archie, 1942, 1947, 1950; Tixier, 1958; Shlumberger Corp., 1958; Komarov and Keivszar, 1962; Carothers, 1968) showed that formation factor increases as porosity and permeability decrease.

On the other hand similar investigations concerning fresh-water aquifers (Alger, 1966; Croft, 1971; Kelly, 1977; Kosinski and Kelly, 1981) showed

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0022-1694/85/$03.30

that the formation factor increased with permeability at constant porosity, while some other researchers (Barker and Worthington, 1973; Worthington, 1977; Heigold et al., 1979) found an inverse relationship between formation factor and permeability.

The problem becomes more complicated if one comes to the case of fissured media where we find that there is a lack in the literature concerning similar investigations except of the work of Pirson (1967) and Aguilera (1979), which was developed for naturally fractured oil reservoirs.

The purpose of this paper is to examine the extent to which the hydraulic conductivity of a fissured aquifer can be assessed from parameters measured by geophysical formation logs.

The hydraulic conductivity of a fissured aquifer is mainly a function of the configuration of its physical discontinuities. By assuming low intact matrix conductivity, the yield of a well could be directly related to the total number of fissures intersected by the well. Of course, detection of even a large number of fissures will never guarantee production. It will only increase the possibility of production. Adequate hydraulic conductivity of each fissure system is necessary for a reasonable production of water, but this is not easy to evaluate from the geophysical formation logs. Expressed simply what is in the aquifer and what will come out of it are often two different matters. The geophysical formation logs pertain chiefly to the former.

DESCRIPTION OF THE DOUBLE POROSITY MODEL

Double porosity models have proven very useful in the study of naturally fractured oil reservoirs (Pirson, 1967; Aguilera, 1979; Sherman, 1983). A similar approach will be followed in the present analysis where the aquifer is treated as a double porosity system. There is a difficulty in applying a two-porosity model to fresh-water fissured aquifers, which stems from the fact that when saturating waters are fresh, the electrical conductivities of the mineral grains can no longer be considered as necessarily negligible and appropriate corrections have to be applied.

A general formula which relates the electrical properties of a heterogeneous material to the volume fractions of its constituent materials is the Hanai-Bruggeman equation (Bruggeman, 1935; Hanai, 1960, 1961). Sen (1980) showed how Archie's law can be derived from the Hanai-Bruggeman equation assuming a nonconductive rock matrix while Bussian (1983) expanded Sen's approach to include a conducting lattice-like matrix.

In the present analysis the term apparent formation factor (Worthington, 1977) will be used. If the aquifer were saturated with brine the measured formation factor, F, would be an intrinsic quantity, since the solid constituents affect the electrical conduction only through purely geometric influences. This implies that F is constant irrespective of the resistivity of the saturating fluid (Biella et al., 1983).

When the saturating liquid is fresh water, the electrolyte salinity is not sufficiently high to suppress the effects of surface conduction; and the measured formation factor becomes an apparent quantity which varies with the resistivity of the pore fluid. A correction factor termed effective formation factor is introduced by the following equation:

$$1/F_a = 1/F + R_w/R_r \tag{1}$$

where R_r is the effective resistivity of the solid constituents of the matrix and R_w the resistivity of the saturating water.

Assuming for the moment that the intact matrix of the aquifer is non-conductive, one can say that the electric current of a logging tool passing through the aquifer will follow two paths, one of which is through the fissures and the other through the saturated pore space of the matrix, thus it is like having two different porosity systems connected in parallel (Fig. 1).

A further assumption is that the model is based on a tortuosity-free, parallel conduction path.

Let S_{AV} be the average cross section; S_f be the fissure cross section; S_o be the voids cross section; $R_o(r_o)$ be the matrix resistivity (resistance) at 100% saturation; $R_w(r_w)$ be the resistivity (resistance) of the water; R_{eq} be the equivalent resistivity; ϕ be the total porosity; ϕ_f be the fissure porosity; and ϕ_o be the matrix porosity. The fissure porosity is modeled as an open volume filled with water.

By considering Fig. 1, the following relations can be written:

$$r_o = \frac{R_o \cdot l}{S_{AV} - S_f} \tag{2}$$

$$r_w = \frac{R_w \cdot l}{S_f} \tag{3}$$

$$r_{eq} = \frac{R_{eq} \cdot l}{S_{AV}} \tag{4}$$

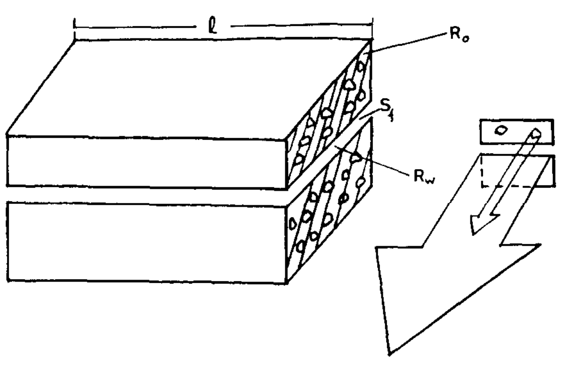

Fig. 1. Double porosity system used to describe the fissured aquifer.

where R_{eq} is calculated from the relation:

$$1/r_{eq} = 1/r_o + 1/r_w \tag{5}$$

from which one obtains the following relation:

$$\frac{1}{R_{eq}} = \frac{S_f}{S_{AV}} \cdot \frac{1}{R_w} + \left(1 - \frac{S_f}{S_{AV}}\right) \cdot \frac{1}{R_o} \tag{6}$$

Obviously for the total porosity one can write:

$$\phi = [(S_{AV} - S_f) \cdot \phi_o + S_f]/S_{AV} \tag{7}$$

Bearing in mind now, that the ratio S_f/S_{AV} represents the fissure porosity, ϕ_f, and solving eqn. (7) in terms of this ratio we take:

$$\phi_f = S_f/S_{AV} = (\phi - \phi_o)/(1 - \phi_o) \tag{8}$$

An important parameter in the study of fissured aquifers is the apportioning of total porosity between matrix porosity and fracture porosity. A quantitative measure of this is introduced below as the fraction of the total pore volume contained in the fractures, f, and will be referred as the fracture (or fissure) index of the aquifer:

$$f = \phi_f/\phi = (\phi - \phi_o)/[(1 - \phi_o) \cdot \phi] \tag{9}$$

Returning to eqn. (6) one can write:

$$\frac{1}{R_{eq}} = \frac{f\phi}{R_w} + (1 - f\phi) \cdot \frac{1}{R_o} \tag{10}$$

Rearranging eqn. (10) and introducing the equivalent formation factor, F_{eq}:

$$F_{eq} = R_{eq}/R_w \tag{11}$$

one obtains:

$$F_{eq} = R_o/[f\phi R_o + R_w \cdot (1 - f\phi)] \tag{12}$$

This is a very important relation because it is the link between the two pore systems.

It is useful to examine the behaviour of eqn. (12) in the following limited cases:

(a) *There are no fractures in the aquifer.* In this case the fissure porosity can be considered as zero, which means that the fissure index of the aquifer is zero. Thus eqn. (12) turns out to be the defining relation for the formation factor of a porous aquifer: $F = R_o/R_w$.

(b) *There are no pores in the aquifer.* In this case the matrix porosity becomes zero, the fissure index of the aquifer becomes one, and since the assumption has been made that the matrix of the aquifer is nonconductive, the term R_o in eqn. (12) must be infinite. Thus one can write:

$$F = 1/\phi$$

$$= \lim_{R_o \to \infty} \frac{1}{\phi + \dfrac{R_w}{R_o}(1-\phi)}$$

indicating that for zero matrix porosity the cementation factor should be close to 1.

Assuming that for a double porosity system the equivalent formation factor is related to the total porosity by a generalized Archie's expression of the form:

$$F_{eq} = \phi^{-m} \quad (13)$$

where m is the equivalent (total) cementation factor for the porous and fissured formation, eqn. (12) can be rearranged as follows:

$$\phi^{-m} = \frac{1}{f\phi + \dfrac{R_w}{R_o}(1-f\phi)} \quad (14)$$

Obviously the term R_o/R_w in the above equation represents the apparent formation factor which is given by (eqn. (1)):

$$R_w/R_o = \phi_o^{m_o} + R_w/R_r \quad (15)$$

Thus, the following very useful formula is obtained:

$$\phi^{-m} = \frac{1}{f\phi + \phi_o^{m_o}(1-f\phi) + \dfrac{R_w}{R_r}(1-f\phi)} \quad (16)$$

This formula correlates the equivalent cementation factor, m (which is usually obtained from a geophysical logging process), with the fissure index of the aquifer, its matrix cementation factor, m_o, and the electrical conductivity of the saturating water and the solid matrix of the aquifer.

Starting from eqn. (16) computer runs were made in order to study some possible combinations of a two-porosity system, which was considered to represent an aquifer. The results obtained, are shown in Fig. 2.

Since the equivalent cementation factor, m, is very useful for the classification of the fissured formation is was decided to investigate to what extent it can be affected by the variation of the electrical conductivity of the saturating water.

Table I shows the variation of m as a function of the resistivity of the water for three different kinds of lithologies, and Fig. 3 is a graphical representation of the obtained results for different values of f.

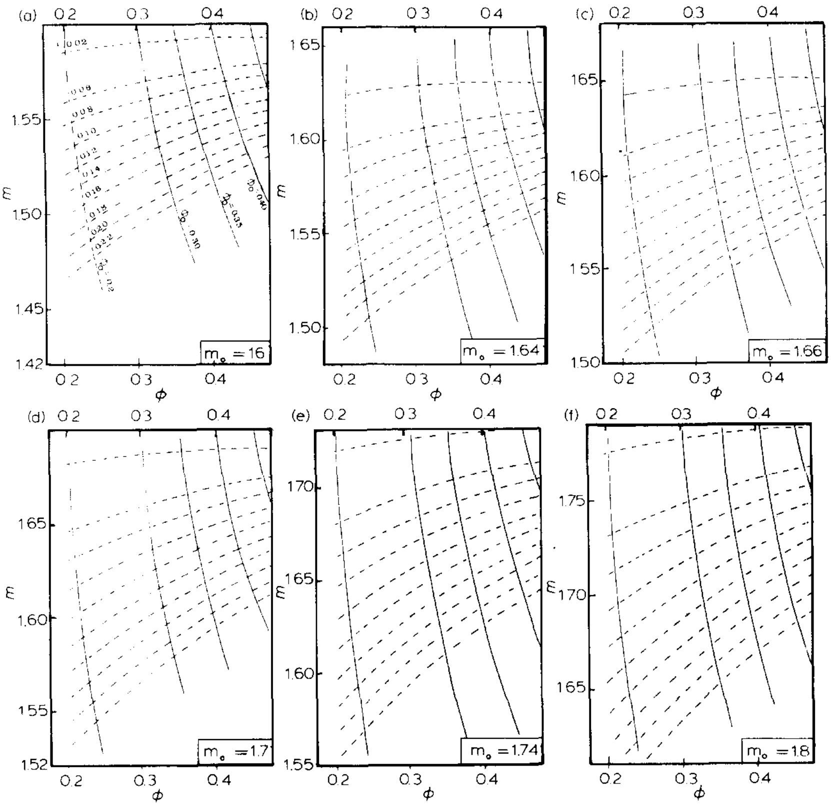

Fig. 2. Relation between the formation parameters of the double porosity model.

TABLE I

Equivalent cementation factor versus effective formation factor $(R_w/R_r)^{-1}$ for three different lithologies and a fissure index of 0.02; a value of $m_o = 2$ was used

Type 1 Limestone $R_r = 3333$ (Ohm m)		Type 2 Clean sandstone $R_r = 125$ (Ohm m)		Type 3 Shaly sandstone $R_r = 11$ (Ohm m)	
R_w/R_r	m	R_w/R_r	m	R_w/R_r	m
0.0006	1.95	0.016	1.76	0.18	0.94
0.0012	1.94	0.032	1.62	0.36	0.57
0.0018	1.93	0.048	1.50	0.54	0.34
0.0024	1.92	0.064	1.40	0.72	0.17
0.0030	1.91	0.08	1.31	0.90	0.04
0.0045	1.90	0.12	1.14	1.36	−0.21
0.0060	1.88	0.16	1.00	1.80	−0.38
0.0075	1.86	0.20	0.88	2.27	−0.52
0.0090	1.84	0.24	0.79	2.72	−0.63
0.0100	1.83	0.28	0.70	3.10	−0.72

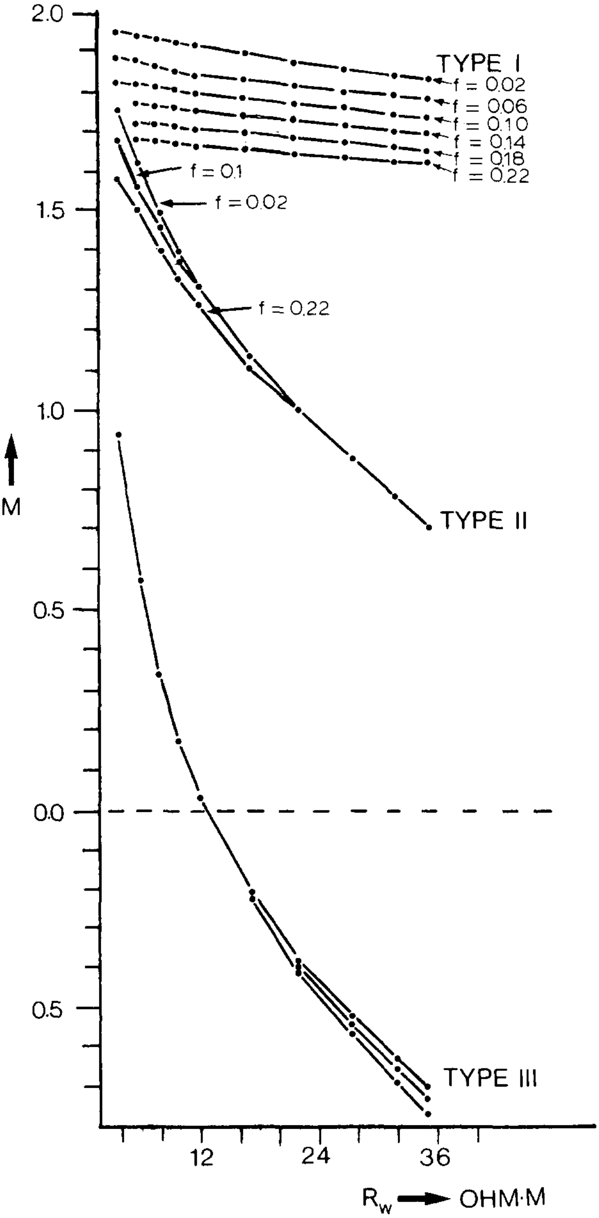

Fig. 3. Equivalent cementation factor versus water resistivity for various degrees of fissuring and for three types of lithology.

DISCUSSION OF THE RESULTS

It is well-known in logging practice that if the aquifer is of low porosity, in most cases the resistivity from a laterolog device is decreased appreciably when the tool's current passes through a fissure system. The amount that the resistivity is lowered is proportional to the ratio of the fissure porosity to the total porosity. Since fissure porosity will decrease the apparent true resistivity to a value below that expected in the same volume of intergranular porosity, one would expect a lower value of the equivalent cementation factor m.

Figure 2 represents in graphical form the relation between the equivalent cementation factor, m, and the total porosity, ϕ, for various values of the fissure index f and matrix cementation factor, m_0. From these charts, one can see the following:

(a) For a constant fissure index, f, the total cementation factor increases with increasing matrix porosity. The effect that the fissure porosity ϕ_f has on the total cementation factor m is shown in Fig. 4. It is obvious that with increasing fissure porosity the equivalent cementation factor, m, decreases; one can note also that the slope of the curves, $m = g(\phi_f)$, becomes less as the initial porosity of the formation increases. In other words, the effect of ϕ_f on m becomes less important with increasing ϕ_0. From the above argument one can say that for a double porosity system the equivalent cementation factor is mainly controlled by the degree of change of the initial porosity, ϕ_0.

(b) For a constant initial porosity, ϕ_0, the equivalent cementation factor, m, increases with decreasing fissure index, f. This is due to the fact that the more compact the "rock" becomes, the larger the cementation factor becomes.

(c) Another important result which is shown on the interpretation charts, and verifies the correctness of the model, is that when the fissure index

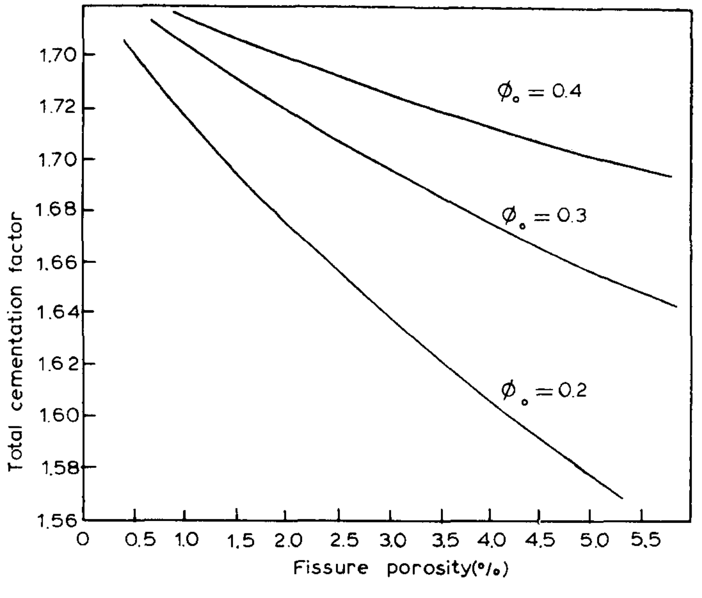

Fig. 4. Equivalent cementation factor versus fissure porosity.

tends to zero, the total porosity tends to the initial porosity; the same also happens when the equivalent cementation factor, m, becomes equal to the initial cementation factor, m_o.

(d) Figure 3 shows the relation between the equivalent cementation factor, m, and the resistivity of the saturating water for various values of the fissure index, f, and for three different types of lithologies.

For Type-1 lithologies (for example, Cretaceous limestone) where the resistivity of the solid constituents of the aquifer's matrix is very high, the equivalent cementation factor, m, is little affected by the variations of the water resistivity, and the effect that the various degrees of fissuring have upon m is clearly shown on the graphs.

For Type-2 lithologies (e.g., clean sandstone) where the resistivity of the solid matrix becomes appreciably less, there is a strong dependence of m upon the resistivity of the water, and as it becomes fresher the effect that fissures have upon m is depressed.

Finally for Type-3 lithologies (e.g., very shaly sandstones) one can see that the dependence of m upon the resistivity of the water is even stronger and on the other hand the effect that fissures have upon m is totally obscured. It should be noted here that when the resistivity of the water passes a certain upper limit, m starts to take negative values.

This example has shown that it is very critical before trying to apply a double porosity model to a fissured aquifer to investigate the dependence of the equivalent cementation factor, m, upon the aquifer's effective formation factor R_r/R_w.

RELATION BETWEEN FISSURE INDEX AND HYDRAULIC CONDUCTIVITY

The dramatic effect of fissures on the hydraulic conductivity of an aquifer is well-established in the literature. In the previous section, a method for measuring the degree of fissuring of an aquifer has been introduced by using for its quantitative measurement the fissure index f. It would be logical now to investigate the existing relation between the fissure index f and the hydraulic conductivity of an aquifer.

The following analysis starts from the fact that f represents the fraction of the total porosity through which a path of least resistance to water flow exists.

By considering a unit block of the aquifer containing a single fissure of width S_f (Fig. 1), and assuming the hydraulic conductivity of the matrix of the aquifer to be negligible, one can write for the equivalent hydraulic conductivity of the block:

$$K = \frac{g}{12v} \cdot (S_f)^2 \qquad (17)$$

Referring to eqn. (8) it becomes obvious that the equivalent hydraulic conductivity of the block can be easily expressed as a function of the aquifer's fissure index f or as a function of the total porosity ϕ:

$$K = \frac{g}{12v} \cdot \left(\frac{\phi - \phi_o}{1 - \phi_o}\right)^2 \tag{18}$$

$$K = \frac{g}{12v} \cdot (f\phi)^2 \tag{19}$$

which, by expressing ϕ in terms of ϕ_o and f, becomes:

$$K = \frac{g \cdot \phi_o^2}{12v} \cdot \left[\frac{f}{1 - f(1 - \phi_o)}\right]^2 \tag{20}$$

By writing K as $\hat{K} \cdot g/v$ where $\hat{K}$ is the permeability, the above formulae can be written as follows:

$$\hat{K} = \frac{1}{12} \left(\frac{\phi - \phi_o}{1 - \phi_o}\right)^2 \tag{21}$$

and:

$$\hat{K} = \frac{1}{12} \cdot \phi_o^2 \cdot \left[\frac{f}{1 - f(1 - \phi_o)}\right]^2 \tag{22}$$

A graphic representation of these relations for a matrix porosity of 30% is shown in Figs. 5 and 6.

By observing Fig. 5 one can deduce that even a small error in the calculation of the fissure index of the aquifer introduces a large error in the calculation of the equivalent permeability. This result demonstrates the great difficulty encountered in practice when we try to measure the hydraulic conductivity of a fissured aquifer using standard geophysical logging techniques.

As it can be seen from eqns. (21) and (22), even for the simple case of an aquifer consisting of parallel fissures, it is necessary to know the total porosity ϕ and the intergranular primary porosity of the formation ϕ_o before being able to make an estimation of the aquifer's hydraulic conductivity.

The initial porosity ϕ_o of the matrix of the aquifer can be taken from a conventional sonic log, while the total porosity ϕ can be estimated either from core analysis techniques or from the less common to hydrology neutron-density logs (Rasmus, 1983).

Since the most important factor in deducing a quantitative estimate of the hydraulic conductivity of fissured aquifers from geophysical formation logs is the degree of accuracy with which this secondary porosity can be measured, it is evident that the higher the initial porosity becomes, the less accurate the evaluation of the hydraulic conductivity. For formations with high initial porosities it is doubtful whether it is possible to obtain accurate

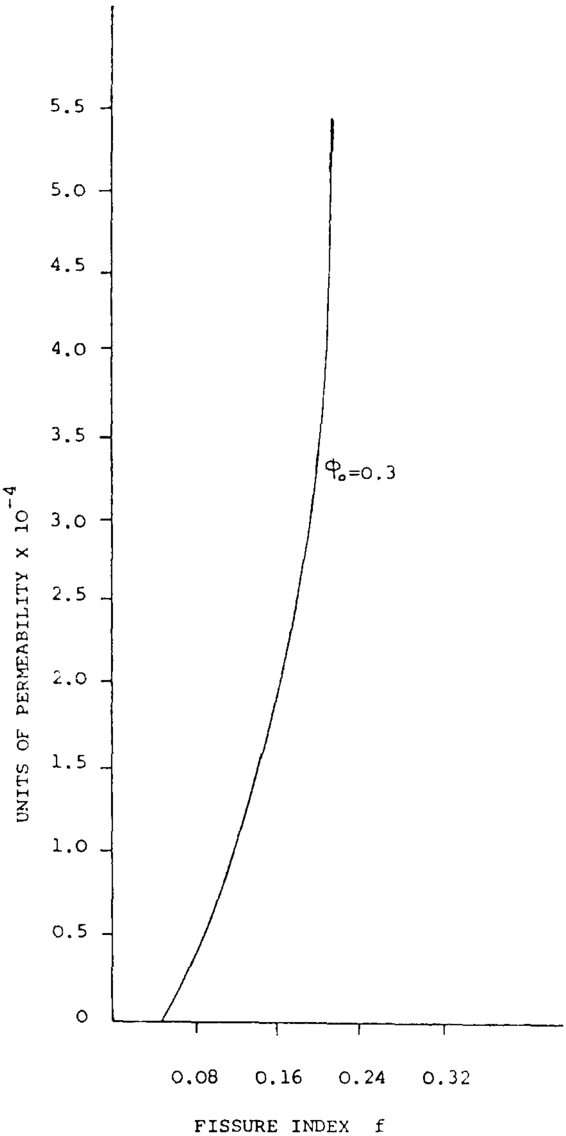

Fig. 5. Permeability versus fissure index.

measurements for the hydraulic conductivity from geophysical measurements alone. For the case of fissured formations with low initial porosity, such as highly cemented limestones, igneous or metamorphic rocks, one should be more optimistic about the existing possibilities of deducing a quantitative measure of the aquifer's hydraulic conductivity from geophysical formation logs alone.

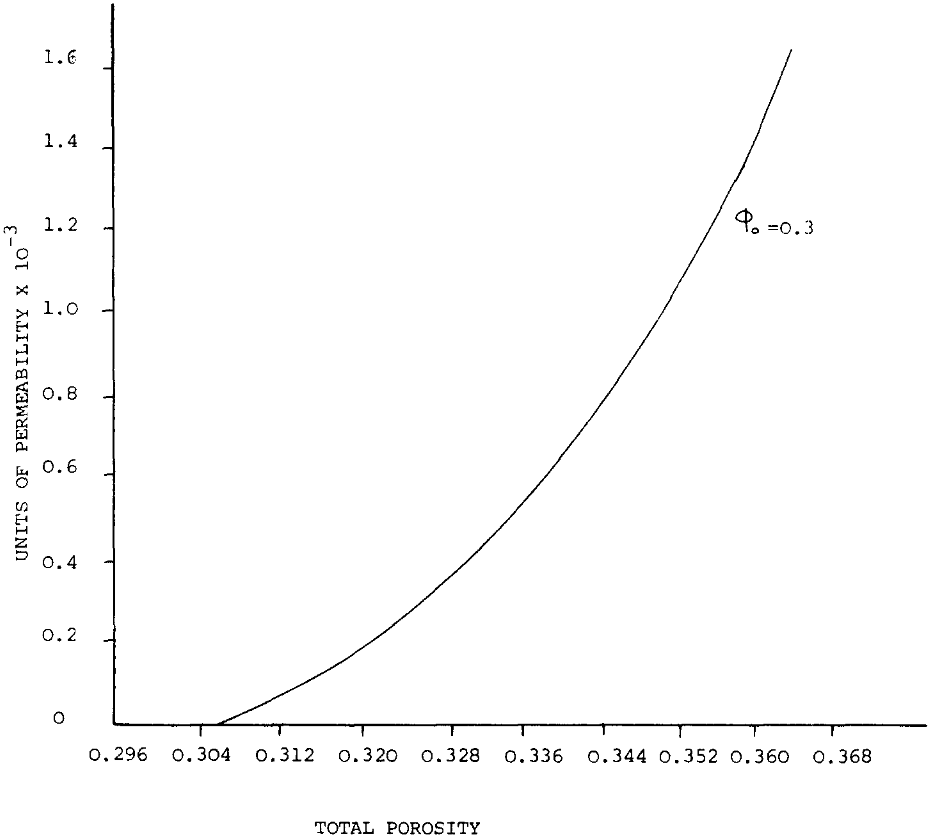

Fig. 6. Permeability versus total porosity.

HYDRAULIC CONDUCTIVITY VERSUS ELECTRIC CONDUCTIVITY

It would be very useful if the mutual relation between hydraulic and electric conductivities could be emphasized, as it is well-known that both of them depend on the degree of fissuring of the aquifer, or in other words its fissure index f.

The main difference between the two conductivities arises from the fact that they originate from two different physical laws: the Hagen-Poissuele and Ohm's law. Because of this, the electric conductivity varies in proportion with the area S of the conductor whereas the hydraulic conductivity in laminar flow varies with S^2.

It is instructive to consider a hypothetical sample consisting of n identical parallel fissures with a total constant cross-sectional area equal to S. Obviously the cross-sectional area of each fissure is:

$$S_i = S/n \qquad (23)$$

Imagine that n is increased beyond any limit, while S is kept constant, thus leaving the electric conductivity of the system unchanged. The hydraulic conductivity, however, is proportional to:

$$n \cdot S_i^2 = n \cdot (S/n)^2 = S^2/n \quad (24)$$

which becomes vanishingly small with increasing n.

From the above simple example, one can see that the determination of the electric conductivity or equivalently, the formation factor, are not enough to determine the hydraulic conductivity, since the first two are sensitive to a different aspect of pore structure whose contribution to the permeability is negligible.

CONCLUDING REMARKS

This paper has examined the existing possibilities of measuring the hydraulic conductivity of a fissured aquifer from geophysical formation logs alone. A simplified double porosity model has been introduced and a quantitative measure of the degree of fissuring of the formation has been defined.

The way that the different formation parameters introduced by the model, correlate with each other has been given in a form of graphs and proved to describe correctly the limiting cases.

A theoretical relationship between the degree of fissuring of the formation and its hydraulic conductivity has been derived and demonstrated the great difficulties encountered in practice when one attempts to deduce a quantitative value of the hydraulic conductivity from geophysical formation measurements alone.

ACKNOWLEDGEMENTS

I thank Dr. M.H. De Freitas of I.C. for his valuable criticisms. The helpful discussions of Dr. T. Bear of LCS, Mr. J. Ellis of SWA, Dr. M. Fleet of WRC, Mr. V. Robinson of NWA and Miss A. Robinson of IGS are acknowledged.

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