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Using borehole electroseismic measurements to detect and describe permeable zones*

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Formulas for the modified Darcy and Ohm laws are obtained. The diffusion coefficient is shown to be a function of the conductivity of the liquid, elastic porous body, and electrokinetic coefficient. A formula for the determination of porosity is obtained.

1: Introduction

Investigation of the collecting properties of oil formations using the core analysis data does not give a full picture of rocks in these formations due to the incomplete core carryover and change in the properties of rocks as they are extracted to the surface.

Methods based on the investigation of borehole operation play an important role in studying the collecting properties of rocks. At the same time, field methods for determining the collecting properties of oil-containing formations give general averaged values of the parameters for the entire cross-section of the packet of layers under exploitation. These data are rather convenient for hydrodynamic calculations. During the exploitation of a deposit, and sometimes even of each borehole in it, a more detailed study of the collecting properties of the formation in its entire thickness is necessary. Methods of petroleum geophysics, which are a powerful tool for the non-core investigation of rocks in the well-bottom zone, can be used for the detailed studies of geological cross-sections of deposits. These methods make it possible to study physical properties of rocks in natural collectors [1].

Cracks or pervious structures in oil formations are important in the investigation and extraction of hydrocarbons. Sandy shales which can be found in sedimentary formations are a very good example of such pervious structures.

In [2, 3], the Stoneley wave was used to estimate the formation and detection of cracks. This wave is sensitive to properties of rocks, such as density, elasticity moduli and, what is most important, permeability. Any change in

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the properties of these parameters due to the rock inhomogeneity leads to change in the characteristics of the Stoneley wave propagation. Therefore, inhomogeneity can be characterized with the help of measurements of the Stoneley wave. Cracks in a borehole are an example of such inhomogeneity. F.L. Paillet and J.E. White [4] observed the attenuation of the Stoneley wave near pervious cracks. B.E. Hornby, D.L. Johnson, K.H. Winkler, and R.A. Plumb [5] showed that pervious cracks also cause the reflected Stoneley waves.

In 1996, O.V. Mikhailov, John Queen, and M. Nafi Toksöz [6] performed field experiments to measure electric fields induced by the borehole Stoneley wave.

The experimental data obtained showed large fracturing of the medium under investigation. Analysis of video images of the borehole showed that it had mainly horizontal cracks. Recording of the cracks' density obtained from these video images demonstrates that there are up to 10 cracks per 1 meter at some depths.

In the experiments, the average frequency of the Stoneley wave was 150 Hz, the dominant wavelength was 9.3 m, and the average velocity was 1400 m/s. To measure the vertical electric field caused by the Stoneley wave, a pair of electrodes placed in the borehole liquid was used in [6]. The vertical electric field measured by the pair of electrodes is a ratio of the potential difference between the electrodes to the distance between them.

Based on the model used in [7], the authors of [6] showed that the normalized amplitude of the electric field (the ratio of the electric field to the pore pressure in the borehole) generated by the Stoneley wave is proportional to porosity:

$$d_0 = \left|\frac{E_z}{P_b}\right| \frac{\alpha_\infty \tilde{\mu}}{|\zeta|\varepsilon} \frac{c_s}{\omega} \left(\sigma_r + \sigma_f \frac{I_1\left(\frac{\omega}{c_s}R_b\right)}{I_0\left(\frac{\omega}{c_s}R_b\right)} \frac{K_0\left(\frac{\omega}{c_s}R_b\right)}{K_1\left(\frac{\omega}{c_s}R_b\right)}\right). \tag{1}$$

Here E_z is the vertical component of the electric field in the borehole, P_b is the pressure in the borehole, $I_0(z)$ and $K_0(z)$ are the modified zero-order Bessel functions of the first and second kinds, respectively, c_s is the Stoneley wave velocity with the circular frequency ω, ζ is the zeta-potential, $\tilde{\mu}$ is the viscosity of the liquid, α_∞ is the tortuosity, ε is the dielectric permeability of the liquid, σ_f and σ_r are the conductivities of the liquid and elastic porous body, respectively, and R_b is the borehole radius.

Note that in accordance with this formula porosity does not depend on some important parameters, such as permeability, as well as on the physical density of the liquid and elastic porous body.

Figure 1 shows distributions with depth of the measured normalized electric field E/P (first curve), conductivity of the elastic porous body σ_r (second curve), the porosity d_0 calculated by formula (1) (third curve), and

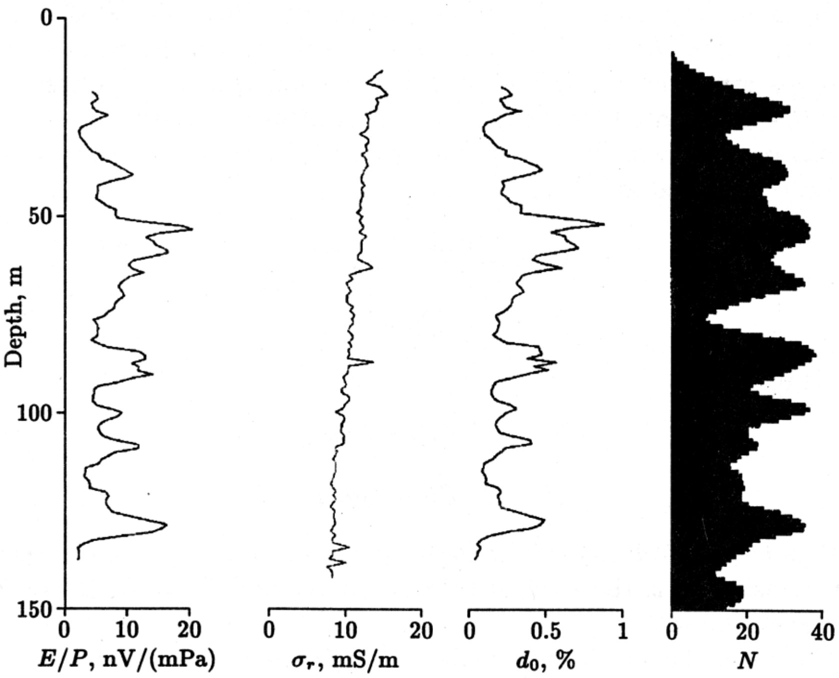

Figure 1

the averaged fracture density N (fourth curve). In the figure, one can see a strong correlation of the normalized amplitudes of the electric field caused by the Stoneley wave with the averaged fracture density.

To determine the permeability k, the following formula is proposed in [8]:

$$k = \frac{d_0 \tilde{\mu}}{\omega_c \alpha_\infty \rho_f} \frac{2}{M}. \tag{2}$$

Here ρ_f is the physical density of the conducting liquid, ω_c is the critical frequency in the Biot theory, and M is a non-dimensional parameter depending on the geometry of pores.

It was assumed in the experiments that the frequency of the Stoneley wave is less than ω_c. This assumption is equivalent to the postulate that the permeability k is smaller than 10 ∂ (darcies) [6]. Unfortunately, no experimental data for permeability are presented in [6].

In this paper, using the mathematical model of a conducting liquid through a conducting elastic porous medium [9, 10], we verify the correctness of the experimental data [6]. Formulas for the determination of porosity and permeability, which differ from (1) and (2), are obtained. The calculated porosity (at the given permeability) is in a good qualitative agreement with that calculated by using formula (1) in [6]. At the same time, the permeability coefficients calculated by the model [9, 10] (at the given porosity found by using formula (1)) differ from the permeability calculated with the help of (2) in [6]. As noted in [1], the permeability coefficient of rocks in oil and gas formations is less than 2 or 3 ∂, and is seldom greater. The permeability calculated by the model confirms this statement.

It has been shown, first, that the modified Darcy and Ohm laws differ from those proposed in [11–13],

$$\boldsymbol{V} = -\frac{k}{\tilde{\mu}}\nabla p - L_1\nabla U, \tag{3}$$

$$\boldsymbol{J} = -L_2\nabla p - \sigma_f\nabla U, \tag{4}$$

and in [14],

$$\boldsymbol{V} = -\frac{k}{\tilde{\mu}}\nabla p - L_1\boldsymbol{E}, \tag{5}$$

$$\boldsymbol{J} = L_2\nabla p + d_0\sigma_f\boldsymbol{E}. \tag{6}$$

Here $\boldsymbol{V}$ is the 3D velocity of the liquid per unit volume, $\boldsymbol{J}$ is the electric current density, U is the electric field potential, and $L_1 = L_2$ is the electrokinetic coefficient.

In this case, the coefficients in the determination of the electric current density depend on permeability (in contrast to [6, 7, 11–14]), as well as on the physical densities of the elastic porous body and liquid.

Second, in contrast to [15], the diffusion coefficient is a function of the conductivity of the liquid and elastic porous body as well as of the electrokinetic coefficient.

Third, in the limiting case the Helmholtz–Smolukhovsky law

$$\boldsymbol{E} = -\frac{\varepsilon\zeta}{4\pi\tilde{\mu}\sigma_f}\nabla p \tag{7}$$

is satisfied.

2. A modified Darcy law with allowance for electric current density

Here we show that the Darcy law modified with allowance for current density is obtained in the particular case of the mathematical model of a conducting liquid through a conducting porous medium in [9, 10]. An equation for the pore pressure distribution is obtained. It turned out here that the diffusion coefficient is a function of the electrokinetic coefficient.

Let us consider the simplest situation in which viscosity and heat conduction effects are not taken into account. With a linear accuracy, the equation of motion of a conducting liquid ($\dot{\boldsymbol{v}} = 0$, $\boldsymbol{u} = 0$, $\boldsymbol{B} = 0$) has the following form (cf. [9, 10]):

$$\rho_l \boldsymbol{v} = -\frac{\nabla p}{\chi\rho} - \frac{\gamma}{\chi}\boldsymbol{E}. \tag{8}$$

Here $\rho = \rho_l + \rho_s$, ρ_l and ρ_s are the partial densities of the conducting liquid and conducting elastic porous body, respectively, χ is the friction coefficient, and γ is the electrokinetic coefficient. These coefficients and the conductivity $\sigma = \sigma_f + \sigma_r$ satisfy the inequality [10],

$$\sigma\chi - \gamma^2 > 0. \tag{9}$$

Note, in particular, that the theory in [9] admits that the Darcy [16] and Helmholtz–Smolukhovsky (7) laws are satisfied. Actually, assuming in (8) that $\boldsymbol{E} = 0$, we obtain the Darcy law

$$\boldsymbol{v} = -\frac{\nabla p}{\chi\rho\rho_l}.$$

At $\boldsymbol{v} = 0$, from (8) we obtain the Helmholtz–Smolukhovsky formula

$$\boldsymbol{E} = -\frac{\nabla p}{\gamma\rho}.$$

Comparing these formulas with (3) (in the case when $L_1 = 0$) and (5), we obtain the following expressions for the determination of the friction and electrokinetic coefficients:

$$\chi = \frac{\tilde{\mu}}{k\rho\rho_l}, \tag{10}$$

$$\gamma = \frac{\beta}{\rho} \equiv \frac{4\pi\tilde{\mu}\sigma_f}{\rho\varepsilon\zeta}. \tag{11}$$

It should be noted that the electrokinetic coefficient is proportional to the viscosity coefficient, but does not depend on the permeability coefficient of the conducting liquid.

Substituting (8) into the definition of the current density [10], we obtain

$$\boldsymbol{J} = -\frac{\gamma}{\chi\rho}\nabla p + \frac{\sigma\chi - \gamma^2}{\chi}\boldsymbol{E}, \tag{12}$$

Following [6], we write equations for the electric field $\boldsymbol{E}$ and the current density $\boldsymbol{J}$,

$$\operatorname{div} \boldsymbol{J} = 0, \tag{13}$$

$$\operatorname{rot} \boldsymbol{E} = 0. \tag{14}$$

Let us represent the electric intensity (12) in terms of the pore pressure and the current density, and substitute the expression obtained into (8). As a result, the modified Darcy law has the following form:

$$\rho_l v = -\frac{\sigma}{\rho(\sigma\chi\gamma^2)}\nabla p - \frac{\gamma}{\sigma\chi - \gamma^2}\boldsymbol{J}, \tag{15}$$

Substituting these relations into the conservation law of mass and taking into account (13), we obtain the following heat conduction equation for the pore pressure:

$$\frac{\partial p}{\partial t} - \frac{\sigma c_f^2}{\rho(\sigma\chi\gamma^2)} - \Delta p = 0.$$

Here c_f is the velocity of the liquid.

Comparing formulas (3), (4) ($-\nabla U = \boldsymbol{E}$) and (5), (6) with formulas (8) and (12), we see that

$$L_1 \neq L_2.$$

3. Pore pressure distribution generated by the Stoneley wave in the near-borehole space

In this section, we solve a model axially symmetric problem for pore pressure distribution generated by the Stoneley wave in an infinite liquid-saturated porous medium with a cylindrical cavity of radius r_0 and infinite length (borehole). A pressure $p_0 \exp(-i\omega t + i\omega z/c_s)$ is specified at the boundary of this medium. Mathematically, the problem is formulated as follows: it is necessary to determine pore pressure distributions from the relations

$$\Big(\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} - \frac{\omega^2}{c_s}\Big)p_c = 0, \quad r < r_0, \tag{16}$$

$$\Big(\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} - \frac{\omega^2}{c_s} + i\frac{\omega}{D}\Big)p = 0, \quad r > r_0, \tag{17}$$

$$p_c|_{r=r_0-0} = p|_{r=r_0+0}. \tag{18}$$

In equation (17), $D = \frac{\sigma c_f^2}{\rho(\sigma\chi - \gamma^2)}$.

Bounded solutions of system (16)–(18) have the following form:

$$p_c(t,r,z) = p_0 \frac{I_0\Big(\frac{\omega}{c_s}r\Big)}{I_0\Big(\frac{\omega}{c_s}r_0\Big)} \mathrm{e}^{-i\omega t + i\frac{\omega}{c_s}z}, \quad r < r_0, \tag{19}$$

$$p(t,r,z) = p_0 \frac{K_0\Big(r\sqrt{-i\frac{\omega}{D} + \frac{\omega^2}{c_s^2}}\Big)}{K_0\Big(r_0\sqrt{-i\frac{\omega}{D} + \frac{\omega^2}{c_s^2}}\Big)} \mathrm{e}^{-i\omega t + i\frac{\omega}{c_s}z}, \quad r > r_0. \tag{20}$$

Thus, the electrokinetic coefficient does not affect the pore pressure distribution in the borehole. It affects the pore pressure distribution in the near-borehole space.

4. Electric field distribution generated by the Stoneley wave in the borehole and near-borehole space

In this section, formulas for the calculation of electric intensity distribution generated by the Stoneley wave in the borehole and near-borehole space are obtained.

It follows from equation (14) that

$$\boldsymbol{E} = -\nabla U. \tag{21}$$

Then the potentials in the borehole and near-borehole space satisfy the Laplace and the Poisson equations, respectively:

$$\Delta U_c = 0, \tag{22}$$

$$\frac{\sigma\chi - \gamma^2}{\chi}\Delta U = -\frac{\gamma}{\rho\chi}\Delta p. \tag{23}$$

On the borehole wall, the electric field potential and the normal component of electric current are continuous,

$$U_c|_{r=r_0-0} = U|_{r=r_0+0}, \quad \sigma_f \frac{\partial U_c}{\partial r}\bigg|_{r=r_0-0} = \frac{\sigma\chi - \gamma^2}{\chi}\frac{\partial U}{\partial r} + \frac{\gamma}{\chi\rho}\frac{\partial p}{\partial r}\bigg|_{r=r_0+0}. \tag{24}$$

The axially symmetric bounded solutions of equations (22) and (23) have the following form:

$$U_c(t,r,z) = A_1 \frac{I_0\left(\frac{\omega}{c_s}r\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)} \mathrm{e}^{-i\omega t + i\frac{\omega}{c_s}z}, \quad r < r_0, \tag{25}$$

$$U(t,r,z) = -\frac{\gamma}{\rho(\sigma\chi\gamma^2)}p(t,r,z) + A_2 \frac{K_0\left(r\sqrt{-i\frac{\omega}{D} + \frac{\omega^2}{c_s^2}}\right)}{K_0\left(r_0\sqrt{-i\frac{\omega}{D} + \frac{\omega^2}{c_s^2}}\right)} \mathrm{e}^{-i\omega t + i\frac{\omega}{c_s}z}, \quad r > r_0. \tag{26}$$

Here $p(t,r,z)$ is determined with the help of formula (20), and A_1 and A_2 are arbitrary constants.

Substituting (25) and (26) into (24), we obtain the following system of linear non-homogeneous algebraic equations for A_1 and A_2:

$$A_1 = -\frac{\gamma}{\rho(\sigma\chi - \gamma^2)}p_0 + A_2, \qquad -\sigma_f A_1 = \frac{\sigma\chi\gamma^2}{\chi} A_2 \frac{I_0\left(\frac{\omega}{c_s}r_0\right)}{I_1\left(\frac{\omega}{c_s}r_0\right)} \frac{K_1\left(\frac{\omega}{c_s}r_0\right)}{K_0\left(\frac{\omega}{c_s}r_0\right)}.$$

Solutions of this system of linear non-homogeneous algebraic equations have the following form:

$$A_1 = -\frac{\gamma}{\rho\chi}p_0\left(\frac{\sigma\chi-\gamma^2}{\chi}+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)^{-1},$$

$$A_2 = \frac{\gamma}{\rho(\sigma\chi-\gamma^2)}p_0-\frac{\gamma}{\rho\chi}p_0\left(\frac{\sigma\chi-\gamma^2}{\chi}+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)^{-1}.$$

Substituting these coefficients into (25) and (26), we obtain a solution for electric potentials in the borehole and near-borehole space. The vertical component of the electric field in the borehole is

$$E_z(t,r,z) = \frac{i\omega}{c_s}\left(\frac{\gamma}{\rho\chi}-p_0\right)\left(\frac{\sigma\chi-\gamma^2}{\chi}+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)^{-1}\times$$
$$\frac{I_0\left(\frac{\omega}{c_s}r\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}e^{-i\omega t+i\frac{\omega}{c_s}z},\quad r<r_0. \tag{27}$$

Hence, using the expression for pore pressure in the borehole (19), we obtain

$$\frac{E_z(t,r,z)}{p_c(t,r,z)} = i\frac{\omega}{c_s}\frac{\gamma}{\rho\chi}\left(\frac{\sigma\chi-\gamma^2}{\chi}+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)^{-1}. \tag{28}$$

Thus, we see that the ratio between the vertical component of electric intensity E_z in the borehole and the pressure distribution in the borehole p_{bh} is a function of porosity and, in contrast to [6], it is also a function of permeability and physical densities of the elastic porous body and liquid.

Using (10) and (11), we obtain from (28) after simple transformations

$$\frac{\rho}{\rho_l} = \frac{k}{\bar{\mu}}\left(\beta^2+|\beta|\left|\frac{p_c}{E_z}\right|\frac{\omega}{c_s}\right)\left(\sigma+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)^{-1}. \tag{29}$$

Hence, using the definitions of partial densities $\rho_l = \rho_l^f d_0$, $\rho_s = \rho_s^f(1-d_0)$ [17], we obtain:

$$d_0 = \frac{\rho_s^f}{\rho_l^f}\frac{\sigma+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}}{\frac{\rho_s^f-\rho_l^f}{\rho_l^f}\left(\sigma+\sigma_f\frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)}\frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)+\frac{k}{\bar{\mu}}\left(\beta^2+|\beta|\left|\frac{p_c}{E_z}\right|\frac{\omega}{c_s}\right)}. \tag{30}$$

Here ρ_l^f and ρ_s^f are the physical densities of the conducting liquid and conducting elastic porous body, respectively.

Notice that this formula fundamentally differs from (1). Moreover, porosity depends on permeability, and on the ratio between the physical density of the elastic porous body and that of the liquid.

5. Numerical modeling. Comparison of results with experimental data for borehole observations

The porosity distribution for granite was obtained from electroseismic experimental data by using formula (30) [6]. The physical density of the conducting elastic porous body and the permeability coefficient k took the following values: $\rho_s^f = 2650$ kg/m^3 [15] and $k = 1.7 \cdot 10^{-5}\ \partial$. Porosity distribution for a depth range from 19 to 137 m is presented in Figure 2. This result is in good agreement with the averaged fracture density experimentally determined (see curve 4 in Figure 1). The calculated distribution of the function $G(z) = \frac{\tilde{\mu}\sigma(z)}{k\rho(z)\rho_l(z)} - \gamma^2(z)$ is given in Figure 3. One can see from the plot of the function $G(z)$ that it is distinctly different from zero, that is, inequality (9) is valid. Physically, this means that the law of entropy increase is satisfied.

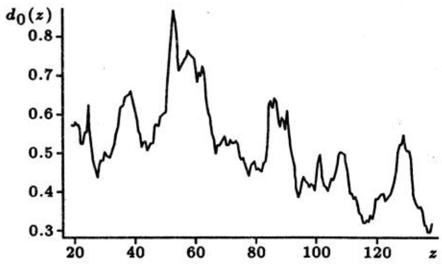

Figure 2

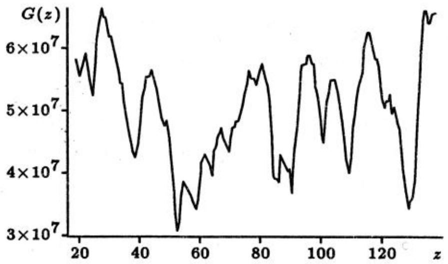

Figure 3

Then, if we assume that the permeability coefficient is unknown and that, in accordance with formula (2), the porosity is known, we have

$$k = \frac{\rho}{\rho_l}\left(\sigma + \sigma_f \frac{I_1\left(\frac{\omega}{c_s}r_0\right)}{I_0\left(\frac{\omega}{c_s}r_0\right)} \frac{K_0\left(\frac{\omega}{c_s}r_0\right)}{K_1\left(\frac{\omega}{c_s}r_0\right)}\right)\left(\beta^2 + |\beta|\left|\frac{p_c}{E_z}\right|\frac{\omega}{c_s}\right)^{-1}\tilde{\mu}.$$

Plots for the permeability coefficients (at the given porosity calculated by using formula (1)), are given in Figures 4 and 5. The permeability coefficients calculated by using the model are different from the permeability calculated by formula (2) [6]. As noted in [1], the permeability coefficient of

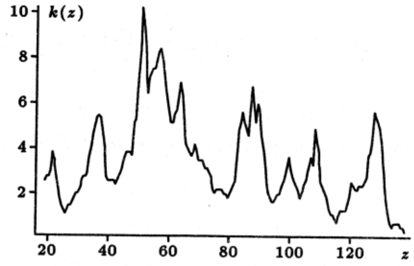

Figure 4

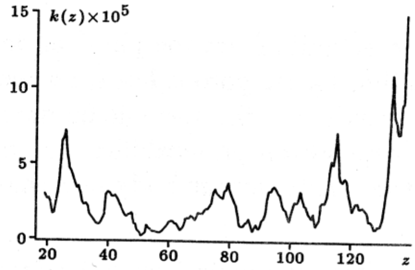

Figure 5

the rocks in oil and gas formations is less than 2–3 ∂, and is seldom greater. The permeability calculated by the model confirms this statement.

Thus, the numerical calculations and their comparison with experimental data show that measurements of electroseismic phenomena caused by the Stoneley wave can be used to characterize the pervious formations.

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