Hydrology and Earth System Sciences, 3(3), *421–427* (1999) © EGS

Hydrology & Earth System Sciences

Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements

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Abstract

Fluid transmissivity (layer thickness times permeability) and electric transverse resistance (layer thickness times resistivity) are important parameters in groundwater and hydrocarbon exploration. Determination of these parameters provides a good knowledge of the potential of porous media, because they relate fluid flow to electric-current conduction, in terms of layer thickness, permeability and resistivity. In this study, both parameters were determined for shallow aquifers (Schleswig-Holstein, northern Germany) and deep reservoirs (Jeanne d'Arc Basin, offshore of eastern Canada), utilizing surface and well-log electric measurements. Direct relationships between both parameters, with coefficients of correlation of 0.99 (for the aquifers) and 0.94 (for the reservoirs), were obtained. The relationships suggest that an increase in both parameters indicate presence of zones of high fluid potential within the aquifers and the reservoirs.

Introduction

Relationships between fluid transmissivity (or simply transmissivity, also known as transmissibility; T_f), electric transverse unit resistance (or simply transverse resistance; T_e) and electric longitudinal unit conductance (or simply longitudinal conductance; S_e) are based on the nature of relationships between hydraulic conductivity (permeability; k) and electric resistivity (R; reciprocal of electric conductivity). Since the mechanisms of fluid flow and electric-current conduction through porous media are generally governed by the same physical parameters and lithological attributes, the hydraulic and electric conductivities are dependent on each other.

Several studies have been carried out to investigate the interconnection between hydraulic and electric parameters that govern fluid flow and electric-current conduction through porous media (e.g., Archie, 1942; Patnode and Wyllie, 1950; Wyllie and Rose, 1950; Jones and Buford, 1951; Wyble, 1958; Schopper, 1966; Zohdy, 1969; Barker and Worthington, 1973; Aguilera, 1976; Henriet, 1976; Worthington, 1976; Brace, 1977; Campbell, 1977; Kelly, 1977; Jackson *et al.*, 1978; Schimschal, 1981; Urish, 1981; Biella *et al.*, 1983; Worthington, 1983; Kelly and Reiter, 1984; Ponzini *et al.*, 1984; Wong *et al.*, 1984; Frohlich and Kelly, 1985; Mazac *et al.*, 1985; Niwas and Singhal, 1985; Worthington, 1986; Alger and Harrison, 1989; Salem, 1994; Hernández and Skianis, 1999; Salem and Chilingarian, 1999a, b).

In nature, the sediments are commonly deposited in such a way that their hydraulic and electric conductivities are greater in the horizontal direction than in the vertical direction. This phenomenon produces flow channels parallel to the bedding planes, which are different from those normally oriented towards the bedding planes, and thus, the medium is described as hydraulically and electrically anisotropic. Variations of hydraulic and electric parameters are greatly affected by the formation anisotropy (λ). For each formation independently, λ can be defined in terms of the hydraulic anisotropy (λ_h) and electric anisotropy (λ_e). The λ_h is due to variations of permeability, k, and λ_e is due to variations of electric resistivity, R, horizontally along the bedding planes and vertically across the bedding planes. The properties of a porous medium are relatively similar in the horizontal (X and Y) directions, but are different in the vertical (Z) direction, and thus, the medium is described as an anisotropic system, with axi-symmetric or transverse anisotropy. When k and R in the horizontal direction are equal to k and R in the vertical direction, the medium is described as an isotropic system. Both hydraulic and electric anisotropies are attributed to various factors, including for instance, lithology; size, shape, type (mineralogy), packing and orientation of grains; shape and geometry of pores and pore channels; magnitudes of porosity, tortuosity and permeability; degrees of compaction, consolidation and cementation; and depth variations.

Areas of investigation

The glacial aquifers of *Schleswig-Holstein (S-H), northern Germany*, are of Pleistocene age. They are saturated with fresh water, and have a thickness ranging from approximately 30 to 70 m, depending on the water-table level. They are composed of glacial deposits that primarily consist of silts, sands and gravels, with a small amount of clays, and a variety of grain size. Large quantities of the sands and gravels were deposited as outwash sediments. They were swept out from the melting glaciers by the melt-water streams and moraines in front of the glaciers. The S-H aquifers are underlain by an aquiclude composed of glacial clays, known as 'Geschiebemergel', and are overlain by the aeration zone which is overlain by the weathering zone.

The Mesozoic-Cenozoic Atlantic Ocean basins, off the eastern margin of North America, including the *Jeanne d'Arc Basin (JDB), offshore of the eastern coast of Canada*, developed sequentially as sea-floor spreading that propagated from south to north. The JDB, of Jurassic-Cretaceous age, is one of the deepest of the Mesozoic basins. Deep reflection seismic and potential measurements revealed that the JDB has a thickness of about 20 km, characterized by trans-basinal fault systems. The JDB-reservoirs are complex systems composed of compacted and consolidated rocks saturated with multi-phase fluids (oil, gas and brine). Lamination and layering, as well as contrasting lithology are distinguishing features of the JDB-reservoirs. The reservoirs, classified as shaly sandstone 'dirty'reservoirs, are composed of mixtures of shalestones, sandstones, siltstones, carbonates (limestones and dolomites), marlstones and conglomerates, with fine to medium grain size. Chemical, physical and tectonical diagenetic effects, occurring in the JDB during and after deposition but before consolidation, continuously change the flow performance, and act to produce directional variations in various physical properties. The presence of considerable amounts of shalestones and siltstones, enriched with plate-like minerals (clays and micas) and elongated-type minerals (feldspars); and the presence of micro- and macro-scaled structural elements resulted from the stress-strain mechanism, enhance the contrasts in the hydraulic, electric, elastic and thermal properties of the JDB-reservoirs.

Theory

Starting with the *hydraulic properties*, the contrast between the horizontal (longitudinal) permeability (k_h) and the vertical (transverse) permeability (k_v) is remarkable for layered media made of unconsolidated sediments or consolidated rocks saturated with water and/or hydrocarbons. For different consolidated sedimentary rocks and unconsolidated sediments, Wyllie and Spangler (1952) showed that the permeability ratio (k_h/k_v), along and across the bedding planes, is related to the square of the ratio of the formation resistivity factor (F_v/F_h), across and along the bedding planes [$F = R_b/R_w = 1/\phi^m$, where F = formation resistivity factor, R_b = bulk resistivity, R_w = pore-water resistivity, ϕ = porosity, m = cementation factor (Archie, 1942)]:

$$(k_h/k_v) = (F_v/F_h)^2. \tag{1}$$

For a column of layers (i to n), each of which has thickness h_i and permeability k_i, the horizontal permeability, k_h, and the vertical permeability, k_v, can be defined, respectively, as (Harr, 1962):

$$k_h = \sum_{i=1}^{n} (k_i h_i) \Big/ \sum_{i=1}^{n} h_i, \text{ and} \tag{2}$$

$$k_v = \sum_{i=1}^{n} h_i \Big/ \sum_{i=1}^{n} (h_i / k_i). \tag{3}$$

The equivalent permeability (k_{eq}) and the effective permeability (k_{eff}) can be defined, respectively, as (Harr, 1962; Moran and Finklea, 1962):

$$k_{eq} = (k_h k_v)^{1/2}, \text{ and} \tag{4}$$

$$k_{eff} = (k_h^2 k_v)^{1/3}. \tag{5}$$

The effective permeability, k_{eff}, falls between k_h and k_v, but it is twice as sensitive to k_h as to k_v. For hydrocarbon reservoirs saturated with multi-phase fluids (oil, gas and water), k_{eff} is a good measure of flow of fluids that interfere with each other during their transport through the pore channels of reservoirs. The effective permeability is different from the absolute permeability that describes flow of a single fluid. It is also different from the relative permeability that is used to indicate the ability of flow of each fluid (oil, gas or water). In addition, k_{eff} is a good measure of permeability variations horizontally and vertically. These characteristics make k_{eff} a sufficient parameter in describing fluid flow in porous media saturated either with a single fluid or multi-fluids (Schlumberger Co., 1992; Salem, 1994; Tiab and Donaldson, 1996).

The transmissivity (T_f; expressed in m^2hr^{-1}, m^2day^{-1} or m^2yr^{-1}) indicates the ability of layer i, with permeability k_i, to transmit fluid(s) through its entire thickness h_i, i.e., $T_f = k_i h_i$ (Theis, 1935). Because of the above-mentioned characteristics of k_{eff}, the layer permeability, k_i, is substituted by k_{eff} in the definition of T_f:

$$T_f = k_{eff} h_i. \tag{6}$$

The hydraulic anisotropy coefficient, λ_h, can be defined in terms of k_h and k_v as (De Marsily, 1986):

$$\lambda_h = (k_h/k_v)^{1/2}. \quad (7)$$

For the same column of layers (i to n), the *electric properties* can be represented in terms of electric resistivity, R_i, and thickness, h_i, for each layer independently. When electric current is conducted through layer i, the current is confronted by resistivity along the bedding planes different from that across the bedding planes, unless the medium is completely uniform. The dependence of resistivity on the direction of electric current constitutes an effective anisotropy caused by the layering and not necessarily by inherent anisotropy within the layers (Keller, 1966). This is due to the fact that the longitudinal (horizontal) resistivity (R_h) along the bedding planes is less than the transverse (vertical) resistivity (R_v) across the bedding planes. The current density along the bedding planes is greater than that normal to the bedding planes, and thus, the horizontal electric conductivity is greater than the vertical one. This indicates that electric current and fluid flow have greater conductivities along the bedding planes than across them. Therefore, electric current and fluid flow behave in the same manner, in terms of conductivity (electric and hydraulic).

For n layers, behaving as resistors connected in parallel, through which the electric current flows parallel to their bedding planes, the longitudinal unit conductance (S_e) (= S_i for layer i) and the total longitudinal conductance (S_t) are defined, respectively, as:

$$S_i = h_i / R_i, \text{and} \quad (8)$$

$$S_t = \sum_{i=1}^{n} (h_i / R_i). \quad (9)$$

Equations (8) and (9) lead to the definition of the horizontal resistivity, R_h, as the total thickness of the layers (H) divided by the total longitudinal conductance, S_t:

$$R_h = H / S_t = \sum_{i=1}^{n} h_i \Big/ \sum_{i=1}^{n} (h_i / R_i). \quad (10)$$

For n layers, behaving as resistors connected in series, through which the electric current flows perpendicular to their bedding planes, the transverse unit resistance (T_e) (= T_i for layer i), and the total transverse resistance (T_t) are defined, respectively, as:

$$T_i = h_i R_i, \text{ and} \quad (11)$$

$$T_t = \sum_{i=1}^{n} T_i. \quad (12)$$

Equations (11) and (12) lead to the definition of the vertical resistivity, R_v, as the total transverse resistance, T_t, divided by the total thickness of the layers, H:

$$R_v = T_t / H = \sum_{i=1}^{n} (h_i R_i) \Big/ \sum_{i=1}^{n} h_i. \quad (13)$$

The effective resistivity (R_{eff}), also known as root mean square resistivity, can be obtained as (Maillet, 1947; Battacharya and Patra, 1968; Schlumberger Co., 1990; Salem, 1994):

$$R_{eff} = (R_v R_h)^{1/2}. \quad (14)$$

Maillet (1947) described Eqs. (8-14), which define the 'Dar Zarrouk Parameters; DZP', as fundamental equations in electrical prospecting. Based on these equations, Maillet (1947) defined the electric anisotropy, λ_e, as:

$$\lambda_e = (R_v/R_h)^{1/2}. \quad (15)$$

The effective resistivity, R_{eff}, can also be obtained in terms of λ_e as (Maillet, 1947; Bhattacharya and Patra, 1968; Schlumberger Co., 1990; Salem, 1994):

$$R_{eff} = \lambda_e R_h = (1/\lambda_e) R_v. \quad (16)$$

Hydraulically and electrically, each layer can be described as a micro-anisotropic unit with hydraulic (λ_h) and electric (λ_e) anisotropy coefficients, each of which has the value of one ($k_h = k_v$ and $R_h = R_v$). Higher values of λ_h, associated with lower values of λ_e, usually correspond to higher potential zones within a porous medium.

Methodology

The transmissivity, T_f, and the transverse resistance, T_e, were determined for the S-H aquifers and the JDB-reservoirs from surface and borehole electric measurements. To determine T_f, the thickness (h_i) and permeability (k_i) are required for each layer independently. For the S-H aquifers, h_i (in m) was obtained from surface electric measurements (vertical electric sounding; VES, using Schlumberger configuration), and k_i (in ms^{-1}) was obtained from empirical equations, with respect to the formation resistivity factor, F. The F was obtained as R_b/R_w (bulk resistivity divided by pore-water resistivity). The R_b (= R_i, in Ω.m) was obtained from VES, and R_w (in Ω.m) was obtained from chemical analysis of the pore water.

Various logs of several wells penetrating the JDB-reservoirs were analyzed at sampling-depth intervals of 0.2 m for a total thickness ranging from about 200 to 600 m. The total thickness was divided into several layers (each of which has a thickness h_i), depending on variations of the lithological and physical properties of the reservoirs. The permeability (k_i), in mD, was obtained in accord with the equation of Timur (1968), which requires the porosity (ϕ) and the formation resistivity factor (F), as well as other parameters. The ϕ was determined from a combination of different logs (gamma ray, sonic, density, and different electric logs), and F was determined as R_b/R_w (where R_b was obtained from the deep induction resistivity log, and R_w was obtained from the spontaneous potential log.

The values of h_i, k_i and R_i, obtained for the S-H aquifers and the JDB-reservoirs, were used in the equations given in 'Theory' to determine T_f and T_e. To compare between the hydraulic parameters determined for the S-H aquifers and those determined for the JDB-reservoirs, the aquifers' permeability (obtained in ms^{-1}, which is usually used for k in groundwater exploration) was transformed into mD. On the other hand, the reservoirs' permeability (obtained in mD, which is usually used for k in petroleum industry) was transformed into ms^{-1}. The aquifers exhibit very high values of k (in comparison to the reservoirs), which makes the ms^{-1}-unit a fair measure of the aquifers' permeability. Meanwhile, the reservoirs exhibit very low values of k (in comparison to the aquifers), which makes the mD-unit a fair measure of the reservoirs' permeability.

The ranges and average values of the thicknesses and the various parameters obtained for both media are given in Table 1. Log-log relationships between T_h and T_e, along with empirical equations and coefficients of correlation (R_c), are given in Fig. 1 (for the S-H aquifers) and Fig. 2 (for the JDB-reservoirs).

Results and discussion

For the S-H aquifers (Fig. 1; Eqn. 17; $R_c = 0.99$) and the JDB-reservoirs (Fig. 2; Eqn. 18; $R_c = 0.94$), the transverse resistance (T_e, in $\Omega.m^2$) is directly correlated to the transmissivity (T_f, in m^2day^{-1}):

$$T_e = 62.926\ T_f^{(0.70203)}. \tag{17}$$

$$T_e = 112.41\ T_f^{(0.2189)}. \tag{18}$$

For the aquifers (Fig. 1; Table 1), T_e has a range from 324 to 58.8×10^3 $\Omega.m^2$ (average = 9013 $\Omega.m^2$), and for the reservoirs (Fig. 2; Table 1), T_e has a range of 16-210 $\Omega.m^2$ (average = 104 $\Omega.m^2$). These ranges of T_e correspond to ranges of T_f of between 10 and 13.3×10^3 m^2day^{-1} (average = 1656 m^2day^{-1}) for the aquifers (Fig. 1; Table 1), and of between 0.002 and 26.4 m^2day^{-1} (average = 3.2 m^2day^{-1}) for the reservoirs (Fig. 2; Table 1). The ranges of T_e and T_f correspond to thicknesses of layers ranging from about 1 to 54 m (average = 14 m) for the S-H aquifers (Table 1), and from 1 to 113 m (average = 35 m) for the JDB-reservoirs (Table 1).

By applying Eqns. (17) and (18), the T_f-values of 20, 10 and 5 m^2day^{-1}, for example, correspond respectively, to the T_e-values of 516, 317 and 195 $\Omega.m^2$ for the S-H aquifers (Eqn. 17), and to the T_e-values of 217, 186 and 160 $\Omega.m^2$ for the JDB-reservoirs (Eqn. 18). This indicates that if T_f of the aquifers and the reservoirs were decreased by 50%, T_e will decrease by 39% for the aquifers and by 14% for the reservoirs. In other words, if T_e were increased by 61% for the aquifers and by 86% for the reservoirs, T_f will increase by 100% for the aquifers and the reservoirs. This observation suggests that the fluid potential (indicated by transmissivity) of the S-H aquifers and the JDB-reservoirs increases considerably with increasing the transverse unit resistance. The progressive increase in both parameters is attributed to the influence of the hydraulic and electric anisotropies, as well as to the variations in lithology, mineralogy and size of the grains, and size and shape of the pores and pore channels.

Table 1 shows that the S-H aquifers exhibit a much greater permeability ($7.8 - 297 \times 10^3$ mD; average = 90.1×10^3 mD) than the JDB-reservoirs (3×10^{-1}–4.1×10^3 mD; average = 237 mD). (Note that in Table 1 values are in Darcy, rather than milli-Darcy (mD)). Table 1 also shows that the S-H aquifers exhibit a much greater resistivity (89–2437 Ω.m; average = 758 Ω.m) than the JDB-reservoirs (0.8–117.3 Ω.m; average = 12.7 Ω.m). It is

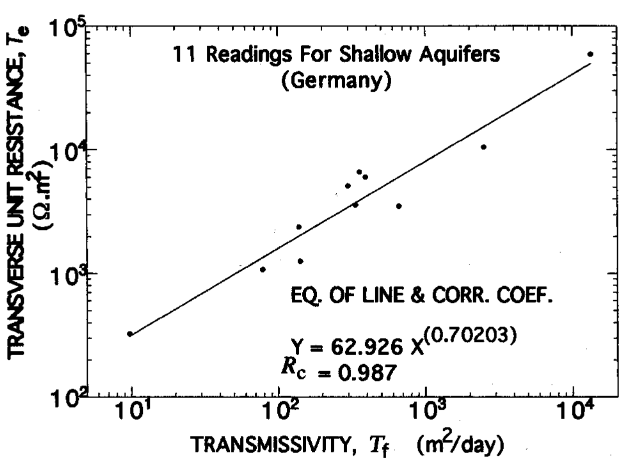

Fig. 1. *Fluid transmissivity (T_f) versus electric transverse unit resistance (T_e) for the Schleswig-Holstein (S-H) aquifers, northern Germany.*

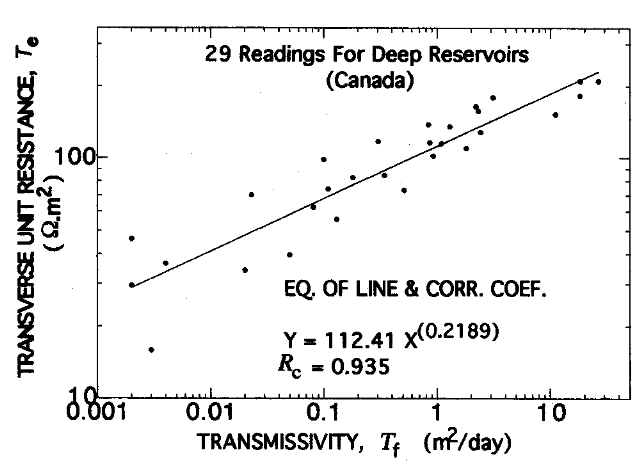

Fig. 2. *Fluid transmissivity (T_f) versus electric transverse unit resistance (T_e) for the Jeanne d'Arc Basin (JDB) reservoirs, offshore of the eastern coast of Canada.*

Table 1. Ranges and average values of thickness (h), in m; effective permeability (k_{eff}), in ms^{-1} and Darcy; effective resistivity (R_{eff}), in Ω.m; fluid transmissivity (T_f), in m^2day^{-1}; and transverse unit resistance (T_e), in $\Omega.m^2$ for shallow aquifers (Schleswig-Holstein, northern Germany) and deep reservoirs (Jeanne d'Arc Basin, offshore of eastern Canada).

Schleswig-Holstein Aquifers (Germany)

	h (m)	k_{eff} (ms^{-1})	k_{eff} (Darcy)	R_{eff} (Ω.m)	T_f (m^2day^{-1})	T_e ($\Omega.m^2$)
Range	0.9–53.6	7.51×10^{-5}– 2.87×10^{-3}	7.8–297	89–2437	10.0–13.3×10^3	324–58.8×10^3
Average	14.1	8.7×10^{-4}	90.1	758	1656	9013

Jeanne d'Arc Basin Reservoirs (Canada)

	h (m)	k_{eff} (ms^{-1})	k_{eff} (Darcy)	R_{eff} (Ω.m)	T_f (m^2day^{-1})	T_e ($\Omega.m^2$)
Range	1–113	2.0×10^{-9}– 4.0×10^{-5}	3.0×10^{-4}–4.1	0.8–117.3	0.002–26.4	16–210
Average	34.7	2.3×10^{-6}	2.37×10^{-1}	12.7	3.2	104

evident that the minimum values of the permeability and resistivity of the S-H aquifers are greater than, or close to the maximum values of the permeability and resistivity of the JDB-reservoirs. These large differences are attributed, primarily, to variations in the grain and pore sizes, presence of great amounts of shales in the reservoirs, and the influence of overburden pressure. The overburden pressure is much more effective in the case of the JDB-reservoirs than in the case of the S-H aquifers, because of the greater depth of the reservoirs. The investigated intervals of the reservoirs are located at depth ranging from about 3 to 5 km under the oceanic water, meanwhile the water table of the S-H aquifers is just a few meters deep.

The S-H aquifers (composed of unconsolidated sediments) have a range of λ_h of 1.0–1.1 and a range of λ_e of 1.33–1.60. The JDB-reservoirs (composed of consolidated rocks) have a range of λ_h of 1.0–6.2 and a range of λ_e of 1.0–1.70. These ranges of λ_h and λ_e agree well with the ranges given by Kunetz (1966) and Tiab and Donaldson (1996) for different saturated sedimentary formations (unconsolidated sediments and consolidated rocks). The differences in the hydraulic and electric anisotropies between both media are attributed to the wide differences in permeability and electric resistivity for the aquifers and the reservoirs, as a result of variations in: lithology, mineralogy, size and shape of the grains; overburden pressure and pore-water resistivity, R_w. For the S-H aquifers, R_w has a range of 13–83 Ω.m (average = 39 Ω.m), representing fresh water, and for the JDB-reservoirs, R_w has a range of 0.001–14 Ω.m (average = 0.5 Ω.m), representing highly saline water 'brine'.

Conclusions

The fluid transmissivity (T_f; layer thickness times permeability) and the electric transverse unit resistance (T_e; layer thickness times resistivity) are important parameters in identifying the zones of high potential, within the water- and hydrocarbon-bearing formations. Both parameters were determined for shallow aquifers in Schleswig-Holstein, northern Germany, which are composed of unconsolidated glacial deposits saturated with fresh water, and for deep reservoirs of the Jeanne d'Arc Basin, offshore of eastern Canada, which are composed of compacted shaly sandstone rocks saturated with oil, gas and brine. Both parameters were determined using surface and borehole electric measurements.

For the aquifers and the reservoirs, T_f and T_e are directly correlated to each other, with high coefficients of correlation. Based on Archie's (1942) equation, given in 'Theory', the formation resistivity factor is a function of bulk resistivity, pore-water resistivity, porosity and cementation factor. An increase in the formation resistivity factor, associated with an increase in the bulk resistivity, corresponds to a decrease in the porosity. The effective porosity and effective permeability are related directly to each other (Salem and Chilingarian, 1999a). This means that an increase in the permeability (associated with an increase in the porosity and a decrease in the formation resistivity factor) is related to an increase in the bulk resistivity. This explains the direct relationship between the fluid transmissivity and the transverse unit resistance for the aquifers and reservoirs investigated.

The permeabilities, determined for the Schleswig-Holstein aquifers and the Jeanne d'Arc Basin reservoirs, agree well with those obtained from laboratory measurements and pump tests for the S-H aquifers (Pekdeger and Schulz, 1975), and with those given in the literature for similar reservoirs (Tiab and Donaldson, 1996). The empirical equations obtained can be applied to similar porous media (aquifers and reservoirs), which enable one to determine the hydraulic transmissivity and the electric transverse resistance of layers, from which the permeability or the electric resistivity can be obtained, if the layers' thicknesses are known.

Nomenclature

F = Formation resistivity factor (dimensionless)
F_h = Horizontal formation resistivity factor along the bedding planes (dimensionless)
F_v = Vertical formation resistivity factor across the bedding planes (dimensionless)
H = Total thickness of a column of layers (m)
R_c = Correlation coefficient (dimensionless)
R = Electric resistivity (Ω.m)
R_b = Bulk resistivity (Ω.m)
R_{eff} = Effective resistivity (Ω.m)
R_i = Resistivity of ith layer (= R_b, Ω.m)
R_h = Horizontal (longitudinal) resistivity along the bedding planes (Ω.m)
R_v = Vertical (transverse) resistivity across the bedding planes (Ω.m)
R_w = Pore-water resistivity (Ω.m)
S_i = S_e = Longitudinal unit conductance of ith layer (mho)
S_t = Total longitudinal conductance of a column of layers (mho)
T_f = Fluid transmissivity (m^2hr^{-1}, m^2day^{-1}, m^2yr^{-1})
T_i = T_e = Electric transverse unit resistance of ith layer ($\Omega.m^2$)
T_t = Total transverse resistance of a column of layers ($\Omega.m^2$)
h_i = Thickness of ith layer (m)
i-n = Number of layers in a column of a porous medium from i to n
k = Permeability (ms^{-1}, mD, Darcy)
k_{eff} = Effective permeability (ms^{-1}, mD, Darcy)
k_{eq} = Equivalent permeability (ms^{-1}, mD, Darcy)
k_i = Permeability of ith layer (ms^{-1}, mD, Darcy)
k_h = Horizontal (longitudinal) permeability along the bedding planes (ms^{-1}, mD, Darcy)
k_v = Vertical (transverse) permeability across the bedding planes (ms^{-1}, mD, Darcy)
m = Cementation factor (dimensionless)
λ = Anisotropy coefficient (dimensionless)
λ_e = Electric anisotropy coefficient (dimensionless)
λ_h = Hydraulic anisotropy coefficient (dimensionless)
ϕ = Porosity (fraction or percentage)
DZP = Dar Zarrouk Parameters
JDB = Jeanne d'Arc Basin
S-H = Schleswig-Holstein
VES = Vertical Electric Sounding

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