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ON-SITE ASSESSMENT OF ROCK DISCONTINUITIES FROM RESISTIVITY LOGS. T-L LOG: A NEW LOGGING TECHNIQUE

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ABSTRACT

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The direct on-site assessment of the vertical distribution of discontinuities to rock masses is very important since it can give a first estimation of the hydraulic properties of the strata and has many practical applications, such as groundwater resources investigations, radioactive and toxic waste disposal, dam foundation site investigations, etc.

In the present work, the effect that fractures have upon some geophysical parameters which can easily be determined from the analysis of conventional normal resistivity logs is examined and a new technique for the on-site processing of resistivity logging data is introduced.

Using a microcomputer in series with the logging unit, a zonation process was applied to the logs, which were interpreted in terms of a series of beds, each having a specific thickness and resistivity, and a new parameter defined by the difference between transverse and longitudinal resistivities was computed (T-L log).

In almost all the cases that the method was applied, the obtained results were satisfactory and the microcomputer-based software and hardware package that was developed for the automatic processing of the data proved to be very efficient.

INTRODUCTION

The importance of being able to assess directly in the field the discontinuities of fractured formations from geophysical measurements inside boreholes is very great. This can be an aid to the solution of many problems such as groundwater resources, radioactive and toxic waste disposal, "hot-dry-rock" geothermal resources, etc.

Over the past, there has been a growing interest concerning the direct or indirect location of rock discontinuities from parameters measured from geophysical logs. The acoustic, caliper and differential resistance logs have been used routinely for the location of changes in borehole diameter. Nevertheless, many times the roughness of a borehole can be due to changes other than fractures.

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In order to resolve the above ambiguity, a complete suite of geophysical measurements is many times necessary. Since fractures and microfractures in rocks usually constitute the main transport paths for both groundwater and electric currents they will govern the resistivity of the rock. Thus, a usual approach to locate fracture zones is to try to establish a relation between the resistivity of the formation as it is given by a logging device, and a quantitative measure of the fracturing of the formation.

It would be very useful if one could assess the location of fractures within a borehole from a single set of simple geophysical logs. The purpose of the present paper is to examine to what extent the discontinuities of a fractured formation can be assessed from parameters inferred from normal resistivity logs.

AN INVESTIGATION OF THE EFFECT THAT FRACTURES HAVE UPON SOME (GEOELECTRIC) PARAMETERS

It is well known that in surface-based resistivity soundings, the measured resistivities are controlled by the average response of very large volumes of rock, with dimensions comparable to the depth to which measurements are being made.

On the other hand, resistivity measurements made in well logging are highly detailed over distances of a few cm to a few m vertically through a well. In the present section we will examine how sensitive these resistivity measurements are for defining fracture zones.

Consider a hypothetical section in a fractured formation consisting of fractures of thickness h_i with resistivity p_1 within a medium of resistivity p_2 (Fig. 1). By definition the transverse resistivity of a section H of the formation is:

$$p_{\mathrm{tr}} = \sum_i h_i \cdot p_i / H \tag{1}$$

which can be written as:

$$p_{\mathrm{tr}} = \left[\left(\sum_i h_i \right) (p_1 - p_2) + p_2 \right] \Big/ H \tag{2}$$

Similarly, the longitudinal conductivity is:

$$\sigma_1 = \sum_i (h_i / p_i) / H \tag{3}$$

which can be written as:

$$\sigma_1 = \left[\left(\sum_i h_i \right) (1/p_1 - 1/p_2) \right] \Big/ H + 1/p_2 \tag{4}$$

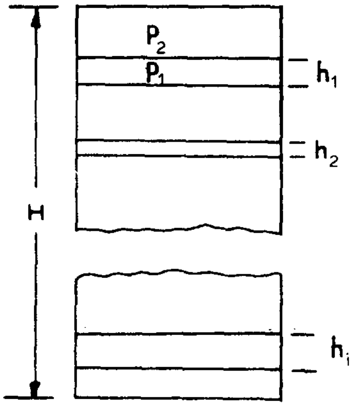

Fig. 1. Parallel-layer model of a fractured formation.

These equations were used to calculate the dependence of the formation's geoelectric parameters upon the percentage of fractures per unit cross-section:

$$\left(\sum_i h_i \times 100\%\right) /H \tag{5}$$

Consider a hypothetical section with $p_1 = 25$ and $p_2 = 150$ Ohm m.

The fraction of fracture beds in this hypothetical section was varied by increasing the amount of low-resistivity beds.

Judging from Fig. 2, we see that the value of longitudinal and transverse

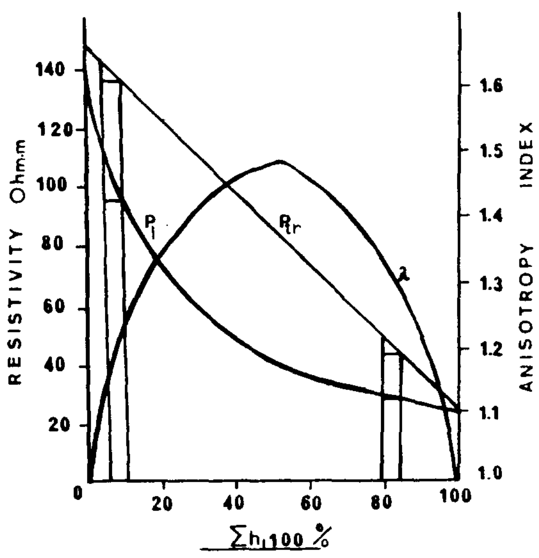

Fig. 2. Longitudinal and transverse resistivity and anisotropy index versus fracture amount.

resistivity varies from 25 Ohm m for the case where the entire section is composed of water to 150 Ohm m in the case where there are no fractures at all.

Referring to the longitudinal resistivity, its value remains close to 25 Ohm m until the total fraction of fractures becomes less than 80%, while on the other hand the transverse resistivity increases rapidly.

Thus, one can say that: (a) the longitudinal resistivity is dominated by the low-resistivity beds in the section; and (b) the transverse resistivity is less sensitive to the low-resistivity beds in the section and depends upon the high-resistivity beds.

Figure 3 is a graphical representation of the ratio p_{tr}/p_l versus the ratio of the resistivity of the fracture zones over the formation resistivity for different percentages of fracture zones per unit cross-section.

The diagram shows that transverse resistivity remains equal to the longitudinal resistivity when the resistivity of the fracture zone is 60% or more of the resistivity of the formation. As the resistivity of the fracture zone decreases there is an increasing difference between p_{tr} and p_l. The diagram also shows that by increasing the percentage of fracture zones there is an increasing difference between p_{tr} and p_l.

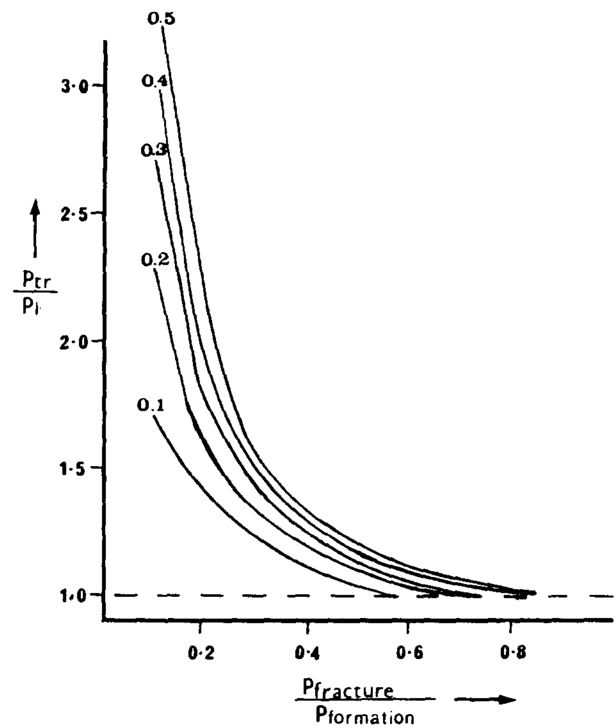

Fig. 3. Transverse resistivity over longitudinal resistivity versus fracture resistivity over formation resistivity.

By looking at the diagrams of Figs. 2 and 3 one can see that fractures have a different effect upon the longitudinal and transverse resistivities. It is then logical to think that calculating the difference between these two resistivities and plotting this difference versus depth would be indicative of the degree of fracturing of the formation.

In the following pages, a theoretical double porosity model based on a tortuosity-free, parallel conduction path assumption is introduced, to assess the dependence of the resistivity measured by a logging tool upon various combinations of formation and fracture resistivities.

Double porosity models have been proved very useful in the study of naturally fractured reservoirs (Pirson, 1979; Aguilera, 1979; Sherman, 1983) and fractured aquifers (Tselentis, 1985).

Assuming a non-conductive formation matrix, one can say that the electric current of a logging tool passing through the formation will follow two paths, one of which is through the fractures and the other through the saturated pore space of the matrix. Thus, it is like having two different porosity systems connected in parallel (Fig. 4).

An important parameter in the study of fissured formations is the apportioning of the total porosity between matrix porosity and fracture porosity. A quantitative measure of this could be the fracture index of the formation defined as the fraction of the total pore volume contained in the fractures.

Let R_0 be the resistivity of the matrix; R_f be the resistivity of the fractures; R_{eq} be the equivalent resistivity (measured by a tool); Φ be the total porosity; and f be the fracture index. The following relation:

$$R_{eq} = R_f \cdot R_0 / [f\Phi R_0 + R_f \cdot (1 - f\Phi)] \tag{6}$$

which is the link between the two pore systems, can be derived (Tselentis, 1985), and it is used to study some possible two-porosity systems considered to represent fractured formations.

Figure 5 shows the dependence of the measured equivalent resistivity

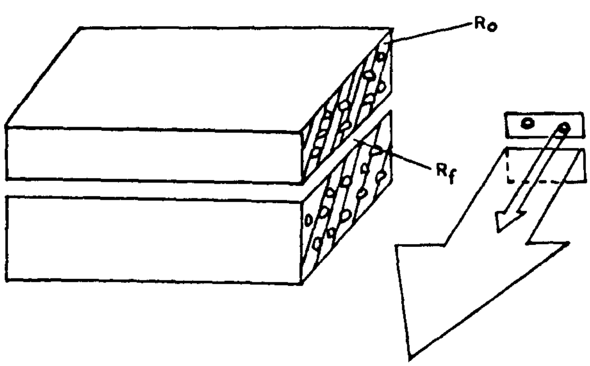

Fig. 4. Two-porosity model of a fractured aquifer. Fracture index = fracture porosity/ total porosity.

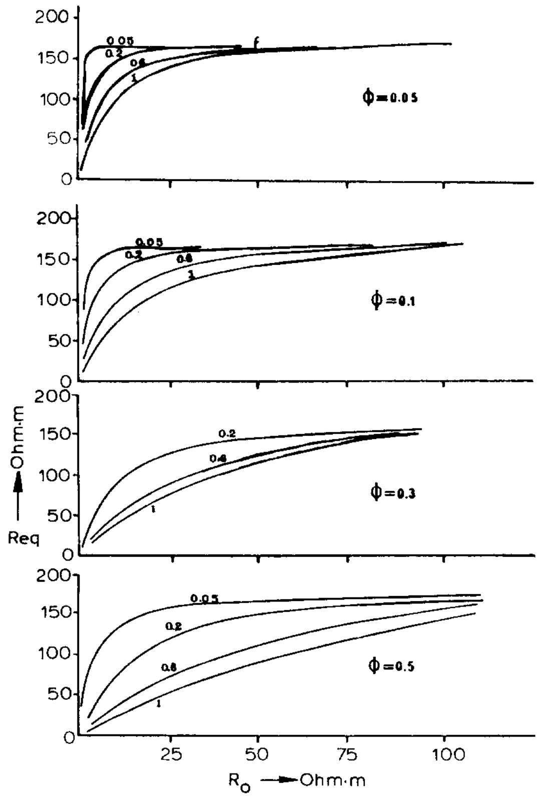

Fig. 5. Equivalent resistivity versus fracture resistivity for different fracture indices and total porosities.

upon the resistivity of the fractures for various degrees of fracturing and for various total porosities.

For low fracture resistivity values, the measured equivalent resistivity depends strongly upon the degree of fracturing of the formation and the resistivity of the fractures.

As the resistivity of the fractures approaches the matrix resistivity (50 Ohm m in our case), the equivalent resistivity reaches a constant value (the earlier it approaches that value, the less the total porosity is). This is more clearly shown in Fig. 6 where R_{eq} is plotted against R_f for various values of total porosity and for a fracture index of 0.3.

In Fig. 7 we show the dependence of R_{eq} upon the variation of matrix resistivity for different fracture indexes and total porosities (assuming a constant fracture resistivity of 25 Ohm m).

Judging from this diagram we can see that for high matrix resistivity values the effect that fractures have upon the equivalent resistivity depends upon the fracture index. The lower the fracture index is, the stronger the dependence between R_{eq} and matrix resistivity becomes. This dependence

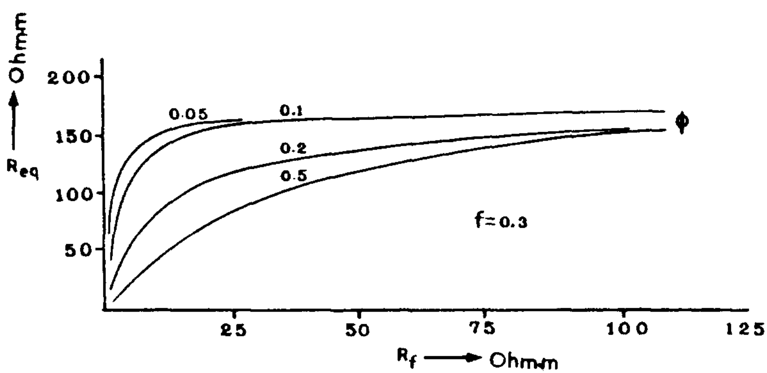

Fig. 6. Equivalent resistivity versus fracture resistivity for various total porosities and for a constant fracture index.

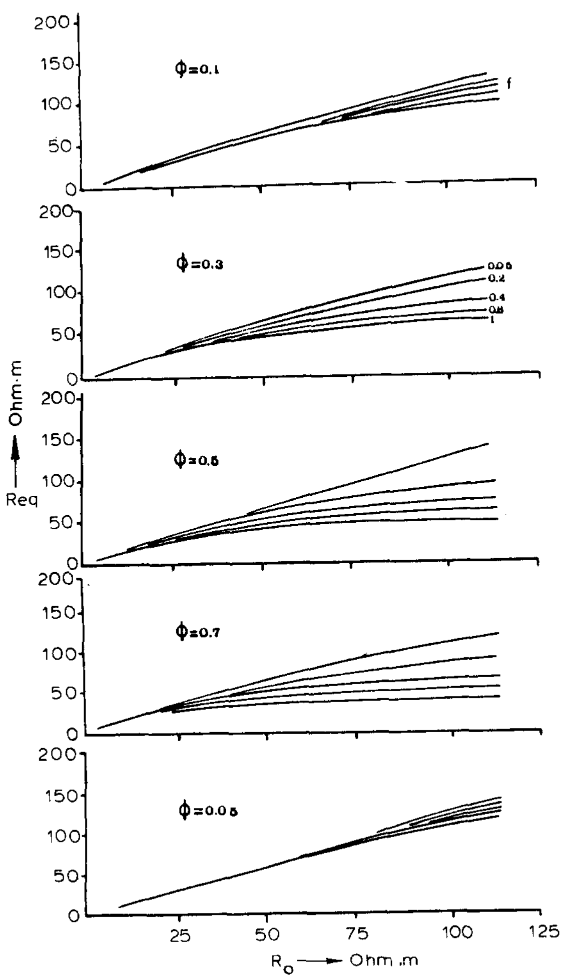

Fig. 7. Equivalent resistivity versus formation resistivity for various fracture indices.

becomes also stronger for lower total porosities as one can deduce from the slope of the curves.

During the above calculations we assumed a non-conductive solid matrix for the formation. Of course, when the saturating formation liquid is fresh-water, the electrolyte salinity is not sufficiently high to suppress the effects of surface conduction.

DEFINITION OF A NEW LOG

We showed above that fractured zones have different effects upon the longitudinal and transverse resistivities. As a result of this it is logical to think that calculating the difference between these two resistivities and plotting this difference against depth would be indicative of the degree of fracturing of the formation.

In actual logging practice it is very difficult to determine the difference between the two resistivities (p_{tr} and p_l). Maillet and Doll (1932) found that the resistivity measured with a system of electrodes aligned perpendicular to the bedding planes is not affected by micro-anisotropy and that the values obtained for the measured resistivity are close to the values of the longitudinal resistivity (paradox of anisotropy).

One can conclude that it is rather impossible to determine actual values of the formation's transverse resistivity at different depths from resistivity logs only. In the present work a different approach for the calculation of the vertical distribution of the difference $p_{tr} - p_l$ is adopted.

A common technique used during the interpretation of geophysical logs is to employ a zonation process. By this method, a number of boundaries that divide the log into intervals are selected so that the measurement being considered is relatively constant compared to the change in the measurement from that interval to the depth-adjacent intervals (Fig. 8).

Using the above technique, the resistivity logs obtained from a logging device, are divided into a number of zones. Thus, a resistivity log would be interpreted in terms of a series of beds, each having a specific thickness and resistivity. By applying next eqns. (2) and (4) it is straightforward to calculate a value for the difference between transverse and longitudinal resistivities for any desired section of the formation.

The difference between transverse and longitudinal resistivities when plotted against depth will be defined as T-L log (transverse—longitudinal).

In the present work, a microcomputer connected with the logging unit via an analog-to-digital converter (Fig. 9) was used for the on-site processing of the data.

A program was written (in machine code) for the automatic zonation of the resistivity logs and the results were output on an X—Y plotter. When necessary, the facility was provided to compensate the measurements for changes of the water conductivity, by keeping the results of a fluid-conductivity log in the memory of the microcomputer.

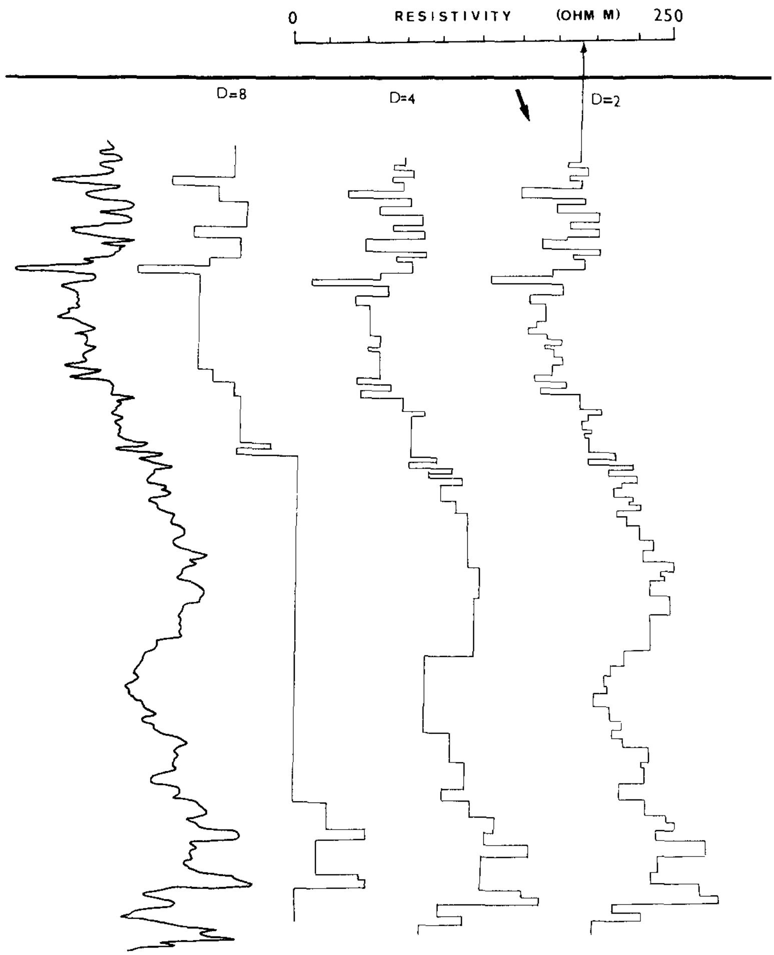

Fig. 8. Zonation of a resistivity log.

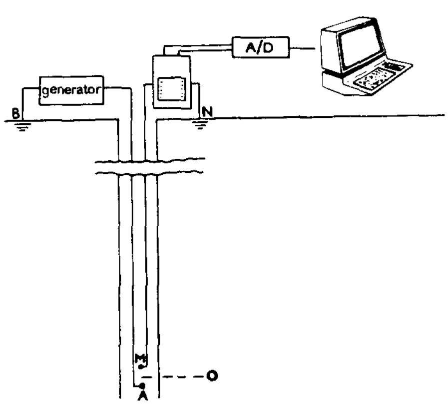

Fig. 9. Instrument arrangement.

All the software necessary for the processing of the resistivity data were kept permanently in an EPROM module as part of the memory of the microcomputer used.

CASE HISTORIES

In the following sections we discuss the results obtained from the application of this logging technique to some actual field cases. The logs were processed directly in the field by an ACORN-ATOM 8-bit, 32K microcomputer, and all the software necessary for data processing were kept in an EPROM MODULE.

Example 1

Figure 10 represents the variation of the difference between transverse

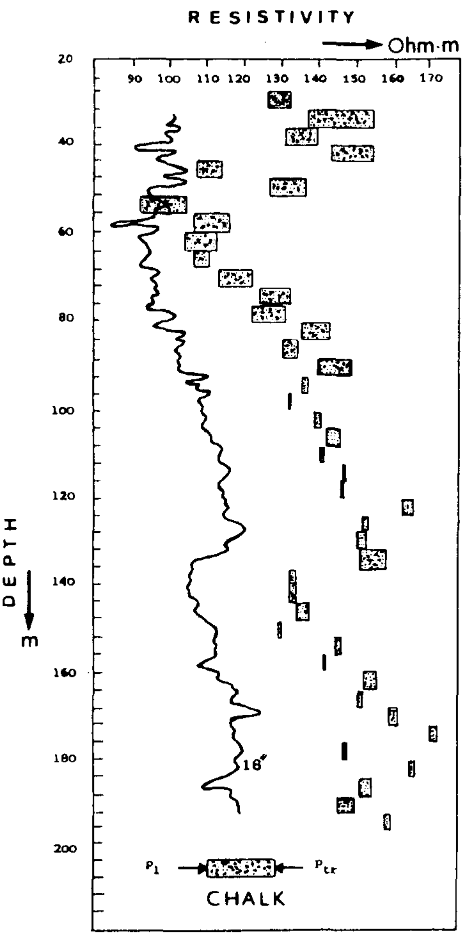

Fig. 10. Transverse—longitudinal resistivity versus depth for a chalk aquifer.

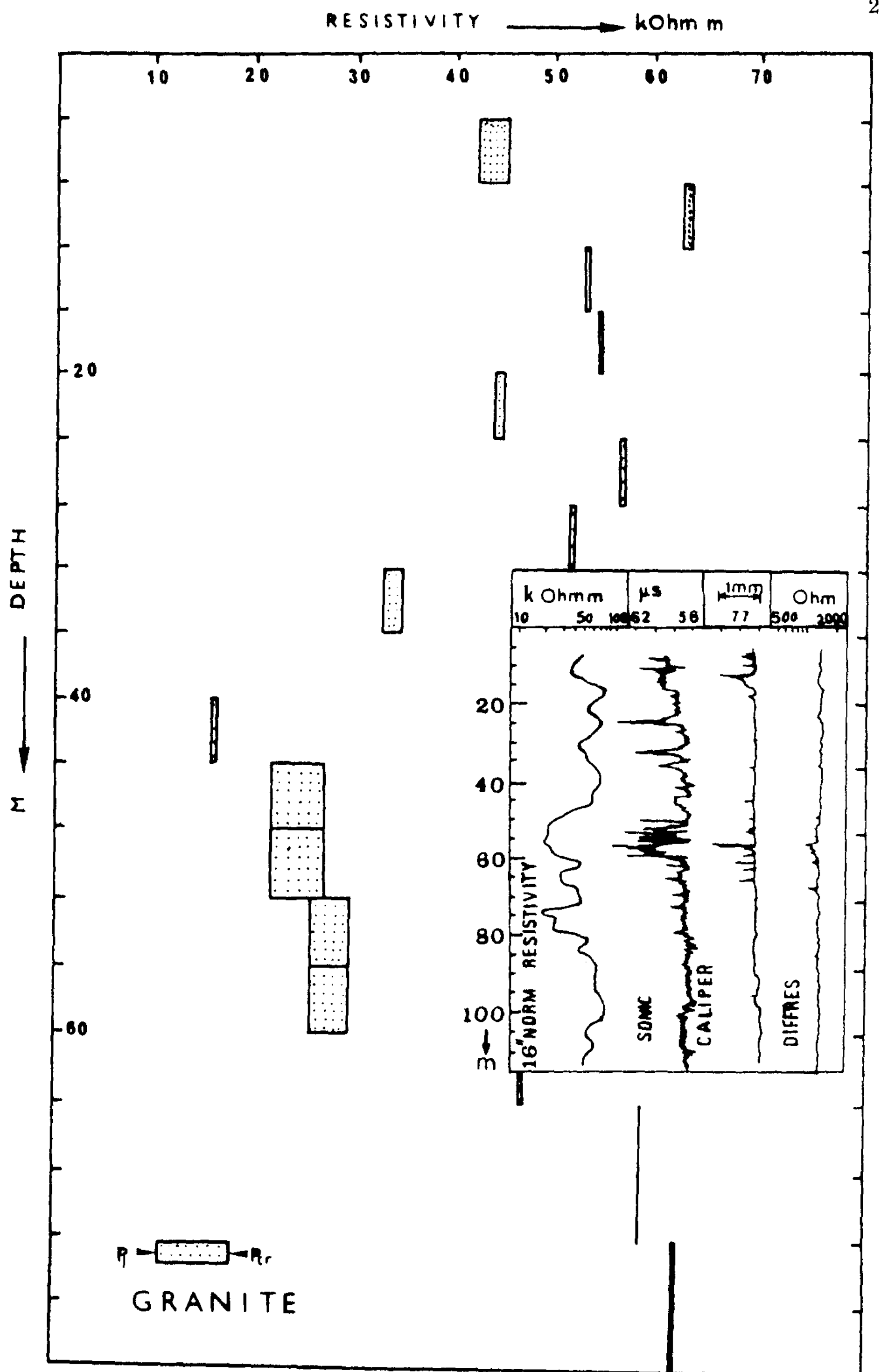

Fig. 11. Transverse—longitudinal resistivity versus depth for a granite.

TABLE 1

Example of an analytic calculation of a T–L log

Depth (m)	p_a (Ohm m)	$p_{a,zon}$ (Ohm m)	Depth int. (m)	h_i (m)	p_i (Ohm m)	$\Sigma h_i \cdot p_i$ (Ohm m)	$\Sigma h_i/p_i \times 10^{-3}$ (Ohm^{-1})	$p_{tr} = (h_i \cdot p_i)/4$ m (Ohm m)	$p_1 = 4/\Sigma h_i/p_i$ (Ohm m)	T–L (Ohm m)
30	210									
31	205									
32	205	208	30–34	4	208	832	0.019	208	208	0
33	208									
34	210									
35	213			1	208					
36	215			3		865	0.018	216.25	216.22	0.03
37	220	219	34–38							
38	223				219					
39	227			4						
40	230				232	928	0.017	232	232	0
41	235	232	38–42							
42	237									
43	225									
44	227									
45	228	227	42–46	4	227	908	0.017	227	227	0
46	225									
47	230			2						
48	227				227					
49	235			2		924	0.017	231	229.88	1.12
50	235	235	46–50		235					
51	236			2	235					
52	235									
53	228	228	50–54	1	228	936	0.017	234	233.91	0.09
54	238	238		1	238					
55	223	221		2						
56	219		54–58		221	862	0.018	215.5	215.47	0.03
57	214			2						
58	212				210					

59	210	210		3	210					
60	207		58—62			825	0.0194	206.25	206.04	0.207
61	206									
62	195	195		1	195					
63	202			3	203					
64	203	203	62—66			824	0.019	206	205.87	0.13
65	205									
66	215	215		1	215					
67	238	235	66—70	2	235					
68	232					912	0.0176	228	227.79	0.21
69	225			2	221					
70	221									
71	220	221								
72	220		70—74							
73	221			4	221	884	0.0181	221	221	0
74	220									
75	200	200		1	200	785	0.0204	196.25	196.04	0.21
76	190	190	74—78	2	190					
77	190									
78	205	205		1	205					
79	190	190		1	190					
80	170	170	78—82	1	170	645	0.0253	161.25	158.17	3.08
81	155	155		1	155					
82	130			1	130					
83	130	130								
84	150	145	82—86	1	130	526	0.031	131.5	129.37	2.13
85	140				145					
86	110			2	106					
87	103			1						
88	103	106	86—90	4	106	424	0.0377	106	106	0
89	106									
90	106									

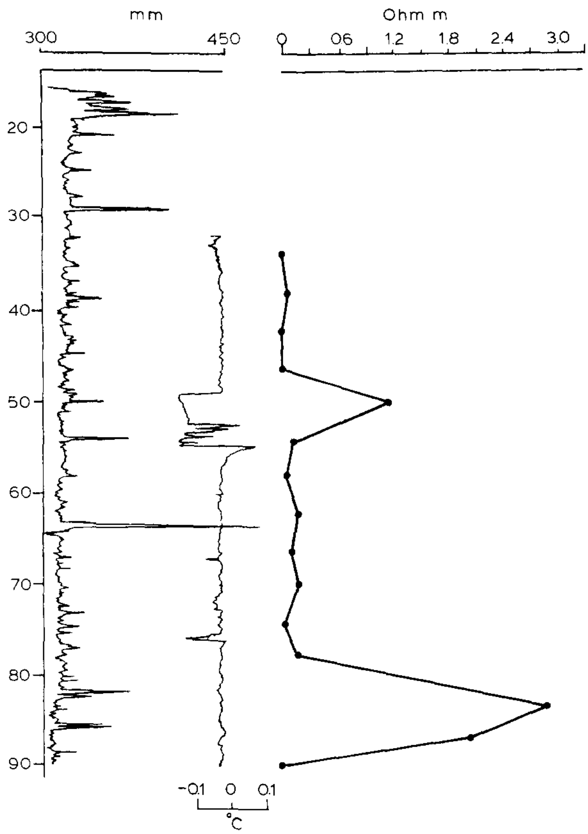

Fig. 12. Caliper, differential temperature and T—L log for a chalk aquifer.

and longitudinal resistivities (calculated every 4 m), against depth for a borehole sunk in a fissured chalk aquifer. It is obvious that the difference of the two resistivities tends to decrease with depth and this is shown more clearly by the regression line fitted through the data. This result is in agreement with investigations in nearby wells which showed that the degree of fissuring of the aquifer decreases with depth.

Example 2

Figure 11 represents the difference between transverse and longitudinal resistivities against depth for a borehole sunk in granite. The sonic, caliper and differential resistance logs indicate that the formation is heavily fractured in the interval between 45—60 m. The same result was also obtained from the T—L log which reached its greatest value in the above interval.

Example 3

Figure 12 shows the calculated T—L log of a borehole driven through a chalk aquifer. A detailed analysis of the calculation of the T—L log for this specific example is shown in Table 1. It is evident that when dealing with small amounts of data the T—L log can be calculated relatively easily by hand as well.

The obtained T—L log suggests that there is a change in the geoelectric properties of the formation at the depths of 50 and 80 m. Since the formation is homogeneous one would suspect the existence of fissure zones at the above levels. A differential temperature log run in the same borehole confirmed the existence of a fissure zone at the depth of 50 m and a similar feature was recorded at the depth of 76 m. The caliper log on the other hand confirmed the existence of the fissure zones, suggested by the T—L log, as well as a number of some other borehole enlargements which proved not to be fissure zones.

CONCLUDING REMARKS

This paper has examined the effect that the discontinuities of a fractured formation have upon the geophysical parameters measured from normal resistivity logs, and a new parameter sensitive to the degree of fracturing of the formation is introduced.

The method was applied to a number of actual cases and there was a satisfactory correlation between the response of the new log and the existing fracture zones within the formation.

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