Journal of Hydrology, 80 (1985) 215—236
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

[3]

THE PROCESSING OF GEOPHYSICAL WELL LOGS BY MICROCOMPUTERS AS APPLIED TO THE SOLUTION OF HYDROGEOLOGICAL PROBLEMS

GERASIMOS-AKIS TSELENTIS*

Imperial College of Science and Technology, Engineering Geology Division, London SW7 2BP (Great Britain)

(Accepted for publication March 15, 1985)

ABSTRACT

Tselentis, G.-A., 1985. The processing of geophysical well logs by microcomputers as applied to the solution of hydrogeological problems. J. Hydrol., 80: 215—236.

Recent developments in microelectronic technology have provided very powerful microcomputers for use at the well site by hydrogeologists or geophysicists to provide timely answers to important hydrogeological questions.

This paper gives a brief and generalized description of the philosophy and the problems involved in applying microcomputers to the organization and processing of borehole geophysical measurements to evaluate various hydrogeological problems.

INTRODUCTION

Borehole geophysical methods provide vital information regarding the lithology, stratigraphy and physico-chemical properties of the fluids filling the borehole and its surrounding formations (Table 1). This information is essential for the solution of a great variety of hydrogeological problems.

Thus, areas of high porosity and permeability, which would produce the most water can be identified, as can zones of salinity; the magnitude and direction of flow through a well and regional groundwater flow patterns might also be indicated.

Many of the applications of geophysical logging techniques in hydrogeology are similar to those used in the oil industry, where the techniques were first developed and where a dazzling variety of physicochemical measurement techniques have been adapted to the borehole environment.

*Present address: Engineering Geophysics Hellas Ltd., 8 Anastasaki Street, Zografou 157 72, Athens, Greece.

0022-1694/85/$03.30

TABLE 1

Formation parameters measured by geophysical logs during hydrogeological studies

Properties to be measured	Parameters measured[a]									
	P_f	C_w	U_w	S_m	Φ	U_m	T	SP	D	γ
depth of contact of aquifers and associated rocks	+				+	+			+	
aquifer total porosity					+	+				
clay or shale content								+		+
fractures, solution openings	+					+	+		+	
moisture content				+						
velocity of water flow in well			+							
water entrance in well		+	+					+		
chemical character of formation water	+	+						+		
specific yield of unconfined aquifers				+						
hydraulic conductivity					+	+				
Type of log	resistivity	conductivity	flow meter	neutron	gamma-gamma	acoustic	temperature	self potential	caliper	natural gamma

[a] P_f = formation resistivity; C_w = fluid electric conductivity; U_w = fluid velocity; S_m = moisture content above the water table; Φ = porosity; U_m = elastic-wave velocity; T = fluid temperature; SP = self potential; D = borehole diameter; γ = natural gamma radiation.

Hydrogeologists have for many years used simple logs, typically a rather common combination of measurements of formation resistivity, natural gamma radiation, and spontaneous potential of the formation surrounding the borehole, together with changes of the borehole diameter. For many years there has been a notable lack of equipment specifically designed for work outside the oil industry but recently some companies have provided a

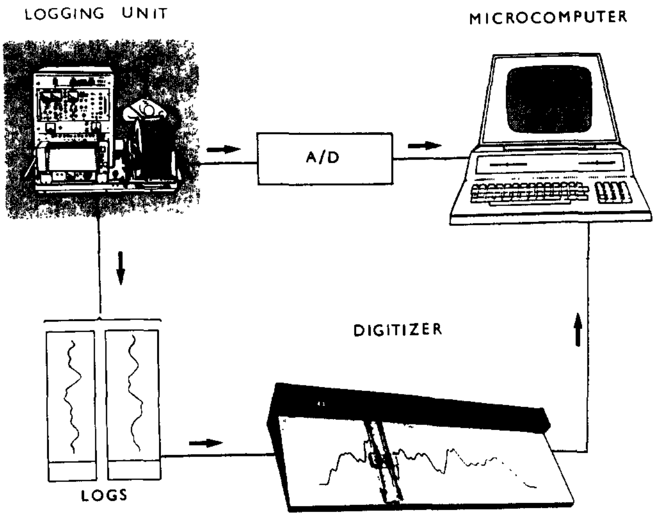

Fig. 1. Typical arrangement for the automatic processing of geophysical logs.

fairly good selection of purpose-designed equipment of minimal diameter for use in various hydrogeological applications (Robinson, 1974; Tselentis, 1983). In the water industry the use of logging devices and interpretive methods for the evaluation of various hydrogeological parameters is increasing and many of the highly sophisticated logging tools used by the oil industry are now available to small organizations.

The geophysical log, a continuous measure of some geophysical variable, contains more information than can be utilized by conventional methods of manual interpretation. Only computer-implemented mathematical techniques are powerful and fast enough to perform the task. A typical hardware arrangement used for the automatic processing of geophysical logs is shown in Fig. 1.

The applications of microcomputers in hydrogeophysical well logging are so many and so diverse that it is impossible to make an exhaustive survey. However, a discussion of the problem of processing geophysical logging data by a microcomputer is followed by a few examples with which the author has had some personal experience.

It is not enough to have all the necessary computer programs for the processing of the logs. It is also very important to optimise the way in which these programs can be combined for fast effective evaluation of the logs. A critical factor in this process is the general memory structure of the microcomputer (memory map), since the operator has to define the parts of the memory which will contain the data, the programs and the intermediate and final results.

Figure 2 is a representation of the processing of the log data. The data from the digitized logs, kept in memory locations D1, 2, . . . , can either be used

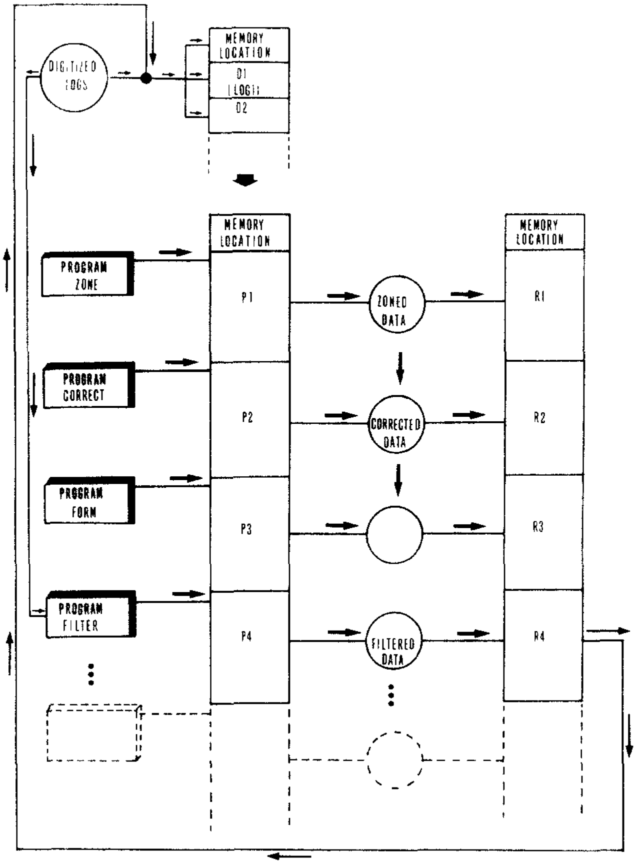

Fig. 2. Operation of the software package.

directly with the programs kept in memory locations P1, 2, . . . ; where filtering is necessary, the data are passed through a filtering process. For example suppose that LOG1 is a normal resistivity log. The data can either be filtered with the help of program "FILTER" or pass directly through a zonation process performed by program "ZONE". Next, program "CORRECT" could be used to compensate for changes of the fluid conductivity. The data are then ready for evaluation of the geoelectric parameters of the formation through a process performed by "FORM".

Obviously the data from all the intermediate stages could be stored in memory locations R1, 2, . . . , or sent to an output device (magnetic tape, disc, printer).

Log sampling and reconstruction

A microcomputer works with discrete values rather than with the continuous signal recorded on a geophysical log. When a continuous geophysical log is to be represented by a set of samples, the precision with which the log should be sampled and the frequency of sampling must be decided. If the sampling rate is too low, information about the detailed fluctuations will be lost; if it is too high, an unnecessarily large number of samples will have to be stored or processed.

The minimal sampling rate for adequate representation of a continuous signal must be at least twice that of the highest frequency which is to be maintained in the signal. Frequencies higher than the limit imposed by the sampling rate will not only be lost, but they will also produce a false signal which will appear as much lower frequency: this effect is described as aliasing (Kulhanek, 1976).

Figure 3 illustrates a 64-inch normal resistivity log together with reconstructed logs sampled at 2, 4 and 8 m intervals; the accuracy of the resulting log depends upon the digitization interval.

A digitization interval of A m and a vertical log scale of B m cm^{-1} implies that a sample is taken every A/B cm of actual log record and that for H m of logged formation, one takes H/A numbers. If a sample is taken every 0.2 m, which is usually adequate to prevent any aliasing effects, and a depth scale of 2 m cm^{-1} is considered, then a number is taken every 1 mm of actual log record and 1000 numbers correspond to 200 m of logged formation. If these 1000 numbers are scaled between 0 and 255 in value then it is possible to allocate only a single byte of computer memory per number instead of four (a set of numbers stored in this way is called a byte vector). This is especially useful when the available memory is restricted as in a microcomputer. Thus in the above case, the memory requirement for storing data corresponding to 200 m of formation is 1 kbyte.

Digital filtering of geophysical logs

The processes of smoothing, predicting, separating signals and removing the noise from geophysical logs are very common to the log analyst. Often such processes are linear transformations on the data; they are thus equivalent to digital filtering since a digital filter is an arbitrary linear operation on the data.

A well log may be defined as the sum of a great number of individual components, each being the result of an impulse generated by some formation condition. Factors which distort the ideal log signal, such as random impulses, equipment noise, formation fluids, filter cake and bed thickness, will each have their particular effect on the response. To a certain extent, the

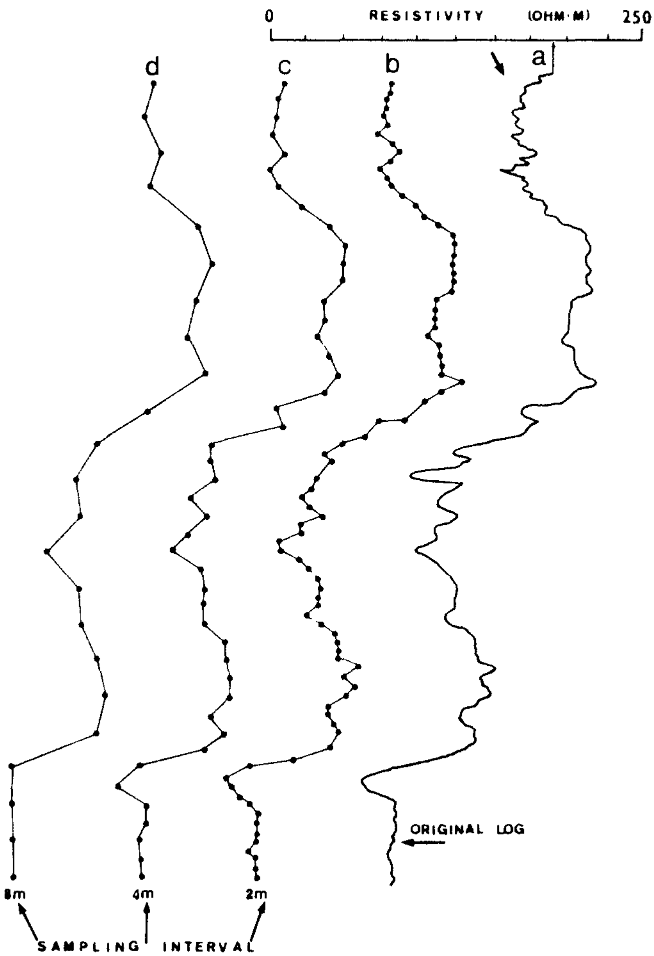

Fig. 3. Example of log digitization with different sampling intervals.

effects of each may be determined and separated; this is attempted to achieve an understanding of the phenomena underlying the observations; digital filters are the main processing tools.

The recorded analogue geophysical signal can be represented by a number of equally spaced samples P_n, of some property $P(h)$, where n is an integer and h is a continuous variable i.e. depth. If the parameter Y_n is computed by the formula:

$$Y_n = \sum_{k=-\infty}^{\infty} c_k \cdot P_{n-k} + \sum_{k=1}^{\infty} d_k \cdot Y_{n-k} \qquad (1)$$

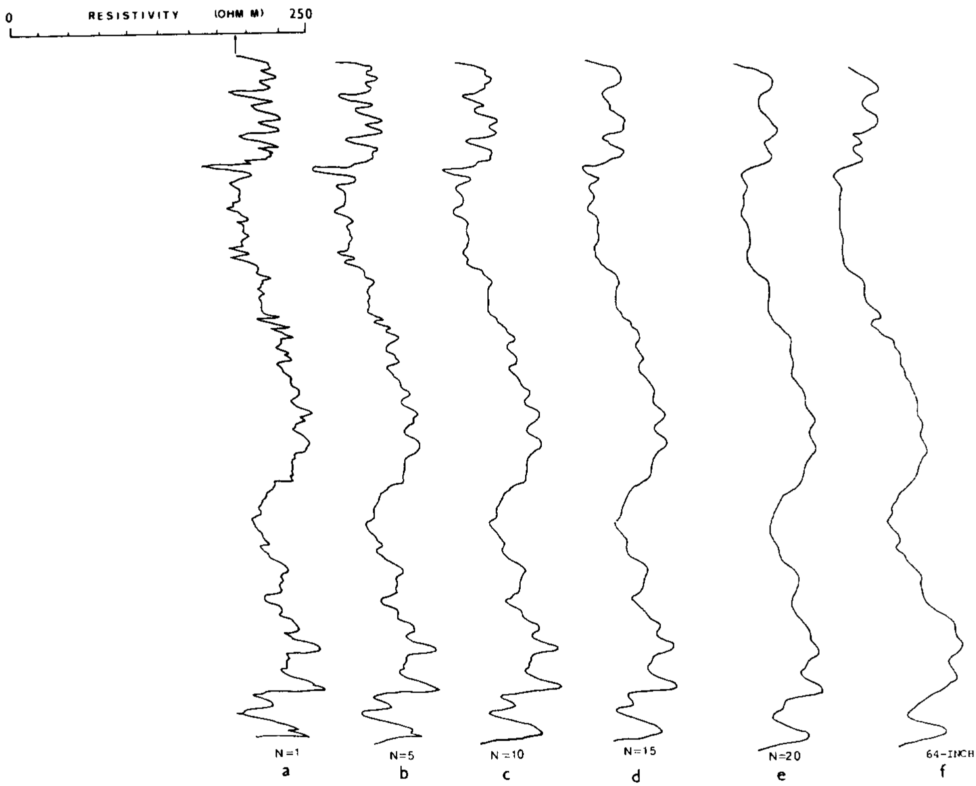

Fig. 4. Example of a 16" normal resistivity log filtered by 5-, 10-, 15-, and 20-term moving average filter and comparison with the 64" normal resistivity log.

then this fomula defines a digital filter. Thus a digital filter may be merely a linear combination of equally spaced samples P_{n-k} of some property $P(h)$, together with the computed values of the output Y_{n-k}. For each successive n, the formula shifts one data point along the string of data points, P_{n-k}.

Figure 4a represents a 16-inch normal resistivity log smoothed in Fig. 4b, c, d, e by 5-, 10-, 15- and 20-term moving average filtering respectively, while Fig. 4f represents the 64-inch normal resistivity log of the same borehole. Increasing the number of terms in the filter emphasizes the long-term features

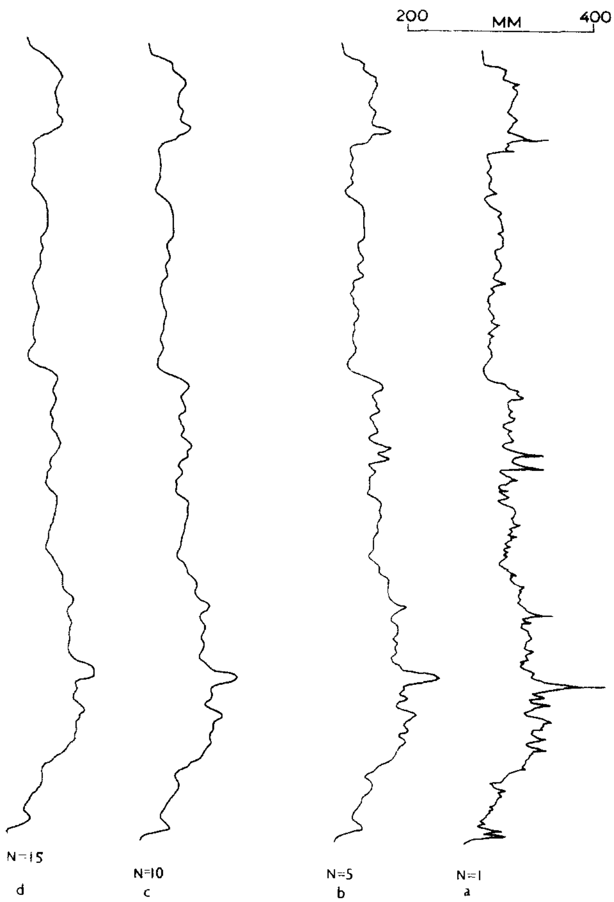

Fig. 5. Example of 5-, 10-, and 15-term moving average filtering of a caliper log.

of the log at the expense of shorter variations. The 20-term filtering version of the 16-inch normal resistivity log is similar in appearance to the 64-inch normal resistivity log.

Figure 5a is the caliper log of the same borehole smoothed in Fig. 5b, c, d by 5-, 10- and 15-term moving average filtering respectively. The high-frequency content of the caliper log is reduced drastically when the moving average filter is more than five terms long. To avoid the loss of useful information contained in the caliper log during a moving average filtering process some other simple types of digital filters may be effective. Figure 6c shows the result of the application of a 21-term "Spencer" filter defined by the equation:

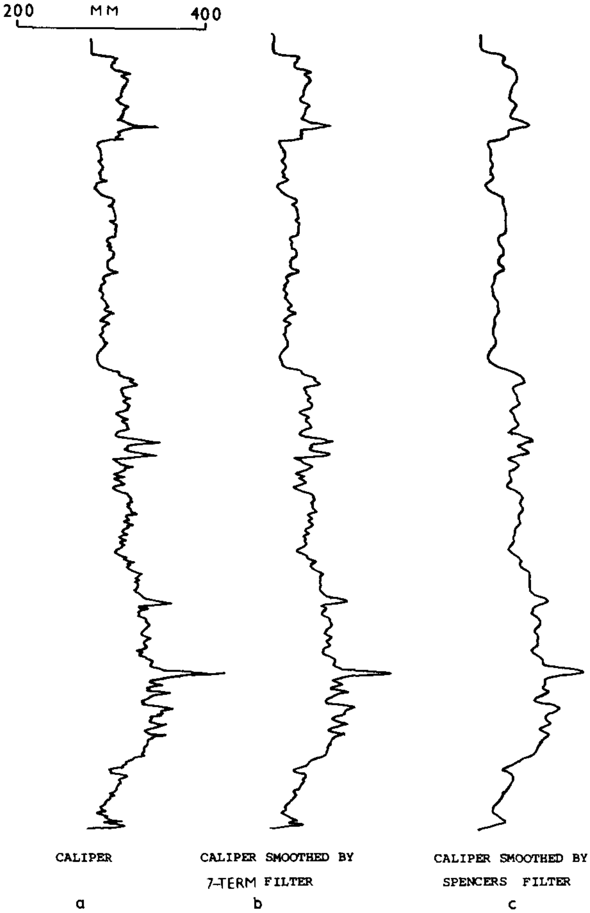

Fig. 6. Example of a caliper log filtered by 7- and 21-term (Spencer) filters.

$$\bar{P}_i = \frac{1}{350}[60P_i + 57(P_{i+1} + P_{i-1}) + 47(P_{i+2} + P_{i-2}) + 33(P_{i+3} + P_{i-3}) + 18(P_{i+4} + P_{i-4}) + 6(P_{i+5} + P_{i-5}) - 2(P_{i+6} + P_{i-6}) - 5(P_{i+7} + P_{i-7}) - 5(P_{i+8} + P_{i-8}) - 3(P_{i+9} + P_{i-9}) - (P_{i+10} + P_{i-10})] \quad (2)$$

and Fig. 6b shows the result of the application of a 7-term filter defined by the equation:

$$\bar{P}_i = \frac{1}{21}[7P_i + 6(P_{i+1} + P_{i-1}) + 3(P_{i+2} + P_{i-2}) - 2(P_{i+3} + P_{i-3})] \quad (3)$$

Log zonation

A common technique in the interpretation of geophysical logs is a zonation process. Log analysts have long used the concept of large concentrated changes in several log properties as indicators of boundaries between adjacent rock units. By this method, boundaries that divide the log into intervals are selected such that the measurement being considered is relatively constant compared to the change in the measurement from that interval to the depth-adjacent intervals.

Although this has proven effective as a means of dividing well log data into groups of measurements corresponding to individual formations, there are many drawbacks to the method when it is applied by hand. Clearly, a need exists for an automated procedure which is fast, efficient, easy to use and yields reproducible results.

Most computer techniques for the automatic zonation of logs are based on algorithms designed for the automatic zonation of sequences of data for use with large digital computers and although valuable to the oil industry, they are of limited use for other geotechnical logging applications because of limitations of portable microcomputers (Testerman, 1962; Webster, 1978; Hawkins and Krooden, 1979).

An algorithm for automatic zonation of a sequence of data representing a geophysical log, uses the variation of the data versus depth, by locating different boundaries at points where the data exceed a predefined threshold value or some functional relation of the data themselves such as their standard deviation or their mean value. Sounder and Pickett (1973), used the N-point moving average method to perform the automatic zonation of geophysical logs. A similar technique, used by the present author, compares the standard deviation of a segment of N data with the standard deviation of the adjacent segment. If the difference between the standard deviations is greater than a predefined threshold value D, the program assigns a zone boundary at the corresponding point, divides the zone by three and computes the mean value of the central portion, assigning the latter to the total interval. Figure 7 is an example of the application of the method to the automatic zonation of a 16-inch normal resistivity log.

By using different threshold values D, one can achieve different levels of accuracy for the zonation of the geophysical log; instead of calculating the formation evaluation parameters for every digitizing increment of depth they can be carried out speedily on a zonal basis, which results in far fewer calculations and in much more meaningful results.

VARIOUS APPLICATIONS

Calculation of the true formation resistivity

Theory and experience demonstrate that the formation resistivity when measured with a normal resistivity device depends upon the conductivity of

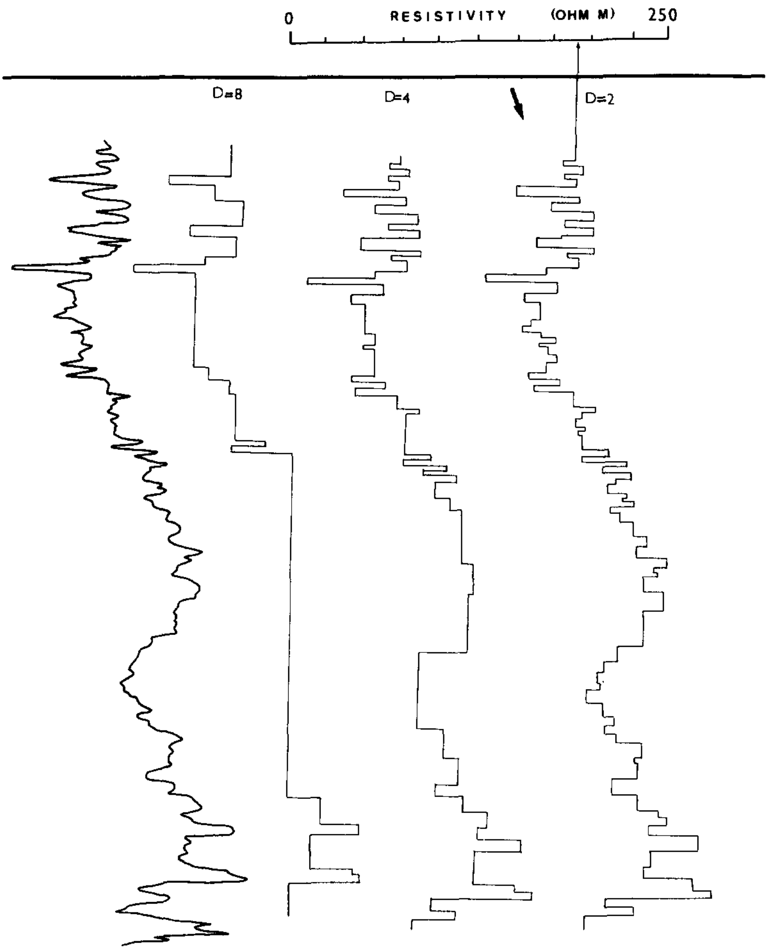

Fig. 7. Example of the zonation of a 16" normal resistivity log.

the fluid column and the diameter of the well. The functional relation between the apparent resistivity shown by the logs, the true formation resistivity, the conductivity of the fluid column and the diameter of the well is given by Schlumberger (1950); it involves the evaluation of a Fourier cosine integral (Fillon, 1928), which is impracticable for a small microcomputer system.

Although there are in the literature powerful algorithms for the automatic correction of resistivity data (Scott, 1978), a useful method is to approximate departure curves already in the literature (Schlumberger, 1950, 1972; Lynch, 1962; Dresser Atlas, 1979) by a cubic polynomial of the type:

$$P_{cor} = P_f[A \cdot (P_a/P_f)^3 + B \cdot (P_a/P_f)^2 + C \cdot (P_a/P_f) + D] \quad (4)$$

where P_{cor}, P_f and P_a is the correct, fluid and apparent resistivity, respectively. The constants A, B, C and D can be calculated by a least squares process.

Lithology discrimination of an aquifer using acoustic and density logs

Acoustic logs measure the shortest time T for a sound wave to travel between transmitter and receiver. The interval transit time T is related to the total porosity of a clean consolidated formation by formulae such as that of (Wyllie and Rose, 1958):

$$\Delta T_{log} = \Phi \cdot \Delta T_{fluid} + (1 - \Phi) \cdot \Delta T_{matrix} \quad (5)$$

where: ΔT_{log} = reading of acoustic log in s ft^{-1} ; ΔT_{matrix} = transit time of the solid rock framework; and ΔT_{fluid} = transit time of the interstitial fluid.

For a clean formation of known matrix density p_{matrix}, having a porosity Φ, and containing a fluid of average density p_{fluid}, the formation bulk density p_b will be, rigorously (Schlumberger, 1972):

$$p_b = \Phi \cdot p_{fluid} + (1 - \Phi) \cdot p_{matrix} \quad (6)$$

Porosity and density logs can be synthesized from a conventional acoustic travel time log by solving eqn. (5) for Φ:

$$\Phi = \frac{\Delta T_{log} - \Delta T_{matrix}}{\Delta T_{fluid} - \Delta T_{matrix}} \quad (7)$$

and substituting this result in eqn. (6):

$$p_b = \left(\frac{\Delta T_{log} - \Delta T_{matrix}}{\Delta T_{fluid} - \Delta T_{matrix}}\right) \cdot p_{fluid} + \left(1 - \frac{\Delta T_{log} - \Delta T_{matrix}}{\Delta T_{fluid} - \Delta T_{matrix}}\right) \cdot p_{matrix} \quad (8)$$

Programming a microcomputer to perform the above calculations is easy.

Figure 8 applies the above procedure to a carbonate aquifer in NW Greece. From other wells in the area it is known that the aquifer contains dolomite sections with high hydraulic conductivity. This can be explained by the increase in porosity and permeability caused by the mineralogical transformation of calcite to dolomite since the crystal lattice of dolomite occupies about 12% less space than that of calcite (Hohlt, 1948).

In Fig. 8 the acoustic log is shown on the left. At the right, the density measurements obtained from a density log are plotted on the same scale as the synthesized density log. Comparing these two logs helps to define lithology changes in regions where individual logs show little variation in response. In the limestone interval the computed and observed density curves are nearly coincident. In the dolomite sections, however, there is a significant separation between the two curves.

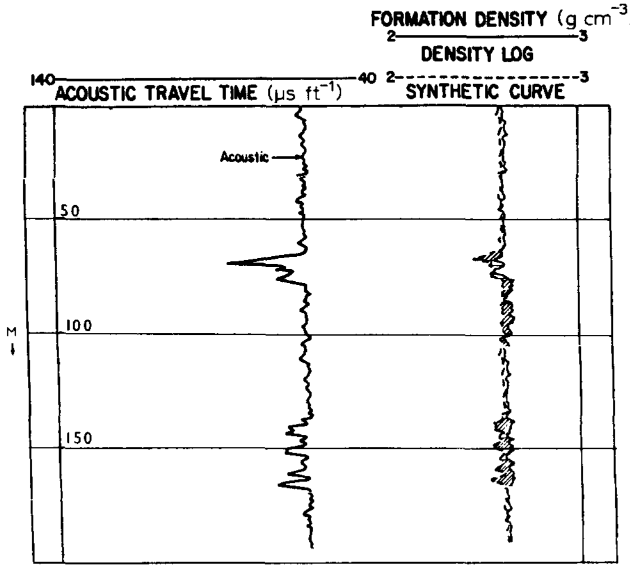

Fig. 8. Comparison between density log and the synthetic derived density log from an acoustic log (velocity of sonic pulses in the matrix was assumed 22,000 ft s^{-1}, and for the fluid 5300 ft s^{-1}).

Resistivity-derived porosity of an aquifer

The generally accepted relationship between formation factor F, and fractional porosity Φ is:

$$F = 0.62 \cdot \Phi^{-2.15} \qquad \text{(Humble formula)} \tag{9}$$

for sands, and:

$$F = \Phi^{-2} \tag{10}$$

for carbonate rocks or rocks that are not granular.

Since the formation factor F is defined as the ratio of the saturated formation resistivity p_f, obtained from a logging tool, over the formation water resistivity p_w, the above equations can be used to calculate porosity.

Usually in freshwater logging applications, the electrolyte salinity is not sufficiently high to suppress the effects of ionic-exchange surface conduction (Tselentis, 1985a), and the measured formation factor varies with the resistivity of the pore fluid. This occurs mainly when clay and/or organic matter are present. An empirical formula such as that of Hill and Milburn (1956), is necessary to reduce the measured apparent formation factor F_a to that which would be observed with a very low electrolyte resistivity of 0.01 ohm m:

$$F_{0.01} = \frac{F_a}{(100p_w)^{(b \log_{10})(100p_w)}} \tag{11}$$

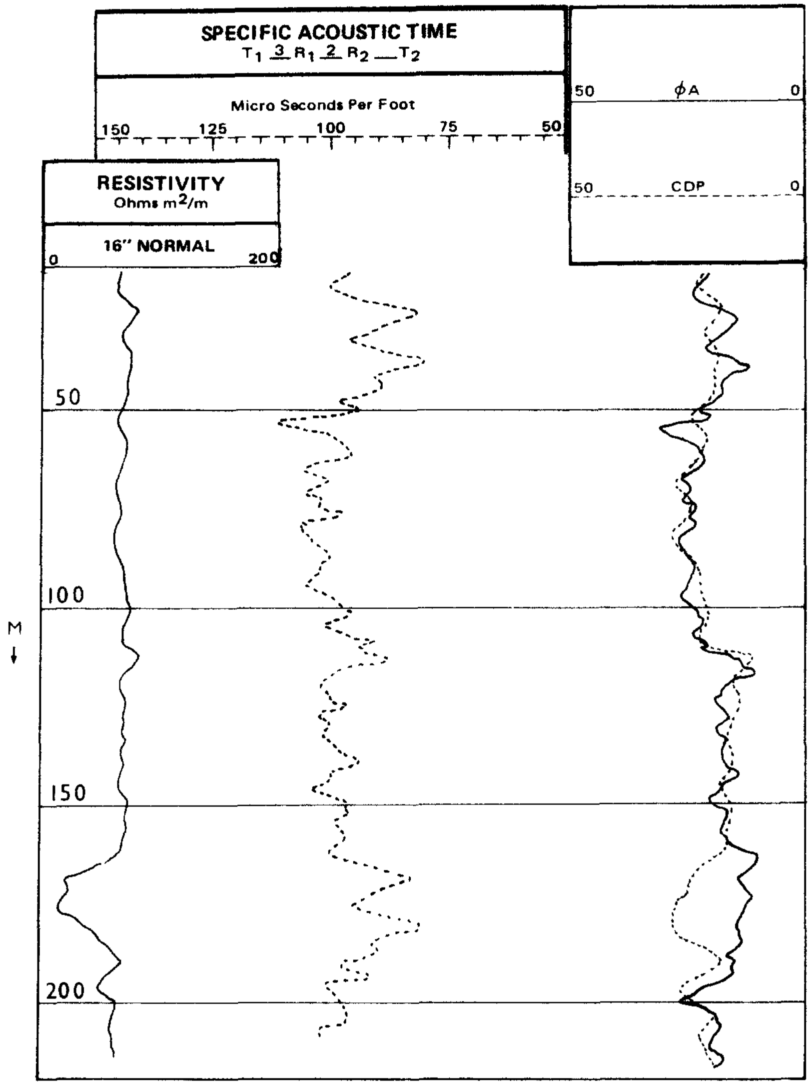

Fig. 9. Comparison between the porosity log derived from acoustic and resistivity logs (velocity of the sonic pulses for the matrix was assumed 18,000 ft s^{-1} and for the fluid 5300 ft s^{-1}).

where b is a measure of the effective clay fraction and can be calculated from:

$$b = -0.135 \cdot (K_e/A) - 0.0055 \quad (12)$$

where K_e is the cation exchange capacity in meq per 100 g of dry sample and A is the water content in g per 100 g of dry sample.

For a combination 16-inch normal resistivity log/acoustic log from a sandstone aquifer in Greece, a porosity log was synthesized from the acoustic log. Laboratory investigation of core-samples suggested a mean value of $b = -0.04$. By applying eqns. (8) and (10) the resistivity-derived porosity was calculated and plotted on the same scale. Figure 9 demonstrates that the two porosities are essentially the same for most of the aquifer apart from its lower part where the resistivity-derived porosity shows a large excursion to the left, indicating saline intrusion.

On-site processing of a resistivity log for the location of fissure zones in an aquifer

Electrical resistivity well logs are now an almost universal adjunct to standard groundwater drilling practice; electrical well logs are a valuable tool to evaluate the hydraulic characteristics of an aquifer and supplement information obtained by more laborious and expensive pumping tests.

In certain cases the direct evaluation of the formation's geoelectric properties can provide an indication of the aquifer's hydraulic properties. The process followed for the automatic evaluation of a new useful geoelectric parameter known as T-L (Transverse-Longitudinal) log, (Tselentis, 1983, 1985b) from a normal resistivity log will be illustrated.

A resistivity log (after a zonation process), can be interpreted in terms of a series of beds, each having a specific thickness and resistivity; for any specific section (H), of formation it is easy to compute transverse and longitudinal resistivity values using the following equations:

$$P_{tr} = \sum_{1}^{n} (h_i \cdot P_i)/H \tag{13}$$

$$P_l = \sum_{1}^{n} (h_i/P_i)/H \tag{14}$$

where h_i is the thickness of layer i and P_i is its resistivity.

The procedure used here is based on the fact that the sums involved in eqns. (13) and (14) were not ordered; thus several beds with the same resistivity could be replaced by a single bed having the same resistivity and thickness equal to the sum of the thicknesses of the single beds. By random sampling of a specific section H of the log, one can estimate the equivalent portion of the section having any particular resistivity and from this construct a resistivity frequency distribution, with a density function $N(p)$. The transverse and longitudinal resistivities may now be computed as follows:

$$P_{tr} = \frac{\int_0^{\infty} p \cdot N(p)\mathrm{d}p}{H} \tag{15}$$

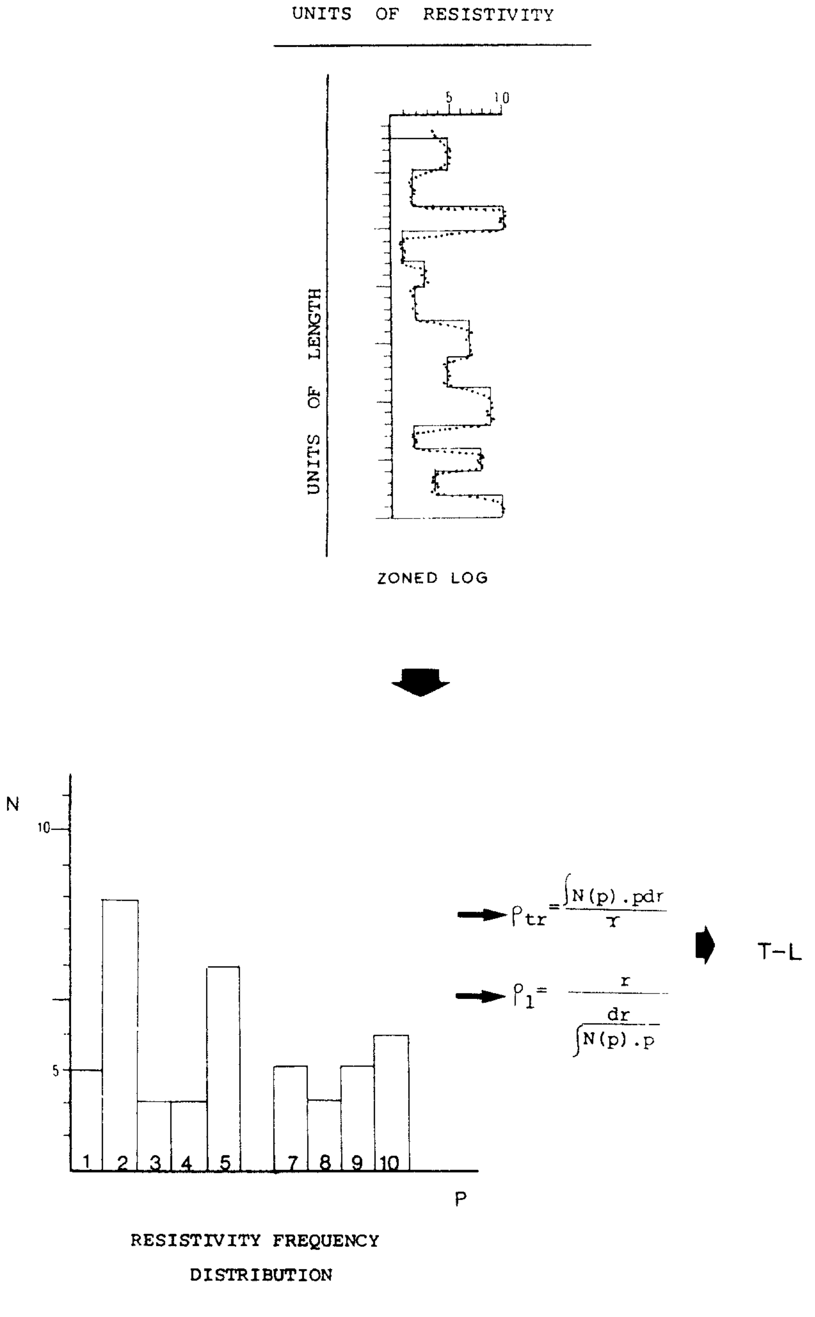

Fig. 10. Evaluation of the T-L log. After the resistivity log has been zoned, the resistivity frequency diagram is constructed from which the transverse and longitudinal resistivities are calculated.

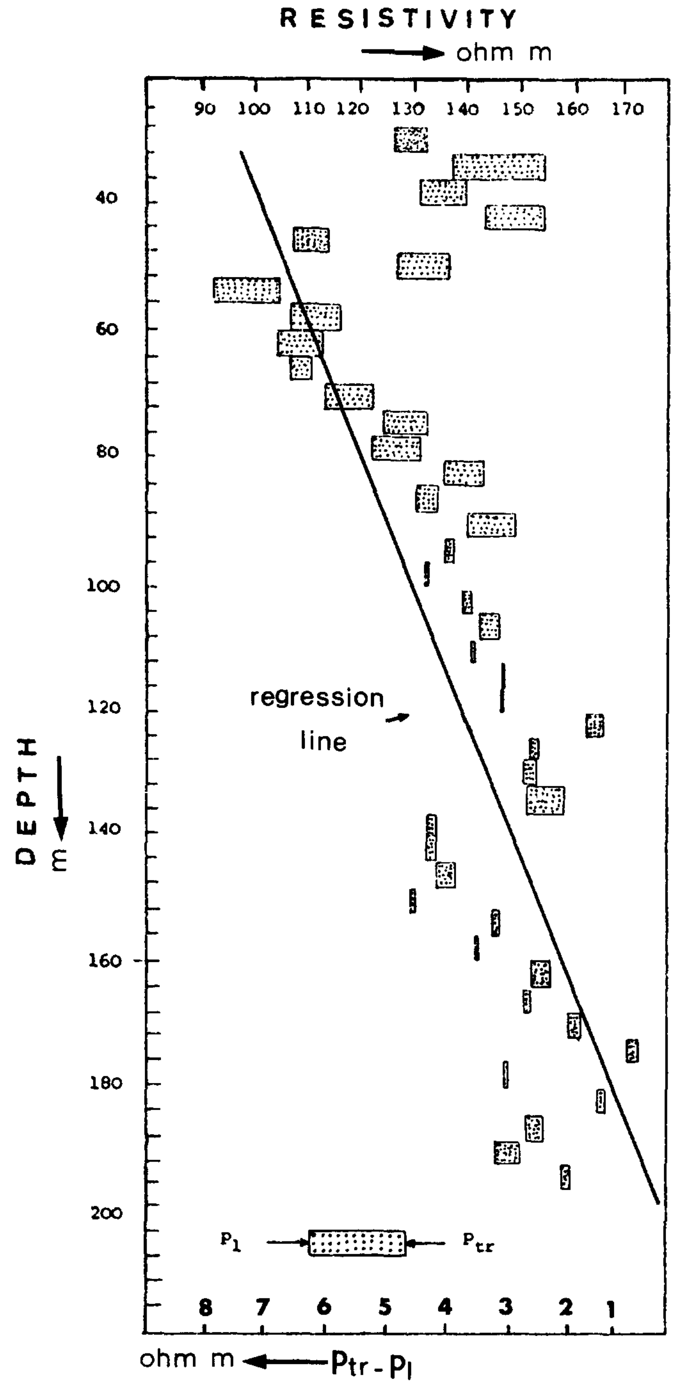

Fig. 11. Difference between transverse and longitudinal resistivity versus depth for a Chalk aquifer.

TABLE 2

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)	$P_l = 4/\Sigma h_i/P_i$ (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						
36	215			3	208	865	0.018	216.25	216.22	0.03
37	220	219	34--38							
38	223				219					
39	227									
40	230			4	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						
52	235				235					
53	228	228	50—54	1	228	936	0.017	234	233.91	0.09
54	238	238		1	238					
55	223	221								
56	219			2	221					
57	214		54—58			862	0.018	215.5	215.47	0.03
58	212			2	210					

59	210	210		3						
60	207		58—62		210	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					
		130								
83	130									
84	150	145	82—86	1	130	526	0.031	131.5	129.37	2.13
85	140			2	145					
86	110				106					
87	103		86—90	1						
88	103	106		4	106	424	0.0377	106	106	0
89	106									
90	106									

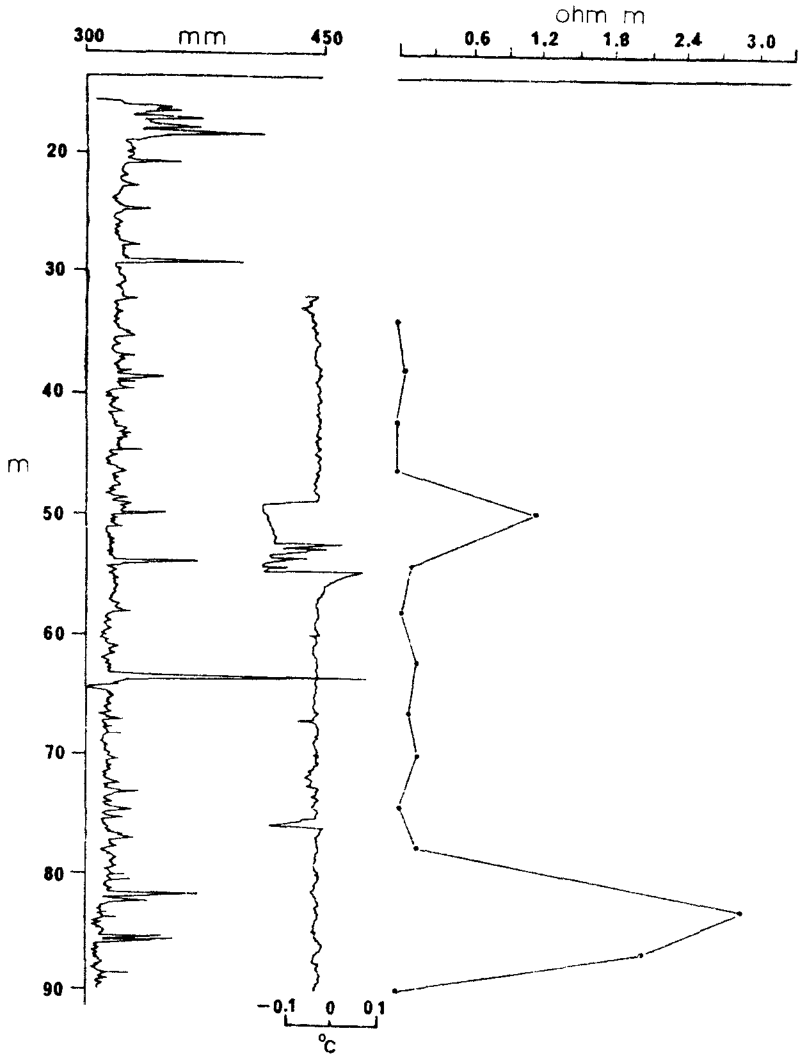

Fig. 12. Caliper, differential temperature and T-L log from a borehole sunk in a Chalk aquifer.

$$P_1 = \frac{H}{\int_0^\infty [N(p)/p]\,\mathrm{d}p} \tag{16}$$

A computer algorithm was designed to perform all the above operations and Fig. 10 shows diagrammatically the way in which the data were manipulated.

Figure 11 applies the above procedure to a 16-inch normal resistivity log from a fractured Chalk aquifer in SE England. The difference between transverse and longitudinal resistivities tends to decrease with depth; this is shown more clearly when a regression line is fitted. This result is consistent with those from other wells in the area; suggesting that the degree of fissuring of the aquifer decreases with depth.

Figure 12 represents the T-L log derived on-site by the above process, for a well in the same area. A detailed analysis of the calculation of the T-L log for this specific example is given in Table 2. The T-L log obtained suggests a change in the geoelectric properties of the formation at depths of 50 and 80 m. Since the formation is homogeneous (Chalk), one would suspect the existence of fissure zones at these levels. A differential temperature log run in the same borehole identified fissure zones at 50 and at 76 m. The caliper log also confirmed the existence of the fissure zones suggested by the T-L log.

CONCLUSIONS

Computer-orientated log interpretation techniques have been used for many years in the oil industry but their application in hydrogeological problems has been restricted.

It is possible for a microcomputer to handle, by relatively simple operations, complex analytical processes which may be used to advantage by the well log analyst in many hydrogeological problems. Discussion of a number of such applications has shown that in geophysics, linked to the data-handling facilities of microcomputers, the water industry has a powerful and underdeveloped logging technology that is ripe for development as a low-cost quantitative investigation technique.

ACKNOWLEDGEMENTS

The author would like to thank: Dr. M.H. de Freitas for his most useful comments and criticisms, Lynton Computer Systems and especially Dr. T. Bear for supplying the digitizer, Southern Water Authority and especially Mr. J. Ellis for field- and logistic support.

REFERENCES

Dresser Atlas, 1979. Log Interpretation Charts. Dresser, New York, N.Y., 93pp.

Fillon, L.N.C., 1928. On a quadrature formula for trigonometric integrals. Proc. R. Soc. Edinburgh, 49:38.

Hawkins, D.M. and Krooden, J.A.T., 1979. Zonation of sequences of heteroscedastic multivariate data. Comput. Geosci., 5: 189—194.

Hill, H.J. and Milburn, J.D., 1956. Effect of clay and water salinity on electrochemical behaviour of reservoir rocks. Trans. AIME, 207: 65—72.

Hohlt, R.B., 1948. The nature and origin of limestone porosity. Quarterly, Colorado School of Mines, 43 (4): 317—323.

Lynch, E.J., 1962. Formation Evaluation. Harper and Row, New York, N.Y., 422 pp.

Kulhánek, O., 1976. Introduction to Digital Filtering in Geophysics. Elsevier, Amsterdam, 168 pp.

Robinson, V.K., 1974. Low cost geophysical well logs for hydrogeological investigations. Eng. Geol. Quart. J., 7: 207—215.

Schlumberger, 1950. Electrical Well Logging-Document. 72 pp.

Schlumberger, 1972. Log Interpretation Principles-Document. 109 pp.

Scott, J.H., 1978. A fortran algorithm for correcting normal resistivity logs for borehole diameter and mud resistivity. U.S. Geol. Surv., Open File Rep., 78—669, 12 pp.

Souder, W.R and Pickett, G.R., 1974. A computerized method for the zonation of digitized well logs. Log Anal., May—June: 3—8.

Testerman, J.D., 1962. A statistical reservoir zonation technique. J. Pet. Technol., 6: 889—893.

Tselentis, G-A., 1983. The assesment of the hydraulic conductivity of a fractured Chalk aquifer from borehole geophysical logging. Ph.D. Thesis, Imperial College of Science and Technology, London University, London, 479 pp.

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

Tselentis, G-A., 1985b. T-L log. A new logging technique indicative of fracture zones. Paper presented at the 47th EAEG Meeting, Budapest.

Webster, R., 1978. Optimally partitioning soil transects. J. Soil Sci., 29: 123—132.

Wyllie, M.R.J. and Rose, W.D., 1958. Some theoretical considerations related to the quantitative evaluation of the physical characteristics of reservoir rock from electrical log data. Trans. AIME, 189: 105.