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COMPARISON OF INTERPRETED RESULTS OF RESISTIVITY SOUNDING CURVES WITH WELL DATA IN EL TATIO GEOTHERMAL FIELD, CHILE

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ABSTRACT

Comparison of the interpreted result of a resistivity sounding curve with the data of a well drilled in the neighborhood of the resistivity station is treated as an important problem of geothermal exploration's aftercare. As a result, it becomes clear that temperature log in the well is correlated with the resistivity step distribution, which is plotted by using the solution of the iterative least-squares interpretation for the resistivity sounding curve.

Some of geoelectrical indications are discussed for the location of permeable levels, which correspond to geothermal reservoir, the variation point of temperature log, the correlation of formations with resistivity layers, and their interface depths from the surface.

INTRODUCTION

In development of geothermal resources a discovery well proves commercially an existence of geothermal fluids. Moreover, it gives important information on geologic sequences, its petrological properties and geothermal reservoirs. At present, geothermal well data include geologic section, alteration index, drillability log, caliper log, temperature log, pressure log, escaped portion and percolated rate of circulating mud water, water table, etc.

On the other hand, universal validity of direct and indirect geophysical indications obtained by the application of geophysical methods to geothermal exploration leads to a useful geothermal exploration method.

Based on the standpoint above, the author carried out the present investigation. The object of this paper is to find the correlation of geoelectrical indications with geothermal well data.

LOCATION OF GEOTHERMAL WELLS AND RESISTIVITY STATIONS

Figure 1 shows the map illustrating the location of geothermal wells and resistivity sounding stations in El Tatio geothermal field. Hot springs are situated in the hatched area. The result of temperature measurements at a depth of 2 m is given by the iso-temperature contour map.

For convenience of comparison, the data of #1, #9, #10, and #7 Wells and the results of interpretation of resistivity sounding curves observed near the site of each well were taken into consideration.

In this geothermal field, as a rule, resistivity sounding curves for the Schlumberger array were observed in the direction of NS and EW spreads of increasing electrode separations. This is a new and good idea in the field work of resistivity soundings to determine strikes and inclinations of formations.

REINTERPRETATION OF RESISTIVITY SOUNDING CURVES

Based on the assumption of multiple-layered model, the iterative least-squares interpretation of resistivity sounding curves were performed by using a current graphic display apparatus connected to the Geothermal Resistivity Interpretation System.

The results obtained are listed in Table 1. The first numeral for the notation of resistivity sounding curves, 1-EW, 9-NS, 10NS, 10EW, and 7-EW, denotes the resistivity sounding station and the next Roman letters show the direction of spreading the electrode system.

In general, this interpretation produces many solutions with preconditions of convergence. These solutions can be grouped by accuracy ranges denoted by κ and depend upon intial values. A best automatic fitting condition can be obtained when convergence factor is sufficient small for the accuracy requried. In the case of interpreting field curves it may be said that the iterate gives a good result, if κ is less than 10 per pent, although it depends upon smoothness of an observed curve.

As listed in the Table, we see that the assumption of a four layer model for the interpretation of the 9-NS curve gives more precise result than that of a five

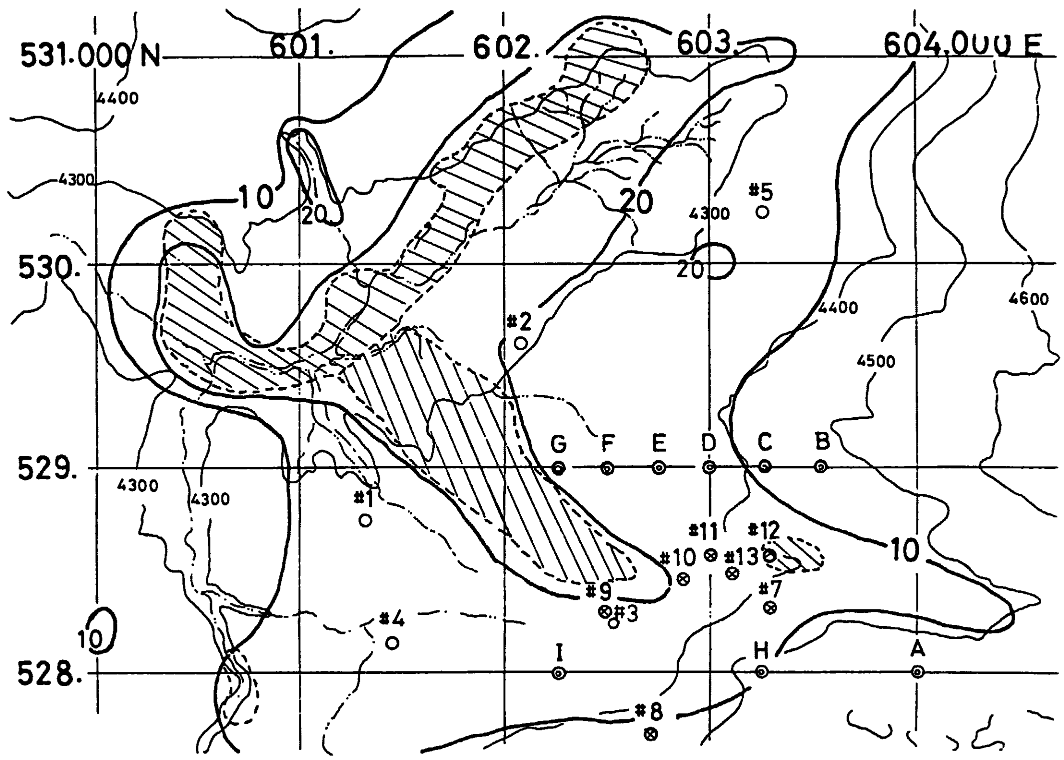

Fig. 1. Map showing the location of wells and resistivity sounding stations in El Tatio geothermal field

Table 1. Numerical values of the solutions obtained by the iterative least-squares interpretation of resistivity sounding curves observed at stations, 1-EW, 7-EW, 9-NS, 10NS, and 10EW

RS curves	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	κ	Curve types
1-EW	340.206	1309.455	108.411	.....	....	6.406	220.707	....	....	0.09126	2(12)
1-EW	346.580	1379.465	76.064	.....	....	6.323	243.151	....	....	0.06781	
7-EW	522.622	67.592	1.670	4.655	207.346	3.176	13.157	84.824	478.269	0.09685	13(2211)
7-EW	567.315	78917	1.773	5.097	824.181	2.886	12.176	185.410	541.282	0.13251	
9-NS	6.878	1.702	2.710	3.787	....	10.473	29.163	443.800	....	0.06170	5(211)
9-NS	6.893	1.740	2.721	3.823	....	10.362	30.620	459.597	....	0.06086	
9-NS	7.222	22.422	0.325	3.078	3.804	3.816	6.833	12.079	506.619	0.21298	5(1211)
10NS	55.060	12.309	0.908	4.876	....	7.989	23.255	88.134	....	0.07994	7(221)
10NS	55.381	13.522	0.863	4.814	....	7.740	22.681	85.435	....	0.08227	
10EW	122.755	28.416	0.942	4.345	....	5.206	20.014	66.009	....	0.06482	7(221)
10EW	137.586	36.205	1.105	4.382	....	4.407	18.176	85.421	....	0.05475	

κ denotes the root mean square of the relative errors of approximations in apparent resistivities (calculated) corresponding to the exact apparent resistivity values (given) for electrode separation available.

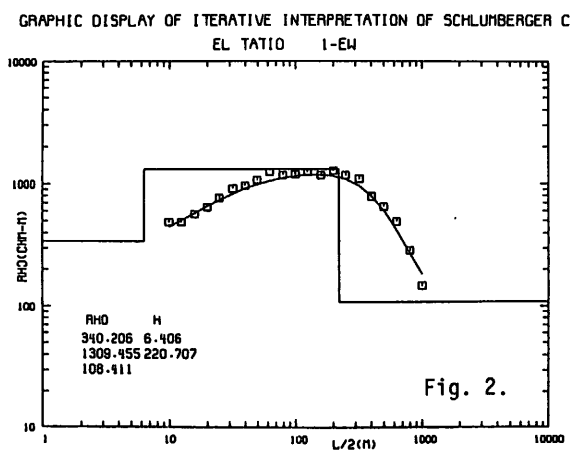

Fig. 2.

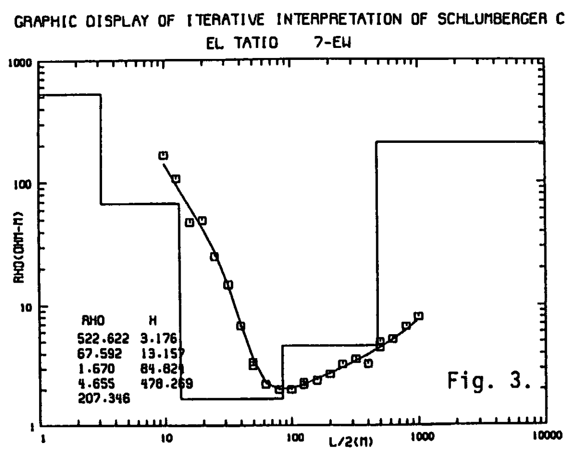

Fig. 3.

layer one.

Some examples of graphic display are shown in Figures 2, 3, and 4. In these

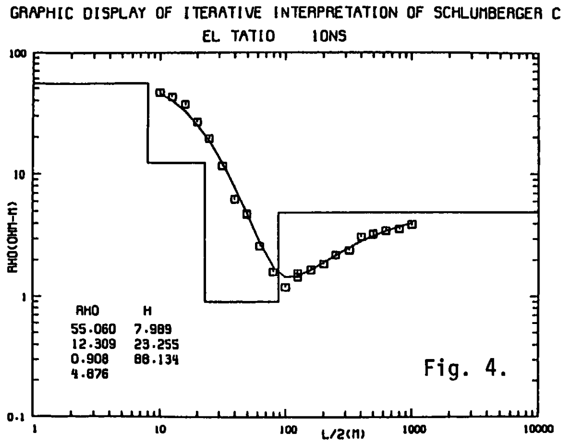

Fig. 4.

Figures, the values of apparent resistivities are plotted as ordinates, and the lengths of half electrode separations of the Schlumberger array as abscissas. Regular square marks represent observed apparent resistivities corresponding to the selected electrode spacings, and the solid curve in each Figure shows the theoretical resistivity sounding curve gained by the automatic curve fitting.

The solution of the iterative least-squares interpretation of resistivity sounding curves is given by the resistivity step distribution, of which numerical values of apparent resistivities in ohm-m for the successive layers and of depths in m of interfaces for the assumed multiple-layered earth are plotted below Labels,RHO and H, respectively, on the left hand lower corner of each Figure.

The resistivity sounding curve of 1-EW observed near #1 Well shows essentially the type 2(12) of a 3-layer case, the 7-EW curve represent the type 13(2211) of a 5-layer case, the 9-NS curve expresses the type 5(211) of a 4-layer case,and the 10NS and 10EW illustrate the type 7(221) of a 4-layer case.

If except for the curve type of 7-EW resistivity sounding curve, the residual curve types of three fall under the category in the classification of the Schlumberger resistivity sounding curves in geothermal fields (Onodera, 1982).

The Well #7, which was drilled into the geoelectrical structure determined by resistivity exploration, produced a useful mixture of steam and hot water. Consequently, the curve type of 13(2211) of the 7-EW resistivity sounding curve should also be included in the statistical table showing the number of production wells per curve type (Onodera, 1982).

EXISTING DATA FOR WELLS

According to A.LAHSEN and P.TRUJILLO (1975), Some of Wells proved the presence of three permeable levels, namely, the first level, formed by volcanic sands and gravels so that its permeabilty is high,is located in the Tucle dacites formation at a depth ranging from 150 m to 245 m; the second one, on the whole low permeability, in the Puripical ignimbrite from 480 m to 600 m; and the third zone in the base of the Rio Salado volcanic group from 745 m to 1580 m. These are listed in Table 2.

Table 2. Permeable levels proved by Wells

Wells	Permeable levels	Depth ranges	Degree of permeabi.	Temper-ature	Formations
7	1st	170-245m	high	160°C	Tucle
	2nd	480-530	----	228	Puripicar
	3rd	745-890	high	260	Penaliri
9	1st	141-180	high	160	Tucle
	2nd	550-600	low	224	Puripicar
	3rd	1150-1580	low	200	Penaliri
10	1st	150-190	high	160	Tucle
	2nd	550-600	low	230	Puripicar
	3rd	700-800	----	235	Penaliri

Further, géologic sections are prepared for #7, #9, and #10 Wells, and their temperature logs are also measured. These will be used for the matter of comparison described later.

COMPARISON OF INTERPRETED RESULTS OF RESISTIVITY SOUNDING CURVES WITH WELL DATA

It needs to research this interesting problem, in order to extract geoelectrical indications of reservoir from resistivity data and to find the real worth of resistivity exploration for geothermal fields.

Comparison of Solution for 7-EW Resistivity Sounding Curve with Data of #7 Well

Plotting the comprehensive figure by use of observed apparent resistivities for the selected half electrode spacings, its solution represented by the resistivity step distribution, of which numerical values are listed in the second major line of Table 1 and is shown in Figure 2, the temperature log for #7 Well, and the geologic section for the well, together with information of permeable levels for the well listed in Table 2, then we have Figure 5.

As seen from the Figure, the comparison between the resistivity step distribution and the geologic section is relatively difficult.

After careful examination, it is demonstrated that the resistivity step distribution is correlated significantly with the temperature log. That is to say, the fourth resistivity layer with 4.655 (or 5.097) ohm-m in resistivity corresponds to the part showing 160 °C of the temperature log and the depth of the fourth interface of 478.269 (or 541.282) m indicates both

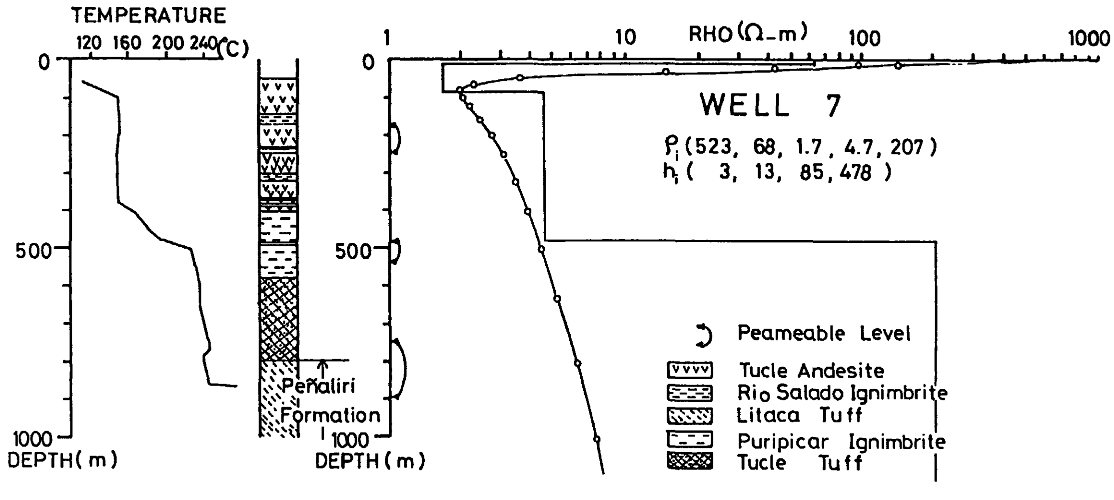

Fig. 5. Comparison of the interpreted result of the 7-EW resistivity sounding curve with the data of Well #7

a variation point from 160 °C to 240 °C of the temperature log and the upper depth of the second level in the Puripicar ignimbrite. In addition, the depth of the third interface of 84.824 m is roughly equal to the first variation point of the temperature log.

Unfortunately, the result of interpretation of the resistivity sounding curve does not reveal the presence of the first and third permeable levels. According to such resolving power of resistivity sounding curve, it is known naturally that either the scale of the second permeable level is larger than that of the first and third ones or it has no resistivity contrast between upper and lower formations.

Correlation of Interpreted Result of 9-NS Resistivity Sounding Curve with Data of #9 Well

Similar to the example above, we can see from Figure 6 that the result of interpretation of the 9-NS resistivity sounding curve is correlated with the temperature log for Well #9. That is, the third interface between the third and fourth resistivity layers indicates the maximum variation point of the temperature log. Especially, it should be remarked that the depth of the third interface of 443.800 m (or 400.000 m) coincides with the upper depth of Puripicar ignimbrite formation.

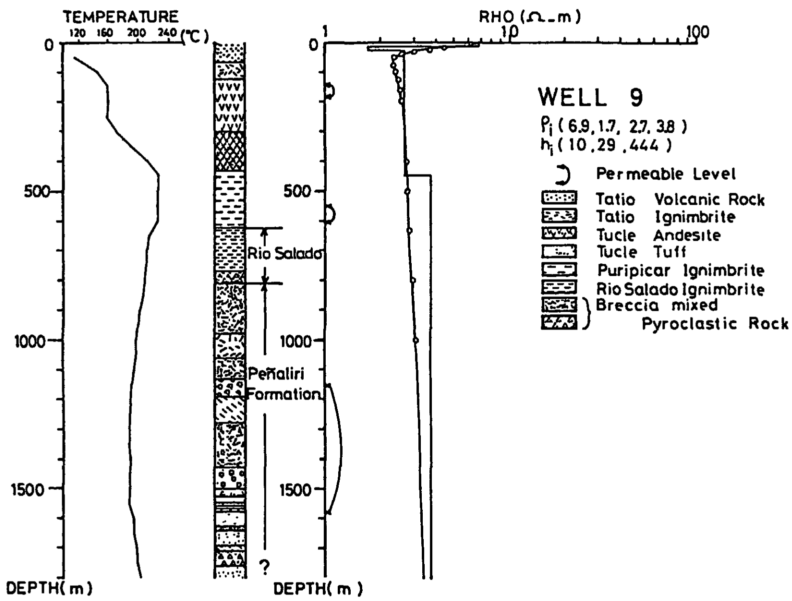

Fig. 6. Correlation of the interpreted result of the 9-NS resistivity sounding curve with the data of Well #9

Correlation of Result Obtained by Interpretation of Resistivity Sounding Curve with Data of #10 Well

Figure 7 shows the example of the resistivity step distribution correlated with the geologic section and the temperature log.

In this case, the depth of the third interface of 88.134 m corresponds to the depth of Tucle andesite, and also indicates the variation point of the temperature log.

A significant reason is that there is no effective resistivity contrast in the successive geological formation below the Tucle andesite, since the observed resistivity sounding curve is very smooth. Note that resistivity exploration can not be applied to an area giving such a

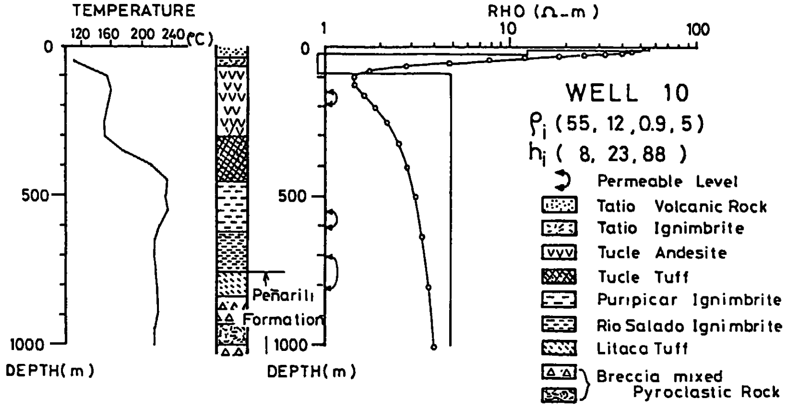

Fig. 7. Correlation of the result obtained by the interpretation of the resistivity sounding curve with the data of Well #10

geoelectrical condition.

COMPARISON OF RESISTIVITY SECTION WITH GEOLOGIC SECTION AND TEMPERATURE PROFILE

Comprising the section of resistivity layers, determined by adequate solutions for the interpretation of resistivity sounding curves, 1-EW, 9-NS, and 7-EW, in the geologic section along Wells, #1, #9, and #7, then we have Figure 8.

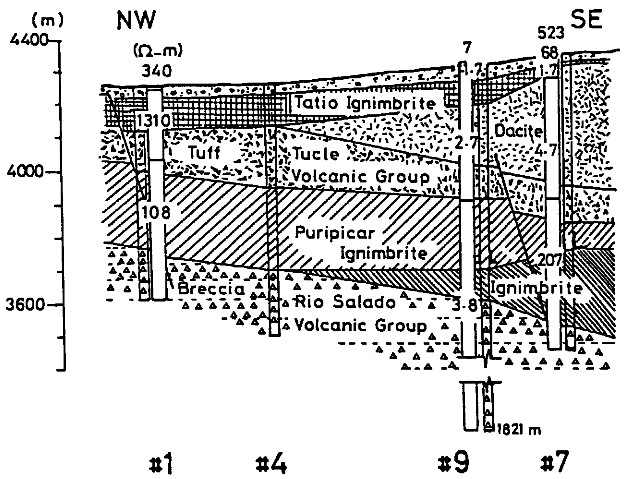

Fig. 8. Correlation of resistivity layers with geologic section and the distribution of permeable levels

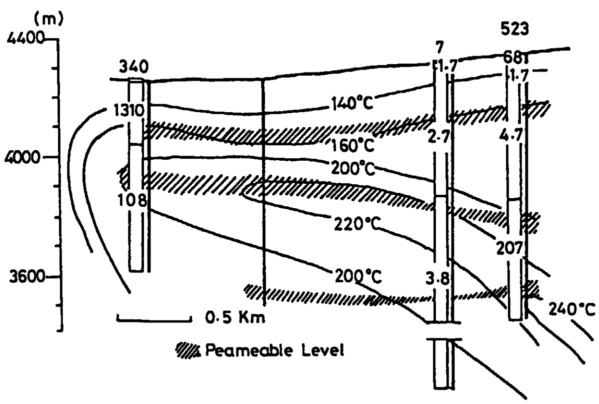

Fig. 9. Correlation of resistivity layers with temperature profiles and the distribution of permeable levels

As a result of comparative studies, it is concluded that the combination of Tatio ignimbrite and tuff formation is indicated by the second resistivity layer of 1309.455 ohm-m; the successive formation (Puripicar ignimbrite and breccia) is given by the third resistivity layer of 108.411 ohm-m; and the depth (260 m from the surface) of the boundary between tuff and breccia formations is roughly equal to the depth of the third interface of 220.70 7 m.

In the last case resistivity measurements in depth determination estimates an error of -15 per cent, approximately. And the resistivity sounding curve has no resolving power of indicating the boundary depth of Tatio ignimbrite and Tucle tuff formation and also that of Puripicar ignimbrite and breccia formation.

In the correlation between geologic section near #9 Well and the interpreted result of resistivity sounding curve at station, 9-NS, only the boundary depth of Tucle volcanic group and Puripicar ignimbrite is given by the third depth of interface of 443.800 m with close accuracy.

Figure 9 shows the correlation of resistivity layers with temperature profile and the distribution of three permeable levels. Appart from the second resistivity layer of 1309.455 ohm-m in the solution of the 1-EW resistivity sounding curve and the fourth resistivity layer of 3.787 ohm-m in that of the 9-NS one, we can find that the deepest interface of resistivity layers for each solution indicates roughly the upper depth of the second permeable level, simultaneously coincides roughly with the upper contour of 200 °C of the temperature profile along the traverse of wells, #1, #9, and #7.

It follows from the fact illustrated above that the basic data to be correlated with the result of interpreting resistivity sounding curves lies significantly in the temperature distribution of the well, which is related to the temperature distribution of underground.

In other words, it is not too much to say that the function of resistivity exploration is dependent upon resistivity contrast controlled by temperature.

CONCLUDING REMARKS

For the sake of comparison between the interpreted result and the well data available, firstly, the author presented appropriate solutions to the observed resistivity sounding curves by making use of the iterative least-squares interpretation. Here, one of principal materials in the present investigation was obatined for the practical grounds of correlation.

Summarizing the results of the research, it was concluded that the solutions of the iterative interpretation for given resistivity sounding curves were correlated with the temperature log in each well drilled in the neighborhood of the resistivity sounding stations, although there is not enough of the necessary basic data.

Resistivity measurements gave the resistivity values of the formations such that 1 ohm-m order for the Tatio ignimbrite, 5 ohm-m order for the Tucle andesite and 100-200 ohm-m order for the Puripicar ignimbrite.

Unfortunately, it was impossible to determine resistivity values of the Penaliri formation, in which the third permeable level exists.

Geoelectrical indications for detecting the first level located in the Tucle formation was given by the segment, gradually increasing state of apparent resistivity curve, past a position of showing the minimum indication of the Schlumberger resistivity sounding curves as shown in Figures 5, 6, and 7.

The schlumberger resistivity sounding curves, which indicated the existence of the second permeable level in the Puripicar formation, were measured at stations, 7-EW and 9-NS.

With the results of interpretation of these curves, similar correlation with the temperature logs for #7 and #9 Wells was observed. In fact, both resistivity and depth of the formations were fairly determined, and the deepest depth of the solutions indicated the variation point of temperature logs.

These practical examples of comparison will be useful as a basis of resistivity soundings in geothermal fields. These are the merit of resistivity soundings, but the method has its demerit that no information for detecting geothermal resources is obtained, as far as resolving power is concerned.

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