

An Electrostratigraphic Study of the Formations in the Coastal Area of Yunlin Hsien, Westcentral Taiwan

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ABSTRACT

A geoelectrical survey was conducted in the coastal area of Yunlin Hsien, westcentral Taiwan, for the study of electrostratigraphy as well as seawater intrusion. The direct current resistivity method was used, and forty-six vertical electrical soundings with Schlumberger array were carried out in the study area. The sounding data were interpreted using the 1-D inversion method. The results indicate that the shallow part of the study area can be divided into three electrostratigraphic units. They are designated, from top to bottom, the A, B and C formations.

The A-formation is a combination of thin layers of medium resistivity and is correlated with the layers of soil and fine sand on the top.

The B-formation is characterized by a thick layer or layers of low resistivity and is correlated with the layers of clay, mud and fine sand with saline groundwater.

The C-formation is characterized by high resistivity and is correlated with the layers of pebble, sand and clay with fresh groundwater.

The parameters in Archie's equation are evaluated with the resistivity interpreted from the VES data, and the results are $a=0.858$ and $m=1.367$. The critical resistivities of salty strata are also evaluated.

There is seawater intrusion in the study area, but it is locally distributed within a small area and is near to or on the surface of the ground. The intrusion was caused by the flooding of seawater during typhoons, storms and storm surges. The main saline groundwater body is the formation water in the B-formation, which is not caused by seawater intrusion but is the connate water in the stratum sedimented in marine environments.

(Key words: DC resistivity, Electrostratigraphy, Seawater intrusion, Coastal plain of Yunlin Hsien)

1. INTRODUCTION

The study area is situated on the coast of Yunlin Hsien, westcentral Taiwan (Figure 1). Formerly, most of the area was rice and sugarcane fields. In the last thirty years many fish ponds were constructed, especially in the area near to the coastline.

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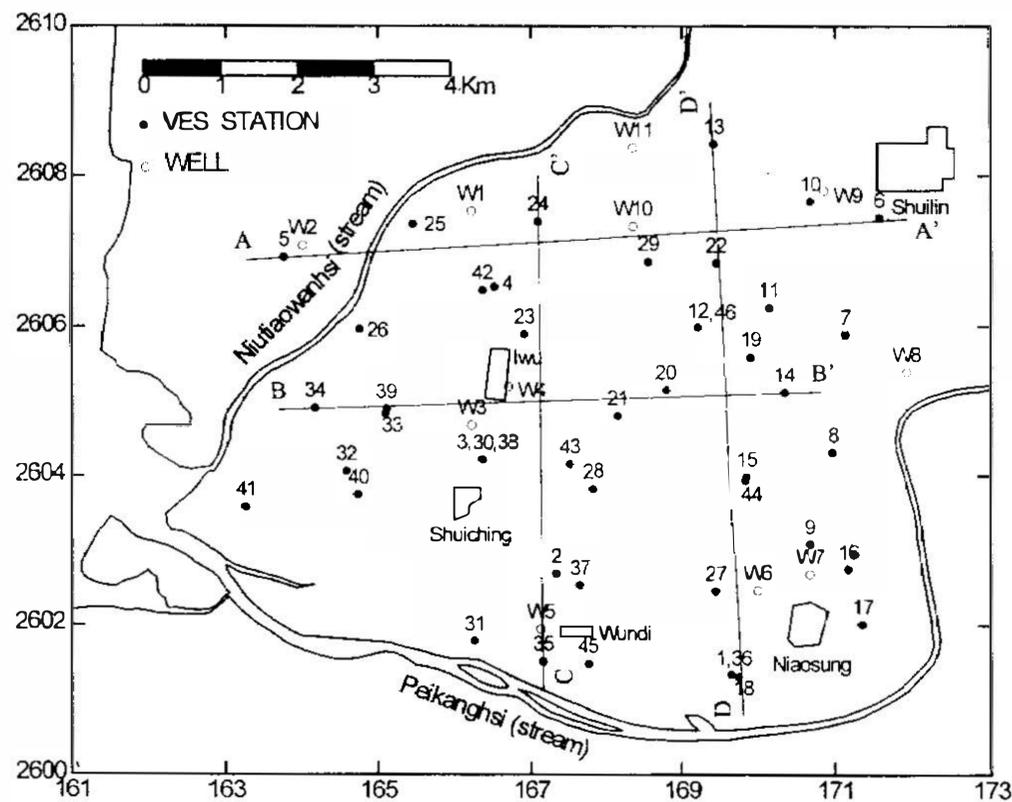


Fig. 1. The locations of the vertical electric soundings showing by the black dots, water wells by circles and four profiles AA', BB', CC' and DD' in the coastal area of Yunlin Hsien.

The surface of the study area is low and flat, with more than sixty percent of the area being lower than five meters in altitude. Hence, several artificial channels were constructed for drainage. Because there was not enough surface fresh water, many water wells were constructed for irrigation and fish rearing, and most of these wells are 90 to 150 meters in depth. The lithologic columns of the wells indicate that the strata belong to the alluvium and are structurally undisturbed. The upper part of the strata (0 to 60 meters in depth) is mainly composed of layers of clay, sandy mud and fine sand. The lower part (60 to 150 meters in depth) is mainly composed of layers of pebble, sand and clay. The total thickness of the layers of pebble and sand is about thirty meters, which is the main confined aquifer in the study area. Because of overpumping, the piezometric surface has declined and was lower than the mean sea level in most areas. According to the measurements from 1962, the lowest piezometric surface of minus 5 meters (below the mean sea level) appeared around the Wundi village on the southern boundary of the study area. At that time, no seawater intrusion was found. The measured data indicated that the piezometric surface declined continuously in the following years, the lowest values being minus 13 meters, minus 20 meters and minus 25 meters in the years 1973, 1977 and 1986 respectively (Liu, 1986; Tsao and Wang, 1984). The overpumping not only caused the lowering of the piezometric surface of groundwater but also caused subsidence in the study area. The surface of the ground in some places was lower than the high tide level. Hence banks were constructed along the sides of channels to prevent flooding by seawater at high tide. But seawater flooding has occurred several times as a result of typhoons, storms and storm surges.

For most wells, the salinity of pumped water is low, being about twenty to one hundred PPM depending on the seasons. For some other wells, the salinity of pumped water is higher

being in the region several hundred to several thousand PPM depending on how long a pumping has been in use and the season (Liu, 1986; Tsao and Wang, 1984).

For the variation of salinity, Liu observed a general phenomenon that the salinity was higher at the beginning of a pumping and decreased as the pumping progressed. Extremely high values appeared at the beginning of a pumping after a long period without operation (Liu, 1986). For the ten to twenty years that the wells have been in use, the salinity of pumped water at some wells was high and remained high over the period of pumping. These wells, such as wells W-5 and W-6 in the southern part of the study area were then abandoned.

According to the aforementioned phenomena, Liu inferred that there was no seawater intrusion in the study area. She also inferred that the high salt content in pumped water was not caused by the dissolving of the residual salt in strata, but was caused by leakage of saline water from the shallow aquifer which was contaminated by seawater floodings (Liu, 1986). A comprehensive study of seawater intrusion for the Yunlin aquifer system was carried out by Tsao and Wang in 1984. They inferred that seawater intrusion had been occurring in the study area, and the paths of seawater intrusion were not only from the coast, but also from the Peikanghsi stream (Tsao and Wang, 1984).

The region of high salt content, the cause of the high salinity of pumped water, and the seawater intrusion are studied from the point view of electrostratigraphy.

2. METHOD

The direct current resistivity method was used in this study to investigate the resistivities of the strata. The Schlumberger electrode configuration was used in vertical electric soundings (VES). In each sounding, the current electrodes were spread out step by step from 2 meters to the maximum spacing with 10 spacings per logarithmic cycle. The maximum spacings of the soundings range from 320 to 800 meters depending on location, most of them being greater than 480 meters. The apparent resistivity curves were plotted on double logarithmic paper in the field for inspecting the qualities of raw data. If a distorted datum appeared, the measurement was repeated or the position of the current electrodes was changed to improve the quality of the datum.

The VES data were interpreted with the 1-D inversion method, since the strata are structurally undisturbed and can be regarded as a 1-D structure. The computer program for 1-D inversion used in this study was developed by the geoelectrical research team at the Institute of Geophysics at National Central University. The forward part is based on the method of digital linear filtering of convolution (Ghosh, 1971; Koefoed, 1979; O'Neill and Merrick, 1984), and the inverse part is based on the second order Marquardt method (Jupp and Vozoff, 1975; Tong, 1988).

The initial models for 1-D inversion were established with an automatic method which was modified from Zohdy's method (Lue, 1994; Cheng and Shieh, 1994; Zohdy, 1989).

3. RESULTS

Forty-six vertical electric soundings (VES) were carried out in the study area, the locations of the VES are shown in Figure 1.

3.1 Types of Apparent Resistivity Curves and Interpretative Results

Every apparent resistivity curve (or VES curve) measured in the study area has one or two minima and an ascending segment on the right-hand branch. The dominant types of the curves are KH, HA and HKH types which implies that the strata contain one or two conductive layers and a resistive bottom layer. Stations 17, 21 and 25 are representative examples; the curves and interpretative results of these Stations are shown in Figure 2. The interpretative results indicate that the bottom layer is more resistive than its overlying layer. At Station 17, there are two conductive layers: the shallower one is minor, and is 2.2 meters thick, being between the depths of 0.5 and 2.7 meters; the deeper one is major, and is 43.7 meters thick, being between the depths of 31.6 and 75.3 meters. At Station 21, there is one conductive layer between 8.9 and 32.4 meters in depth, which is correlated with the major conductive layer of Station 17. At Station 25, there is one conductive layer between 3.3 and 6.7 meters in depth, which is correlated with the minor conductive layer of Station 17.

The interpretative results of all the VES measured in the study area indicate that the shallow formation (0 to 100 meters in depth) can be divided into four to seven layers by resistivity. These layers include one or two conductive layers and a resistive bottom layer. The bottom layer has a resistivity ranging mainly from 40 to 70 ohm-m. Except for the northwestern part of the study area, the bottom layer is overlain by a thick conductive layer. The conductive layer is about 10 to 55 meters thick and has a resistivity of between 0.9 and 12 ohm-m. In some places, there is a thin conductive layer several meters thick on or near to the ground surface.

3.2 Resistivity Distribution

The interpretative results of the VES indicate that the resistivities of the strata vary with position. The resistivities of the strata at twelve different depths are shown in Figure 3. The most remarkable feature in Figure 3 is the distribution of the low resistivity region (with a resistivity of lower than 12 ohm-m), as shown by the shaded regions in Figure 3. The low resistivity regions are mainly distributed between depths of 5 and 60 meters, and as shown in Figure 3, the central part does not connect with the sea. The area of the cross-section of the low resistivity region is small at depths less than 10 meters, and expands with depth, reaching the maximum at about 30 meters deep and then shrinking. In a few isolated small areas this occurs at about 60 meters in depth and disappears at a depth of 100 meters.

3.3 Electrostratigraphic Units and Resistivity Profiles

Three electrostratigraphic units can be specified based on the characteristics of the layers interpreted from the VES data. They are designated, from top to bottom, the A, B and C formations. Geoelectric resistivity profiles AA' BB' CC' and DD' in Fig. 1 depict the electrostratigraphic units in Figures 4~7. The A-formation is characterized by a combination of thin layers (less than 15 meters thick) of medium resistivity (mostly of 16 to 60 ohm-m). At a few stations, such as Stations 25 and 30, a thin conductive layer is included also. The lithologic units correlated to the A-formation are the layers of soil and fine sand on the top, as shown in Figures 4~7.

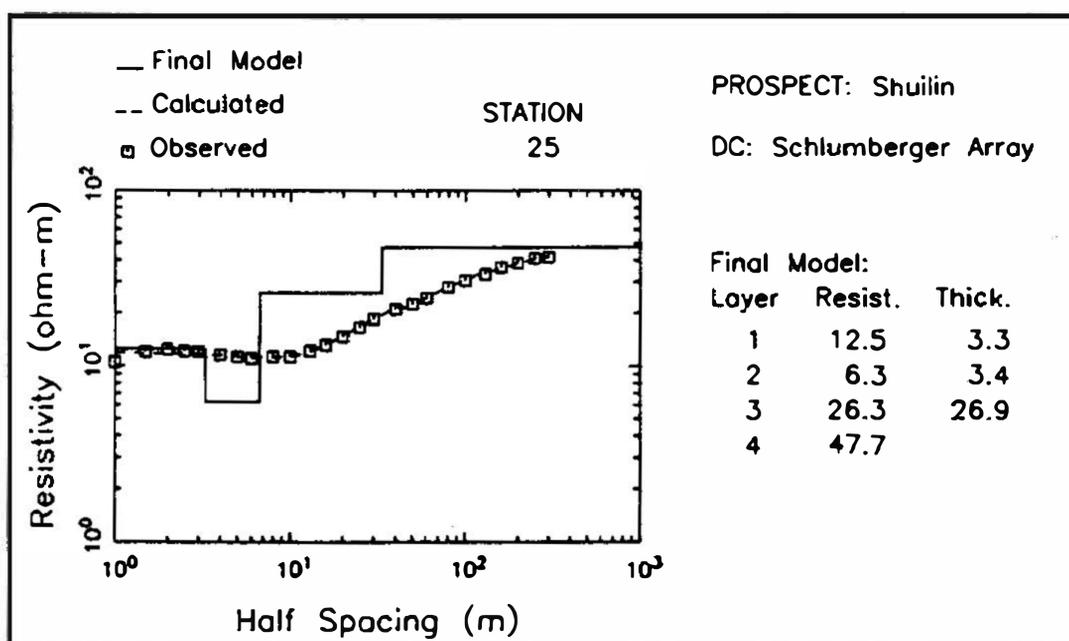
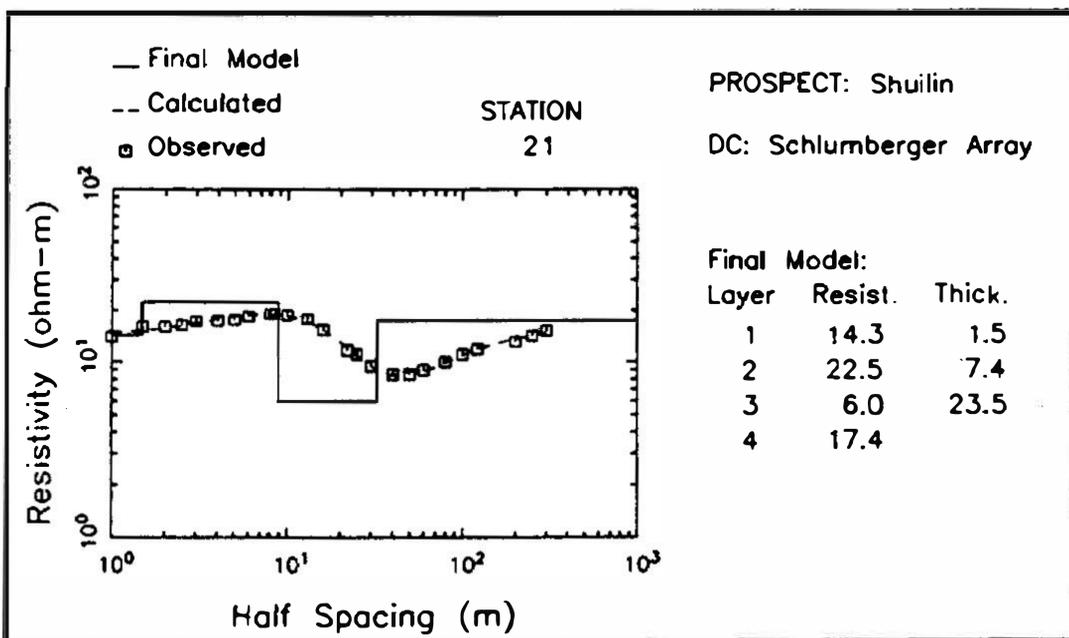
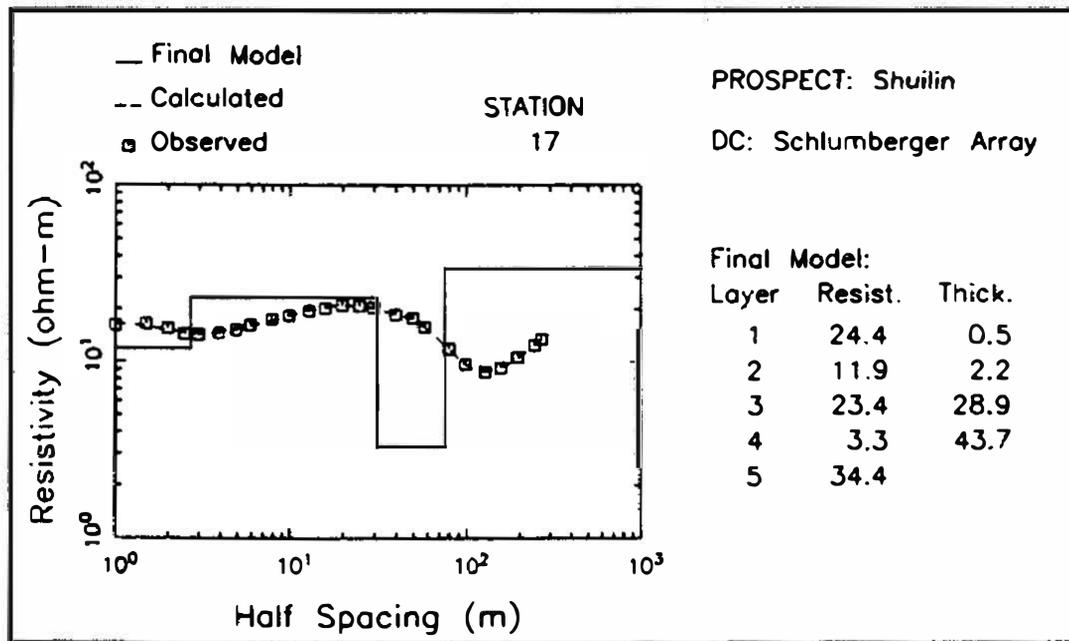


Fig. 2. The apparent resistivity curves and the interpretative results of the Stations 17, 21 and 25.

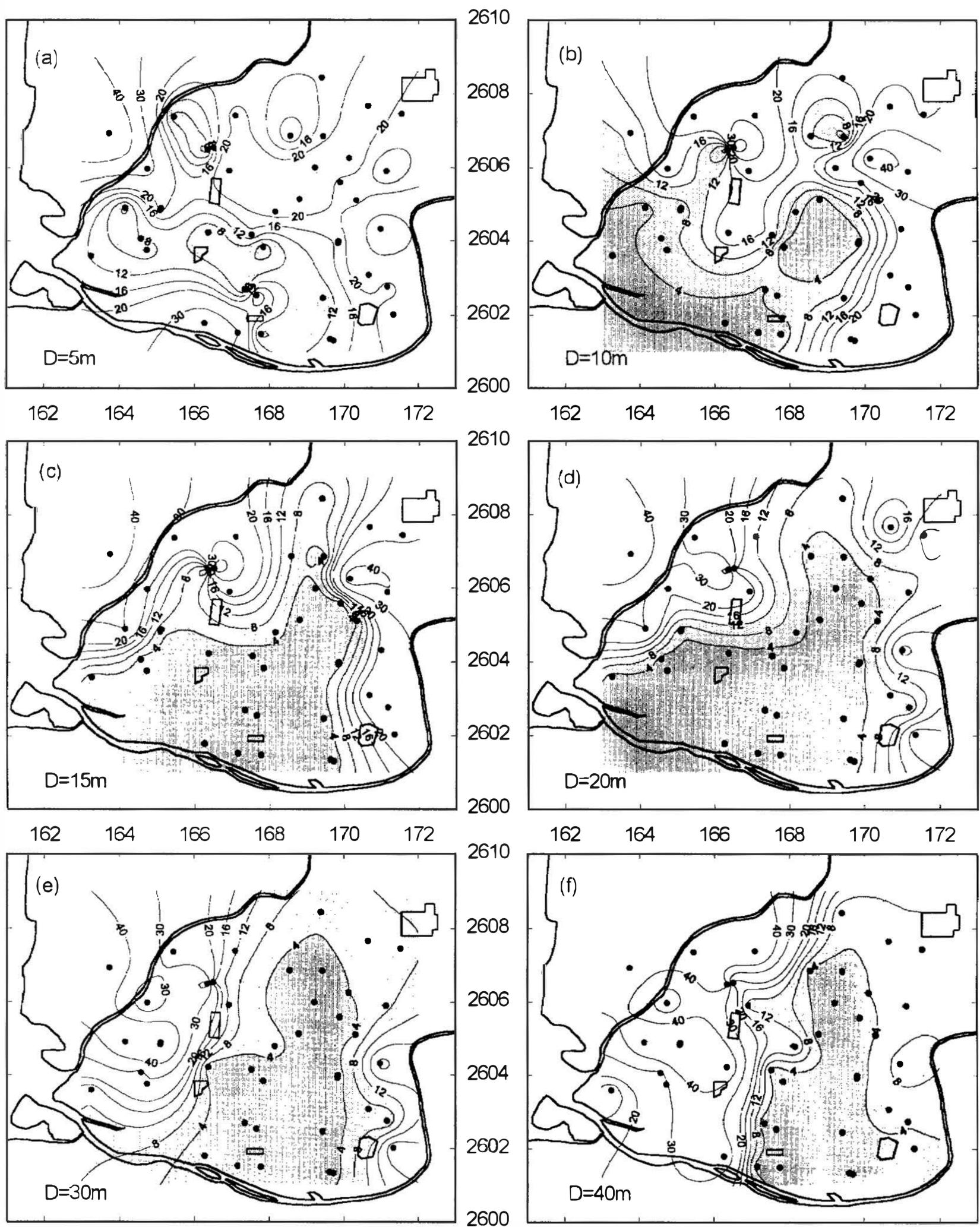


Fig. 3. The resistivities of strata at twelve different depths. Depths are denoted on the left-lower corner of each diagram. The shaded region is the area of resistivity lower than 12 ohm-m.

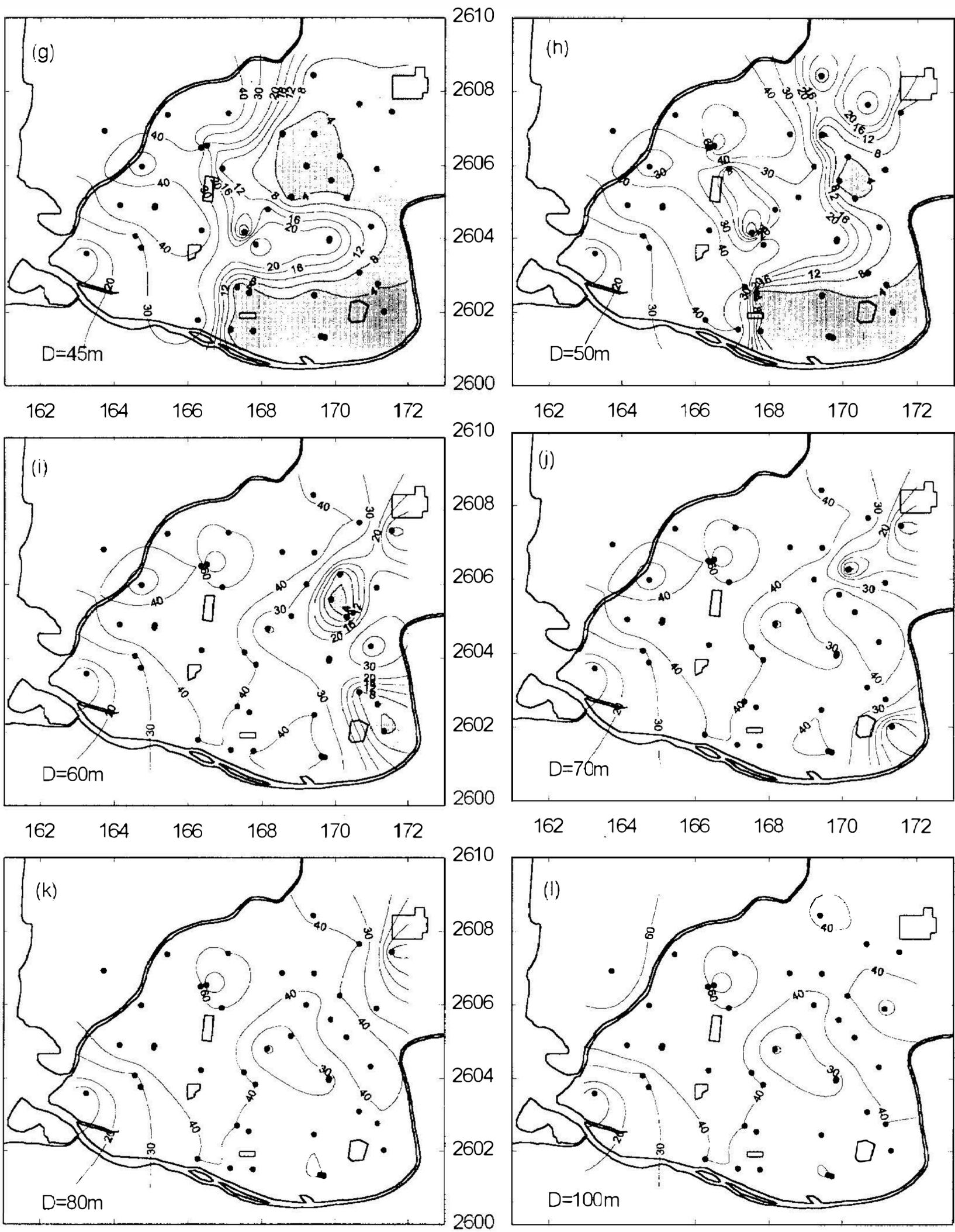


Fig. 3. (Continued.)

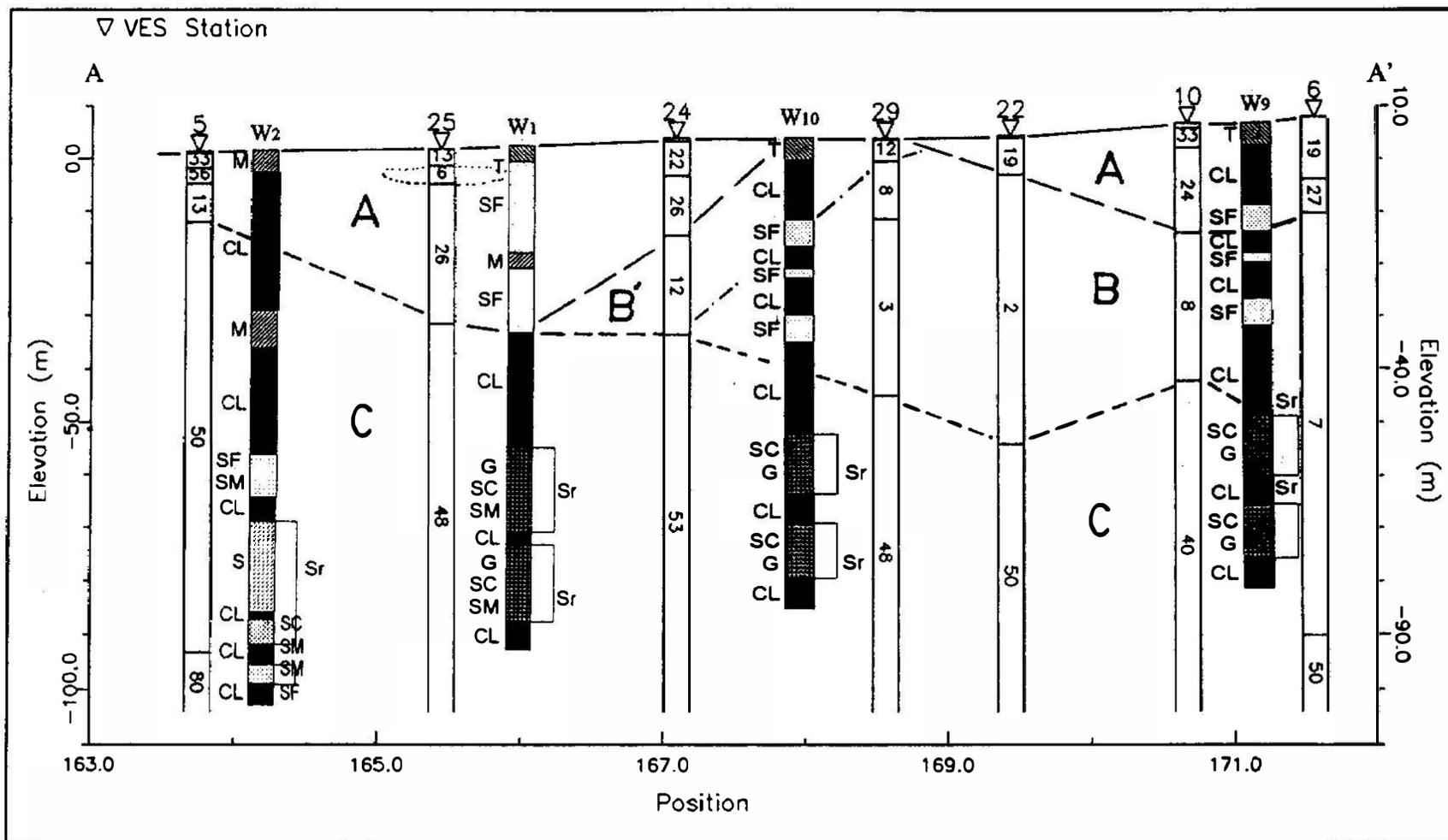


Fig. 4. Geoelectric resistivity profile AA'. Top soil T, Mud M, Clay CL, fine sand SF, medium sand SM, coarse sand SC, sand (fine to coarse) S, and gravel (pebble) G. Sr indicates the positions of well screens.

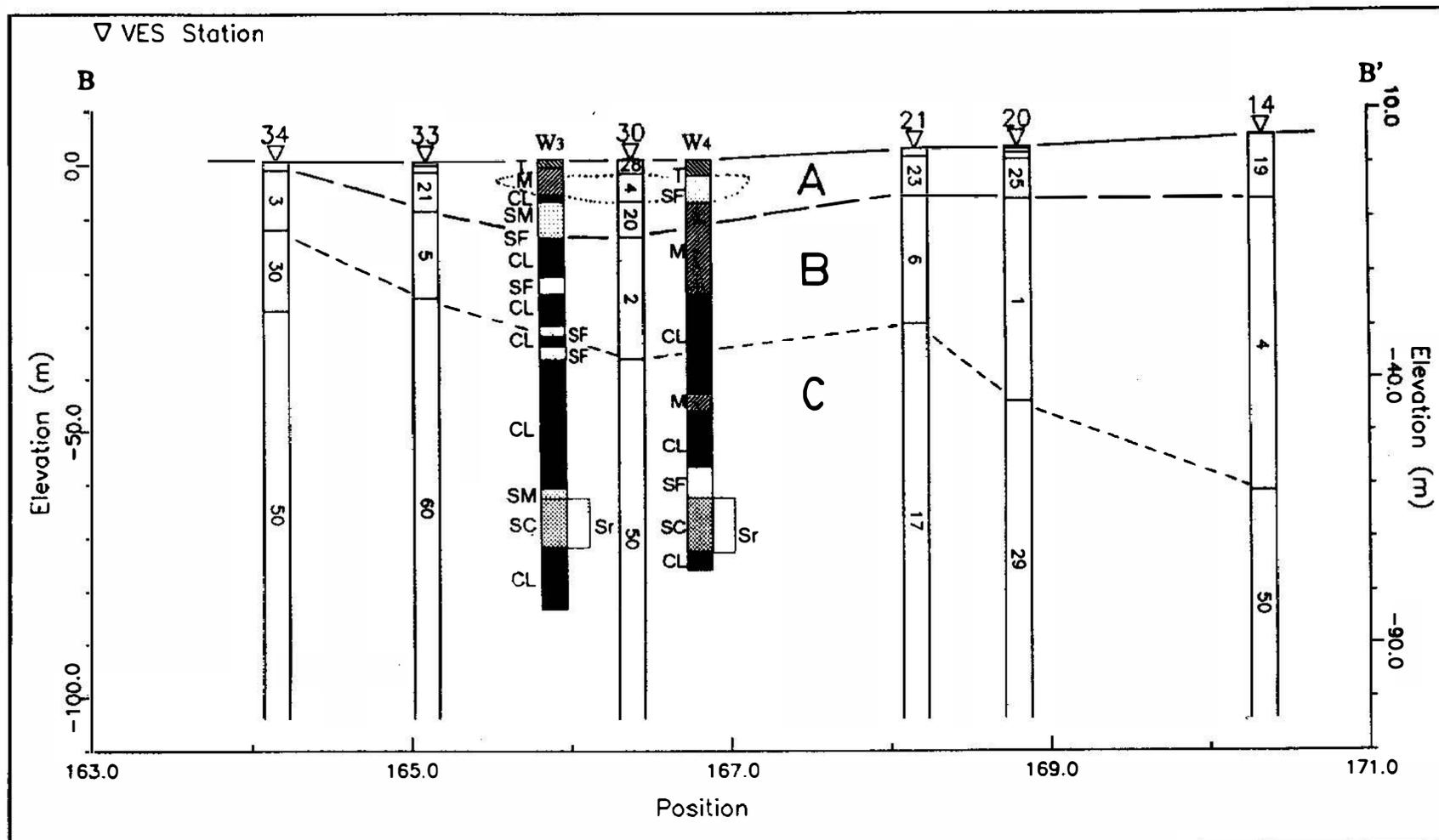


Fig. 5. Geoelectric resistivity profile BB'. The symbols are the same as in Figure 4.

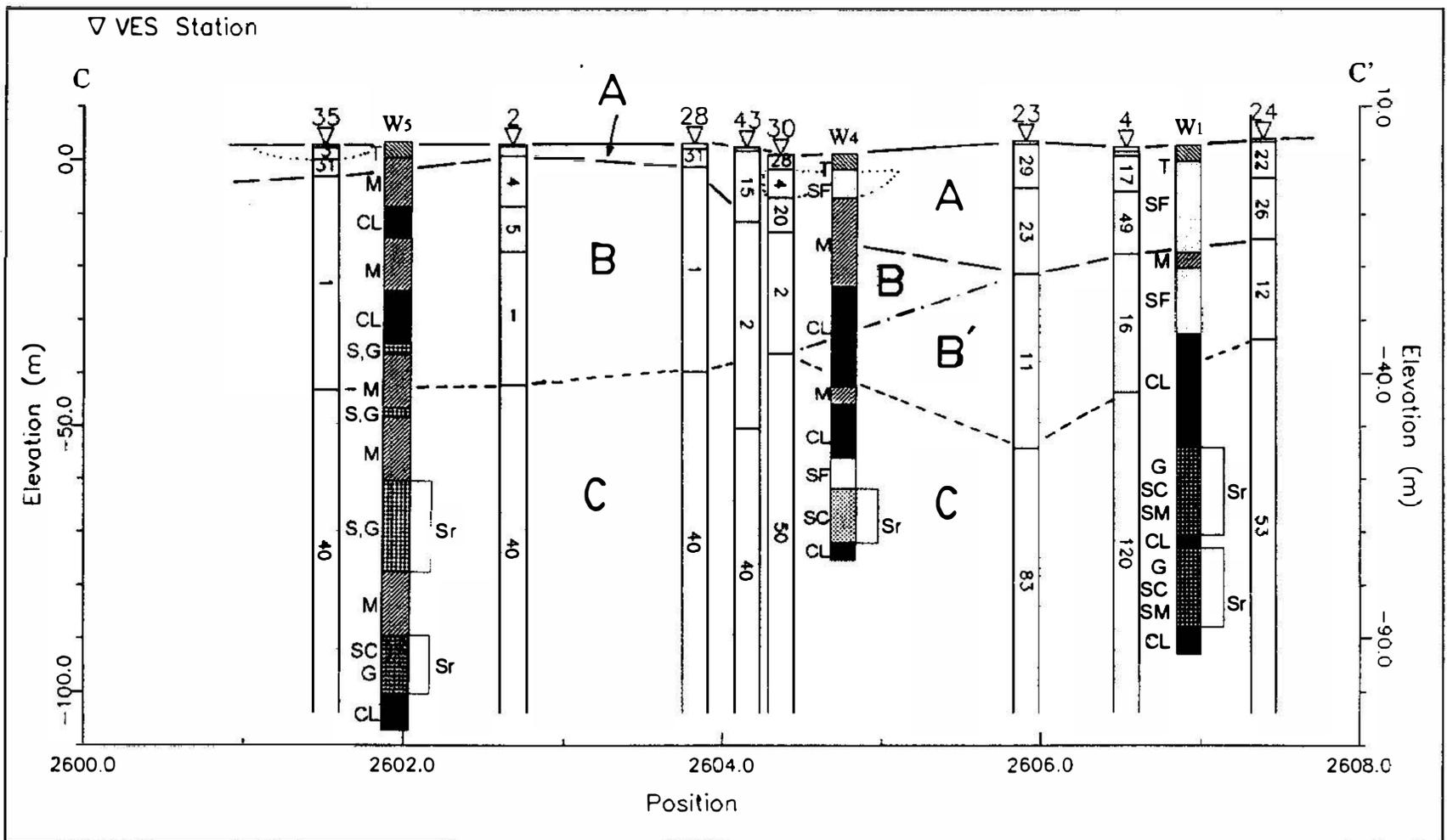


Fig. 6. Geoelectric resistivity profile CC'. The symbols are the same as in Figure 4.

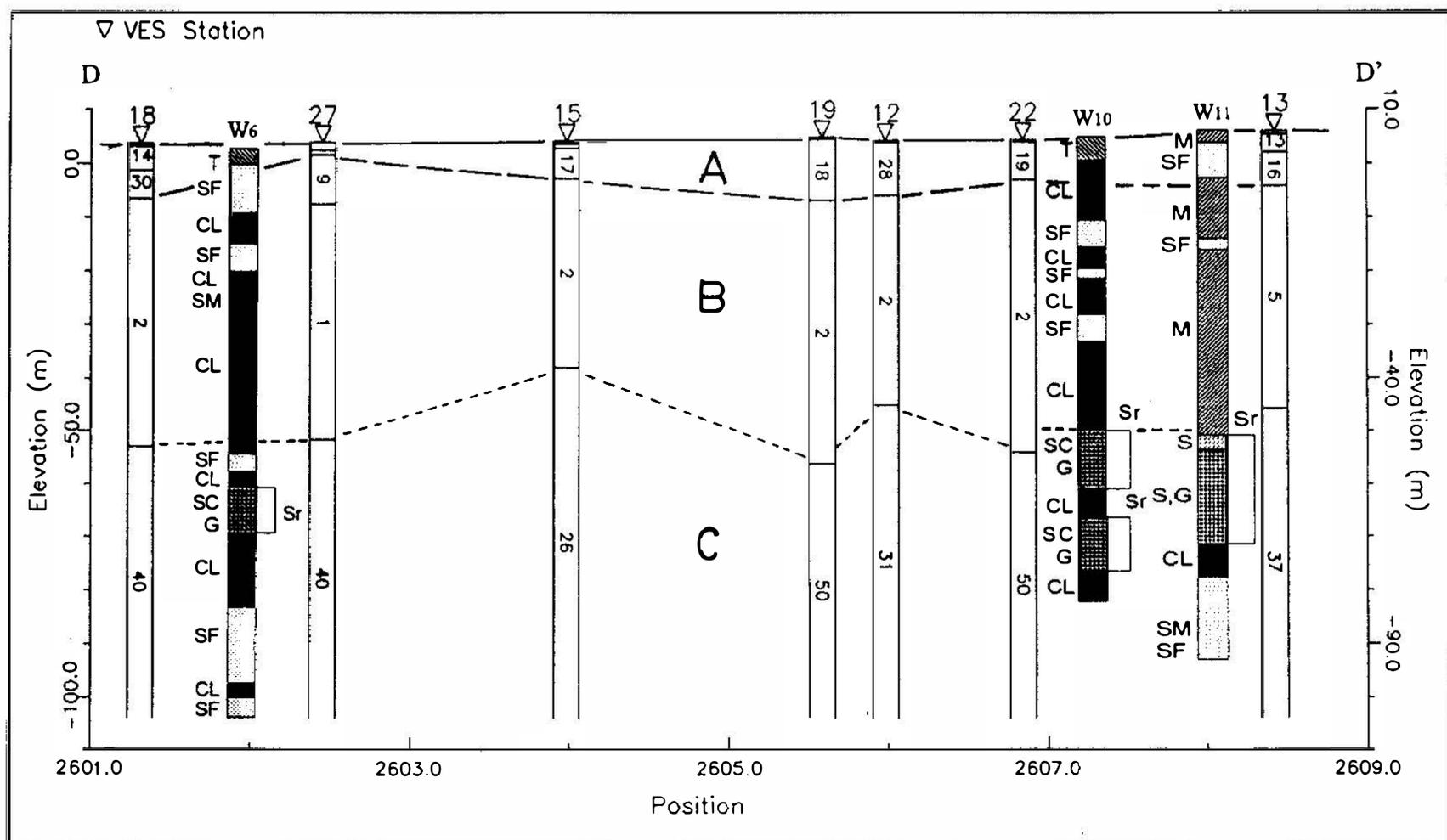


Fig. 7. Geoelectric resistivity profile DD'. The symbols are the same as in Figure 4.

The B-formation is characterized by a thick layer or layers of low resistivity. The thickness of the B-formation ranges from 10 to 55 meters and the resistivity is lower than 12 ohm-m (predominantly lower than 5 ohm-m). The B-formation is absent in the northwestern part of the study area (Figures 4 and 6). A transition zone of resistivity ranging from 12 to 16 ohm-m exists between the areas with and without the B-formation, as denoted with B' in Figures 4 and 6. The lithologic units correlated to the B-formation are the layers of clay, mud and fine sand.

The C-formation is characterized by higher resistivity ranging mainly from 40 to 70 ohm-m. The lithologic units correlated to the C-formation are the layers of pebble, sand and clay. The C-formation is also correlated with the main confined aquifer in the study area.

3.4 Parameters for Archie's Law

Archie's law is a satisfactory expression for the resistivity of a water-bearing rock (Nabighian, 1988). It is an empirical equation, for a water-saturated stratum, and is written as

$$\rho = a\rho_w\phi^{-m}$$

where ρ and ρ_w are the resistivities of the stratum and the formation water respectively, ϕ is the porosity of the stratum, a and m are parameters of the stratum.

The values of a and m in Archie's equation have not been determined in the study area. Owing to the lack of resistivities measured directly on samples or by well loggings, the resistivities of strata interpreted from the VES data were used to evaluate the values of a and m . The data for the evaluation are listed in Table 1.

Table 1. Data for evaluation of the parameters a and m in Archie's equation. Porosity ϕ , resistivity of formation water ρ_w , resistivity of formation ρ . ρ_{est} is the estimated resistivity of the stratum by the Archie's equation with $a=0.858$ and $m=1.367$.

well No.	$\phi(\%)$	$\rho_w(\text{ohm-m})^*$	$\rho(\text{ohm-m})$	ρ/ρ_w	$\rho_{est}(\text{ohm-m})$	error(%)
1	39	16.7	50	2.99	51.9	3.8
2	45	20.4	50	2.45	52.1	4.2
3	47	25.0	60	2.40	60.2	3.3
4	46	11.8	30	2.54	29.3	-2.3
5	50	20.8	46	2.21	46.0	0
6	42	18.7	50	2.67	52.5	5.0
7	42	17.2	48	2.79	48.3	0.6
8	39	18.2	60	3.30	56.6	-5.7
9	45	18.2	48	2.64	46.5	-3.1
10	30	8.33	37	4.42	37.1	2.7

*The resistivity of formation water is the reverse of the conductivity measured by Liu (1986).

Except for well W5 where a lack of water resistivity prevented it, ten sets of data were collected. The values of a and m were evaluated by power regression analysis. The results are $a=0.858$ and $m=1.367$, and the correlation coefficient is 0.987. The estimated resistivities of the strata and the errors percentages are listed in the right-hand column of Table 1.

3.5 Resistivity and Salinity

The relationship between the resistivity and the salinity of solutions has been found. The resistivity varies with the salinity and the temperature. With of salinities of less than 35‰ (the mean salinity of seawater) at a constant temperature, the resistivity varies approximately inversely to the salinity. The resistivity for various salinities at 26°C are shown in the top row of Table 2 (Keller and Frischknecht, 1966).

Based on Archie's law, the resistivity of a stratum can be estimated if the resistivity of the formation water, the porosity and the parameters a and m are known. The resistivities of strata evaluated using Archie's equation for various salinities of formation water are listed in Table 2. Alternatively, the resistivity and the salinity of formation water can be evaluated if the resistivity of the stratum is known.

The porosities of strata used for evaluating the resistivities of strata in Table 2 are the middle values or the representative values taken from the textbooks on groundwater hydrology (Bouwer, 1978; Todd, 1980).

Table 2. Resistivities of strata estimated by Archie's law with $a=0.858$ and $m=1.367$ for various salinity of formation water at 26°C.

formation water*	salinity(‰)	35	29.2	17.5	5.85	2.92	1.66	0.79	0.59
	seawater (%)	100	83.5	50	16.7	8.35	4.73	2.26	1.67
	resistivity(ohm-m)	0.17	0.21	0.33	0.93	1.76	3	6.28	8.2
Stratum	Porosity	Resistivity (ohm-m)							
Clay	0.50	0.38	0.46	0.73	2.06	3.90	6.64	13.9	18.1
Sandy mud	0.49	0.39	0.48	0.75	2.12	4.00	6.83	14.3	18.7
Fine sand	0.45	0.43	0.54	0.84	2.38	4.50	7.67	16.1	21.0
Medium sand	0.40	0.51	0.63	0.99	2.79	5.28	9.01	18.9	24.6
Coarse sand	0.35	0.61	0.76	1.19	3.35	6.34	10.8	22.6	29.6
Pebble	0.28	0.83	1.03	1.61	4.55	8.60	14.7	30.7	40.1

* The relationship between resistivity and salinity of formation water is taken from Electrical Methods in Geophysical Prospecting (Keller and Frischknecht, 1966)

4. DISCUSSION

4.1 The Values of a and m for Archie's Equation

Normally, the resistivities of strata used for determining the values of a and m in Archie's equation are measured on rock samples or by well loggings. Usually, a lot of samples are needed for the determination if the samples are small in dimension with respect to the stratum.

The resistivity interpreted from the VES data is a representative value for a stratum of wide extension and of a thickness similar in dimension to the stratum considered in Archie's law. Therefore, the resistivity interpreted from VES data may be regarded as the mean resistivity of many samples.

The values calculated for n and m are 0.858 and 1.367 respectively. They approximate to the values 0.88 and 1.37 for weakly-cemented detrital rocks suggested by Nabighian (1988), and are within the ranges described by Keller and Frischknecht (1966). The correlation coefficient is 0.987 and the errors are lower than 6%. The results are reasonable and acceptable.

4.2 Criterion of Salty Stratum

Saline groundwater is a term referring to any groundwater containing more than 1000 total dissolved solids (TDS). Electrical conductivity is often used to estimate the TDS in water for classification of water quality. An approximate relationship for most natural water in the range 100 to 5000 $\mu S/cm$ leads to an equivalence 1 $mg/l=1.56 \mu S/cm$ at 25°C. An increase of 1°C increases the conductivity by about 2 percent (Todd, 1980). According to the relationship, the equivalent resistivity for 1000 mg/l TDS is 6.41 ohm-m at 25°C or 6.28 ohm-m at 26°C. This may be regarded as the critical resistivity of saline water. Any water having a resistivity lower than the critical value is considered saline, otherwise it is considered fresh. A salty stratum is so-called because its formation water is saline. The critical resistivities of salty strata are evaluated according to Archie's law and the parameters previously evaluated. They are 13.9 ohm-m for clay, 14.3 ohm-m for sandy mud, 16.1 ohm-m for fine sand, 18.9 ohm-m for medium sand, 22.6 ohm-m for coarse sand, and 30.7 ohm-m for pebble, as shown in the second column from the right in Table 2. They are evaluated at 26°C for which is the approximate average temperature of the formation water in the study area.

Figures 4~7 show that, where the water well screens are in position, the resistivities of strata are higher than the critical resistivities of salty strata. This confirms that the formation water is fresh if the resistivity of a stratum is higher than the critical value.

4.3 Seawater Intrusion

At some places, the A-formation contains a layer of low resistivity. This low resistivity layer is locally distributed according to the locations of channels. This low resistivity layer is salty and is on or near to the ground surface with a depth of less than ten meters. The low resistivity of this layer is explained as a result of seawater intrusion. The seawater advanced inland and infiltrated the ground during typhoons, storms, and storm surges. The lowest resistivity of this layer is 4 ohm-m, the corresponding salinity of formation water is 2.92 ‰ which is equivalent to 8.35% seawater.

The lowest resistivity of the B-formation is 0.9 ohm-m, and the corresponding salinity is about 14‰ which is equivalent to about 41% seawater. Though the B-formation is salty, the pattern of the resistivity distribution (Figure 3) indicates that the central part of the B-formation does not connect with the sea. That implies that the saline water in the B-formation does not come from the sea. The saline water does not come from the overlying or the underlying layer either, for both of them have a lower salinity than the B-formation, and also the flushing

action would not render a thick layer to such high salinity. It is confirmed that the saline water in the B-formation is the connate water in the stratum which sedimented in marine environments.

The high salinity of water which is pumped from the aquifer of the C-formation at some wells seems to contradict the inference that the groundwater in the C-formation is fresh. This phenomenon can be explained with a model of migration. The saline water in the B-formation was migrating into the C-formation as the piezometric surface of the groundwater in the C-formation was declining, so more saline water would accumulate for a longer migration time. Therefore the salinity is higher at the beginning of a pumping and then decreases with time since the rate of migration of saline water is slower than the rate of pumping. Extremely high values would appear at the beginning of a pumping after a long period without operation.

A large amount of saline water would migrate into the C-formation during a pumping if the grout seal around the well casing was destroyed. This would keep the salinity of pumped water at a high level. The grout seal might not have been in place for many years of operation of the wells. That would most probably happen when the area of the piezometric surface was severely reduced. This is consistent with the cases of wells W5 and W6.

5. CONCLUSIONS

Several conclusions can be drawn from this study.

(1) Three electrostratigraphic units can be specified corresponding to the strata less than one hundred meters in depth. From top to bottom, they are designated the A, B, and C formations.

The A-formation is a combination of thin layers with resistivity ranging from 16 to 60 ohm-m in most cases. At a few places, a thin conductive layer with resistivity ranging from 4 to 12 ohm-m is included also. The A-formation is between about 5 and 30 meters thick. Its correlated lithologic units are layers of soil with fine sand on the top.

The B-formation has a resistivity ranging from 0.9 to 12 ohm-m, and is between about 10 and 55 meters thick. The correlated lithologic units are mainly layers of clay, mud, and fine sand.

The C-formation has a resistivity ranging mainly from 40 to 70 ohm-m and is greater than several tens of meters thick. The correlated lithologic units are layers of pebble, sand, and clay.

(2) The resistivity of a stratum interpreted from the VES data can be used for evaluating the parameters in Archie's equation, $\rho = a\rho_w\phi^{-m}$. Suitable values for a and m are obtained, and these are 0.858 and 1.367 respectively. The formation factor (ρ / ρ_w) ranges from 2.21 to 4.41 and varies with the porosity of a stratum, which increases with decreasing porosity.

(3) The resistivity of groundwater can be evaluated from the resistivity interpreted from VES data, if the porosity and the parameters of stratum in Archie's equation are known. The resistivity of a stratum offers a criterion for the salinity of groundwater. The groundwater in the B-formation is saline, but that in the C-formation is fresh.

- (4) There is seawater intrusion in the study area, but it is locally distributed and in strata less than 10 meters deep. The seawater intrusion was caused by seawater floodings which happened during typhoons, storms and storms surges. In these cases the seawater advanced inland and infiltrated the ground.
- (5) The saline water in the B-formation is the main saline groundwater body. It is not caused by seawater intrusion, but is the connate water in stratum sedimented in marine environments.
- (6) The high salt content in the aquifer of the C-formation found at some wells was not a case of seawater intrusion, but was a case of migration of saline water from the B-formation. This happened at the places where the piezometric surface was severely diminished. If the grout seal around the well casing was destroyed, a large amount of saline water would migrate into the aquifer and keep the salinity of pumped water at a high level during a pumping.

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