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Electrostratigraphic Study of the Tainan Coastal Plain, Southwestern Taiwan

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ABSTRACT

In order to study the electrostratigraphy, the depositional environments and the change of shoreline, a geoelectric survey was carried out on the Tainan coastal plain. The DC resistivity method was used, and the sounding data were interpreted by the 1-D inversion method.

Based on the electric resistivities and the thicknesses of the layers derived from the sounding data, three electrostratigraphic units are found and specified. They are designated as the T, R, and S facies corresponding to the strata from the surface to 200 meters in depth. The T-facies is characterized by layers of resistivity ranging from 12 to 400 ohm-m at the top of the layer sequence. This unit is less than 100 meters thick and is widely distributed in the area studied. The S-facies is characterized by a thick layer or layers of resistivity less than 5 ohm-m, and is generally accompanied with thin layers of resistivity less than 12 ohm-m. The S-facies is 50 to 200 meters thick and is mostly overlain by the T-facies in the western and the central parts of the coastal plain, and is absent in the eastern part. The R-facies is characterized by a thick layer or layers of resistivity ranging from 12 to 70 ohm-m. It is overlain by the T-facies in the east and by the S-facies in the west. The R-facies intertongues with the S-facies in the north-center and is absent in the south-center. The T-facies was deposited in terrestrial and estuarine environments during the Holocene. The S-facies was deposited in marine environments in the late Pleistocene to Holocene. The upper part of the R-facies in the east was deposited in terrestrial and estuarine environments in the late Pleistocene. These three units are similar in lithology being mainly composed of layers of clay, mud, silt, and fine sand.

A marine transgression occurred when the strata between the depths of 200 and 40 meters were deposited in the area studied except for the Tainan tableland, and was then followed by a marine regression. At the peak period of the marine transgression, the shoreline reached the line connecting Anding, Hsinhua, and the east of Gueizen. Since the beginning of the re-

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gression, the shoreline has retreated about 22 km westward in the north, and about 14 km westward in the south. The Tainan tableland was formed by an anticlinal uplifting beginning at the time when the stratum at 80 meters depth was deposited.

(Key words : Geoelectric resistivity, Electrostratigraphy, Coastal plain of southwestern Taiwan)

1. INTRODUCTION

The Tainan coastal plain is situated in southwestern Taiwan, and is bounded to the north and the south by the Tsengwenchi and Erhjenchi streams, respectively (Fig. 1). Most of the area is low and flat. Except for the Tainan tableland in the south-center, the altitude of the area studied is about 30 to 50 meters high in the east and decreases gradually westward to sea level on the west margin.

The shoreline in this area has retreated as much as ten kilometers since the early Holocene (Lin, 1957). A retreat of 500 to 5000 meters occurred in the last century (Chang et al., 1996). Two transgressions and two regressions occurring in the Holocene were suggested: the Tainan transgression and regression, and the Tahu transgression and regression. The former occurred between 6500-4000 yBP, and the latter between 4000-2700 yBP (Sun, 1964; Lin and Chou, 1974). According to the results of a study of dating and foraminifera analysis on a continuous core drilled at Baoan in the southeast of the Tainan tableland (W9 in Figure 1), Chen (1993) inferred that only one transgression and regression occurred there in the Holocene.

The electric characteristics and the depositional environments of the formations, the development of the Tainan tableland, and the change of coastline are studied from the point view of electrostratigraphy in this study.

2. GEOLOGICAL SETTING

The area studied is covered with alluvium which was differentiated into seven units, the Tainan Formation and the younger units, by photogeologic study (Sun, 1964). The Tainan Formation is dominant for its predominant thickness and coverage (Sun, 1964; Lin and Chou, 1974). The thickness of the Tainan Formation ranges from 16 to 36 meters in the central part, and increases toward the west to 175 meters at Anping on the western margin of the area studied (Ho, 1975; Hsu, 1984). Under the coastal plain, the Tainan Formation is underlain by the Liushuang Formation, which is the youngest unit of the Pleistocene and has a thickness of 500 to 830 meters. They lie horizontally, but their relation seems to be disconformable. According to the results of faunal and lithological studies of cores, both of the formations are of mixed sedimentary environments, including lagoonal, deltaic, estuarine, beach, shallow marine, and eolian. It is very difficult to set a boundary between the Tainan and the Liushuang Formations in the coastal plain area because their lithology and the faunas contained in them are almost identical (Hsu, 1984).

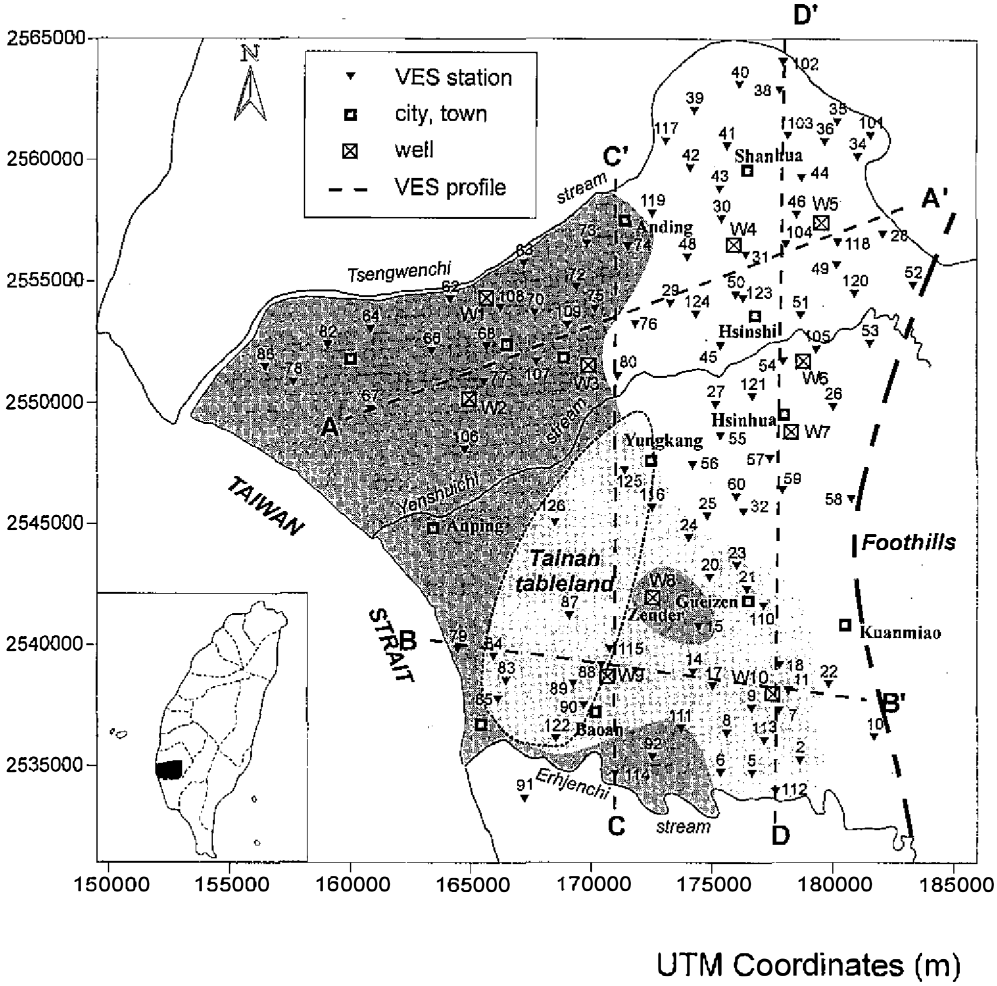


Fig. 1. The locations of the vertical electric soundings are shown by solid triangles, wells by crossed squares, along with four geoelectric resistivity profiles A-A', B-B', C-C' and D-D' in the Tainan coastal plain. Dark-shading indicates the area of the VES curves which are the minimum and ascending-type of extremely low resistivity, and light-shading indicates the area of the VES curves which are the descending-type.

The Tainan tableland is a special landform on the coastal plain, which has an ellipse-like boundary with a majoraxis of about 12 kilometers in the NNE-SSW direction and a minoraxis of about 4 kilometers in the SWW-NEE direction. This tableland was inferred to be an anticlinal structure with the topographic maximum as its axial part trending in the direction parallel to the majoraxis of the ellipse. The eastern flank of the anticline was cut by the Houchiali fault (Sun, 1964). The highest part of this tableland is 25 to 30 meters in altitude, and is about 18 to

23 meters higher than the lowland on the eastern side of the fault.

3. DATA ACQUISITION AND PROCESSING

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 along a straight line step by step from 1 or 1.5 meters to the maximum spacing with 10 measurements per logarithmic cycle. The apparent resistivity curve was plotted on double logarithmic paper in the field to inspect the quality of raw data. If a distortion in data appeared, the measurement was repeated or the positions of the current electrodes were changed to improved the quality of data. One hundred and three VES were conducted in the area studied. Their locations are shown in Figure 1. The locations of the soundings were distributed in the area studied with separation of about two to three kilometers, except in urban areas, salt fields, and fishponds where there was not enough space to spread the current electrodes. The maximum spacings of the VES are greater than 400 meters, and most of them are 800 meters.

The VES data were interpreted using the 1-D inversion method, since the formations are nearly horizontal and can be regarded as a 1-D structure. The forward part of the 1-D inversion is carried out by the method of digital linear filtering based on the theory of convolution and Fourier transformation (Ghosh, 1971; Koefoed, 1979; O'Neill; Merrick, 1984). 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 the Zohdy's method (Zohdy, 1989).

4. RESULTS AND DISCUSSIONS

4.1 Types of VES Curves and Their Interpretation

The types of VES curves can reveal the electrical resistivity structure of the formations. The curves of the VES measured in this area can be classified into the following four types: the minimum, the descending, the alternating, and the ascending types. Typical examples and their interpretative results are shown in Figure 2.

Minimum type – The minimum type is characterized by a distinctive minimum of apparent resistivity lower than 5 ohm-m on the middle portion of the curve (e.g., Station 107, Figure 2a). This implies that the formations contain a conductive zone of resistivity lower than 5 ohm-m overlain and underlain by relatively resistive layers. Most of the stations of this type are located in the western part of the area studied (the dark-shaded region in Figure 1).

The interpretative results of this type indicate that the strata can be divided into three sections by ranges of resistivity. The top section consists of 1 to 3 layers of resistivity ranging from 5 to 40 ohm-m and is 3 to 10 meters thick. The middle section consists of thick layers of resistivity mainly ranging from 0.4 to 1 ohm-m and is 50 to 130 meters thick. The basal section has a resistivity mainly ranging from 4 to 30 ohm-m.

Descending type – The descending type is characterized by a distinctive descending seg-

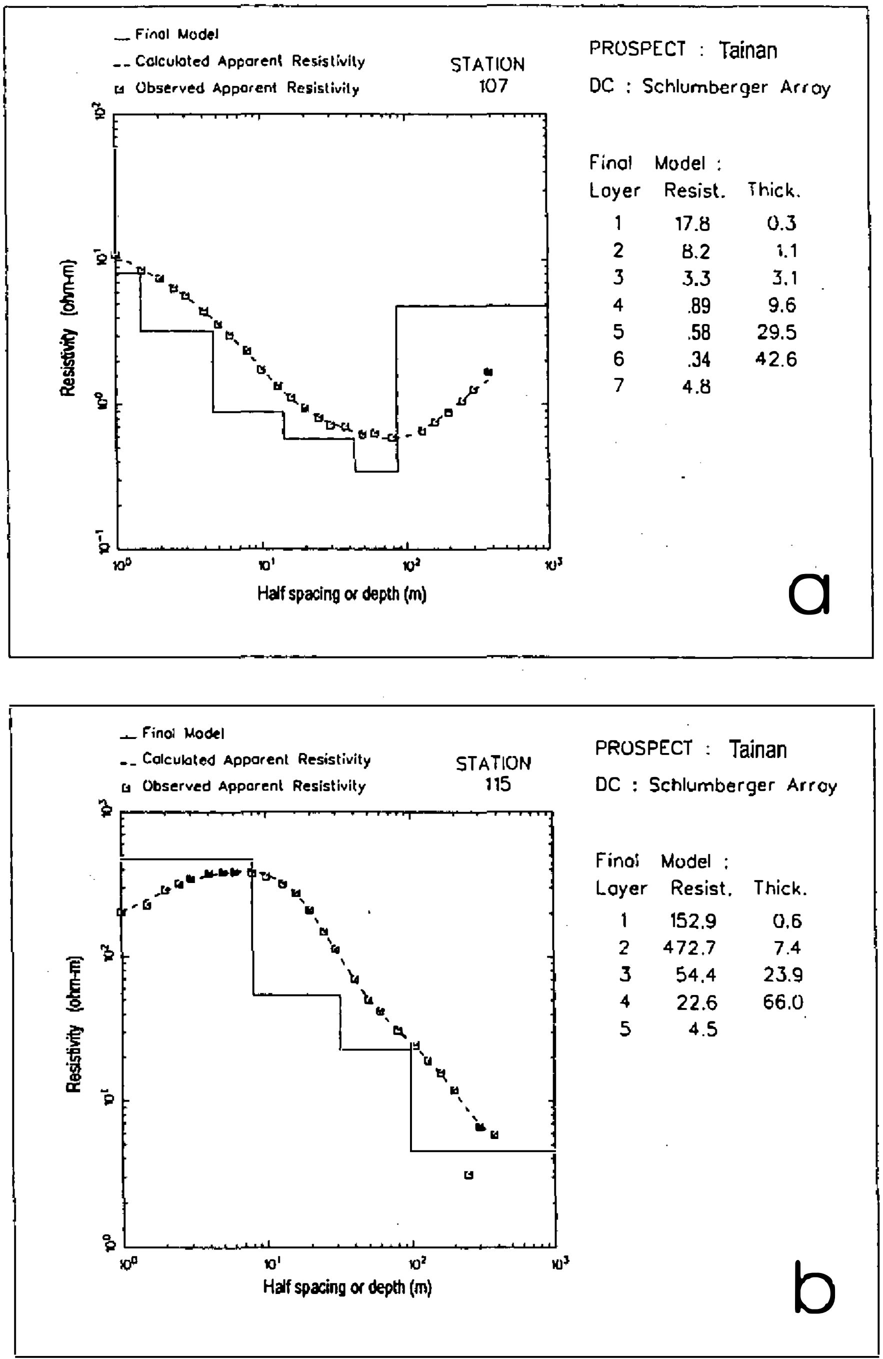
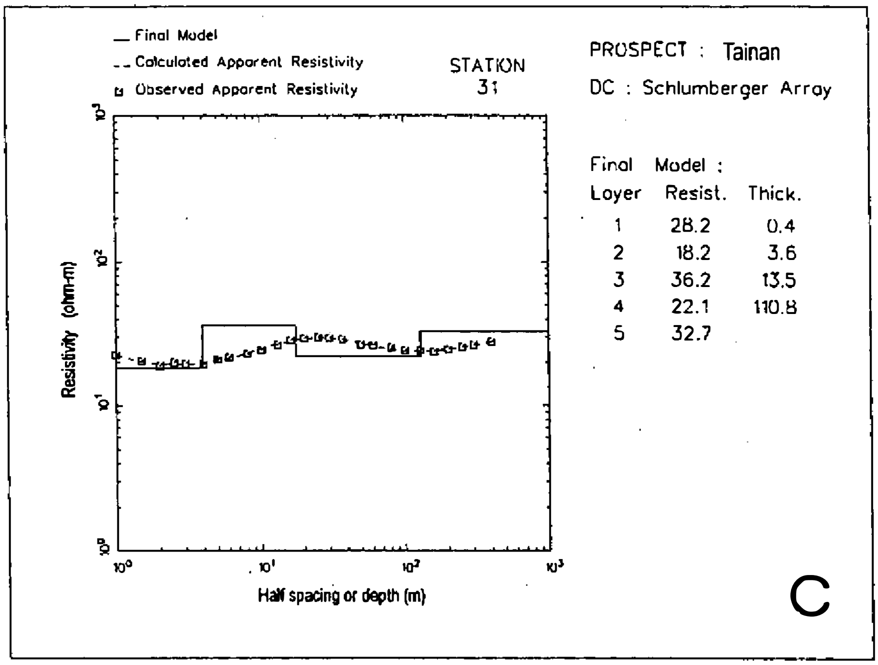
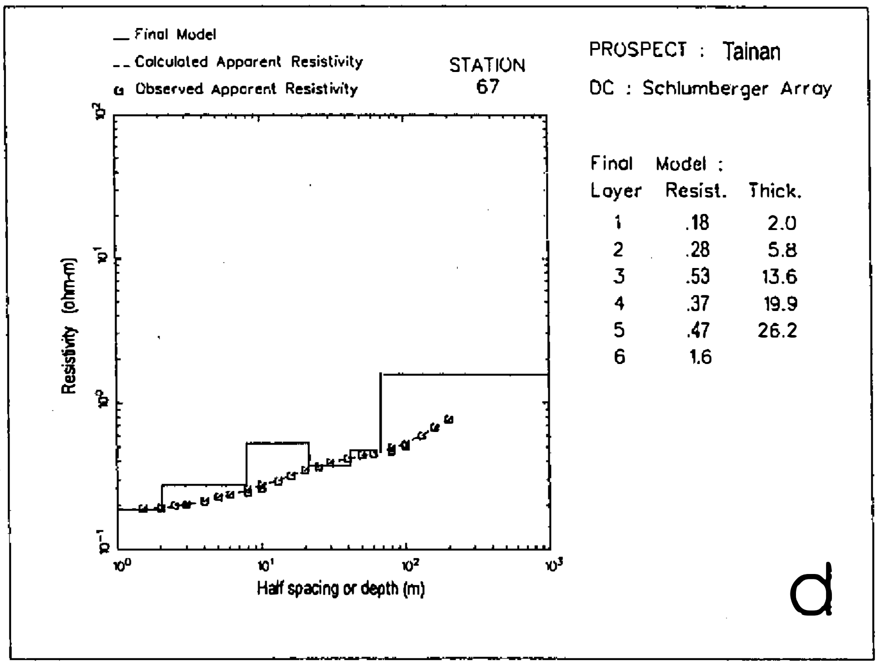


Fig. 2. Apparent resistivity curves and interpretative results for Stations 107, 115, 31, and 67.





(*Fig.* 2. continued)

ment on the right-hand part of the curve. The apparent resistivities for large electrode spacings are usually lower than 10 ohm-m (e.g., Station 115, Figure 2b). this implies that the resistivity of the formations decreases with depth, and the bottom layer is conductive. All stations of this type are located in the south-central part of the area studied (the light-shaded region in Figure 1).

The interpretative results of this type indicate that the formations can be divided into three sections by ranges of resistivity. The top section consists of 1 to 3 layers of resistivity ranging from 50 to 400 ohm-m and is 10 to 35 meters thick. The middle section has a resistivity ranging from 15 to 40 ohm-m and is 40 to 70 meters thick. The basal section has a resistivity mainly ranging from 1 to 3 ohm-m.

Alternating type – The alternating type is characterized by smooth fluctuations in apparent resistivity between 10 and 70 ohm-m (e.g., Station 31, Figure 2c). This type implies that the resistivity sequence is alternative, and the true resistivities will be slightly higher than the corresponding maxima for relative resistive layers, and will be slightly lower than the corresponding minima for relative conductive layers. All the stations of this type are located in the eastern part of the area studied (unshaded region in Figure 1).

The interpretative results of this type indicate that the strata have resistivity ranging from 8 to 120 ohm-m.

Ascending type – The ascending type is characterized by apparent resistivity increases with electrode spacing, and all the apparent resistivities are less than 2 ohm-m (e.g., Station 67, Figure 2d). Stations of this type are located in the saltpan area near the coast. The interpretative results of Station 67 indicate that the true resistivities of the strata are less than 2 ohm-m. The resistivity of 0.18 ohm-m for the top layer is the lowest value found in this area.

4.2 Electrostratigraphic Units

Three electrostratigraphic units are found and specified based on the ranges of resistivity, the thickness and the sequence of the layers interpreted from the VES data. They are designated as the T, S, and R facies. The ranges of the resistivity and the thickness of the units are shown in Table 1.

Table 1. Ranges of the Resistivity and thickness of the electrostratigraphic units, and the evaluated resistivity and salinity of the formation waters. W, C, and E represent the western, the central, and the eastern part, respectively.

Facies	Bulk resistivity (ohm-m)	Thickness (m)	Water resistivity (ohm-m)	TDS, Salinity (g/l, ‰)
T	W : 12 – 40 C : 12 – 400 E : 12 – 120	0 – 10 10 – 100 5 – 20	6.1 – 21 6.1 – 206 6.1 – 61	1.0 – 0.3 1.0 – 0.03 1.0 – 0.1
S	W : 0.18 – 12 C : 0.6 – 12	50 – 200 100 – 200	0.09 – 6.1 0.3 – 6.1	>68 – 1.0 >20 – 1.0
R	W : 12 – 18 E : 15 – 70		6.1 – 9.3 7.7 – 36	1.0 – 0.7 0.8 – 0.2

The T-facies is characterized by layers of resistivity ranging from 12 to 400 ohm-m at the top of the layer sequence. It is less than 100 meters thick and is widely distributed in the area studied, except in the area of salt fields where the resistivities of the strata are always less 2 ohm-m.

The S-facies is characterized by a thick layer or layers of resistivity lower than 5 ohm-m and maisly ranging from 2 to 0.4 ohm-m which generally accompany thin layers of resistivity lower than 12 ohm-m. The S-facies is about 50 to 200 meters thick, and is generally overlain by the T-facies in the western and central parts of the area studied, except the area of salt fields. The S-facies is absent in the eastern part (unshaded region in Figure 1).

The R-facies is characterized by a thick layer or layers of resistivity ranging from 12 to 70 ohm-m . This unit is overlain by the S-facies in the western part, and is overlain by the T-facies in the eastern part.

4.3 Lithology and Age

In order to identify the lithology of the formations, ten lithologic columns of wells were collected from the area under study (Fig. 3). The locations of the wells, W1 to W10, are shown in Figure 1.

Figure 3 indicates that the formations are mainly composed of layers of clay, mud, silt, and fine sand, except for W1 in which thick layers of coarse sand exist. Few layers of medium to coarse sand and pebble exist below depths of 80 meters in the northern part, as shown in lithologic columns from W3, W4, W5, and W6 (Fig. 3). Generally, the T, S, and R facies are similar in lithology. All the layers in the shallow part are unconsolidated. Consolidated strata, mudstone and sandstone, appear below a depth of 210 meters at W8.

The ages of some samples of the formations were determined by C-14 dating. Most of the samples are correlated to the T-facies and the upper part of the S-facies, and their ages were determined to be younger than 9810 yBP. Two samples are correlated to the R-facies. One is 34080±430 yBP in age, and the other is older than 47600 yBP (Wu, 1990; Chen, 1993).

4.4 Resistivity and Salinity of Formation Water

The resistivity of formation water can be evaluated from the bulk resistivity by using Archie's formula. For water saturated strata, the formula can be written as

$$\rho_w = \rho / F = \rho \phi^m / a,$$

where F is the formation factor, and is defined as the ratio of the bulk resistivity ρ to the resistivity of formation water ρ_w. The formation factor is a function of porosity ϕ and parameters a and m. The values of a and m were considered to be constants in a region of similar environments of sedimentation, and can be determined from a group of measurements (Keller and Frischknecht, 1966). The values for a and m were determined to be 0.858 and 1.367, respectively (Cheng, 1996), and the porosity of strata is measured to be 0.53-0.57 on samples of cores. Using these values, the formation factor F is calculated to be 1.93-1.95. The ranges of the resistivity of the formation waters in the T, S and R facies are evaluated and shown in Table 1.

The total dissolved solids (TDS) and the salinity of formation water can be evaluated by

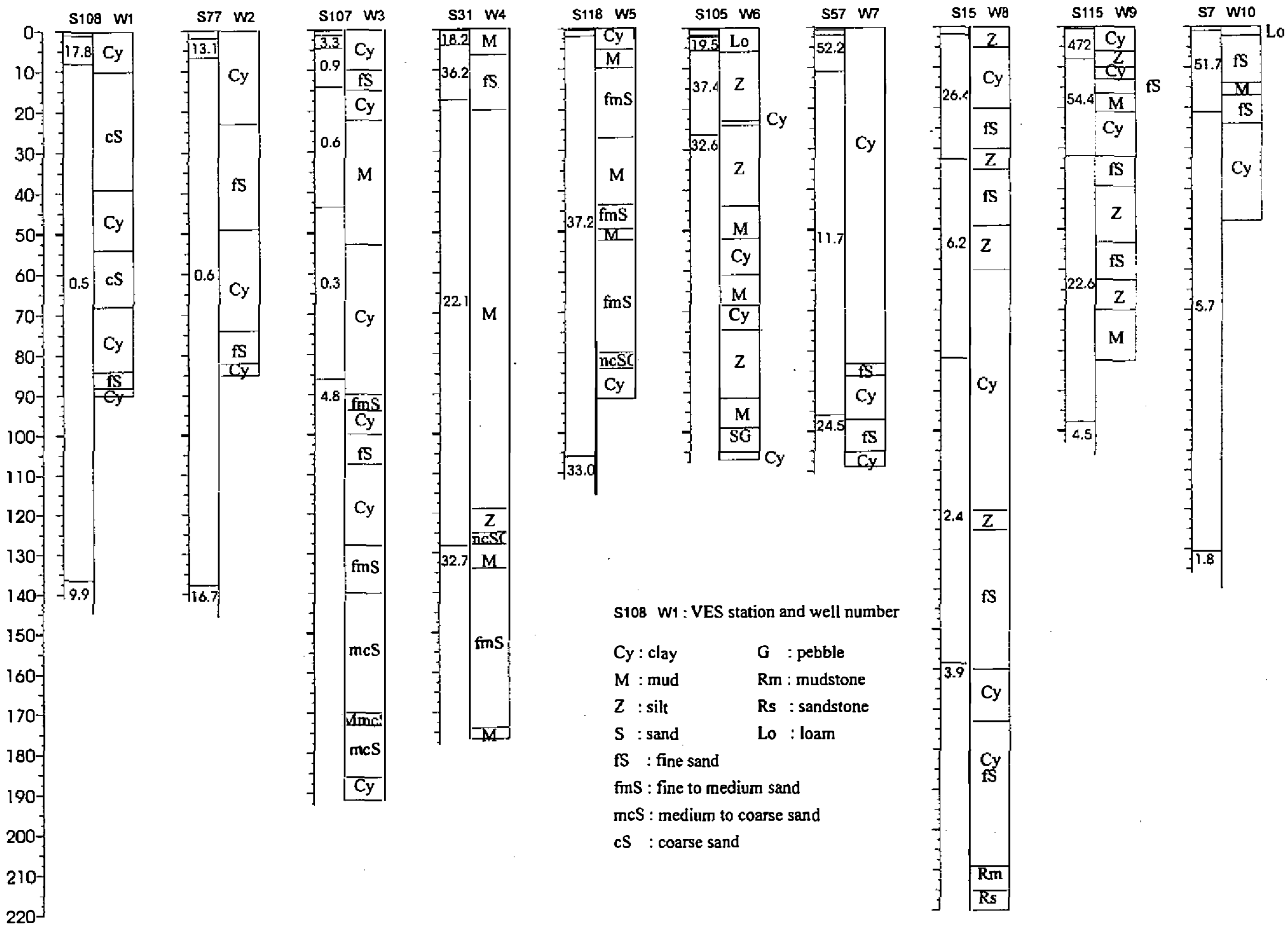


Fig. 3. Lithologic columns of wells accompanied with the interpretative results of their nearby soundings.

the relationship between the TDS and the electric conductivity. An approximate relation for most natural water in range of 0.01 to 0.5 S/m leads to an equivalence 1 g/l = 0.156 S/m at 25° C. An increase of 1° C increases conductivity by about 2 % (Todd, 1980). According to these relations an equivalence 1 S/m = 6.28 g/l is taken at 26° C. As for water conductivity greater than 0.5 S/m, the TDS value equivalent to 1 will be greater than 6.28 g/l since the mobility of the ions reduces as the ion concentration increases (Keller and Frischknecht, 1966). Based on these relations the ranges of the TDS value of the formation waters are calculated, and the results are listed in Table 1.

The TDS values evaluated from the electric conductivity can be regarded as the salinities of the formation waters because the electric conduction is predominantly electrolytic and one liter of formation water has a mass of approximately 1000 grams.

Generally, strata of clay, mud, and silt have a very low hydraulic conductivity (Bouwer, 1978; Todd, 1980). Since the strata are mainly composed of these materials, and no high hydraulic gradient would exist in the formations because of the lack of a plentiful source of fresh groundwater, the connate water in the T, S, and R facies would remain in the formations for a long time. Therefore the resistivity of formation water will indicate the environments of deposition.

The TDS in the pore water of the S-facies is evaluated to be mainly in the range of 6.1 to 30 g/l which corresponds to a bulk resistivity mainly ranging from 2 to 0.4 ohm-m. This implies that the S-facies was deposited in marine environments since the TDS value is greater than the criterion of saline groundwater of 1 g/l (Todd, 1980). A resistivity of 0.3 ohm-m is found at depths of several tens of meters at Stations 62, 79, and 87. The salinity of pore water corresponding to a bulk resistivity of 0.3 ohm-m is evaluated to be greater than 41 ‰. This implies that when the S-facies was deposited, the seawater had a higher salinity than the present average value at these places. The salinity of the formation water is evaluated to be higher than 68 ‰ and this corresponds to the bulk resistivity of 0.18 ohm-m (Table 1).

Both the T and the R facies have a salinity ranging from the value of fresh water to that of brackish water (Table 1). This implies that the strata of these two facies were deposited in terrestrial and estuarine environments.

4.5 Depth Sections

The interpretative results of the VES data indicate that the resistivities of the strata vary with position. The resistivity distribution at twelve different depths is shown in Figure 4. It shows that the resistivity decreases westward from 30-70 ohm-m to a value which is generally less than 2 ohm-m.

The bulk resistivity for a stratum containing 1 g/l of TDS in pore water is evaluated to be 12.2 ohm-m which corresponds to the critical salinity of groundwater being saline. Therefore, strata of resistivity ranging from 10 to 15 ohm-m may be regarded as formations deposited in or near to littoral zones. The region between the isoresistivity contours of 10 and 15 ohm-m is temporarily called the "transition zone" and is cross-hatched on each depth section in Figure 4. The shifting of the transition zone with depth is related to the marine transgression and regression. Figure 4 indicates that except in the south-central part, the transition zone generally

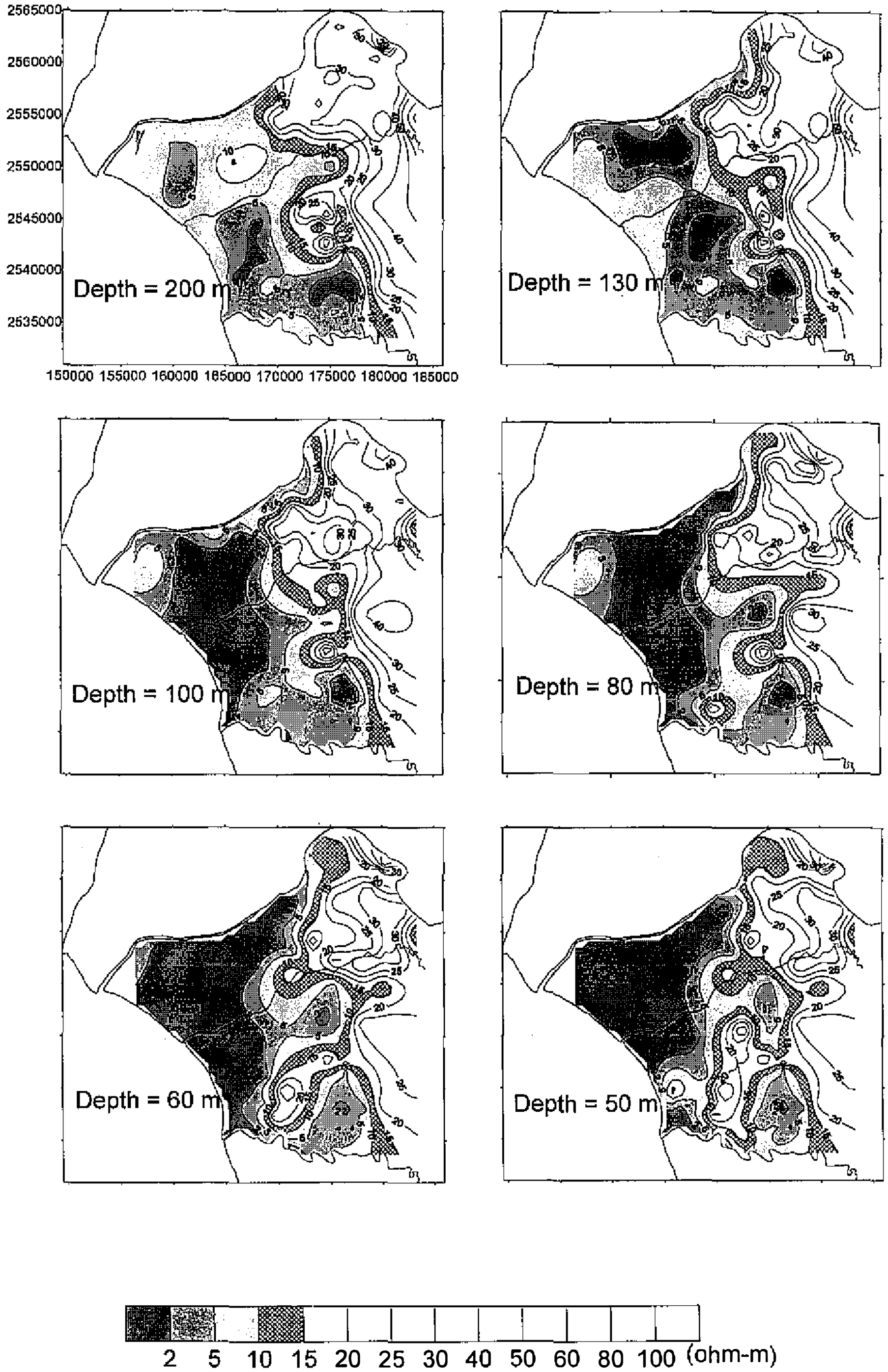
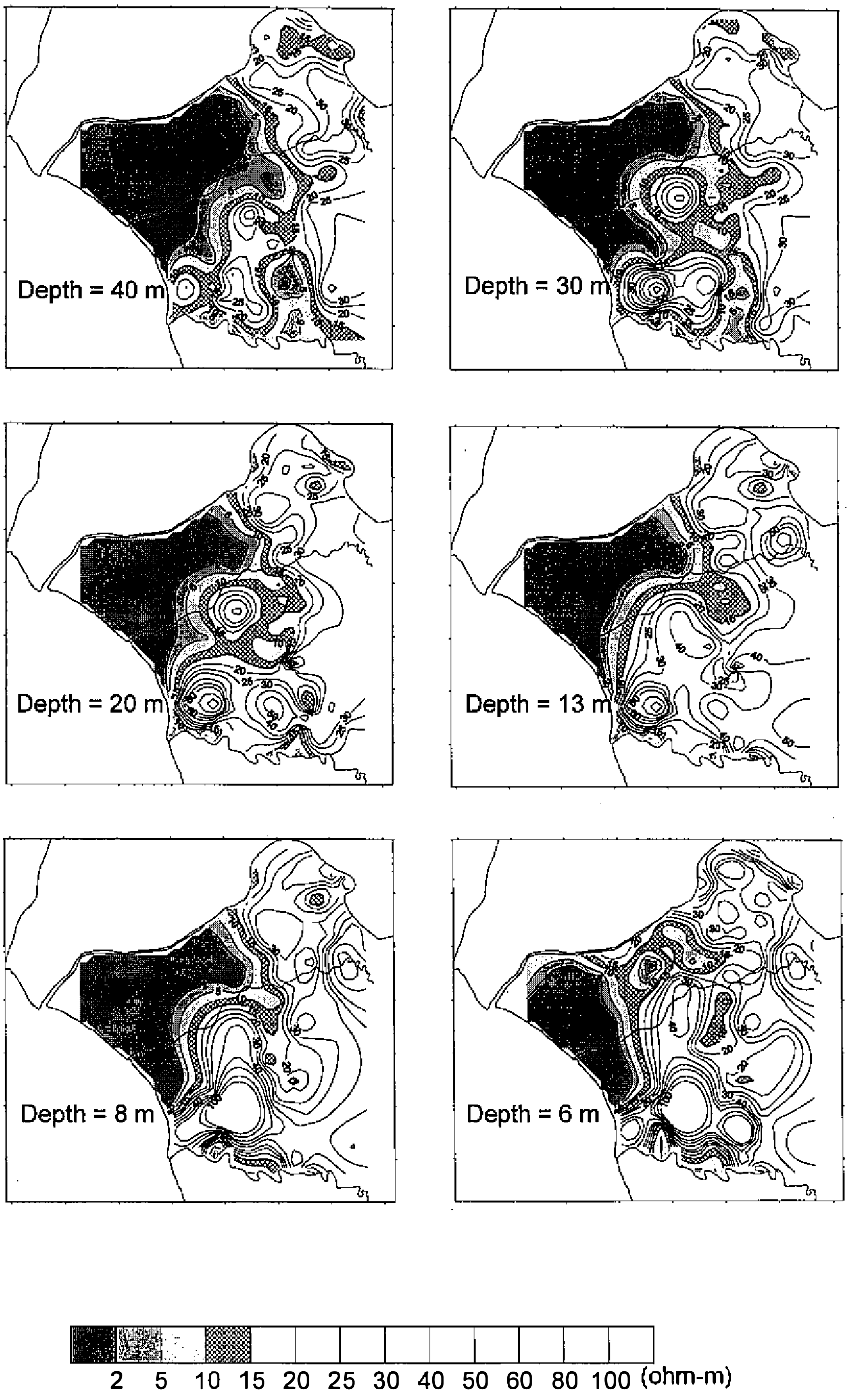


Fig. 4. Resistivity distribution of the formations at twelve different depths. The transition zone is cross-hatched.



(*Fig. 4.* continued)

shifts landward (eastward) in the area studied as depth decreases from 200 to 40 meters. This implies that the period when the strata between the depths of 200 and 40 meters were deposited was dominated by marine transgression. In the northern part, the transition zone stays around the line connecting Anding, Hsinhua, and the east of Gueizen as depth decreases from 40 to 13 meters, and then rapidly shifts seaward. This implies that the marine transgression reached and stayed at an apex when the strata between 40 and 13 meters deep were deposited. The transition zone shifts seaward rapidly as depth decreases from 13 to 6 meters, and this implies that the Tsengwenchi stream carried a large amount of deposits into the northern area in that period.

One or two isolated resistivity highs appear in the south-central part of the Tainan tableland in depth sections between 80 and 20 meters (Fig. 4). These isolated highs expand and then connect with the eastern part resulting in a rapid seaward shifting of the transition zone in the southern part as depth decreases from 60 to 6 meters. This implies that from the time that the stratum at 80 meters depth was deposited, an anticlinal uplifting occurring which led to the formation of the Tainan tableland.

4.6 Geoelectric Resistivity Profiles

Four geoelectric resistivity profiles A-A', B-B', C-C', and D-D' are drawn to display the contact relationship between the electrostratigraphic units and the resistivity distribution of the formations (Fig. 5).

Profile A-A' (Fig. 5) indicates that the lower part of the R-facies is the basal formation which is overlain by the upper part of the R-facies in the east and by the S-facies in the west. Profile C-C' indicates that the R-facies intertongues with the S-facies in the north-central part. This implies that the upper part of the R-facies in the east is the formation deposited in terrestrial and estuarine environments corresponding to the S-facies deposited in marine environments.

A graben appears on the top of the S-facies between Stations 115 and 17 on Profile B-B' (Fig. 5). This implies that a subsidence might occur there and that faults might exist near these two stations. Two faults named the "Houchiali fault" and the "Liuchiatien fault", which are near Stations 115 and 17 respectively, were inferred from photogeologic studies (Howard, 1962; Sun, 1964). These are consistent with the results of this study. The scarps of the graben indicate that the throws of the Houchiali and Liuchiatien faults are about 60 and 80 meters, respectively.

5. CONCLUSIONS

(1) The strata from the surface to a depth of 200 meters are divided into three electrostratigraphic units, and are designated the T, S, and R facies. The T-facies is characterized by layers of resistivity ranging from 12 to 400 ohm-m at the top of the layer sequence. It is less than 100 meters thick and is widely distributed throughout the area studied. The T-facies was deposited in terrestrial and estuarine environments in the Holocene. The S-facies is

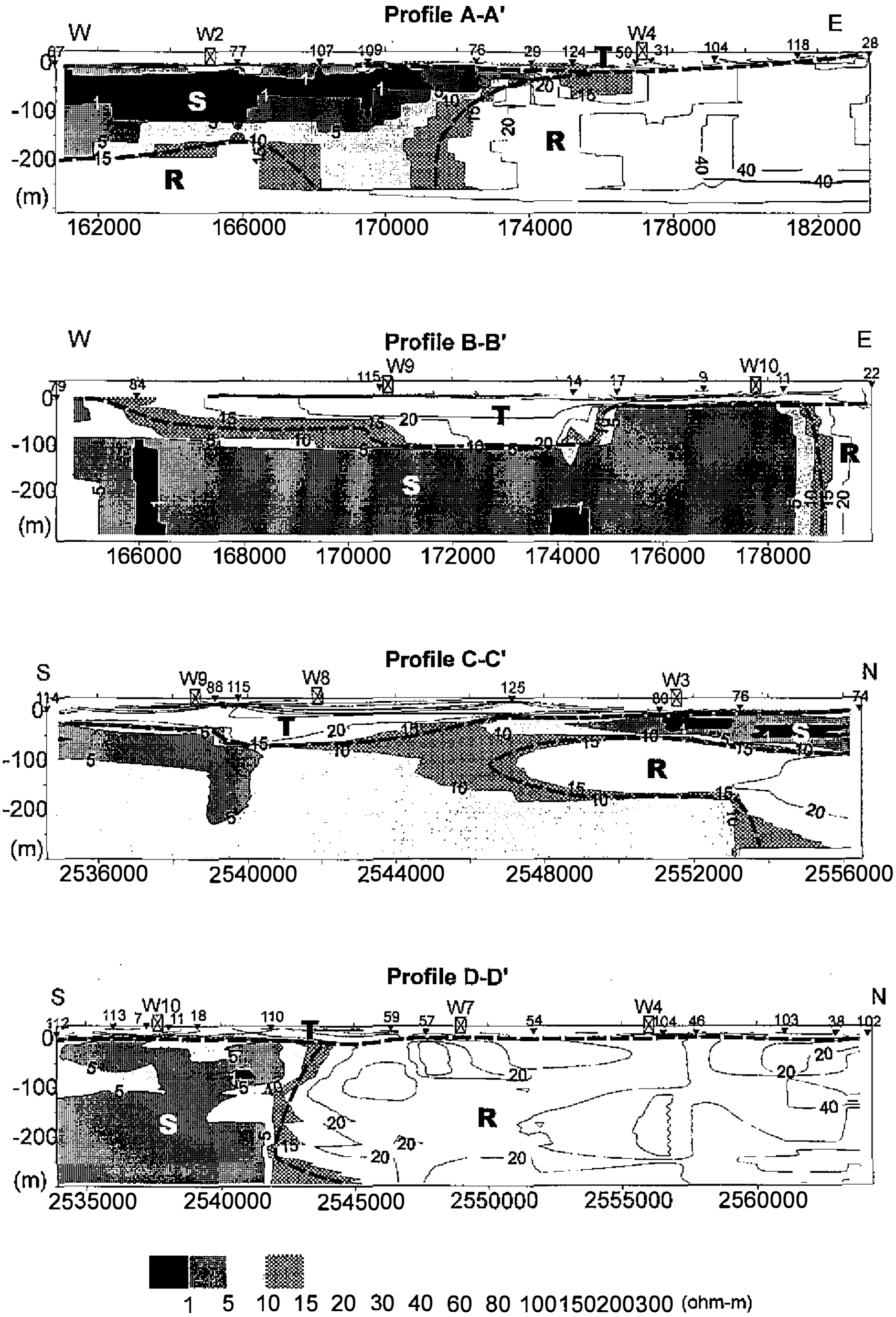


Fig. 5. Geoelectric resistivity profiles of A-A', B-B', C-C' and D-D' shown in Figure 1, where T, S, and R are electrostratigraphic units.

characterized by a thick layer or layers of resistivity lower than 5 ohm-m, and is generally accompanied by thin layers of resistivity lower than 12 ohm-m. This unit is 50 to 200 meters thick and is usually overlain by the T-facies in the western and the central parts of the area studied, and is absent in the eastern part. The S-facies was deposited in marine environments in the late Pleistocene to Holocene. The R-facies is characterized by a thick layer or layers of resistivity ranging from 12 to 70 ohm-m. It is overlain by the S-facies in the west and by the T-facies in the east of the area studied. The upper part of the R-facies in the east was deposited in terrestrial and estuarine environments in the late Pleistocene.

(2) The T, S, and R facies are similar in lithology. They are mainly composed of layers of clay, mud, silt, and fine sand. In the northern part, these facies contain few layers of medium sand, coarse sand, and pebble.

(3) The formation factor is evaluated as 1.93-1.95 and the critical resistivity is evaluated as 12.2 ohm-m for a stratum of porosity 0.53-0.57 being saline. The pore water in the S-facies is saline. The TDS in the pore water of the S-facies is evaluated as mainly in the range 6.1 to 30 g/l which corresponds to a bulk resistivity mainly ranging from 2 to 0.4 ohm-m. The lowest resistivity of stratum is 0.18 ohm-m, which appears on the surface of a saltpan on the western margin of the area studied.

(4) Except in the Tainan tableland, a marine transgression occurred when the strata between the depths of 200 and 40 meters were deposited in the area studied. At the apex of the marine transgression, the shoreline reached the line connecting Anding, Hsinhua, and the east of Gueizen, and then a marine regression occurred. Since the beginning of the marine regression, the shoreline has retreated about 22 kilometers westward in the north, and about 14 kilometers westward in the south.

(5) The Tainan tableland was formed by an anticlinal uplifting which began when the stratum at a depth of 80 meters was deposited. The eastern flank of the anticline has been cut by the Houchiali fault, and the throw of the fault is evaluated to be 60 meters.

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