WESTERN PACIFIC EARTH SCIENCES
Vol.1, No.1, P.85-98, 5 Figs., 1 Tab., February, 2001

AN ELECTROSTRATIGRAPHIC STUDY OF THE CHIAYI COASTAL PLAIN, SOUTHWESTERN TAIWAN

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ABSTRACT

A geoelectric survey containing two hundred and thirty-eight vertical electric soundings was conducted in the area of the Chiayi coastal plain for the study of electrostratigraphy and environmental changes. The sounding data were interpreted by the 1-D inversion method.

Based on electric resistivities and layer thicknesses derived from the sounding data, three electrostratigraphic units, T, S, and R-facies, are differentiated and specified. They are found in the strata from the surface to 200 meters in depth. T-facies covers layers of resistivity mainly from 10 to 50 W -m lying on the top of the sequence. It is considered as deposited in lagoonal, estuarine, and terrestrial environments during Holocene. Its thickness is about 100 meters in the south-center and decreases to 40 meters toward the north and 10 meters toward the east. This unit transforms to S-facies as the resistivity reduced. S-facies contains a thick layer or layers of resistivity lower than 8 W -m, and considered as deposited in a marine environment. It is about 35-100 meters thick and mostly overlain by T-facies in the western part, and absent in the eastern part. R-facies is a thick layer or layers of resistivity ranging from 16 to 80 W -m at the bottom of the sequence. It is overlain by S-facies in the western part and by T-facies in the central and eastern parts.

R-facies can be correlated to late Pleistocene formations. The boundary between the Tainan and Liushuang Formations can be set by the electric resistivity structures, although they are similar in lithology and faunal content.

A particular conductive layer usually exists in the strata during a marine transgression. The age of the conductive S-facies is found to agree with the period of the Tainan marine

transgression. But no conductive zone is found corresponding to the previously suggested Tahu transgression and regression.

Key words: geoelectric resistivity, groundwater, coastal plain of SW Taiwan

INTRODUCTION

The study area covers about 1000 square kilometers with a N-S length of about 35 km and a W-E width of about 30 km including the coastal plain of Chiayi Hsien, the northern part of Tainan Hsien, and the southern part of Yunlin Hsien (Fig. 1). The Peikanghsi and Bazhanghsi streams flow southwestly through the north and the south, respectively. Most of the area is low and flat, and generally higher in the east (20-50m) and decreases gradually in altitude westward to about sea level on the west margin.

Most of the study area is covered with alluvial deposits named the Tainan Formation (Lin and Chou, 1974; Ho, 1975; Hsu, 1984), which has a thickness of about ten meters in the east and more than one hundred meters in the west, and is underlian by the Liushuang Formation. They lie horizontally, but their relation seems to be disconformable. Both 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 Liushuang Formations in the coastal plain area because their lithology and fauna are almost identical (Hsu, 1984).

The electric characteristics and depositional environments of the formations, the boundary between the Tainan and Liushuang Formations, and a model of marine transgression and regression are studied from the view point of electrostratigraphy.

METHOD

The direct current resistivity method was used to investigate the resistivities of the strata. The Schlumberger array was used in vertical electric soundings (VES). The array consists of four electrodes arranged symmetrically along a straight line with the outer two for current injecting and the inner two for potential measuring. Spacing between the current electrodes is greater than four times of the spacing between the potential electrodes. In each sounding, current electrodes were spread out step by step from 2 meters to 600 meters or greater, the maximum spacing, with 10 measurements per logarithmic cycle. Potential electrodes were spread out when the measured potential was lower than 1 mV for available current intensity. Apparent resistivities were calculated in the field for inspecting the data quality. If a distortion in data appeared, measurement was repeated or the current electrode positions were changed to improve the quality of data.

The sounding data were interpreted by the 1-D inversion method, since the strata are nearly horizontal and structurally undisturbed and can be regarded as a 1-D structure in the study area. The forward part of the 1-D inversion computer program is based on the theory of convolution and Fourier transformation (Ghosh, 1971; Koefoed, 1979; O'Neill and 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 by the Zohdy's method (Zohdy, 1989).

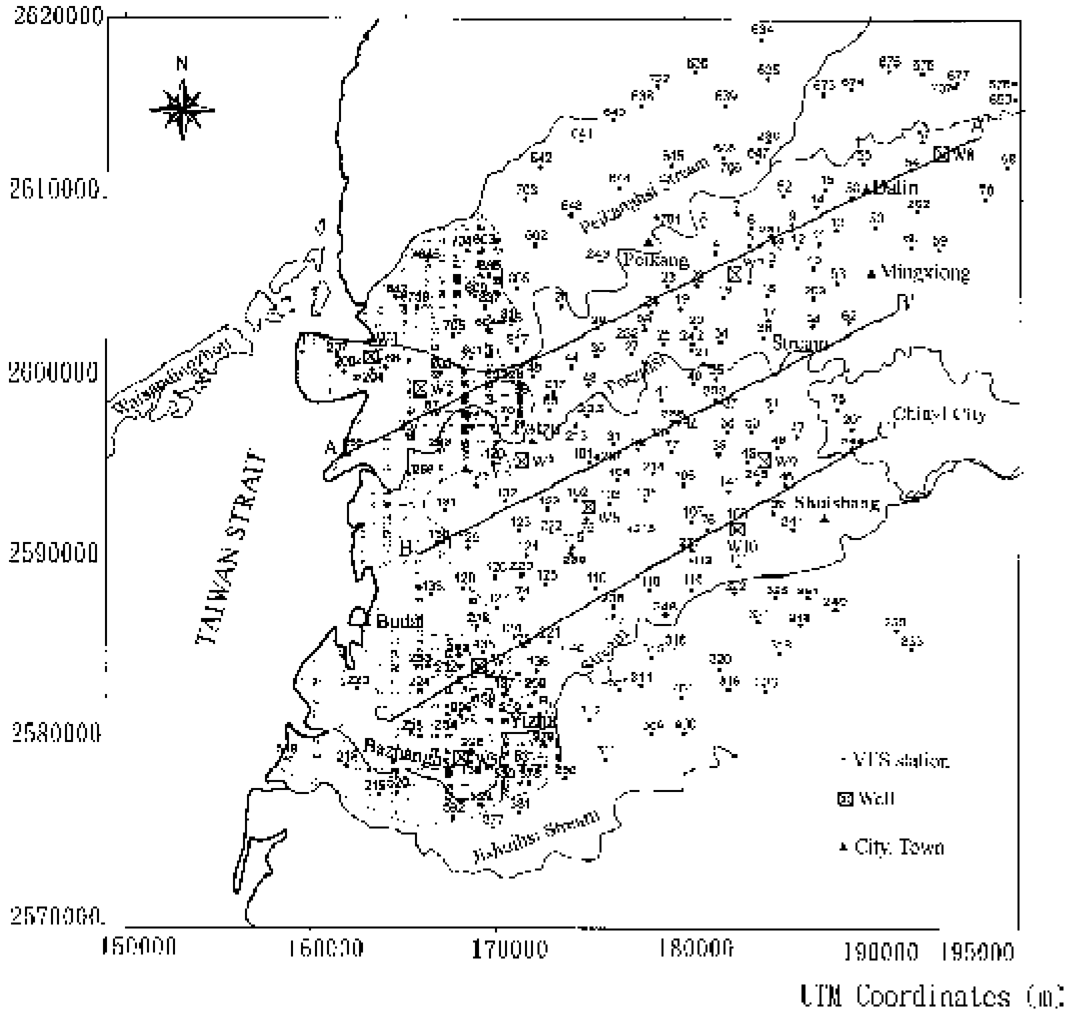

Figure 1. The locations of the vertical electric soundings are shown by spots, wells by crossed squares, along with three geoelectric resistivity profiles A-A', B-B' and C-C' in the Chiayi coastal plain. Shading indicates the area of the VES curves which have an apparent resistivity lower than 10 Ω-m.

RESULTS AND DISCUSSIONS

Two hundred and thirty-eight VES were conducted; their locations are shown in Figure 1. Locations of VES were distributed with a separation distance of about two to three kilometers among them, except in urban areas and the western margin which is occupied by fishponds and saltfields.

Types of VES Curves and Interpretative Results

The type of a VES curve can reveal resistivity ranges and sequence of the formations. The curves measured can be classified into three types: the minimum, fluctuating, and ascending. They are closely correlated with their locations. Typical examples and their interpretative results are shown in Figure 2.

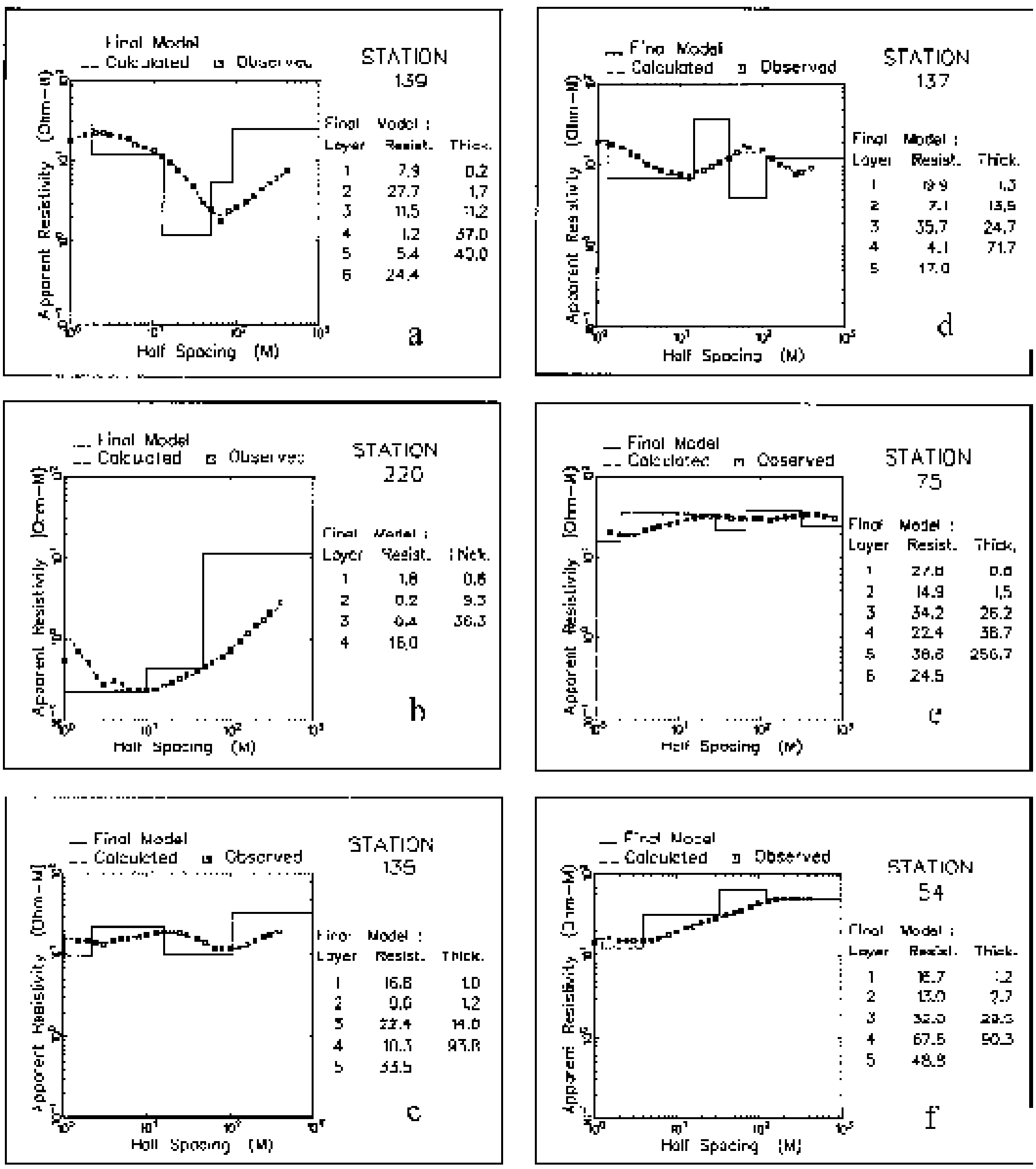

Figure 2. Apparent resistivity curves and interpretative results for stations 139, 220, 135, 137, 75, and 54.

Minimum type - The minimum type is characterized by a distinctive minimum of apparent resistivity lower than 5 Ω-m in the middle portion of the curve (e.g., Station 139, Fig. 2a). This implies that the formations contain a conductive zone overlain and underlain by resistive layers. All the stations of this type are located in the western part. Their interpretative results indicate that the strata can be divided into three sections by the range of resistivity. The top section is 1-20 meters thick consisting of 1-3 layers of resistivity greater than 8 Ω-m. The middle one is 30-100 meters thick consisting of 1-2 layers of resistivity 0.3-5 Ω-m. The basal one has a resistivity greater than 10 Ω-m. Stations in saltpans are special cases (e.g., Station 220, Fig. 2b) where the resistive top section is absent, and the middle and basal sections have lower resistivities than the other places.

Fluctuating type - The fluctuating type is characterized by smooth fluctuation in apparent resistivity between 5 and 60 Ω-m. Most stations of this type are located in the central and eastern parts. In general, the fluctuation is moderate for the stations near the west, and gentle or indistinctive for the stations far from the west.

A moderate fluctuation curve usually has two minima of apparent resistivity ranging from 5 to 15 Ω-m implying that the strata contain two conductive zones. Station 135 is a representative example, located about 2 km northwest of Yizhu in the southwestern part. Its curve and interpretative results are shown in Figure 2c, indicating that the strata contain two conductive zones of resistivity 4-12 Ω-m separated by a resistive layer, usually 10-30 meters thick and 20-50 Ω-m in resistivity. The upper conductive zone is usually 1-4 meters thick; but an abnormal thickness of 10-14 meters appears in a local area near Yizhu (Station 137, Fig. 2d). The lower conductive zone is about 30-50 meters thick in the north and 40-100 meters thick in the south for a belt near the west in the central part.

Usually, the apparent resistivities of the gentle and indistinctive fluctuation curves are higher than 10 Ω-m. Station 75 is a representative example, located about 5 km southeast of Potzu. The curve and interpretative results of Station 75 are shown in Figure 2e, indicating that the strata usually contain two less-resistive zones mainly ranging from 6 to 18 Ω-m within the depth of 1-100 meters.

Ascending type - The ascending type is characterized by apparent resistivity increasesing with electrode spacing. Usually, the apparent resistivities are higher than 20 Ω-m for half-spacings greater than 10 meters. All stations of this type are located in the central and eastern parts. Station 54 is a representative example, located in the northeast. The curve and interpretative results of Station 54 are shown in Figure 2f, indicating that the resistivities of the formations mainly range from 20 to 60 Ω-m, except the top layer, which is usually about 0.3~4 meters thick and about 8-20 Ω-m in resistivity.

Electrostratigraphic Units

Three electrostratigraphic units are differentiated and specified based on the ranges of resistivity, thickness and layers sequence interpreted from VES data. They are designated as T, S, and R facies. Resistivity profiles A-A', B-B', and C-C' in Figure 1 depict the electrostratigraphic units in Figure 3.

T-facies is characterized by layers of resistivity mainly ranging from 10 to 50 Ω-m and locally interbedded with a thin layer of resistivity 5-10 Ω-m at the top of the sequence. It is underlain by S-facies in the west and by R-facies in the east. Thickness of T-facies is less than 10 meters in the west, 10-100 meters in the center, and 5-40 meters in the east.

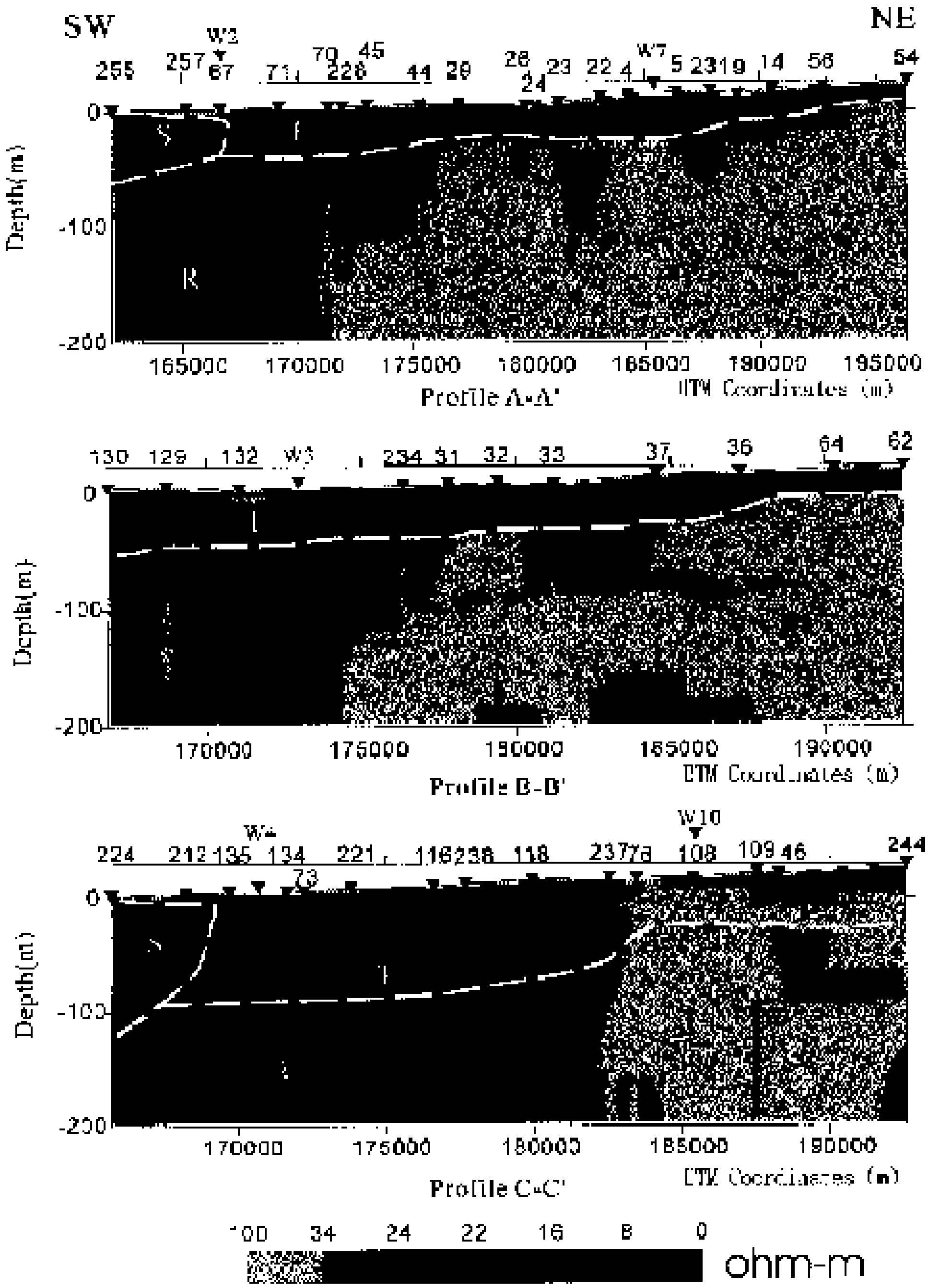

Figure 3. Geoelectric resistivity profiles of A-A', B-B', and C-C' shown in Figure 1, where T, S, and R are electrostratigraphic units.

S-facies contains thick layers of resistivity lower than 8 Ω-m. It includes a thick conductive zone interpreted from the minimum-type curves and the lower conductive zone interpreted from the fluctuating-type curves. It is about 35-100 meters thick dominating in the western part, and absent in the eastern part. It is partly overlain by T-facies and partly exposed to the air. R-facies is represented by thick layers of resistivity ranging from 16 to 80 Ω-m at the bottom of the sequence. The boundary between R and T-facies in the eastern part is set at the bottom of the lower conductive zone or the less-resistive zone interpreted from the data of the fluctuating -type curves.

Lithology and Age of the Electrostratigraphic Units

Ten lithologic columns of wells were collected to study lithology of the electrostratigraphic units. The locations of wells, W1 to W10, are shown in Figure 1. The lithologic columns of the wells and the interpretative results of their nearby soundings are shown in Figures 4 and 5. The formations in the western part are mainly composed of layers of clay, mud, fine sand, and medium sand, as shown in the lithologic columns of W1, W3, W4, and W5, except for W2 in which two thick layers of coarse sand exist. They are mainly composed of layers of fine to coarse sand, and pebble in the central and eastern parts , as shown in the lithologic columns of W6 to W10.

Figures 4 and 5 indicate that lithology of T-facies are medium sand, top soil, mud and clay, and fewer coarse sand. That of S-facies are fine sand, mud and clay, and medium sand. As for R-facies, its lithology is similar to T-facies except for fewer pebbles. There is little difference in lithology among these electro-facies. S-facies seems to be smaller in grain size than T and R-facies.

E-log, lithology and age of the core of W5, and the interpretative results of its nearby Stations 139 and 226 are shown in Figure 5, indicating that T-facies is about 10 meters thick and has a resistivity in the range of 10-20 Ω-m. S-facies is about 80 meters thick between the depths of about 10 meters and 90 meters. It consists of two low-resistivity layers with a boundary at the depth of about 50 meters. R-facies is correlated to the basal layer of resistivity about 23 Ω-m. The boundaries around the depths of 50 meters and 90 meters also appear in E-logs. There are sharp increases from 8 to 12 Ω-m resistivity, and from 1450 to 1640 mV around the depth of 50 meters in the long normal resistivity log (64N) and the SP log, respectively. A sharp increase from 20 to 30 Ω-m appears around the depth of 90 meters on the long normal resistivity log (Fig.5).

Some dating results on core samples were collected to study the age of the electrostratigraphic units (Tab. 1). The electro-facies of the samples were determined by correlating the depths of the samples with the interpreted results of their nearby soundings (Figs. 4 and 5).

Table 1 indicates that the sample belonging to S and T facies are young than 11000 yBP. It is inferred that T and S facies were deposited in Holocene, and are correlated to the Tainan Formation. R-facies was deposited in late Pleistocene, and is correlated to the Liushuang Formation.

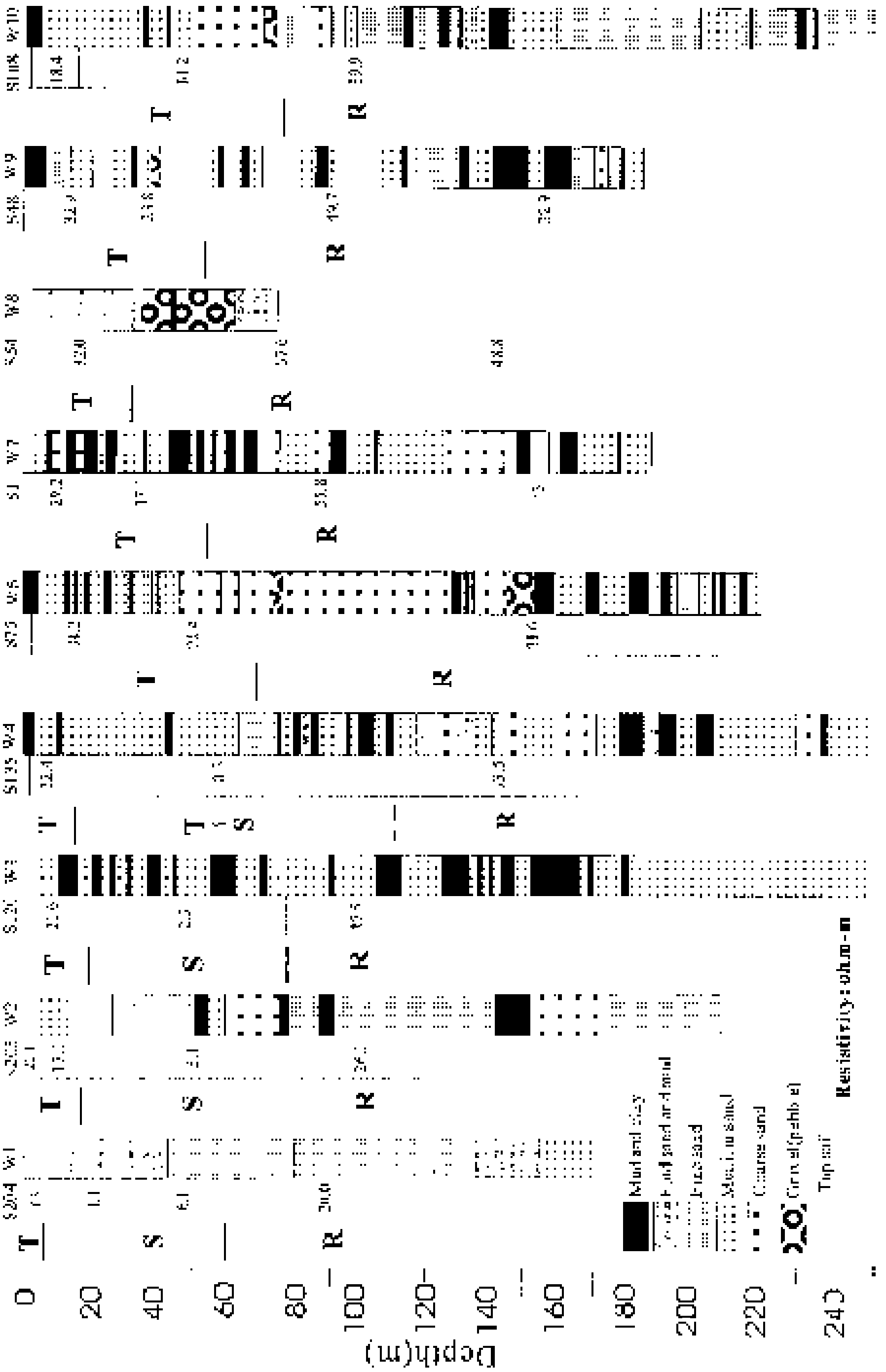

Figure 4. Lithologic columns of wells accompanied with the interpretative results of their nearby soundings. The figures in the VES columns showing resistivities in Ω-m. T, S, and R are electro-facies.

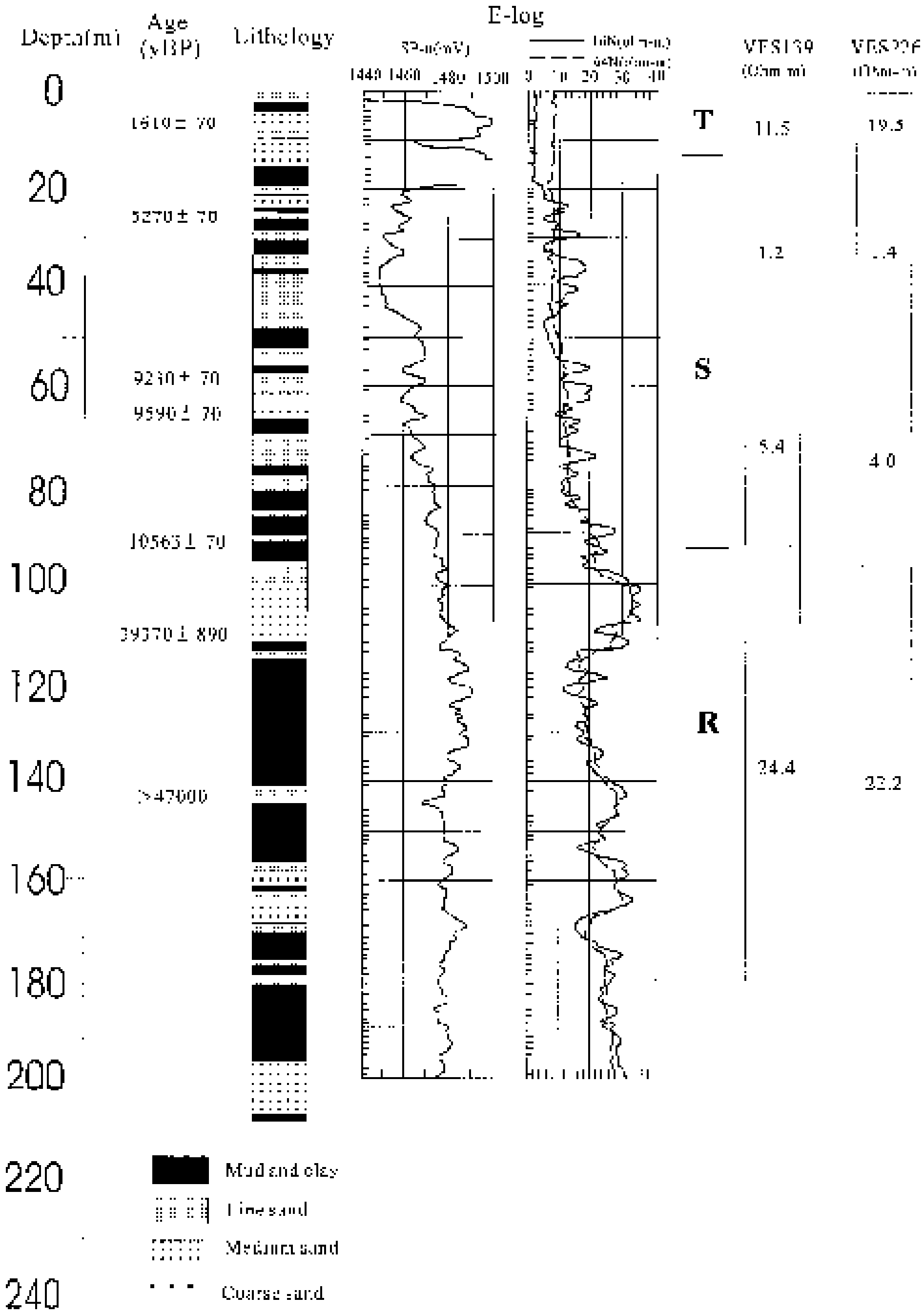

Figure 5. Lithologic column, age of core, E-log in borehole of the well at Yizhu (W5), and the interpretative results for Stations 139 and 226.

Table 1. Ages and electo-facies of some core samples in the Chiayi coastal plain.

Well	Depth (m)	Age (yBP)	Electro-facies	Epoch
W3*	56.1	9930 ± 190	S	Holocene
W4*	54.8	9652 ± 80	S	Holocene
W4*	95.7	37520 ± 1550	R	Late Pleistocene
W5	6.5	1610 ± 70	T	Holocene
W5	26.8	5270 ± 70	S	Holocene
W5	58.5	9220 ± 70	S	Holocene
W5	85.4	10563 ± 70	S	Holocene
W5	109.5	37370 ± 390	R	Late Pleistocene
W6*	50.2	10240 ± 160	T	Holocene
W6*	73.0	48590 ± 3400	R	Late Pleistocene
W7*	45.95	9440 ± 70	T	Holocene
W7*	50.9	27320 ± 440	R	Late Pleistocene

* Taken from the report of Central Geological Survey, Taiwan, R.O.C.

Conductivity and Salinity of Formation Water

Salinity of water can be evaluated from conductivity of water. Total dissolved solid (TDS) is a term usually used instead of salinity in groundwater. Experiments have proved that TDS in water is proportional to conductivity in a certain salinity range (Keller and Frischknecht, 1966). An approximate relation of most natural water in the range of 0.01 to 0.5 S/m leads to an equivalence 1000 P.P.M. = 0.156 S/m or 6410 P.P.M. = 1 S/m at 25°C. An increase of 1°C increases conductivity by about 2 % (Todd, 1980).

Conductivity of formation water (C_w) can be estimated from the bulk resistivity of the formation using Archie's formula. For a water-saturated stratum, the formula can be written as

$$C_w = r_w^{-1} = F r^{-1} = a\, j^{-m} r^{-1} \quad ,$$

where F is the formation factor, and defined as the ratio of the bulk resistivity r to the resistivity of formation water r_w. It is a function of porosity j, and parameters a and m. The values of *a* and *m* were determined to be 0.858 and 1.367, respectively (Cheng, 1996). Porosity of the strata was measured to be 0.53-0.57 on the core samples, and F was calculated to be 1. 93-1.95 (Cheng, *et al*, 1999). The conductivity and TDS of the formation water in T-facies are estimated to be 0.195-0.0386 S/m and 1250-247 P.P.M., respectively, corresponding to a bulk resistivity in the range of 10-50 Ω-m. In S-facies, they are estimated to be higher than 0.241 S/ m and 1540 P.P.M., respectively, corresponding to the bulk resistivity lower than 8 Ω-m. In R-facies, they are estimated to be 0.121-0.024 S/m and 154-77 P.P.M., respectively, corresponding to the bulk resistivity in the range of 16-80 Ω-m.

Both T and S facies are mainly composed of fine materials, especially in the western part. They usually have low hydraulic conductivity (Bouwer, 1978). Most of the connate water in T and S facies would remain in the formations, because these two facies are very young and have low hydraulic conductivity. Therefore, TDS of these two facies indicates their depositional environments.

Saline groundwater is a term referring to any groundwater containing more than 1000 P. P.M. TDS (Todd, 1980). The bulk resistivity is estimated to be 12.5 Ω-m corresponding to the critical salinity of 1000 P.P.M. TDS. Hence the strata of resistivity lower than 12.5 Ω-m may be regarded as marine facies, and those between 12.5-20 Ω-m as estuarine and lagoonal facies.

TDS value is estimated to be higher than 1540 P.P.M. (equivalently higher than 4.4 % of seawater) for S-facies formation water, implying that S-facies was deposited in marine environments. It is estimated to be 1250~247 P.P.M. for T-facies formation water, implying that T-facies was mainly deposited in estuarine and lagoonal environments.

R-facies was deposited in late Pleistocene. It might have suffered a longer time of leaching, hence TDS in the formation water might have been lowered down, and would not reveal its depositional environments.

Transgression and Regression

Two transgressions and two regressions, Tainan and Tahu, occurring in the Holocene were previously suggested: the former occurred around 6500-5000-4000 yBP, and the latter around 4000-3500-2700 yBP (Sun, 1971; Lin and Chou, 1974).

The resistivity sequence in sediments can reveal changes of sedimentary environments, because marine deposits usually have resistivity lower than estuarine and terrestrial ones. About ten percent of VES measured in the study area do display two minima in their curves (e.g., Station 135 and 137, Figs.2c and d). We interprete that the formations contain two conductive zones of resistivity less than 12 Ω-m, separated by a relatively resistive layer greater than 16 Ω-m. In general, the upper conductive zone appears between the depths of 1 and 5 meters and the lower one between the depths of 15 and 100 meters. Station 137 and 209 are exceptions, where the upper conductive zone extends from 1 meter to 15 meters in depth.

A conductive zone overlain and underlain by resistive layers might generally be considered as deposited during the period of a marine transgression and regression. However, a local subsidence of unimportance is easy to be misinterpreted. The age of some samples of S-facies covers a range of 10563-5270 yBP (Tab. 1), which overlaps the earlier period of the suggested

Tainan transgression and regression. It is inferred that S-facies is the formation deposited during the period of the Tainan transgression and regression which began around 10500 yBP and extended to a time later than 5270 yBP. The upper conductive zone belonging to T-facies between the depths of 1 and 5 meters is younger than 1610 yBP, the age of a core at 6.5 meters deep in W5 (Tab. 1). This age is however inconsistent with the suggested period of the Tahu transgression and regression (4000-3500-2700 yBP). The upper conductive layer is therefore considered as deposited on a saline area of a local subsidence in late Holocene.

CONCLUSSION

(1) The strata from the surface to a depth of 200 meters are divided into three electrostratigraphic units, and are designated as T, S, and R facies. T-facies is characterized by layers of resistivity mainly ranging from 10-50 Ω-m and locally interbedded with a thin layer of resistivity 5-10 Ω-m at the top of the layer sequence. It is less than 10 meters thick in the western part, 40-100 meters thick in the central part, and 5-40 meters thick in the eastern part of the Chiayi coastal plain.

S-facies contains a thick layer or layers of resistivity lower than 8 Ω-m. It is about 35-100 meters thick dominating in the western part, and absent in the eastern part. It is exposed or overlain by T-facies and underlain by R-facies.

R-facies is a thick layer or layers of resistivity ranging from 16 to 80 Ω-m at the bottom of the layer sequence. It is overlain by S-facies in the western part, and by T-facies in the central and the eastern parts.

(2) T and S facies were deposited in Holocene and are correlated to the Tainan Formation. R-facies was deposited in late Pleistocene and is correlated to the Liushuang Formation. There is little difference in lithology among them. T-facies is composed of layers of medium sand, soil, mud and clay, and fewer find sand and coarse sand. S-facies is composed of layers of fine sand, mud and clay, and fewer medium sand. R-facies is similar to T-facies, except for fewer pebble layers. The boundary between the Tainan and Liushuang Formations can be set by electric resistivity structures, although they are similar in lithology and faunal content.

(3) T-facies was mainly deposited in estuarine and lagoonal environments. TDS in its formation water is evaluated to be 1250-247 P.P.M. corresponding to a bulk resistivity of 10-50 Ω-m. S-facies was deposited in marine environments. TDS is evaluated to be higher than 1540 P.P.M. corresponding to a bulk resistivity lower than 8 Ω-m.

(4) A conductive zone can be regarded as sediments deposited in the paleosea. A thick conductive zone, S-facies, may correspond to the suggested Tainan transgression and regression. But, no conductive zone is found corresponding to the suggested Tahu transgression and regression. A thin conductive layer is found on the top of the formation. It is younger than 1610 yBP, and considered to be sediments deposited in a saline area of a local subsidence in late Holocene.

ACKNOWLEDGMENTS

The author are grateful to the diligent field crew of the geoelectric group at the Institute of Geophysics, National Central University, Taiwan. We thank the Director Mr. C. S. Lee, engineer Mr. W. F. Chen, TSC Groundwater center, and Professor L. C. Wu, Department of Geology, Chinese Culture University, for their help in the collection of lithologic columns. This study was supported by the National Science Council, R. O. C under grants NSC85-2111-M-008-001 and NSC88-2116-M-008-010.

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