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An Electrostratigraphic Study of the Hsinying-Matou Coastal Plain, Southwestern Taiwan

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ABSTRACT

One hundred and two vertical electric soundings were conducted in the Hsinying-Matou coastal plain in southwestern Taiwan, for the study of electrostratigraphy and the changes in sedimentary environments. The sounding data were interpreted using the 1-D inversion method.

The results indicate that the strata from the surface to 180 meters depth can be divided into three electrostratigraphic units. They are designated, from top to bottom, as the T, S, and R facies.

The T- facies is a combination of thin layers of resistivity ranging from 5 to 45 ohm-m, and is 10 to 60 meters thick. The S- facies is characterized by thick layers of resistivity lower than 5 ohm-m, and is 80 to more than 130 meters thick in the west but absent in the east. The R- facies is characterized by thick layers of resistivity ranging from 5 to 50 ohm-m. These three units are similar in lithology; they are mainly composed of clay, mud, silt, and fine sand. The S- facies was sedimented in lagoonal, beach, and shallow marine environments. The T and the R facies were sedimented in non-marine environments in the east, and in lagoonal and estuarine environments in the west. The resistivity of stratum is controlled mainly by the salinity of formation water where the water is saline, and by the grain size and the amount of clay contained where the water is fresh.

It is inferred that the period from 40 to 8 Ka is transgressive dominant, and the period since 8 Ka is regressive dominant. The mouth of the Tsengwenchi stream was located about 20 Km east of the present coastline at 9 Ka. The Tsengwenchi stream developed westwardly since 9 Ka till recent times, and then changed southwestwardly to the present location.

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

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1. INTRODUCTION

The Hsinying-Matou coastal plain is situated in the central part of the Chianan coastal plain in southwestern Taiwan. The study area is bounded on the north and the south by the Pachangchi and the Tsengwenchi streams respectively, on the west by the coast, and on the east by the foothills (Figure 1). It covers about 750 square kilometers with a N-S length of approximately 25 kilometers and a W-E width of approximately 30 kilometers. Most of the area is low and flat. In general, the altitude is higher in the east with an average height of approximately 20 meters, and decreases gradually westward to about sea level on the west margin. The area near the coastline mainly consists of salt fields and fish ponds while the inland part is mainly fields of sugarcane, rice, and dry crops.

The study area is covered with alluvial deposits, which were differentiated into eight units by photogeologic study (Sun, 1970). The Tainan Formation is the dominant, for it covers more than half of the study area and has more predominant thickness than the others.

The thickness of the Tainan Formation ranges from 16 to 36 meters around the Tainan area, and increases toward the west to 175 meters at Anping and northwestward to 60-80 meters at Putai(Ho, 1975; Hsu, 1984). Beneath the coastal plain, the Tainan Formation is underlain by the Liushuang Formation with a thickness of 500 to 830 meters. 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 the Liushuang Formations in the coastal plain area because their lithology and fauna are almost identical (Hsu,1984).

Great changes in environments have been occurring in the study area. The shoreline has retreated more than 20 kilometers since the Necha Period (early Holocene)(Lin, 1957). The rates of tectonic subsidence and sediment accumulation for the last 12 Ka in the Zeikang area have been found to be as high as 3 and 8 mm/yr, respectively (Liu et al., 1997).

Transgressions and regressions have actively occurred in this area since the late Pleistocene. Different models of transgression and regression were suggested (Sun,1970; Lin and Chou, 1974; Chen, 1993). The electric characteristics of the formations and the changes of the sedimentary environments are studied from the point view of electrostratigraphy in this study.

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 along a straight line step by step from 2 meters to the maximum spacing with 10 measurements per logarithmic cycle. The apparent resistivity curves were plotted on double logarithmic paper in the field for inspecting the qualities of the raw data. If a distorted datum appeared, the measurement was repeated or the positions of the current electrodes were changed to improve the quality of the datum. One hundred and two VES were conducted in the study area; their locations are shown in Figure 1. The locations of the soundings were distributed in the study area with a separation distance of

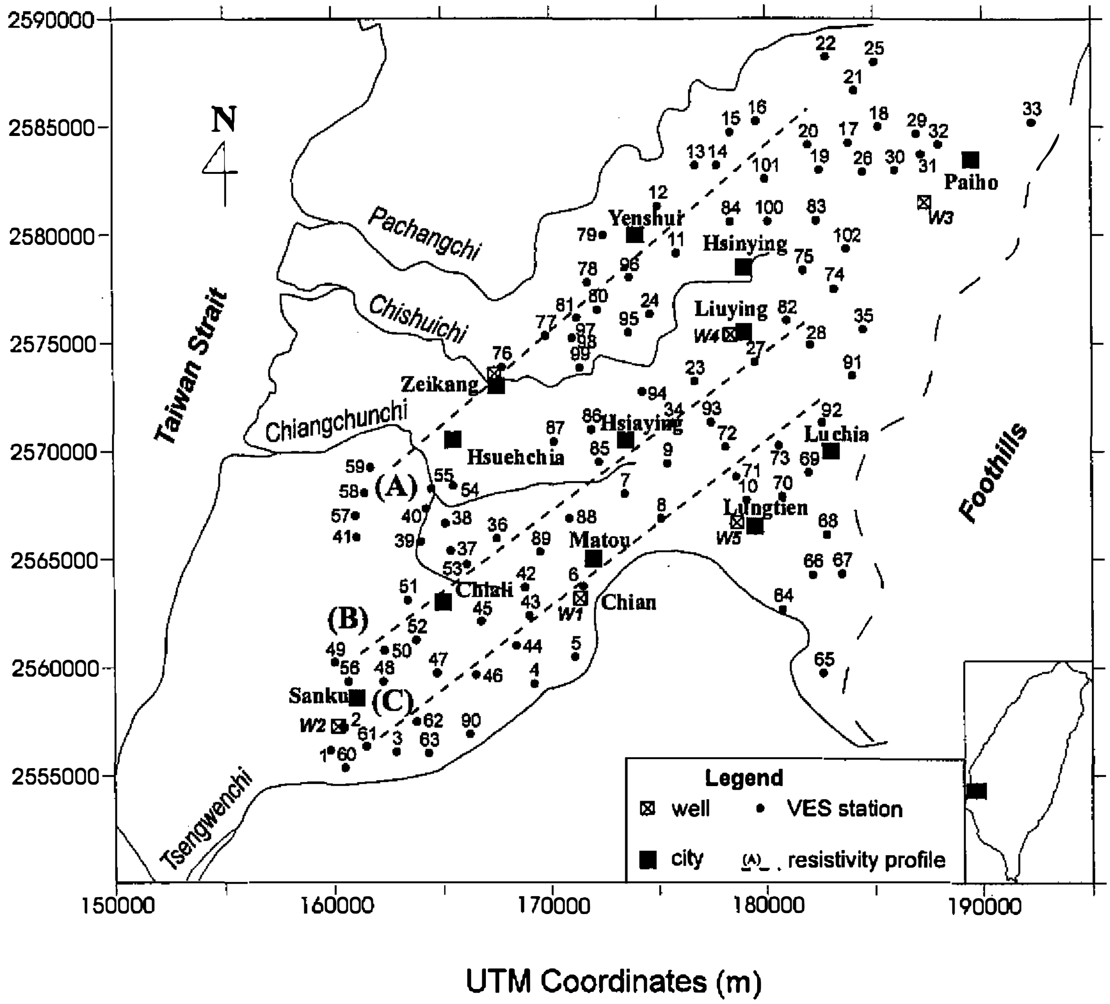


Fig. 1. The locations of the vertical electric soundings indicated by the black dots, wells by crossed squares, and three geoelectric resistivity profiles A, B, and C in the Hsinying-Matou coastal plain.

about two to three kilometers among them, except in city, salt field, and fishpond areas for lack of adequate space to spread the current electrodes. The maximum spacing of the VES are greater than 600 meters, most of them are 800 meters.

The VES 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. 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 carried out by the method of digital linear filtering based on the theory of convolution and Fourier transform (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 an automatic method which was modified from Zohdy's method (Zohdy, 1989; Lue,1994; Cheng and Shieh, 1994).

3. RESULTS AND DISCUSSIONS

3.1 Types of Apparent Resistivity Curves and Interpretative Results

The apparent resistivity curves (or VES curves) measured in the study area can be grouped into two categories: (1) the curve with a distinct minimum of apparent resistivity lower than 10 ohm-m indicating a conductive zone of resistivity less than 10 ohm-m, and (2) the curve without such a minimum as (1), implying no conductive zone or that the conductive zone is thin. The VES curve types are closely correlative with their locations. All the stations reporting curves belonging to the first category are located in the west, while curves belonging to the second category were reported in the east. Stations 76, 6, and 48 are representative examples of the first category; they are located in the northwest, the west-center, and the southwest, respectively (Figure 1). The curves and the interpretative results of these stations are shown in Figure 2, which indicates that the half-spacings corresponding to the minimum on the curves are different among these stations. This implies the depth and the thickness of the conductive zone vary from place to place. The interpretative results (Figure 2) indicate that the conductive zone (resistivity lower than 5 ohm-m) is 44.2 meters thick, i.e., between depths of 7.2 and 51.4 meters at Station 76 in the northwest; and is 112.3 meters thick, i.e., between the depths of 48.7 and 161 meters, at Station 6 in the west-center. The conductive zone includes all the layers, except for the top thin layer at Station 48 in the southwest, a thickness of 129.2 meters for the second and the third layers is shown. The thickness of the conductive zone may be greater than 200 meters at Station 48. The resistivity of 0.3 ohm-m for the third layer at Station 48 is the lowest resistivity in this area.

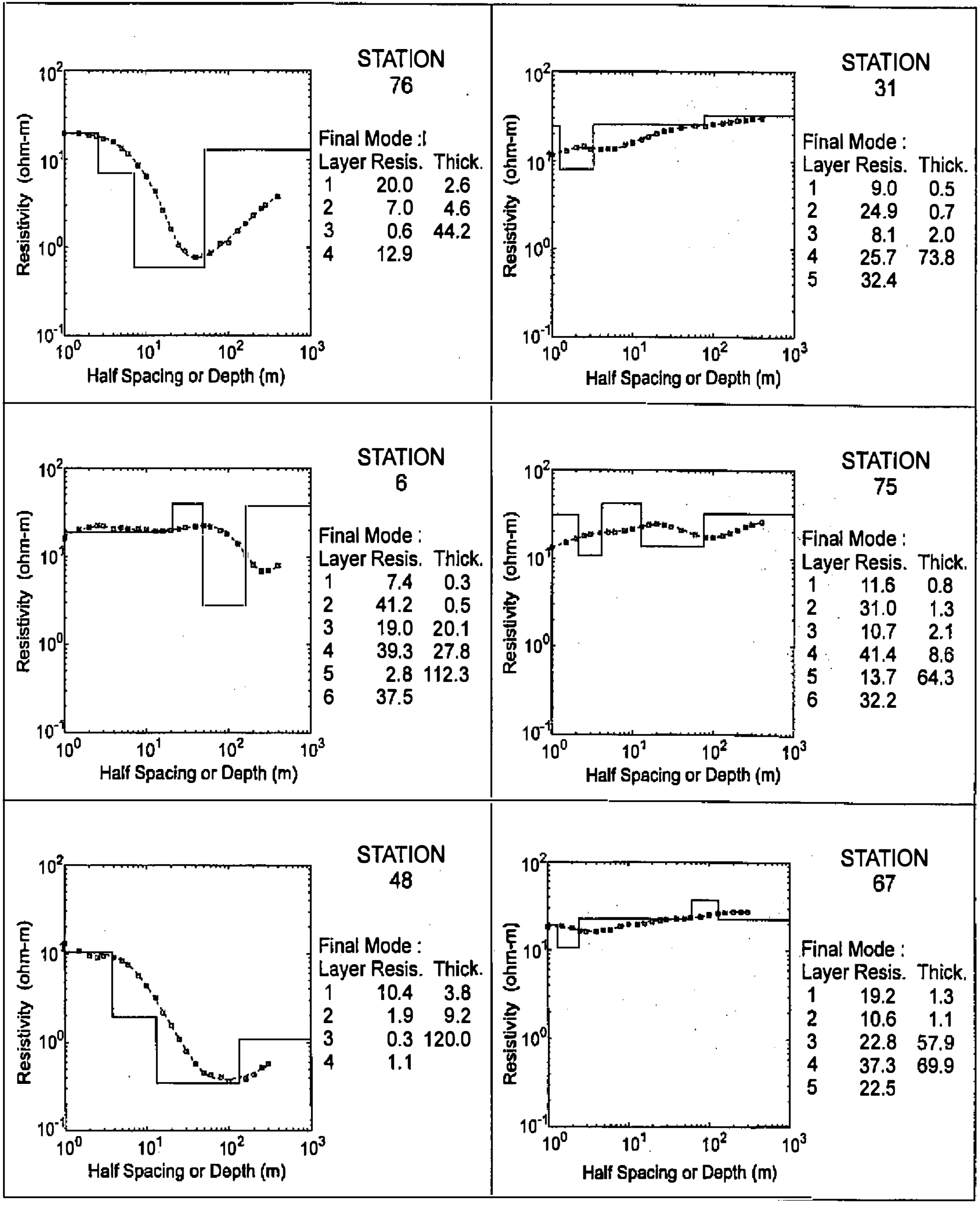
Stations 31, 75, and 67 are representative examples of the second category; they are located in the eastern part of the study area (Figure 1). The curves and the interpretative results of these stations are also shown in Figure 2. The interpretative results of these stations indicate that all the resistivities of the deep layers (deeper than 10 meters) are higher than 10 ohm-m.

The interpretative results of the VES conducted in the study area indicate that the strata contain a conductive zone of several tens to more than one hundred meters thick in the west but disappearing eastward. The results also indicate that the resistivity of the basal layer ranges from 5 to 20 ohm-m in the southwest to more than 40 ohm-m in the northeast.

3.2 Electrostratigraphic Units and Resistivity Profiles

Three electrostratigraphic units can be specified based on the resistivities, the thicknesses, and the sequences of the layers interpreted from the VES data. They are designated, from top to bottom, as the T, S, and R facies. Resistivity profiles A, B, and C in Figure 1 depict the electrostratigraphic units in Figure 3.

Figure 3 indicates that the R- facies is the basal unit, characterized by thick layers of



STATION 76

Final Mode :

Layer	Resis.	Thick.
1	20.0	2.6
2	7.0	4.6
3	0.6	44.2
4	12.9	

STATION 31

Final Mode :

Layer	Resis.	Thick.
1	9.0	0.5
2	24.9	0.7
3	8.1	2.0
4	25.7	73.8
5	32.4	

STATION 6

Final Mode :

Layer	Resis.	Thick.
1	7.4	0.3
2	41.2	0.5
3	19.0	20.1
4	39.3	27.8
5	2.8	112.3
6	37.5	

STATION 75

Final Mode :

Layer	Resis.	Thick.
1	11.6	0.8
2	31.0	1.3
3	10.7	2.1
4	41.4	8.6
5	13.7	64.3
6	32.2	

STATION 48

Final Mode :

Layer	Resis.	Thick.
1	10.4	3.8
2	1.9	9.2
3	0.3	120.0
4	1.1	

STATION 67

Final Mode :

Layer	Resis.	Thick.
1	19.2	1.3
2	10.6	1.1
3	22.8	57.9
4	37.3	69.9
5	22.5	

Fig. 2. The apparent resistivity curves and interpretative results of the Stations 76, 6, 48, 31, 75, and 67.

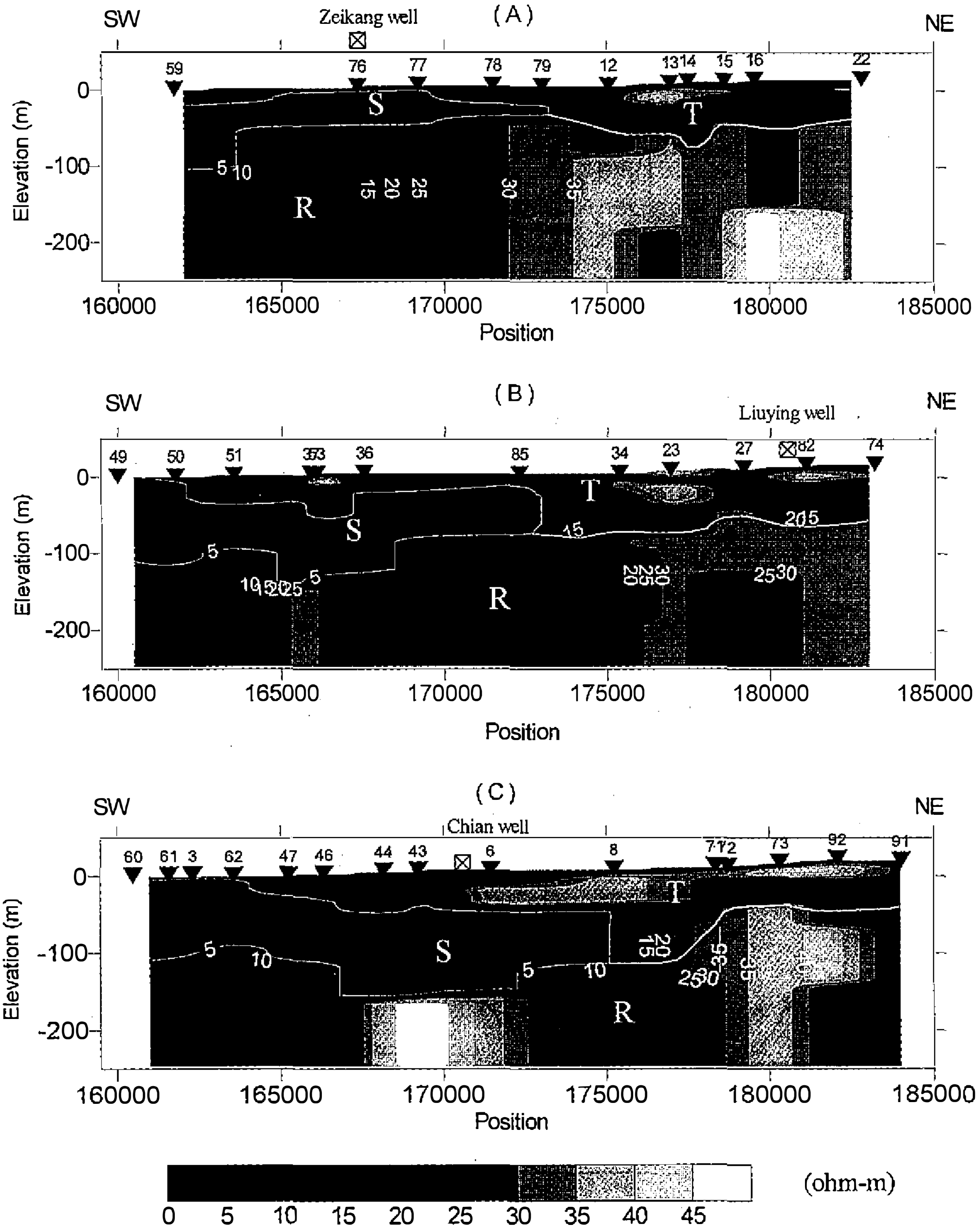


Fig. 3. Geoelectric resistivity profiles of A, B, and C shown in Fig. 1, (A) in the north ,(B) in the middle, and (C) in the south.

resistivity ranging from 5 to 20 ohm-m in the west and from 20 to 50 ohm-m in the east of the study area. The R- facies is overlain by the S- facies in the west and by the T- facies in the east.

The S- facies is characterized by thick layers of resistivity lower than 5 ohm-m, which are dominant in the west but absent in the east. The resistivity of the S- facies ranges from 0.3 to 2 ohm-m in the western part and increases eastward to 5 ohm-m in the middle part. The S- facies is thinner and shallower in the north and is thicker and deeper in the south. It is approximately 80 to over 130 meters thick in the western part, and approximately 15 meters thick, i.e., between the depths of 30 and 45 meters, in the north-center, and approximately 80 to 100 meters thick, i.e., between the depths of 50 to 150 meters, in the south-center (Figure 3).

The T- facies is the top unit, which overlies the S-facies in the western and the central parts, and overlies the R-facies in the eastern part. The T-facies is about 10 to 60 meters thick and is characterized by a combination of thin layers of resistivity ranging from 5 to 45 ohm-m. In general, the resistivity is lower in the west and higher in the east.

3.3 Lithology of the Electrostratigraphic Units

More than twenty lithologic columns of wells in the study area were collected to study the lithology of the electrostratigraphic units. Six of them were selected as local representatives. They are located at Chian, Sanku, Paiho, Liuying, Lungtien, and Zeikang (Figure 1). The lithologic columns of the wells at Chian, Sanku, Paiho, Liuying, and Lungtien together with the interpretative results of their nearby soundings are shown in Figure 4. The lithologic column, age of the core, sodium concentration in formation water, the E-log in borehole of the well at Zeikang and the interpretative results of Station 76 near the well are shown in Figure 5. Figures 4 and 5 indicate that the T, S, and R facies are similar in lithology. They are mainly composed of layers of clay, mud, silt, and fine sand. Occasionally, fewer layers of medium to coarse sand and pebble are contained in the east. The low resistivity layer (0.7 ohm-m) at VES Station 76 is closely correlated with the high Na-concentration section of the core at Zeikang (Figure 5). This implies the resistivity of formation is mainly controlled by the salinity of formation water where the water is saline, but is mainly controlled by the grain size and the amount of clay contained where the water is fresh.

3.4 Resistivity and Salinity of Formation Water

The resistivity of formation water can be estimated from the bulk resistivity of a stratum by Archie's law. For a water-saturated stratum, which is written as

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

where ρ is the bulk resistivity, ρ_w is the resistivity of formation water, ϕ is the porosity, a and m are parameters determined from a particular group of measurements (Keller and Frischknecht, 1966). The values of a and m are considered to be constants in a region similar in sedimentary environments. The values of a and m were determined to be 0.858 and 1.367 respectively in the coastal area of southern Yunlin Hsien about 25 km north of the study area (Cheng, 1996). The study area is similar in lithology, age, and sedimentary environments to the coastal area of southern Yunlin Hsien. Using those a and m values, the resistivity of formation water for various bulk resistivity and porosity is estimated, the results are shown in Table 1.

The salinity of water is a function of resistivity and temperature. The relationship between resistivity and salinity at various temperatures has been found. For example, the resistivity is 0.21, 0.93, 1.76, 8.2, and 16.2 ohm-m, corresponding to salinity 29.23, 5.845, 2.923, 0.5845, and 0.2923g/l, respectively, at 26°C(Keller and Frischknecht, 1966). Based on that relationship, the corresponding salinity for each formation water resistivity at 26°C(the average temperature of groundwater in the study area) was calculated; the results are also listed in Table 1.

Table 1 indicates that, for a given bulk resistivity, the resistivity of formation water decreases and salinity increases with decreasing porosity. The porosity of a stratum varies with grain size and grade of consolidation. Fine-textured deposits tend to have a greater porosity than coarse-textured deposits. Archie's equation indicates that for a given salinity or resistivity of formation water, bulk resistivity increases as porosity decreases; hence the coarse-textured deposits tend to have a greater resistivity than fine-textured deposits.

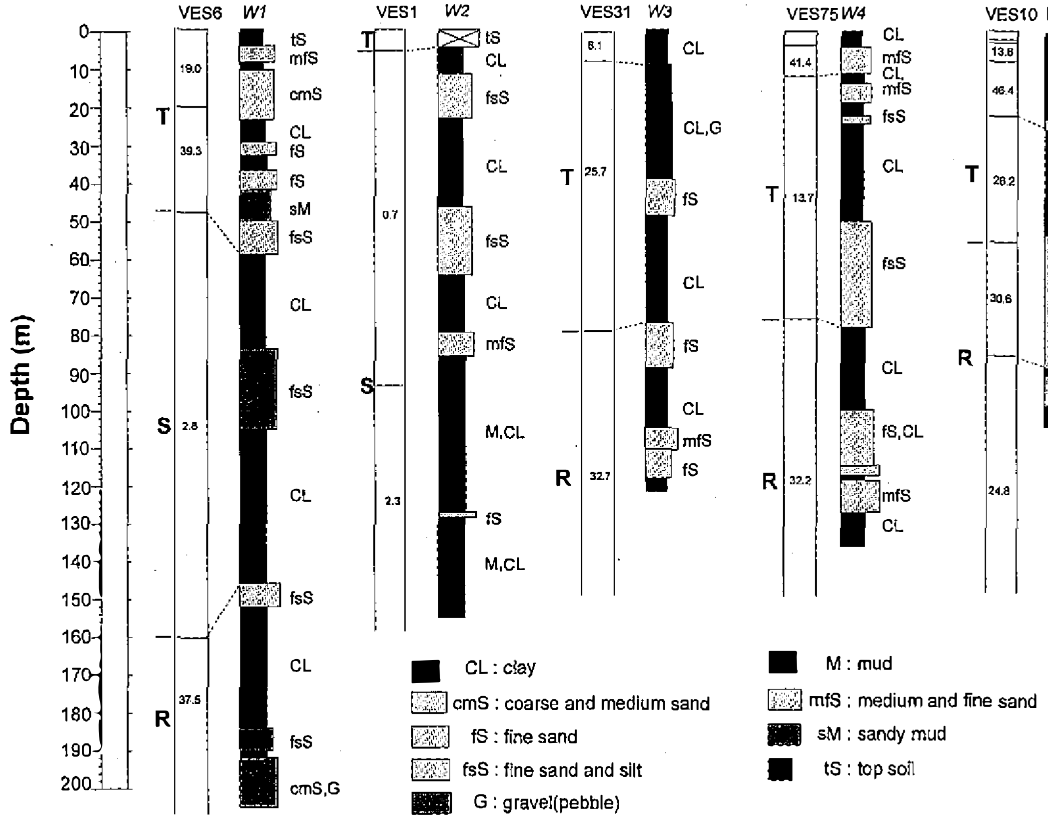


Fig. 4. Lithologic columns of the wells locate at Chian (W1), Sanku (W2), Paiho(W3), Liuying (W4), and Lungtien (W5) acompanied with the interpretative results of their nearby soundings.

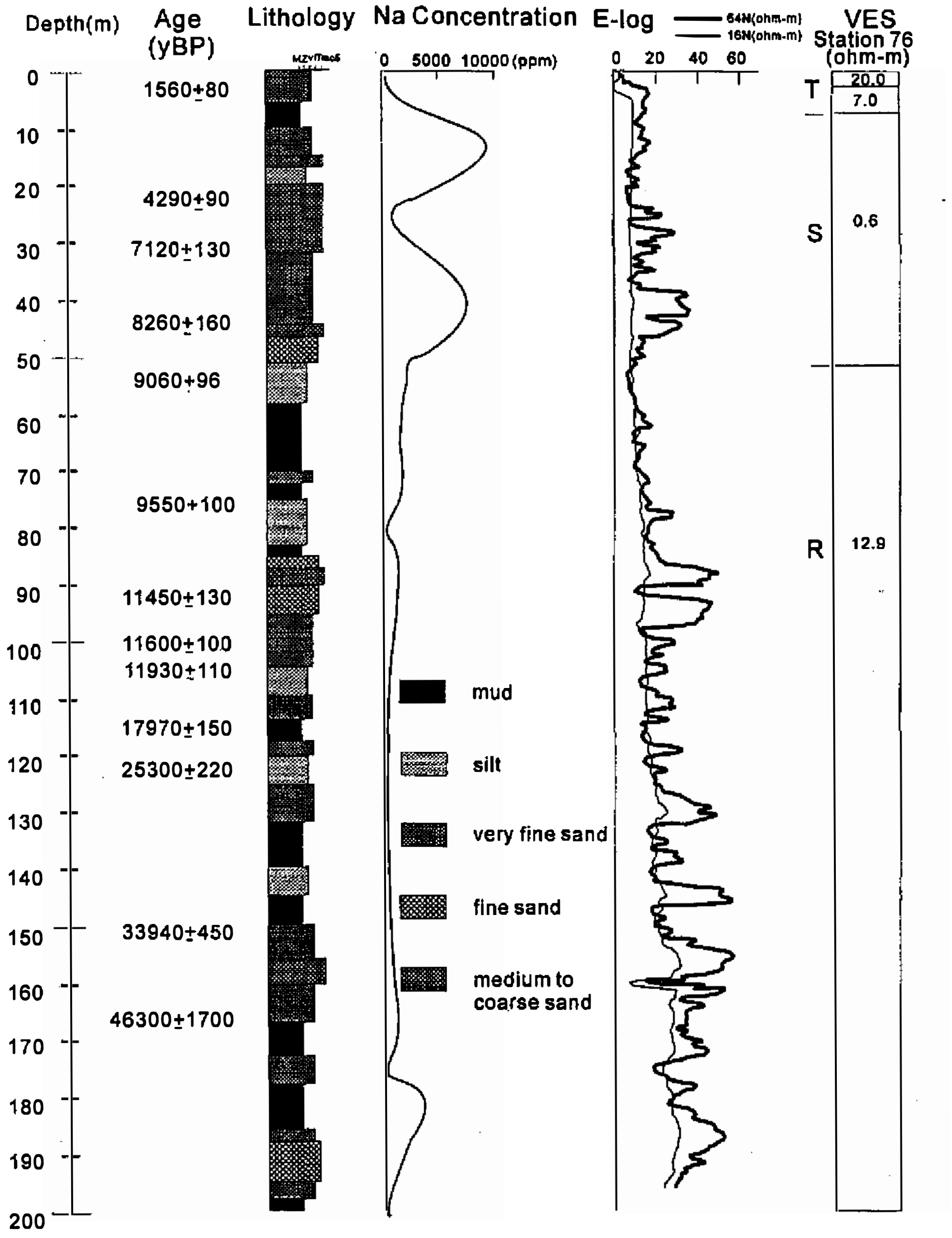


Fig. 5. Lithologic column, age of core, sodium concentration in formation water, E-log in borehole of the well at Zeikang and the interpretative results of VES Station 76 located at Zeikang. MZvffmcS at the top of lithologic column represents different grainsize: M = mud; Z = silt; S = sand; vf = very fine-grained; f = fine-grained; m = medium-grained; and c = coarse-grained.

Table 1. Resistivity and salinity of formation water estimated by Archie's law for various bulk resistivity ρ and porosity ϕ of strata. The values 0.858 and 1.367 are used for parameters a and m respectively in Archie's equation. ρ_w and S are the estimated resistivity and salinity of formation water at 26°C respectively, and P is the ratio of the estimated salinity to the average salinity 35 ‰ of present seawater.

ϕ	ρ (ohm-m)	0.3	0.6	5.0	10	15	20	40
0.60	ρ_w(ohm-m)	0.17	0.35	2.89	5.78	8.67	11.6	23.1
	S (‰)	36	18	2.2	1.1	0.72	0.54	0.27
	P (%)	103	51	6.3	3.1	2.1	1.5	0.77
0.55	ρ_w(ohm-m)	0.15	0.31	2.57	5.15	7.72	10.3	20.6
	S (‰)	41	20	2.4	1.2	0.81	0.61	0.31
	P (%)	116	58	6.9	3.4	2.3	1.7	0.89
0.50	ρ_w(ohm-m)	0.14	0.27	2.26	4.52	6.78	9.04	18.1
	S (‰)	46	23	2.8	1.4	0.93	0.70	0.35
	P (%)	133	66	7.9	4.0	2.7	2.0	1.0
0.45	ρ_w(ohm-m)	0.12	0.23	1.96	3.91	5.87	7.83	15.7
	S (‰)	54	27	3.2	1.6	1.1	0.80	0.40
	P (%)	153	77	9.2	4.6	3.1	2.3	1.1
0.40	ρ_w(ohm-m)	0.10	0.20	1.67	3.33	5.00	6.67	13.3
	S (‰)	63	31	3.8	1.9	1.3	0.94	0.47
	P (%)	179	90	10.1	5.4	3.6	2.7	1.4

Most of the detrital sediments have a porosity range from 0.3 to 0.6; generally, 0.4 to 0.5 for sand, 0.5 to 0.6 for clay and silt (Bouwer, 1978; Todd, 1980). The formation water of the S-facies will have a resistivity lower than 2.89 ohm-m and have a salinity higher than 2.2‰, since the bulk resistivity is lower than 5 ohm-m and the porosity is less than 0.6 (top rows of the fifth column from the right in Table 1).

The formation water of the R and the T facies in the eastern part of the study area has a resistivity ranging from 6.67 to 23.1 ohm-m, and a salinity ranging from 0.27‰ to 0.94‰ respectively, since the bulk resistivity ranges mainly from 20 to 40 ohm-m, and has a porosity ranging from 0.4 to 0.6 (the first two columns from the right in Table 1).

It is doubtless that the bulk resistivity of the S- facies is 0.3 ohm-m at Station 48, for the apparent resistivity is as low as 0.37 ohm-m (Figure 2). This is the lowest bulk resistivity interpreted in this area. The corresponding salinity is 36‰ if the porosity is 0.6, and will be higher if the porosity is less than 0.6. That indicates the S- facies was sedimented in water of salinity higher than the average salinity of present seawater at some places. It might be that the salinity of ancient seawater was higher than now or the area was arid and closed, and the seawater was evaporated to a higher salinity when the S- facies was deposited.

3.5 Critical Resistivity of Salty Strata

Saline groundwater is a term referring to any groundwater containing more than 1000 mg/

l total dissolved solids (TDS)(Todd, 1980). A salty stratum means its formation water is saline. An approximate relation for most natural water in the range 100 to 5000μS/cm leads to a equivalence 1 mg/l = 1.56 μ S/cm at 25°C; an increase of 1°C increases conductivity by about 2 percent (Todd, 1980). Based on these relations, the resistivities of groundwater for 1000 mg/l TDS at 24°C, 26°C, 28°C, and 30°C are evaluated to be 6.54, 6.28, 6.03, and 5.77 ohm-m respectively, which may be regarded as the critical resistivities of saline groundwater at relevant temperatures. They are listed in the first two columns from the right of Table 2 . The critical resistivity of salty strata for various porosity and temperature are estimated by Archie's equation. The results are shown in Table 2.

Table 2 indicates that the critical bulk resistivity of saltiness increases as porosity decreases for a constant temperature. The lithologic columns (Figures 4 and 5) indicate that the formations are composed of layers of clay, mud, silt, fine sand and a little medium to coarse sand and pebble. Hence, the formations will have a porosity ranging from 0.4 to 0.6, and a critical bulk resistivity of saltiness ranging from 10.8 to 18.8 ohm-m for the groundwater is about 26°C.

The S-facies is salty, since the bulk resistivity is lower than the critical value. Most layers of R and T facies in the east have a resistivity higher than 18.8 ohm-m, which indicates that the formation water is fresh.

The materials of the T, S, and R-facies have a very low hydraulic conductivity (Todd, 1980) to retard migration of groundwater, and most of the connate water will remain in the formations. According to the resistivity of formations, the sedimentary environments are inferred: the S-facies was sedimented in lagoonal, beach, and shallow marine environments, for it has a low resistivity corresponding to high proportion of seawater. The R and the T facies were sedimented mostly in non-marine environments in the east and mostly in lagoonal and estuarine environments in the west, for the formation water is fresh in the east but slightly saline in the west.

3.6 Distribution of Resistivity

The interpretative results of the VES indicate that the true resistivities of the strata vary with position. The resistivities of the strata at six different depths are shown in Figure 6. Figure 6 indicates that the resistivity of the strata at a common depth is generally higher in the north-

Table 2 Critical resistivity of salty strata estimated by Archie's equation with a =0.858 and m=1.367 for various porosity ϕ , $\rho_{w,cs}$ is the critical resistivity of saline groundwater, T is the temperature, and $\rho_{c,s}$ is the estimated critical resistivity of salty strata.

ϕ	0.40	0.45	0.50	0.55	0.60	$\rho_{w,cs}$ (ohm-m)	T℃
$a\phi^{-m}$	3.00	2.56	2.21	1.94	1.72		
$\rho_{c,s}$ (ohm-m)	19.6	16.7	14.5	12.7	13.3	6.54	24
	18.8	16.1	13.9	12.3	10.8	6.28	26
	18.1	15.4	13.3	11.7	10.4	6.03	28
	17.3	14.7	12.8	11.2	9.95	5.77	30

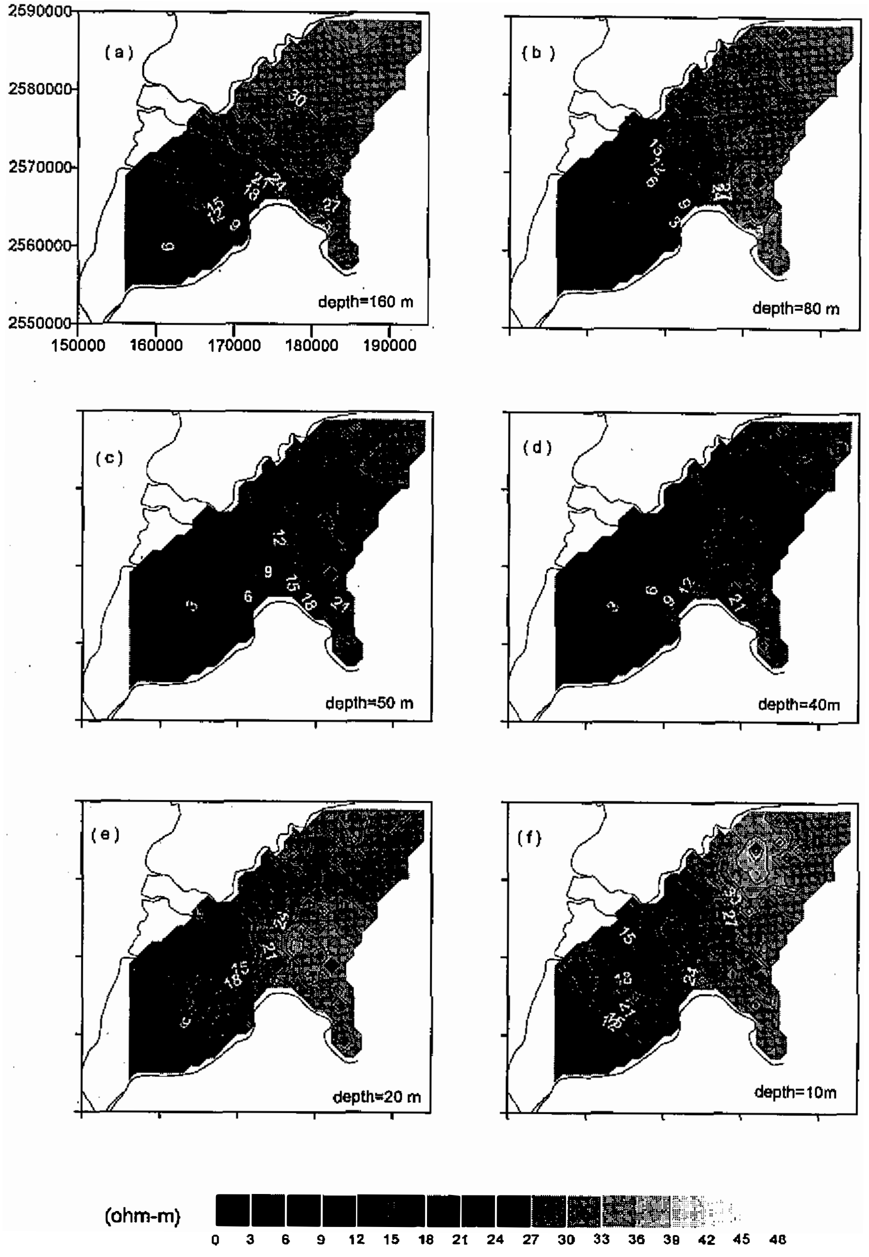


Fig. 6. Resistivity distribution of the strata at six different depths. The bold contour is 15 ohm-m, located in the middle of the zone of greatest resistivity gradient. The contours shift landward as depth decreases from 160 to 50 meters, shift landward in the north and shift seaward in the south as depth decreases from 50 to 40 meters, and shift seaward as depth decreases from 40 to 10 meters.

east and decreases southwestward. The isoresistivity counters are generally in the NW-SE direction for strata greater than 80 meters in depth and change gradually to the N-S direction as depth decreases. This implies that the grain size is coaser in the northeast and fines down southwestward for deeper strata. The NE-SW trend of grain size distribution gradually changes to the E-W direction at decreasing depths. This means that the deposits were coming from the northeastern mountains when the strata below 80 meters depth were sedimented, and so the deposits from the eastern mountains became dominant gradually.

The bold contour in Figure 6 is that of 15 ohm-m, located in the middle of the zone of greatest resistivity gradient. The 15 ohm-m counter may be very close to the paleo-coastline where the gradients of salinity and resistivity should be greatest.

Figure 6 indicates that the contours shift landward (eastward or northeastward) generally, as depth decreases from 160 to 50 meters, which implies the period of sedimentation of strata at that depth– about 40000 to 9000 years before present (yBP)(Figure 5) – was a transgressive dominant period. A westward convex of contours develops as depth decreases from 50 to 10 meters in the south, which indicates the locations of the channel and mouth of the Tsengwenchi stream at that time. The mouth of the Tsengwenchi stream was located near Matou (Figure 1), about 20 km east of the present coastline (Figure 6c) at about 9000 yBP, the age of strata at 50 meters depth(Figure 5). Later on, the Tsengwenchi stream developed westward along a path near the channel of the Chiangchunchi stream till recent times, which implies the Chiangchunchi stream was the main channel of the Tsengwenchi stream in that period – from 9000 yBP till recent. The present channel of the Tsengwenchi stream was developed recently, not earlier than 1 Ka, which is consistent with the dating results of sand dune along the Chiangchunchi stream (Chang et al. 1996).

The contours shift landward in the north of the study area and shift seaward in the south, as depth decreases from 50 to 40 meters (Figures 5 c and d). The seaward shift in the south is inferred to have been influenced by the westward development of the Tsengwenchi stream. So, the transgressive dominant period lasted to about 8000 yBP, according to the dating results, the age is 8090±95 yBP of the core at 38 meters depth (Liu et al. 1997).

The contours shift seaward as depth decreases from 40 to 10 meters (Figures 5d ~ f). Consequently, the period since 8000 yBP has been a regressive dominant period.

4. CONCLUSIONS

(1) The strata from the surface to 180 meters depth are divided into three electrostratigraphic units. They are designated, from top to bottom, as the T, S, and R facies.

The T- facies is the top unit, which is characterized by a combination of thin layers of resistivity ranging from 5 to 45 ohm-m. It is about 10 to 60 meters thick and is widely distributed in the study area.

The S- facies is characterized by thick layers of resistivity lower than 5 ohm-m. It is about 80 to over 130 meters thick in the west, about 15 to 100 meters thick in the middle, and absent in the east of the study area.

The R- facies is the basal unit, characterized by thick layers of resistivity ranging from 5 to

20 ohm-m in the west and from 20 to 50 ohm-m in the east of the study area.

(2) The three electrostratigraphic units are similar in lithology, composed of layers of clay, mud, silt, and fine sand, and occasionally, a little medium to coarse sand and pebble. They have a critical bulk resistivity of salty stratum ranging from 10.8 to 18.8 ohm-m.

(3) The resistivity of strata is controlled mainly by the salinity of formation water where the water is saline, and by the grain size and the amount of clay contained where the water is fresh.

(4) The S- facies is salty; its formation water has a salinity higher than 2.2‰. It was sedimented in lagoonal, beach, and shallow marine environments. The R and the T facies were sedimented in non-marine environments in the east, and mostly in lagoonal and estuarine environments in the west of the study area.

(5) The period from 40000 to 8000 yBP is transgressive dominant, and the period since 8000 yBP is regressive dominant.

(6) The mouth of the Tsengwenchi stream was located near Matou, about 20 km east of the present coastline at 9000 yBP. The Tsengwenchi stream developed westwardly along the channel of the Chiangchunchi stream since 9000 yBP till recent, and then changed south westwardly to the present location.

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