

Mapping of Groundwater With the Direct Current Resistivity Method in the Area Between the Pachang-Chi and Tsengwen-Chi, Southern Taiwan

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ABSTRACT

Direct current (DC) resistivity soundings with Schlumberger arrays are utilized to map the vertical and horizontal distributions of resistivity in the area between the Pachang-chi and Tsengwen-chi, southern Taiwan. This makes it possible to map the paleo depo-and hydro-environment of the study area. In addition, the transverse resistance computed from the field sounding data measured near the wells can be related to the transmissivity measured directly within the wells. An empirical relation between the tranverse resistance and transmissivity could thus be derived. The hydraulic parameters at the DC sounding locations without any well information could still be estimated from such empirical relationships. Thus, the locations of fresh groundwater zones and the most promising sites for future drilling could be determined.

Results of this study indicate that the DC resistivity method can be used to map the depositional process of the study area, and it can also be applied to predict the hydraulic parameters in locations without available well information in a recent alluvium covered area in southern Taiwan. This is of great benefit to the future management of groundwater in the study area.

(Key words: DC method, Groundwater, Paleo-environment)

1. INTRODUCTION

The Chianan coast, S.W. Taiwan, has always been one of the important agricultural areas in Taiwan. Recently, this region has been steadily industrialized. Increasing numbers of factories yet, and the overpumping of groundwater for fishing ponds have led to a stronger demand for water supply than before ever. Groundwater reservoirs may serve as one of the

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important sources of water supply in the future. However, in the case of an improper usage of groundwater which might lead to serious problems, such as a groundwater shortage and contamination in this area, a three-year (1994-1997) integrated project, financially supported by the National Science Council, ROC has been studying the hydrogeologic situation along the Coastal Plain from the Pachang-chi to Erhjen-chi. In the first year, the aim concentrated on the investigation of the hydrogeological situation in the area between the Pachang-chi and Tsengwen-chi. The Geoelectric group of National Central University was appointed to map the distribution of aquifers and to estimate the hydraulic parameters of these aquifers. This has been one of the most important steps in controlling the maximum amount of groundwater that may be extracted from the wells located at the site and in its surrounding areas. This project also makes it possible to make an optimum deployment of water wells for the future. It is for these reasons that detailed hydrogeologic structures of the study area had to be mapped.

A pumping test is traditionally the standard method use to evaluate the hydraulic parameters of the subsurface characteristics of aquifers. However, surface direct current (DC) resistivity measurements, which were earlier extensively used for mapping the aquifers, can also be simultaneously used to determine the hydraulic parameters of aquifers. Furthermore, early hydrogeologists used DC resistivity measurements to qualitatively assess the permeabilities of deposits (Zohdy(1965); Page(1969) and Meidav(1960)). In addition, quantitative correlations of electrical resistivity and the permeability of fresh-water were also studied (Kelly,1977; Heigold *et al.*; 1979; Kosinski and Kelly; 1981; Sri Niwas and Singhal, 1981; Biella *et al.*, 1983; Singhal and Sri Niwas, 1983; Ponzini *et al.*, 1984; Mazac and Landa, 1985; Huntly, 1986). It is a fact that the geoelectric method has long provided a fast, economic and non-invasive way to study aquifers.

The objective of this study is to map the paleo-depositional and hydrogeologic environment by using DC resistivity measurements in the Coastal Plain of Taiwan. In addition to tracing the paleo-environment from geoelectric layer distribution, correlating the electrical and hydrological parameters of aquifers is also one of the most important aims of this research. To accomplish these goals, during the period of 1994 to 1995, a total of 102 vertical electric soundings (VES) with the Schlumberger array were carried out in the Coastal Plain from the Pachang-chi to Tsengwen-chi. .

The surface geology in the study area is quite simple; most of the area is covered by recent alluvium. In addition to previously explored water wells, three proposed well positions were located in this study to meet the requirements of the paleo-depositional study. Two of them, the Zeikang and Shanliauwang wells were then drilled. The depth of each well was extended to the main aquifers, i.e, to the alternations of sand and clay layers. The maximum depth of those wells was 220m.

The relation between the geoelectric and hydraulic parameters was studied at the well locations with previously conducted electric soundings nearby. Water bearing zones were recognized either from these or characteristic of DC sounding curves. Correlations of the electrical properties of the water saturated zones to the hydraulic parameters were obtained directly from pumping tests. An empirical relation between transverse resistance and transmissivity was then established. Finally, the hydraulic parameters at any location without any well information could be inferred from this linear relationship by using the transverse resis-

tance computed from the sounding data on site. This study was also extended to predict the locations of potential aquifers. All of these hydraulic parameters will be of great benefit in the future planning of groundwater management.

2. GEOLOGIC SETTINGS

The study area was located in the central part of the Chianan Plain , southwest of Taiwan (Figure 1). It is bounded by the Pachang-chi to the north, the Tsengwen-chi to the south, the Taiwan Strait to the west and the foothill belt to the east. It occupies an area of about 7 km². From the criteria of tonal contrast, characteristic distribution and contact relationships of the deposits shown in aerial photographs as well as the relationships of the positions of deposits with the present sea, Sun (1971) carefully made distinctions among the different sediment deposits in the Tainan-Hsinying Coastal Plain. Listed in ascending order, these are: the Tainan Formation, the lagoon and marsh deposits, the terrace deposits, the delta deposits, the younger lagoon deposits, the offshore bar deposits, the younger delta deposits and the present lagoon deposits (Figure 2). The major groundwater recharge area of the study area is located in the eastern hills, where the groundwater supply is a direct result of the infiltration of precipitation and the seepage of streams.

3. GEOELECTRIC SURVEYS AND INTERPRETATIONS

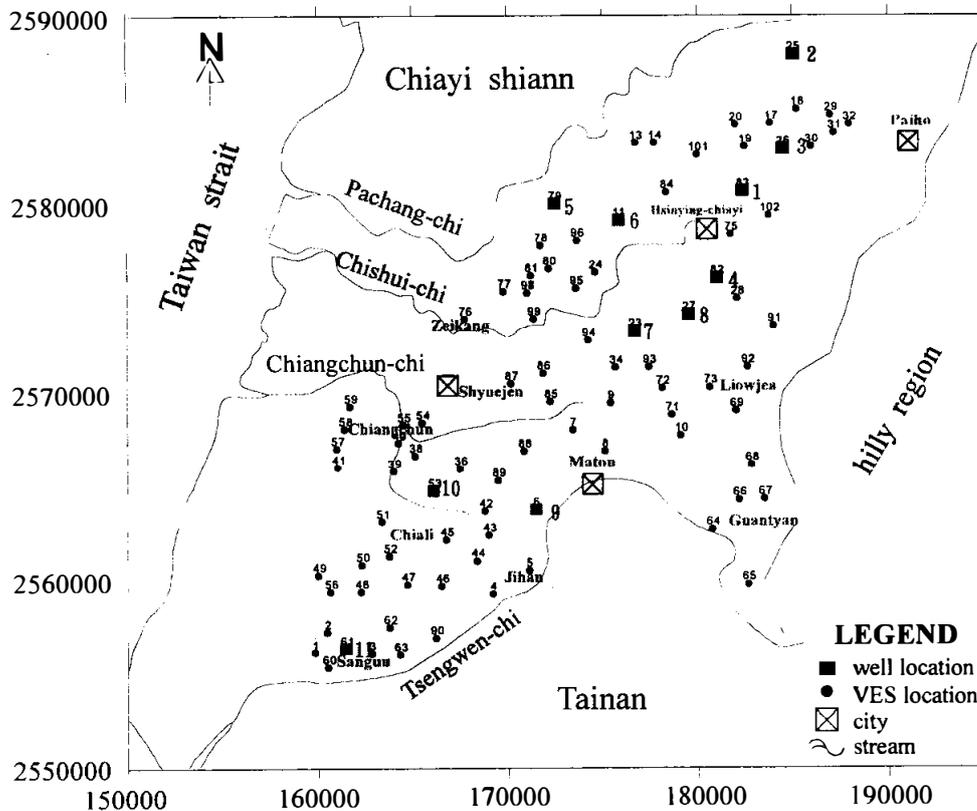


Fig. 1. Site map indicating approximate VES and well locations. Numbers shown in the coordinates are in terms of 2° TM.

gional apparent resistivity with respect to depth. Such resistivity information gives a clue as to the paleo-depositional environment in the study area. As shown in the contour maps, the apparent resistivities in the southwestern part of the survey area is lower than those in the northeastern district. An increasing sounding depth (i.e. an increase in the distance between the two current electrodes) does not severely affect the pattern of apparent resistivity distribution. The trend of apparent resistivity distribution indicates that the deposition/transportational direction and/or transgression/regressional direction may be both/either the southwest and/or northeast direction.

Based on the features of vertical electric sounding (VES) curves which are related to the local geology, the study area can be grouped into five zones which are indicated in Figure 4 as A, B, C, D and E. The geographic distribution of these zones with their typical sounding curves are also shown in the Figure. Sounding results reflect, geoelectrically, four or six layer-curve types, i.e. AA Type for Zone A, HKHK for Zone B, KH Type for Zone C, QH Type for Zone D, and AKHA for Zone E. Referred the final resistivity models obtained from the VES curves

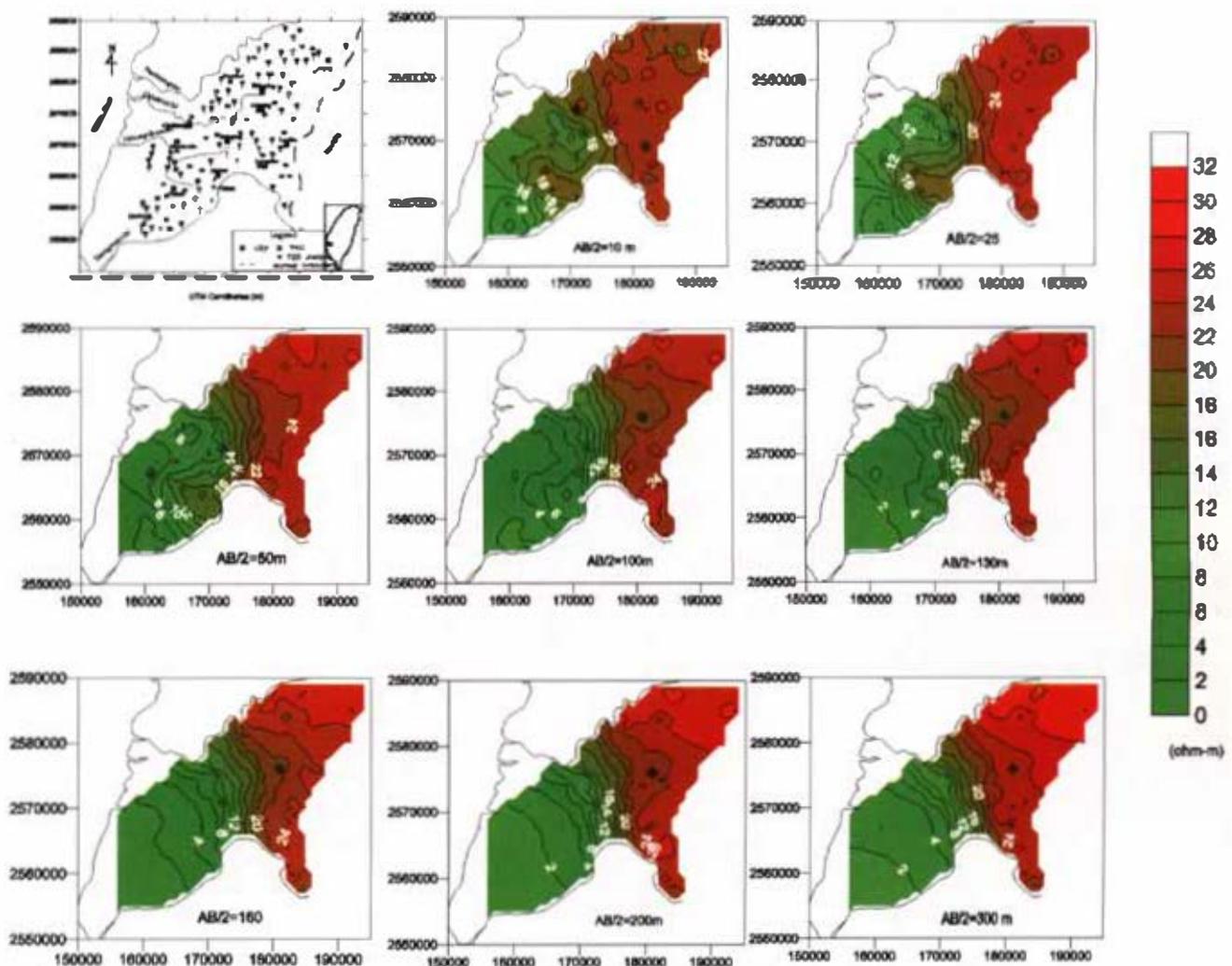


Fig. 3. Contour maps of apparent resistivity with various current electrode half-spacings. In the figures, AB is the distance between the current electrodes. Numbers shown in the coordinates are in terms of 2° TM.

to the corresponding lithology logs obtained from nearby well, the resistivity spectra for each aquifer could be determined. Higher apparent resistivity zones shown in the northeastern part (Figure 3) are considered an area which has better groundwater potential reservoirs than the lower apparent resistivity zones in the southwestern part. However, the VES curves shown in the northeastern part (Figure 4) are rather flat and below 30 ohm-m. The lithologies in this part are inferred to be fine to medium sands and/or more clayey media. Dominated muddy rock units in its eastern recharge area may have caused this. The presence of the low apparent resistivity (1 ohm-m) zone in the southwestern survey area is considered as poor alluvial aquifers, which is attributed to either subsurface lithologies dominated by mudstone and/or residue of saline water contained in alluvium during the past depositions.

3.2. Quantitative Interpretation

The field sounding curves are interpreted in terms of final layer parameters using a computer program viz. the automatic iterative method of resistivity sounding interpretation (Zodhy, 1989). The layer parameters thus obtained were compared with the corresponding lithologies from nearby wells. In Figure 5, a comparison is made between geoelectric layers obtained from soundings at VES location 76 and logs of the relative sea level change (T is transgression and R is regression) and the ¹⁴C age obtained from the Zeikang well. As shown in the

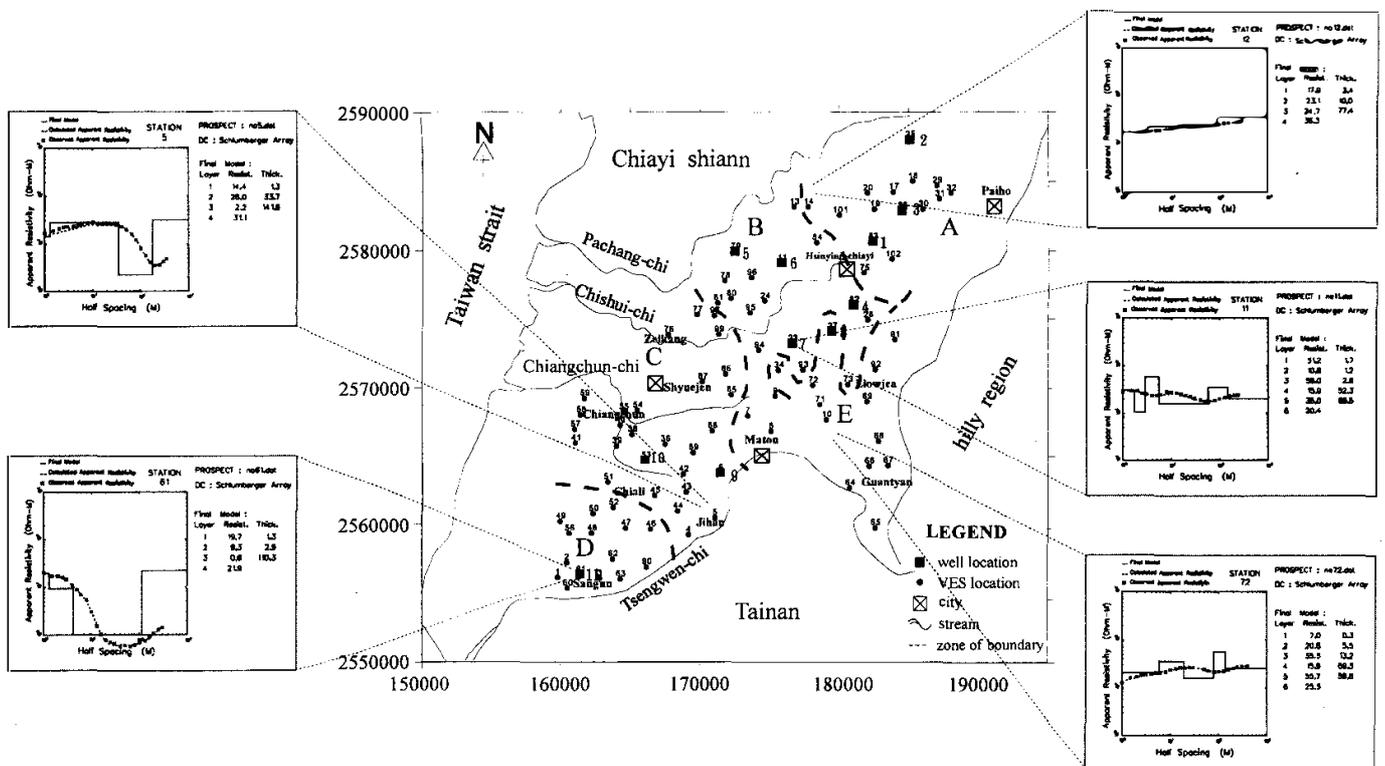


Fig. 4. Display of typical vertical electric sounding curves for each sounding point. Numbers shown in the coordinates are in terms of 2° TM. Similar type of curves are grouped into zones indicated as A, B, C, D and E.

Figure, the first three layers with resistivities 11.9 ohm-m , 6.5 ohm-m and 14.1 ohm-m and a total thickness of 7.4 m are related to the top sandy soil. Since the interpreted resistivity model for the top layers (less than 5 m) are easily affected by cultural disturbance and/or seasonal variations, correlating the top layers to the sea level changes is meaningless. The fourth and fifth layers have a thickness of 62.4m and 33.7m with a resistivity of 0.8 ohm-m and 3.6 ohm-m which may reflect the characteristics of silty soil and sandy soil. Low resistivity in this layer is attributed to past marine transgression. The last higher resistivity (15.3 ohm-m) is interpreted as clay layer interbedded with sand or peat layer, so it may be in regression. The average low resistivity in the study area is due to the Tainan transgression in the whole area, and the Tainan Formation was deposited in this way. All the deposited materials may have come from the eastern hill region. The Tainan regression then quickly followed after the deposition of the Tainan Formation, and most of the Tainan Formation has been uplifted above sea level since then.

Figure 6 is a contour map of subsurface resistivity at different depths. The maximum interpreted depth is 200 m. In general, resistivity distribution shown in each map reveals a trend with decreasing values from northeast to southwest, indicating that the source of deposi-

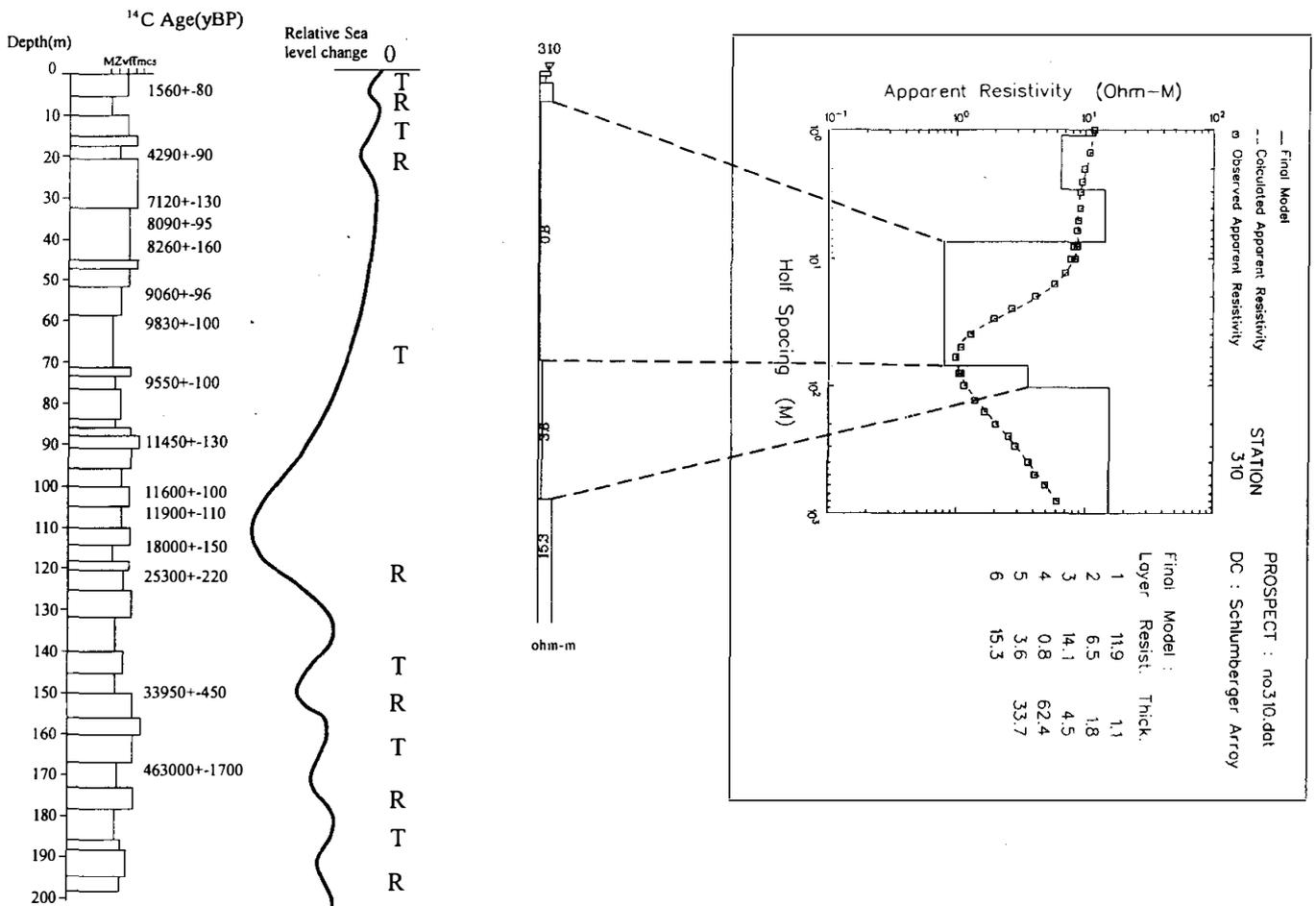


Fig. 5. Comparison of the geoelectric model computed from the VES curve at VES location 76, and the logs of relative sea level change and the ¹⁴C age from the Zeikang well. Transgression and regression are indicated as T and R in the figure.

tion was on the northeastern hill. The grain size of the deposition medium also decreases from the northeast to southwest. Starting from the depth 200 m, the range of low resistivity zones (less than 16 ohm-m) in the southwest increases and also extends toward the northeast with decreasing depth. The extension of the low resistivity zone may be interpreted as marine transgression. At the depth of 35 m, the low resistivity zone diminishes its size with deca-

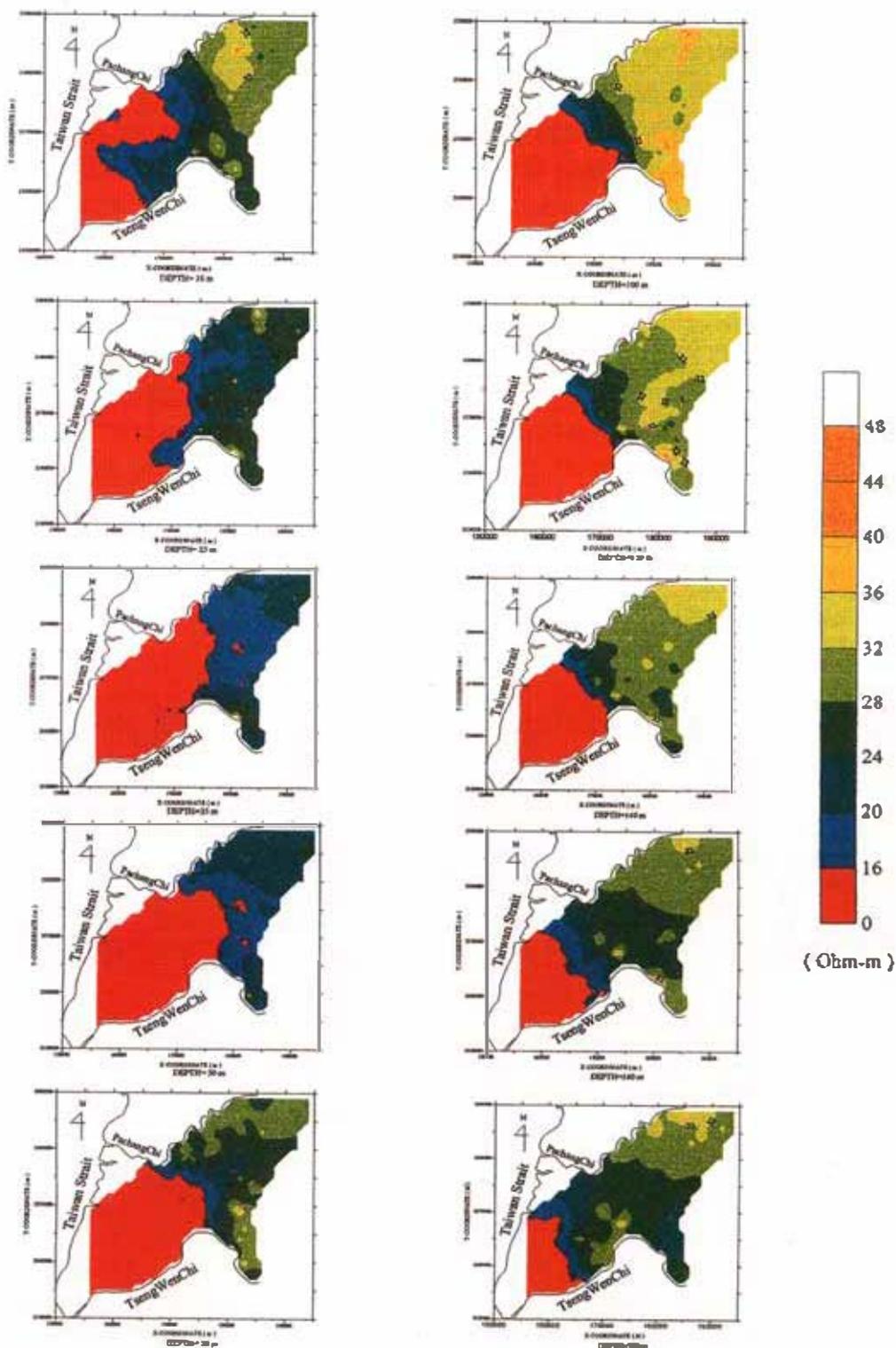


Fig.6. Contour maps of resistivity for different depths. Numbers shown in the coordinates are in terms of 2° TM.

ing depth, which may reflect the presence of a regressive sea. It is worth noting that at the depth of less than 25 m, a higher resistivity zone (16 to 20 ohm-m) at the southeastern part of the survey area expands toward the northwest as the depth decreases. This may be caused by sea regression accompanying an increased rate of river deposition and/or the uplift rate of land. However, based on the well study, the original formation water contained in the layers at depths beyond 100m was leached by groundwater. Thus, the resistivity of these layers was selected to be around 28 ohm-m; then an addition of regression event may exist at a depth from 100m to 140m. The shallow depth (less than 25m) of resistivity contour maps (Figure.6) also indicates that an extended high resistivity zone (16 to 20 ohm-m) is in the northern bank of Tsengwen-chi. This zone may be related to an earlier change in the river course of the Tsengwen-chi.

4. EVALUATING THE PHYSICAL PARAMETERS OF THE AQUIFERS

The relationships between hydraulic parameters and electric parameters were previously studied by Sri Niwas and Singhal (1981). They determined that:

$$T = K \times \sigma \times R \quad (1)$$

where T is the transmissivity of an aquifer, K is hydraulic conductivity, σ is electric conductivity, and R is transverse resistance.

Equation (1) was modified by Singhal and Sri Niwas (1983) by taking into consideration a “modified aquifer resistivity”. The modification factor is defined as the ratio of the average aquifer water resistivity to the aquifer water resistivity at a particular location. Though there is no information as to the water resistivity of wells, using Equation (1) for a preliminary study, the results are still reliable. If the local product of the hydraulic conductivity and the electric conductivity ($K \times \sigma$) is a constant, the local transmissivity can be computed from the sounding data with that established local empirical relationship of hydrological parameters and electrical parameters.

Four paralleled profiles in a direction of northeast to southwest are selected as shown in Figure 7. These profiles (Figures 8a, 8b, 8c and 8d) show that two major aquifers within a depth of 200 m can be recognized. The depth of a shallow aquifer is less than 50 m and consists of sandy soil and fine silty soil. The deeper one (major aquifer) is down to depth of 200 m and consists of muddy sand and/or alternations of sand and clay. The resistivity of these aquifers is lower than expected, which implies that an aquifer was formed by less porous muddy media. The yield of groundwater in this area is less than other alluvium in the western Coastal Plain.

The contours of iso-resistivity of the shallow aquifers and main aquifer can be inferred from Figures 9a and 9b. The resistivity of the deeper aquifer is greater than the shallower ones. On the basis of some known production water wells, the resistivity distribution does reflect the deeper aquifer playing an important role in the groundwater supply.

Figures 10a, 10b and 10c show plots of $K \times \sigma$ vs. the wells located in Regions A, B, and C and D.. In Region A, hydraulic conductivities are measured from wells labeled 1, 2, 3 and 4. In Region B for wells numbered 5, 6, 7 and 8, and in Regions C and D for wells numbered 10, 11, 12 and 13. Resistivities were computed from the VES sounding data. During

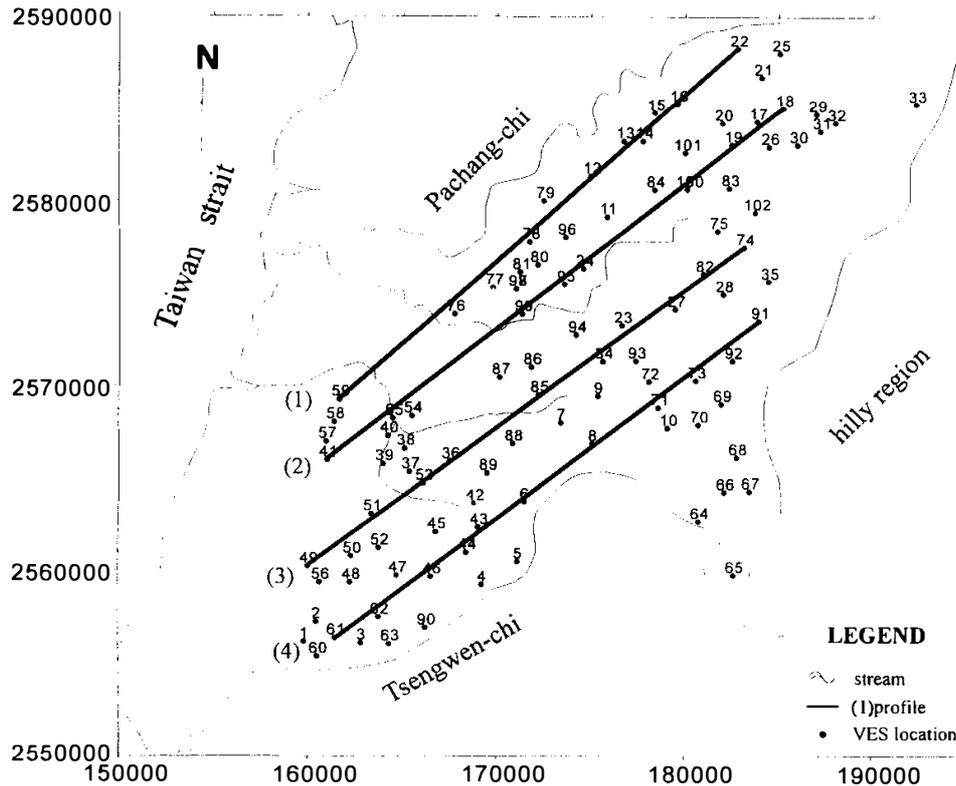


Fig. 7. VES sounding profiles indicated as (1), (2), (3) and (4) for resistivity interpretation. Numbers shown in the coordinates are in terms of 2° TM.

the computation, all the available locations of soundings were being selected near one of the wells mentioned above. Variations in the values of $K \times \sigma$ at each well can be recognized from these figures. In Regions A and B, deviations of the $K \times \sigma$ each point from its mean values are not serious. Thus, an average value for each region can be obtained. Based on this value, a linear relation between the values R and T can be derived from Equation (1). The computation errors may be due to the anisotropic properties of aquifers (mainly sand and clay alternations) with lateral variations of thickness. To determine the ranges within which constants being valid were limited by using a few well information, it was necessary to establish with statistically representative samples. Statistical uncertainties arising from Equation (1) can be a serious problem in the quantitative evaluation of hydraulic parameters. Regions C and D, the relationship between transverse resistance and hydraulic conductivity does not fit Equation (1). This may be due to the fact that Zones C and D must be considered separately. In addition, the high salinity of layers in this area and/or the amount of available well information are limited.

Based on the hydrogeologic conditions and also the transverse resistance results in the northeast part of the survey area, the computed transmissivity contour map of aquifers can be compiled as shown in Figure 11a. Comparing this computed transmissivity map with the observed ones (Figure 11b) compiled from the data collected at monitor wells by the Water Resources Planning Commission (1981), both figures have the same features. That is at the northeastern part of the survey area, it is indicated that the average transmissivity of the northeast is smaller than that in the southeast. The same conclusions can be obtained for hydraulic

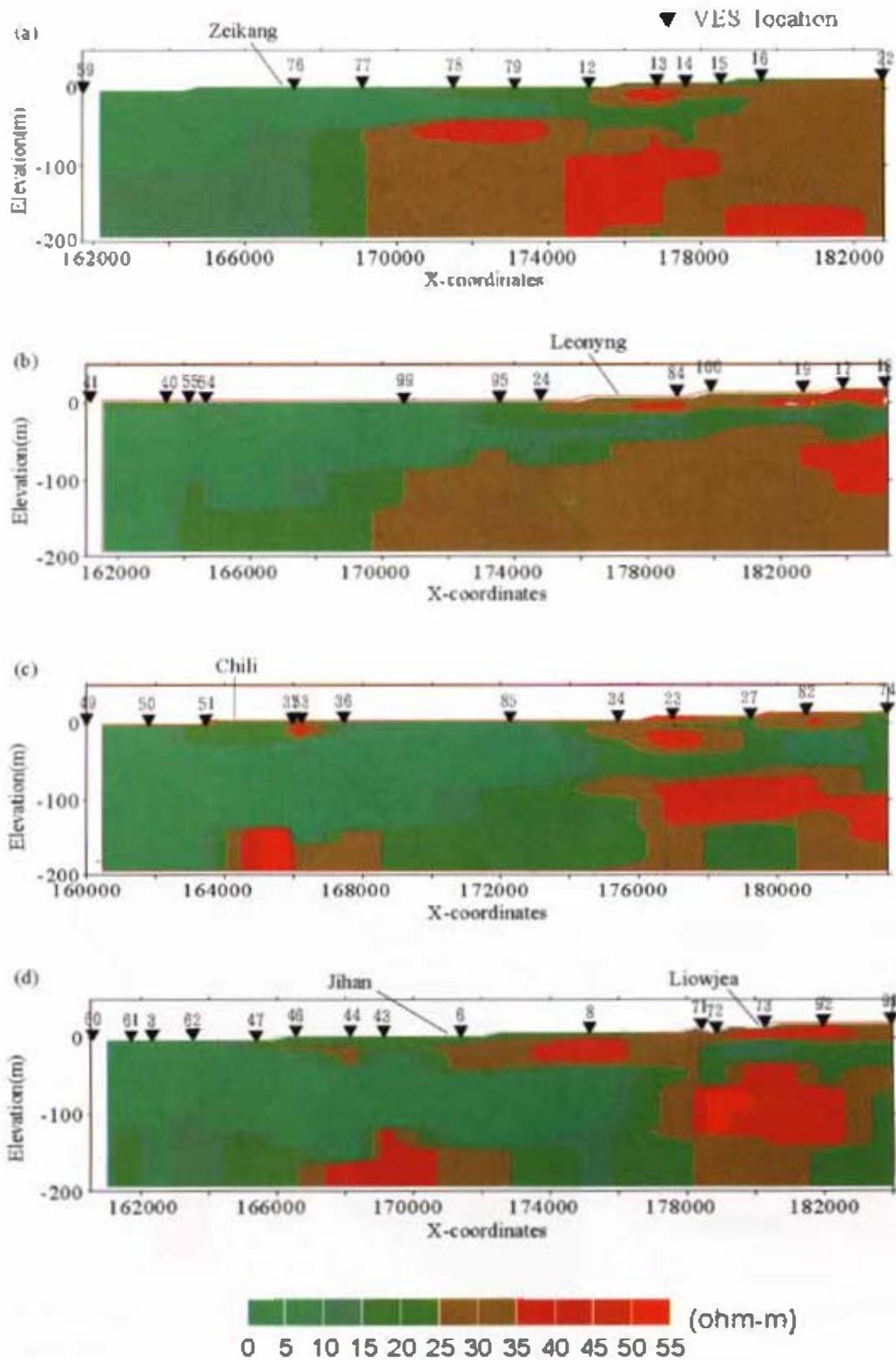


Fig. 8. Resistivity profiles along the profiles shown in Figure 7. (a) for profile 1, (b) for profile 2, (d) for profile 3, and (c) for profile 4. Numbers shown in the horizontal axis are in terms of 2° TM.

conductivity maps (Figures 12a and 12b). It should be pointed out that the hydraulic parameters used for this research were collected in 1981, while the geoelectric parameters were obtained in 1994. If the transmissivity of aquifers in the study area have not significantly

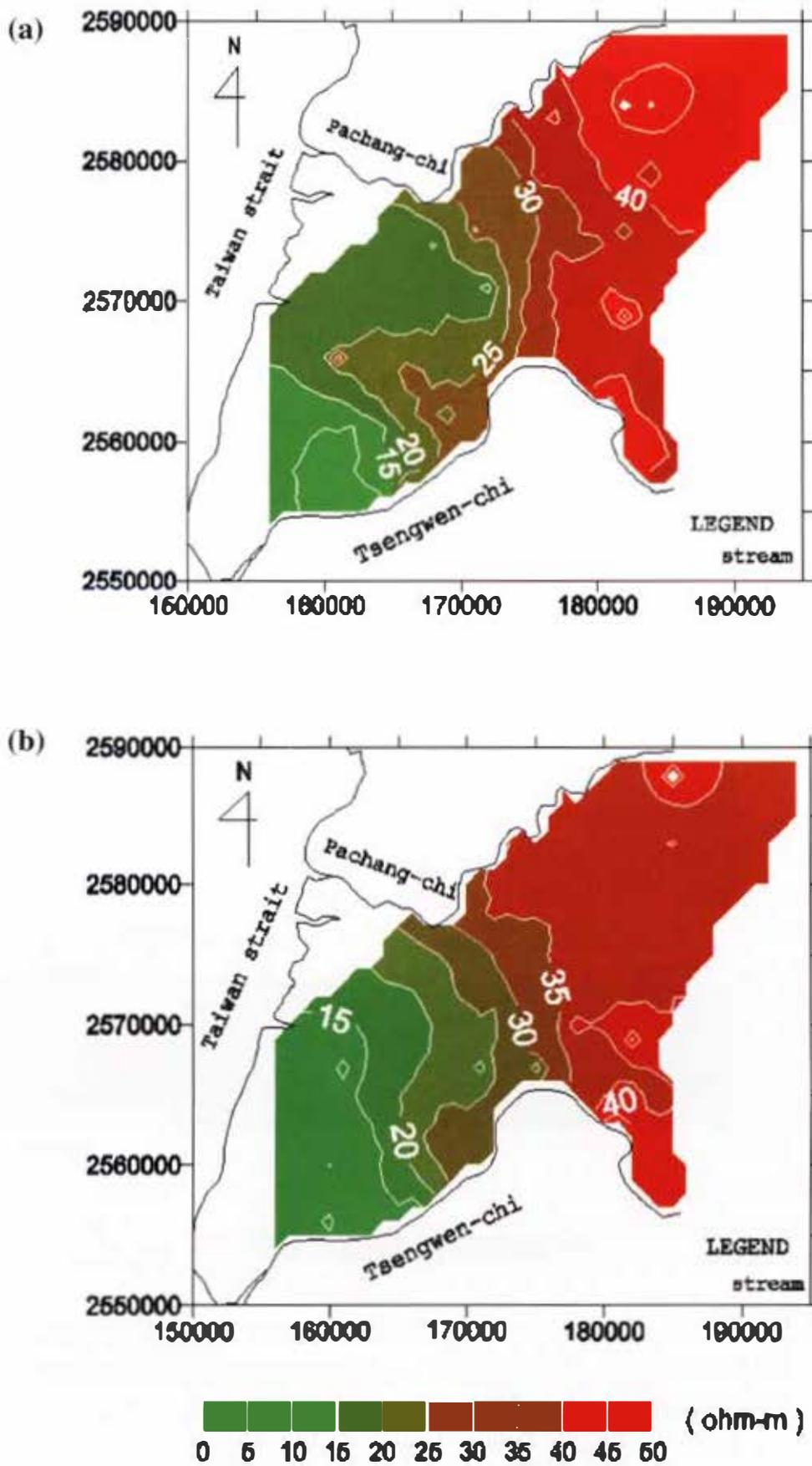


Fig. 9. Contour maps of resistivity for (a) shallow aquifer. (b) deeper aquifer. Numbers shown in the coordinates are in terms of 2° TM.

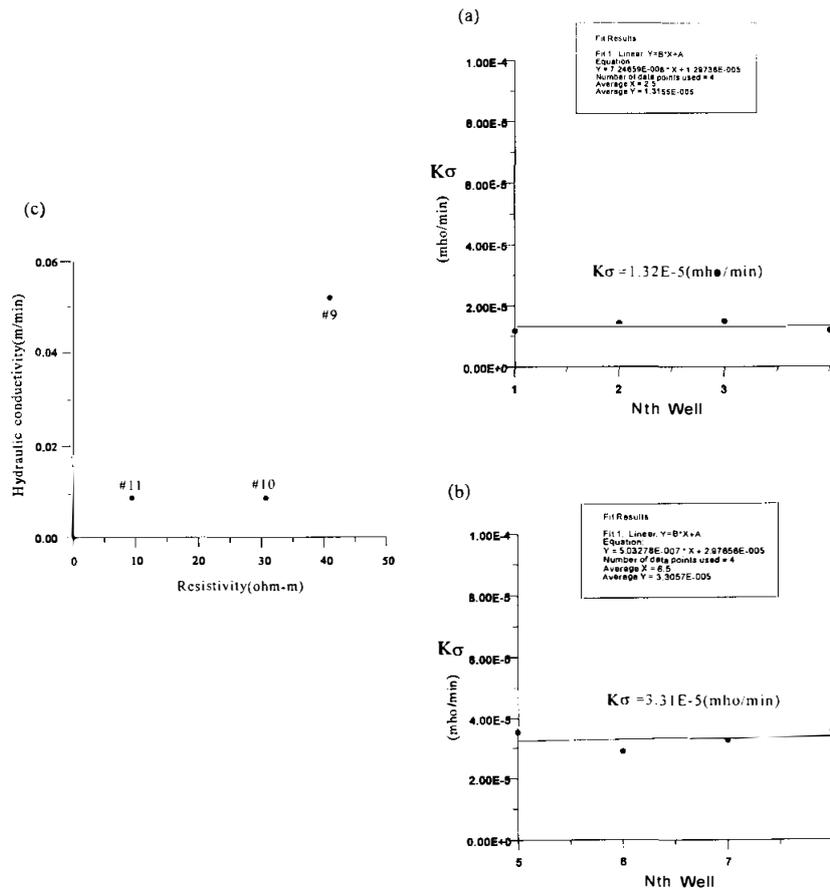


Fig. 10. Product of transmissivity of aquifers and conductance vs. wells.

changed in the past, these data and the DC results can be used to estimate local transmissivities. The final average computed transmissivities is about 80% to 90% of the average transmissivities obtained from wells in 1981. The average computed hydraulic conductivities is also less than the hydraulic conductivities obtained from wells in 1981. The overpumping of groundwater has lowered the water level since 1981, thereby decreasing the thickness of aquifers yearly. Instead of clayey aquitard, most aquitard consists of silty soil. Part of the groundwater has vertically recharged underneath the aquifers by infiltrating the aquitard. The local high resistivity zone shown in the northern bank of the Tsengwen-chi is a region having potential aquifers. This region is recommended for the future drilling of water wells. Local low hydraulic conductivity dominating in the northeast may be reflected in an abundance of interlayered clayey sand locality.

5. CONCLUSIONS

Qualitative and quantitative studies on the DC resistivity response are helpful in the determination of the paleo-environment of the study area. Besides, the hydraulic parameters of the aquifers and a promising potential reservoir can also be estimated. Results of the survey are summarized as follows:

- (a) Major marine transgression and regression patterns inferred from the DC resistivity results can be delineated; the direction of these events is clearly in the southwest to northeast. This

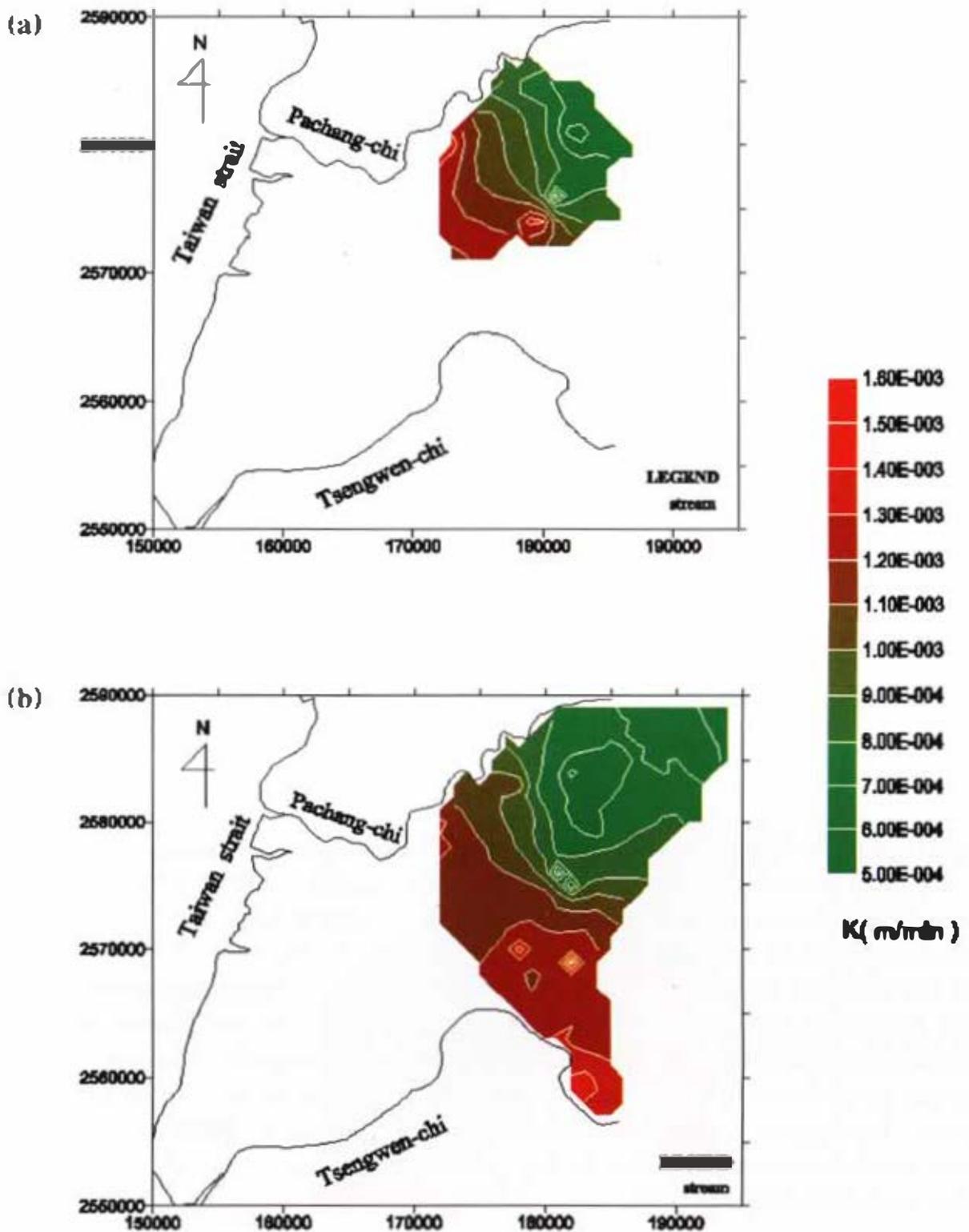


Fig.11. Contour maps for (a) computed transmissivity, and (b) observed transmissivity. Numbers shown in the coordinates are in terms of 2° TM.

can be correlated from the drilling results.

(b) On the northeastern part of the survey area, the average hydraulic conductivity and transmissivity values of the northeast side are smaller than those computed on the southwest

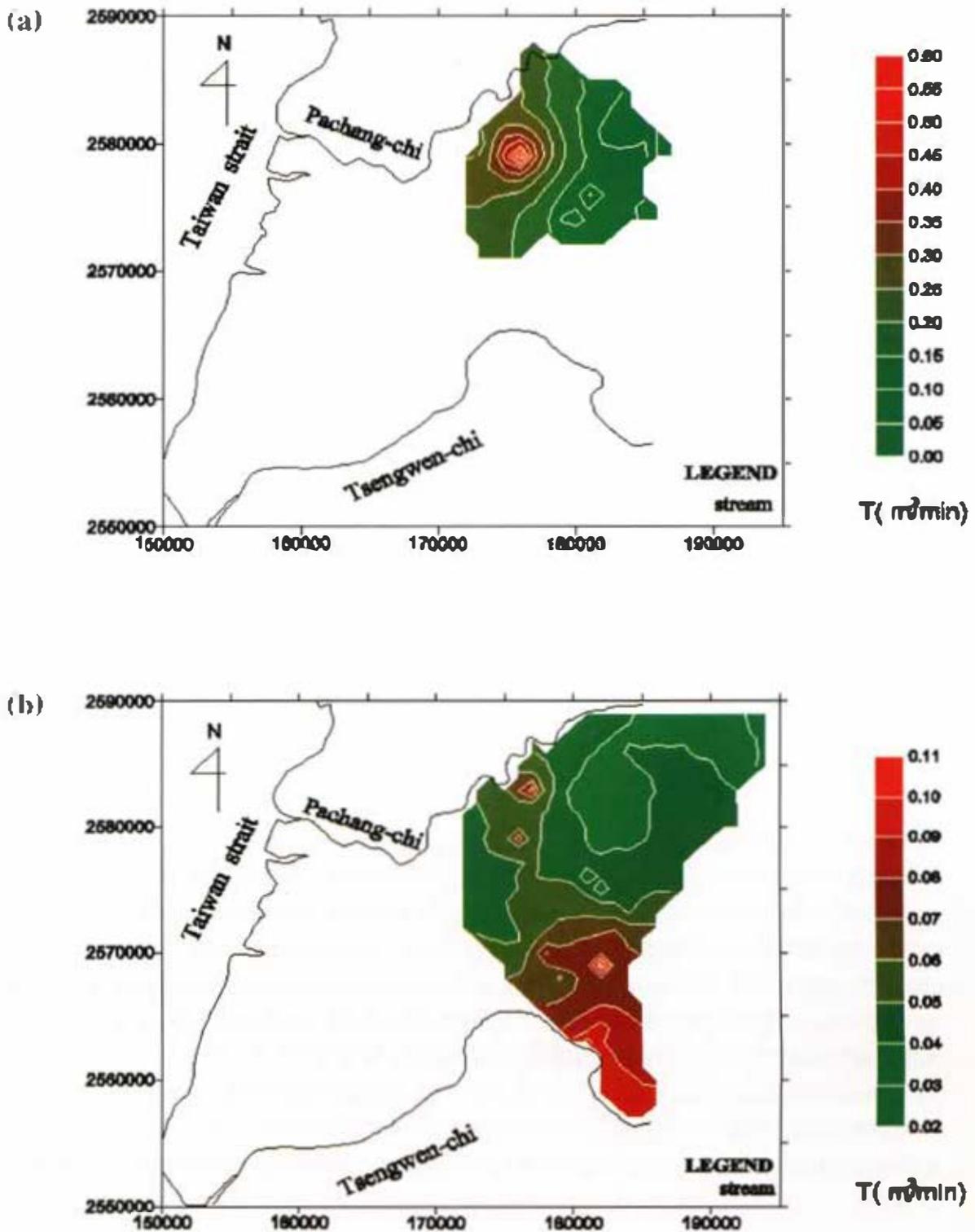


Fig.12. Countour maps for (a) computed hydraulic conductivity, and (b) observed hydraulic conductivity. Numbers shown in the coordinates are in terms of 2° TM.

side. A high resistivity zone may be related to a buried channel in a northwest-southeast direction; groundwater is supplied by the water flow from the northern bank of the Tsengwen chi. This zone may have potential aquifers.

(c) The techniques used here have a reasonable degree of accuracy. With a small amount of hydraulic transmissivity information from wells, a fairly good idea of the transmissivity of the aquifer at other locations can be obtained from geoelectrical soundings.

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