Geothermal conceptual model inferred from magnetotelluric and well-logging data in South Ilan Plain, Taiwan

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Keywords: *magnetotelluric, well-logging.*

ABSTRACT

The Ilan Plain is located in the northeastern part of Taiwan. Geologically, it is the southwestward extension of the Okinawa Trough, which is a part of the subduction system with the Philippine Sea Plate being hidden under the Eurasian Plate. Based on the surface geothermal manifestations and higher temperature gradient, this area is a hot spot for the developments of geothermal resources in Taiwan.

An exploration well based on the geophysical model, mainly through the magneto-telluric method, was drilled in 2016 but failed to get the expected result. The failed outcome suggests that the cap layer represented by the low-resistivity zone in the traditional resistivity model may be unsuitable for metamorphic areas.

The aim of this study is to first reaffirm the previous MT results with well-logging data and additional MT data, then examine any other possible factors other than the clay cap that could create the resistivity anomaly, and finally build a better geological model in this metamorphic terrane. Our preliminary analysis confirms the MT outcome and proposes three possible scenarios of resistivity variation for better modeling.

One interpretation is that the low resistivity zone may be caused by a sandstone layer containing plentiful iron sulfide, e.g. pyrite, instead of a clay cap. Mixing with different resistivity components from the groundwater and the amount of carboniferous materials in the formation are also possibly affecting the resistivity. Further work needs to be done to identify the most likely factors to explain the resistivity disparity.

1. INTRODUCTION

Since more and more people pay attention to the renewable energy resources, Taiwan government decided to develop geothermal energy. The research team chose the southwestern part of Ilan Plain as a target area based on the surface geothermal manifestation and high temperature gradient. In 2016, the geophysics team created various cross-sections out of the initial conceptual model based on the resistivity model, the gravity data and seismic reflection data. Two wells, HCL1 and HCL2, for exploration drilling, were determined from those sections. However, the drilling results were not as expected. The reason could be that the South Ilan Plain is underlain by metamorphic terrane instead of volcanics.

In order to confirm whether MT data correctly indicated the low resistivity zone, we use well-logging data to verify the resistivity model. If the model is correct, then there must be

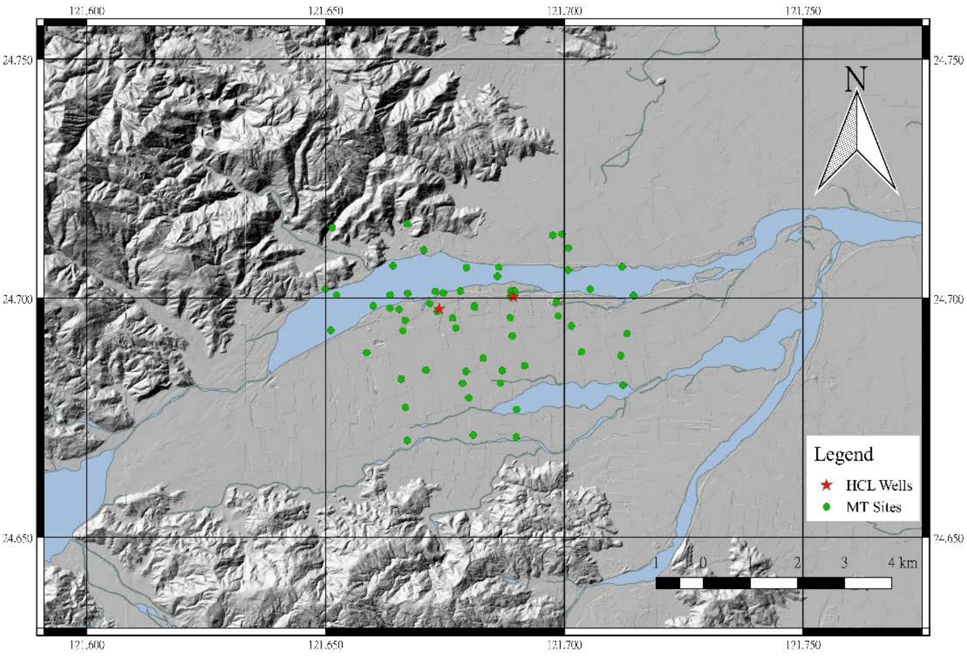


Figure 1: Location of the exploration area, green points are MT sites and red stars are two exploration wells. HCL1 is in the west and HCL2 is in the east. All of them are located on the South Ilan Plain.

other factors controlling the resistivity. For the purpose of the current study, we construct a three-dimensional resistivity model, combined with well-logging data, to show the special correlations of geophysical features in a three-dimension framework.

2. GEOLOGICAL SETTING

Taiwan constitutes the collision zone between the Philippine Sea plates and the Eurasian plates. In the northeastern part of Taiwan, the Philippine Sea plate is subducting beneath the Eurasian plate, leading to the formation of Ryukyu Arc. And the Ilan plain is taken shape from the extension of Okinawa Trough, the back-arc basin. It is thought that the Ilan plain deposits the sediments from Lanyang River over a graben bounded by the normal faults. According to Chiang (1976) and Hsu et al. (1996), they have depicted both WSW faults and ENE faults beneath the unconsolidated sediment by the result of seismic reflection and magnetic-anomaly data. Those normal faults might be considered a good hydrothermal fluid conduit from the deep reservoir to the shallower subsurface.

Tong et al. (2008) have indicated a magnetic-anomaly zone located below the Ilan plain and extended to Kueishantou Island known for an active volcano. It may exist an active magma chamber in the shallow crust implying the existence of geothermal resources.

Tectonically, Taiwan can be roughly divided into Coastal Range, Central Range, Hsuehshan Range, Western Foothills and Coastal Plain (Chen et al. 2016). The northwestern boundary of Ilan Plain is Hsuehshan Range and the southwestern boundary is Central Range (Fig. 1). According to Chiang (1976), Huang et al. (2012) and Shih (2011), most linear structures under the Ilan Plain trend east-westly, and the Zhuoshui fault could be a significant geologic boundary separating the Sueishan Range and Central Range. Base on drilled cutting, we thought the drilling wells sit on Sueichan Range. Most of the formations of Sueishan Range are submetamorphic rock. There are some differences between those formations that could impact the resistivity, like metamorphic grade and mineral composition. In order to realize the relationship between those factors and the resistivity, we briefly describe the formation of Sueishan Range below (Fig. 2).

- Kankou formation:

The thickness of this formation is between 600 meters and 1200 meters. The main components are dark gray argillite with 5-20 centimeters fine sandstone layer and mixed with a little of basaltic pyroclastic rocks. The standard geologic column of Kankou formation can be separated into three parts: the lower part is about 250 meters to 300 meters, composed of pure argillite with lenticular muddy siltstone. The middle part is about 150 meters thick, composed of argillite and muddy siltstone which even could be 2 meters thick. There are strong bioturbations in this part. The upper part is about 100 meters to 150 meters thick, composed of pure argillite with lenticular muddy siltstone, which are more and thicker than the one of the lower part.

- Szeleng Sandstone:

The thickness of this formation is between 900 meters and 1000 meters. The main components are thick grayish-white metasandstones with argillite layers. There is a conformity boundary between the Kankou Formation and the Szeleng Sandstone.

- Hsitsun formation:

The thickness of this formation is about 550 meters. The formation contains thick argillites with thin metasandstone layers. It is the oldest formation we can find from the outcrop in the north Sueishan Range. There is a conformity boundary between the Szeleng Sandstone and Hsitsun Formation.

3. DATA COLLECTION AND ANALYSIS

3.1 *THE ANALYSIS OF MAGNETOTELLURIC DATA*

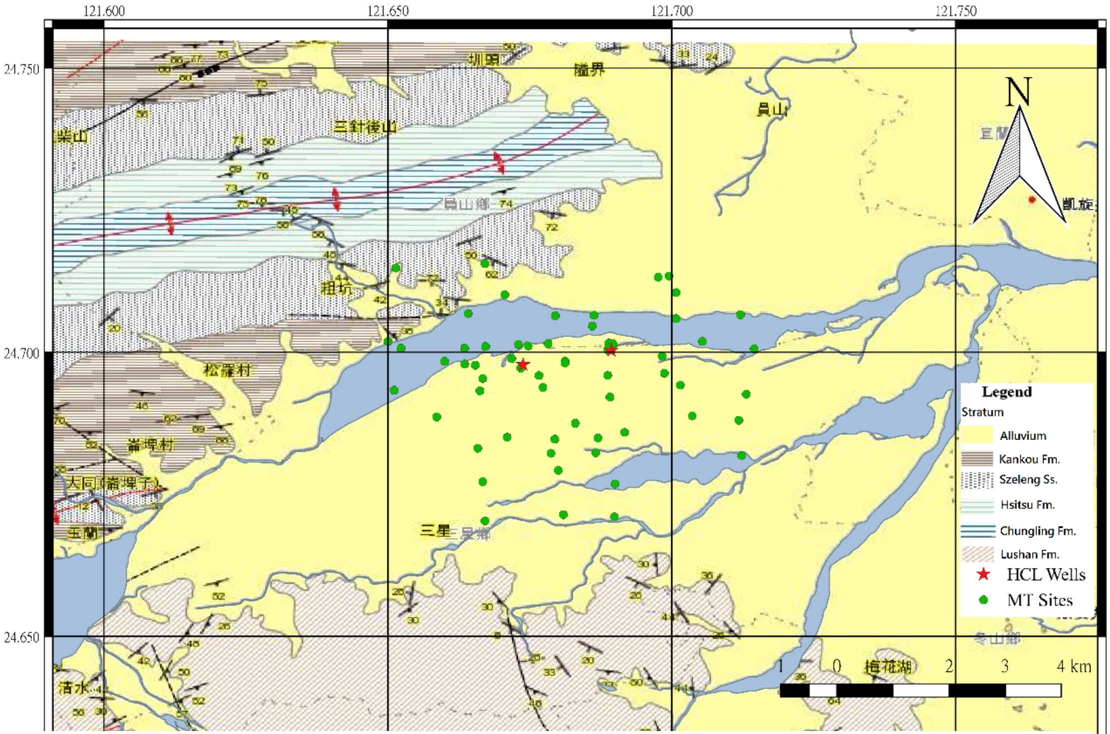


Figure 2 : The geology map at the exploration area, Ilan plain is located between Hsuehshan Range and Central Range.

In the study area, we chose 65 MT stations distributed nearby the two wells. Each time-series data of these stations was measured about 24 hrs to improve the data quality. These MT data were divided into two categories: the old ones (52 MT stations) and the new ones (13 MT stations). The former was collected and processed between 2013 and 2016 by Yang (2017). And the other category was what we collected in 2017, and we processed with remote reference for better data quality. The measurement period at each MT site was between 10^{-4} seconds – 1 second, and processed using statistically robust algorithms. The impedance in each station was separated into 20 parts, and we can pick out some parts with good quality and delete those with lots of noises to increase the data quality.

Dimensionality analysis can help us to evaluate a best modelling method (Swift, 1967; Larsen, 1977; Bahr, 1988). According to Yang (2017), he analyzed the dimensionality of those MT data, and all indicated 3D inversion was the most suitable method, no matter from Swift's skew, Larsen's skew or Bahr's skew.

We choose the data from 65 MT sites to build up the 3D resistivity model using the software-MODEM, developed from Anna Kelbert, to conduct the resistivity model inversion. MODEM was provided for the academic research and published from Egbert et al. (2012) and Kelbert et al. (2014), adapting algorithms developed from 1993 (Mackie and Madden 1993; Newman and Alumbaugh 2000; Sasaki 2004), and using nonlinear conjugate gradient method for inversion. We can set the trade-off parameter to control the roughness of the model. Sometimes the models would be overshooting due to the data integrating process (Aster et al. 2013).

Our initial model is constructed with 29(x) $\times$ 34(y) $\times$ 43(z) = 42398 cells. The horizontal mesh space was between 111 meters and 1266 meters, which was distributed by the density of the MT stations. The denser the distribution of MT stations, the smaller the grids are cut. The vertical mesh space begins with 2 meters and gradually increases the spaces downward to the depth of 4 km. The background resitivity is set as homogeneous half-space of 100 ohm-m. The model reiterated 81 times, and achived the root mean square (RMS) of 5.2.

3.2 *THE ANALYSIS OF WELL-LOGGING DATA*

The well-logging data was collected by Chinese Petroleum Corporation (CPC) from 2016 and 2017. The exploration program team selected two sites on the south side of Lanyang River for the exploration wells, one was HCL1 while the other was HCL2. It was about 1.5 km between these two sites, and the drilling depth of HCL1 was 2200 meters and the resistivity data of HCL1 were collected every 0.1 meter apart; and the

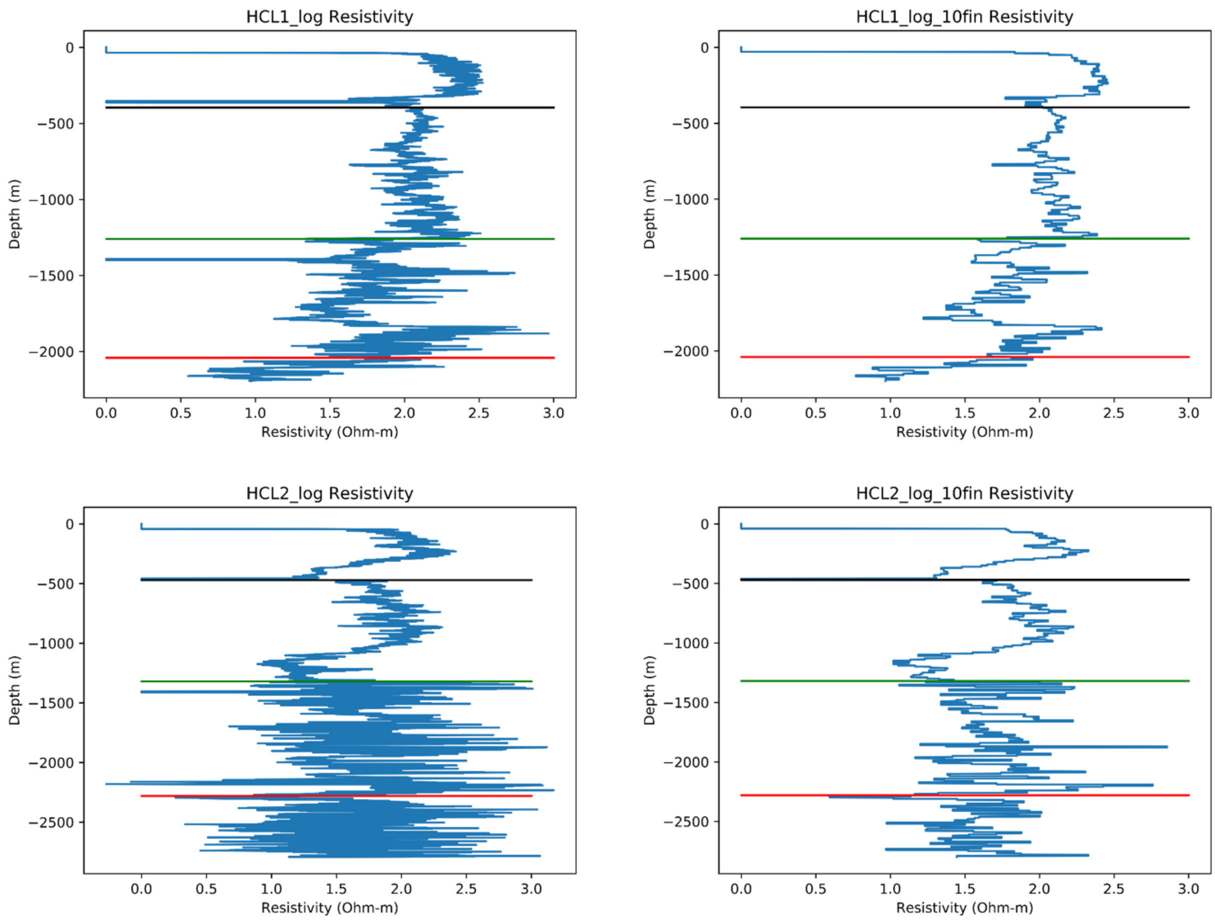


Figure 3: Well-logging data was processed to change the scale be more close to model scale. Two left pictures were processed by log10 per meter; two right pictures were processed by log10 per 10 meters. Black line is the upper boundary of Kankou formation; green line is the upper boundary of the Szeleng Sandstone; red line is the upper boundary of Hsitsun formation.

drilling depth of HCL2 was 2800 meters with resistivity data in 0.15 meter interval. Since the vertical mesh space was bigger than 2 meters, we decided to average the well-logging data per 10 meters to make the scale closer. While all the resistivity data from well-logging were linear, we took log base 10 to compare with the inversion resistivity model (Fig. 3).

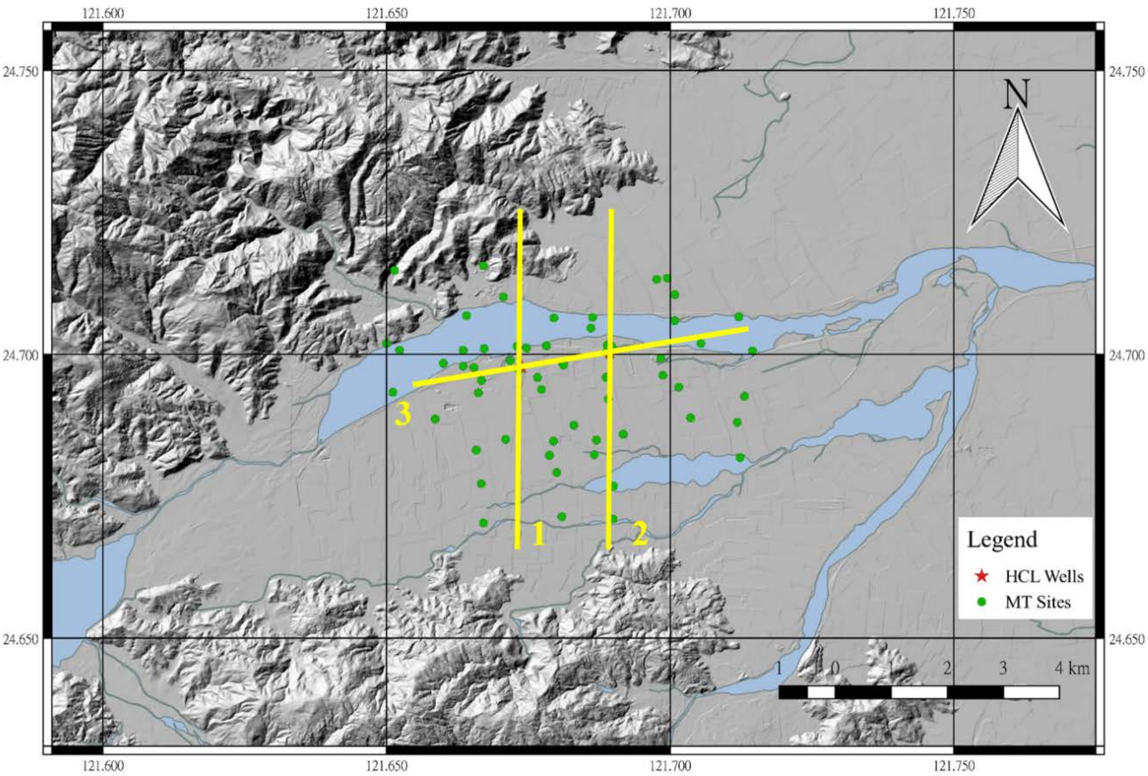
4. 3D RESISTIVITY MODEL WITH WELL-LOGGING DATA

After 3D model inversion, we imported the well-logging data and the 3D resistivity model into the software-Voxler for display. We selected three sections to depict the relationships between the resistivity model and the well-logging data. Section 1,located on HCL1, has a length of 6 km and trends from North to South. Section 2 is located on HCL2, and has the same length and trend as section 1. Section 3 passes through the first 2, is also 6 km long and trends West to East (Fig. 4). We observe that there are different low to intermediate resistivity anomalies under the two drilling sites (Fig. 5). A major conductive region with resistivity of less than 30 Ohm-m is identified below depths of 400 m under the HCL1. An intermediate resistivity anomaly (60-100 ohm-m) lies below500 m depth under HCL2. There was a high resistivity covering those two regions.

After processing, we observe that there is a lower resistivity toward the deeper area of the HCL1. But at the HCL2, there is no trend with depth. In Figure 3, from the well-logging, the Black line is the upper boundary of Kankou formation; green line is the upper boundary of Szeleng Sandstone; red line is the upper boundary of Hsitsun formation. Above the black line area is alluvium. There is a big difference at the Szeleng Sandstone between HCL1 and at HCL2 since the resistivity of Szeleng Sandstone at HCL2 is very chaotic. According to the National Energy program-Phase II (NEPII) final report and Wang (2018), the former indicated there is a fracture zone at the depth of 1800 m – 2300 m; the latter indicated the fracture zone is at the depth of 1500 m – 1800 m. No matter which interpretation is correct, both of them believe the fracture zone is within the Szeleng Sandstone. That is the reason why the resistivity at that depth of HCL2 is so chaotic.

Although the well-logging data do not have the same measurement values at the same depth of the model, they show the same trend. However, we still have some problems to solve. According to the NEP-II report, we know there is a fracture zone with water influx at the bottom of HCL2 and the formation under the HCL1 is complete. But the low resistivity area under the HCL2 is bigger than the one under the HCL1. There is a contradiction because we thought the resistivity of the zone with lots of water would be lower than the zone with less water.

To solve this contradiction, we suggest some possible scenarios. First, the different components in the ground water influenced the resistivity. Aizawa (2011) explained the fracture network could be a conduit for sea water mixing with the shallow ground water beneath sea level, causing the resistivity to be reduced. Chung (2016), indicated the fracture zone had a relation with the Lanyang River fault. So we inferred there were some spring water or brine water mixing with the water coming from the Lanyang River and causing the different resistivity.



HCL1; section 2 crossed over the HCL2; section 3 crossed over the both wells.

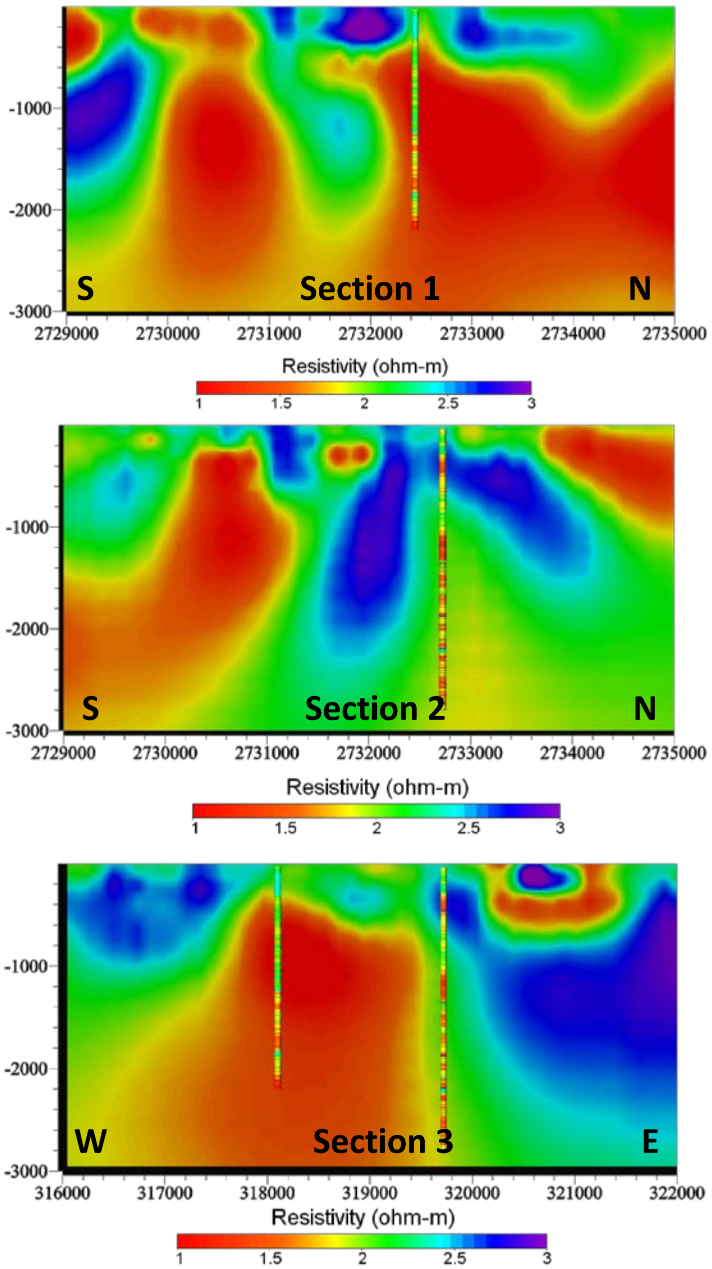


Figure 5: The upper image is cross-section 1; there is low resistivity below 400m depth. The middle image is section 2; there is intermediate resistivity below the depth of 500m. The lower image is section 3; there are different resistivities below the two wells.

Another possible situation is the high conducting mineral in the formation. In the Chingshui geothermal exploration area which is 3 km away from the southwest of HCL geothermal exploration area, we find plentiful pyrite in the layer. Huang (2016) showed that pyrite appeared at 300℃ or below. It could also impact the resistivity.

The other possibility is the carbonaceous material in the argillite. In the submetamorphic zone, we could see lots of argillite in the formation even in the Szeleng Sandstone, and those argillites contain carbonaceous material which could be metamorphosed into graphite. This also could make the resistivity lower.

5. FUTURE WORK

We will continue to examine the drilling cores and identify more evidences to better analyze the possible factors that cause the variations in resistivity.

6. REFERENCES

Aster, R. C., B. Borchers, and C. H. Thurber.: Parameter Estimation and Inverse Problems, 2nd *ed., Academic Press, 360 pp.* (2013).

Aizawa, K., W. Kanda, Y. Ogawa, M. Iguchi, A. Yokoo, H. Yakiwara, and T. Sugano, Temporal changes in electrical resistivity at Sakurajima volcano from continuous magnetotelluric observations. *J. Volcanol. Geotherm. Res., 199(1–2), 165–175, doi:10.1016/j.jvolgeores.2010.11.003.* (2011).

Bahr, K.: Interpretation of the magnetotelluric impedance tensor: regional induction and local telluric distortion, *J. Geophys. Res., Vol. 62, No. 2, pp. 119-127*. (1988).

Chiang, S. C.: Seismic reflection survey in Ilan Plain. Mining Technology, 14(6), 215-221. (1976)

Chung, C. T.: Exploration of the geothermal structures in Sansing, Ilan. *National Central University, Master degree thesis.* (2016).

Egbert, G. D., and A. Kelbert.: Computational recipes for electromagnetic inverse problems. *Geophys. J. International, Vol. 189, No. 1, pp. 251-267*. (2012).

Huang, H. H., J. B. H. Shyu, Y. M. Wu, C. H. Chang, and Y. G. Chen.: Seismotectonics of northeastern Taiwan: Kinematics of the transition from waning collision to subduction and postcollisional extension. *J. Geophys. Res., Vol. 117, doi: 10.1029/2011JB008852*. (2012).

Huang, Y. H., Song, S. R.: Simulating Mineral Scaling in Slate-CO2-Water Interactions. *National Taiwan University, Master degree thesis.* (2016).

Hsu, S. K., J. C. Sibuet, and C. T. Shyu.: High-resolution detection of geologic boundaries from potential-field anomalies: An enhanced analytic signal technique. *Geophysics*, 61, 373-386. (1996).

Kelbert, A., N. Meqbel, G. D. Egbert, and K. Tandon.: ModEM: A modular system for inversion of electromagnetic geophysical data. *Computers & Geosciences, Vol. 66, pp. 40-53*. (2014).

Larsen, J. C.: Low Frequency Electromagnetic Study of Deep Mantle Electrical Conductivity Beneath the Hawaiian Islands. *Geophys. J. International, Vol. 43, No. 1, pp. 17-46*. (1975).

Mackie, R. L. and T. R. Madden.: Three-dimensional magnetotelluric inversion using conjugate gradients. *Geophys. J. Int., 115, 215-229, doi: 10.1111/j.1365-246x.1993.tb05600.x.* (1993).

Newman, G. A. and D. L. Alumbaugh.: Three-dimensional magnetotelluric inversion using non-linear conjugate gradients. *Geophys. J. Int., 140, 410-424, doi: 10.1046/j.1365-246x.2000.00007.x.* (2000).

Sasaki, Y.: Three-dimensional inversion of static-shifted magnetotelluric data. *Earth Planets Space, 56, 239-248, doi: 10.1186/BF03353406.* (2004).

Shih, C. C.: Investigating the basement depth and tectonic evolution in Ilan Plain by seismic reflection method. *National Central University, Master degree thesis.* (2011).

Swift, C. M.: A magnetotelluric investigation of an electrical conductivity anomaly in the southwestern United States. *Massachusetts Institute of Technology, Doctoral dissertation*. (1967).

Tong, L. T., S. Ouyang, T. R. Guo, C. R. Lee, K. H. Hu, C. L. Lee, and C. J. Wang.: Insight into the geothermal structure in Chingshui, Ilan, Taiwan. *Terr. Atmos Ocean. Sci., **19**, 413-424, doi: 10.3319/tao.2008.19.4.413(T).* (2008).

Wang, M. H.: Raman Spectrum and Cleavage Microstructure Analysis of Slate Carbonaceous Material in HongChaiLin Geothermal Well and Surrounding Area in Lanyang Plain, Taiwan. *National Taipei University of Technology, Master degree thesis.* (2018).

Yang, Z. X.: The geothermal structure inferred from magnetotelluric data beneath southern part of Ilan Plain, north-eastern Taiwan. *National Central University, Master degree thesis*. (2017).

Chen, W. S.: Introduction to Taiwan geology. *Geological Society of Taiwan*. (2016).