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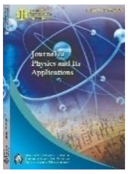

Identification of "WS" field geothermal system by analyzing TE, TM, and TE-TM mode of 2D magnetotelluric inversion models

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ABSTRACT

Magnetotelluric survey has been carried out at the "WS" geothermal field to analyze the resistivity models resulting from 2D inversion of magnetotelluric data in TE, TM and TE-TM modes. Base on the thesemodels, the mode is determined to produce the most representative model to assist interpretation of the "WS" geothermal system. The results of the three modes show that TE mode is dominated by low resistivity with a range of values less than 10Ωm and medium resistivity with a value range of 35-250 Ωm. TE mode producesa vertical resistivity contrast. The TM mode describes the high resistivity in southwest and the center of the linewith a value of more than 470Ωmso that resulting in lateral resistivity contrast. While the TE-TM mode is combination of TE and TM mode, but in this study the TE-TM mode is more similar to TM mode. TE-TM mode describes the distribution of resistivity both vertically and laterally. Based on the analysis of the three modes, it can be concluded that the TE-TM mode is the most representative model. Low resistivity distribution (less than 10 Ωm) is interpretedas a cap rock zone, medium resistivity (35-380 Ωm) as reservoir rock, high resistivity (more than 380 Ωm) as resistif zone, and the existence of the three of faults structures in the study area as controller system of the "WS" geothermal.

1. Introduction

Geothermal exploration activities which are consist of geological, geophysical and geochemical surveys is always needed to obtain potential geothermal hotspots. Geophysical methods are used to investigate the physical properties of rocks such as density, conductivity, susceptibility, and others. The magnetotelluric method or MT method is one of the geophysical methods that are considered effective in geothermal exploration.

Magnetotelluric method is one of the passive electromagnetic methods that involves measuring fluctuation in the electric field and natural magnetic fields on the earth's surface which can be used to determine the conductivity values of rock beneath the earth from shallow depths to tens of kilometers. The MT method uses frequencies in the range of 10^{-5} Hz-10^{3} Hz [1]. The wide frequency interval in the magnetotelluric method can investigate earth's resistivity from the surface deeperthanother geophysical methods [2]. Resistivity is a geophysical parameter that is most effective in detecting potential reservoirs and determining the location of initial exploration wells [3].

Magnetotelluric geothermal surveys have been carried out on several tyes of geothermal system. The survey is intended to target the structure of the cap rock and reservoir by knowing its conductivity.[4] From the description above it can be stated that the magnetotelluric method is very effective and efficient in geothermal exploration. This is evidenced by the many studies of experts on geothermal exploration using the magnetotellurric method [4].

The effectiveness of MT method can be used to detect the depth of geothermal structure. This method has been validated often byother methods such as the gravity method, magnetic method, and so on [5]. This is intended to predict more accurately the location of geothermal components, such as the location of the cap rock and reservoir. To identify geothermal components, it is necessary to do several steps of MT data processing and modeling. The focus of this research is only 2D processing and modeling because it feel~~s~~ more able to describe geothermal systems more accurately.

Processing and modeling of magnetotelluric data were separated into TE (Transverse Electric) mode, TM (Transverse Magnetic) and TE-TM.Electric field in TE mode is assumed parallel to the direction of the strike while magnetic field is perpendicular to one. Magnetic field in TM mode is assumed parallel to the direction of the strike while electric field is perpendicular to one [6]. Electric current in TE mode flows in the direction of the geolectrical strike to induce a conductor,so that produces a vertical magnetic field. Whereas in TM mode free charge accumulates through the lateral boundary plane [7].

There have been many studies of MT method, but still rare to include analysis polarization mode. Even though theTE, TM and TE-TM modes will each produce a model that describes conductivity properties. Focus of this research is to find out the characteristics of each mode in the research area. Application of the magnetotelluric method in the "WS" geothermal had been carried out previously by the PSDG in 2011 and 2014, but both had never been analysed polarization mode in the area. Therefore, through this research it is exected to be refinement in the process of interpretation. To assist the interpretation process, this research is supported by geological map in **Fig.1**.

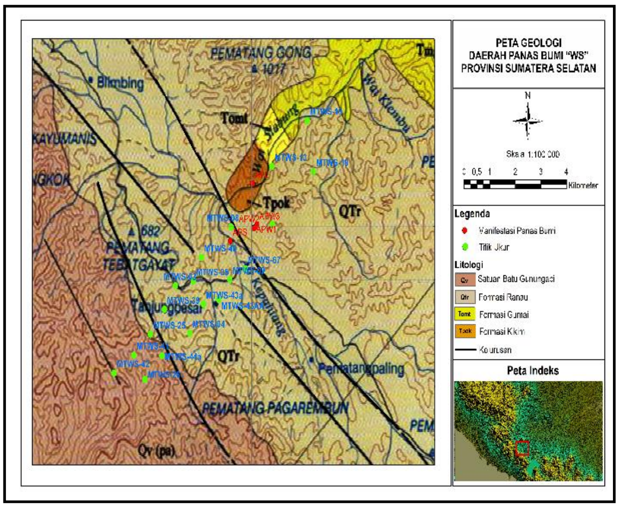


Fig. 1: Geological map of the "WS" geothermal area.

2. Methods

The data in this study is secondary data from magnetotelluric acquisition carried out by the Coal and Geothermal Mineral Resource Center in the "WS" geothermal field, South Sumatra. The data used in this study amounted to nineteen points. Data at each point consists of data *.TS (time series data from the measurement results), *.TBL (data site parameters), *.CLC (sensor calibration data), and *.CLB (tool calibration data). Design survey of the research area can be seen in **Fig.2**.

The software used in this study are consist of SSMT 2000, MT editor, WinGlink, supporting software, like: Surfer 11, Corel Draw, Global Mapper and ArcGIS. The MT Data was processedby SSMT 2000 program,which is the format *.TS, *.TBL, *.CLC, and *.CLB are needed. The time limit has been determined by Fourier transform parameter. The Fourier transform of TS to FT is a step to convert data which has a time domain into frequency domain. Robust processing was done to reduce noise on magnetotelluric data and calculate the apparent resistivity values at each measurement point.

The smoothing curve of MT data was processed by MT editor software. The data were displayed in the apparent resistivity curve and phase vs frequency. The amount of crosspower used is 100, but there are some data that have damage so that the data uses crosspower 60 and 80, rotation parameter is -45^o because of main structure that develop at the area is northwest-Southeast.

The last process is processing data in WinGlink software. The first step is to create a line profile. In this step, data also rotated by -45^0 to clarify the subsurface depiction of the TE and TM data. The data smoothing process is done by setting D+ (Err 5% and Err 5%). To reduce the static effect on the data, static correction is performed using TDEM data. Modeling using 2D inversion with making an initial model through mesh settings. The next step is set inversion parameters such as mode, tau value, data error (10% for resistivity and 5% for phase), and error floor (5% for resistivity and phase). The inversion process is conducted by 100 iterations.

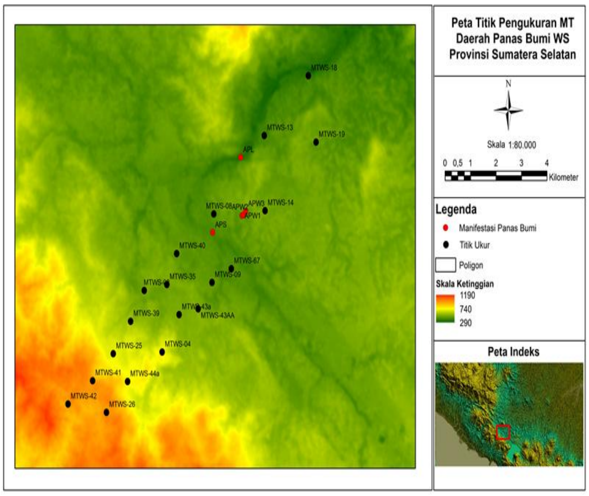
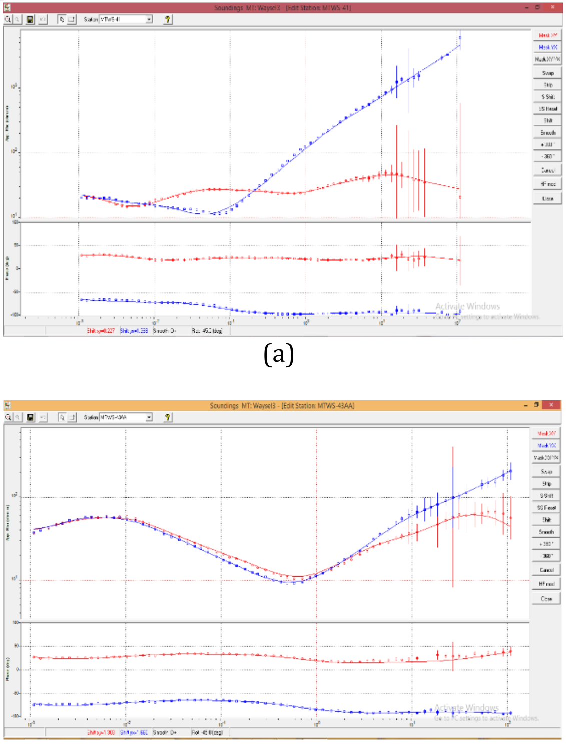


Fig.2: Design survey of research area

Each path consists of three 2D inversion models with different modes, namely TE, TM, and TE-TM. The model of the best mode of each line will be interpreted to determine the geothermal system components and structures that affect the geothermal area.

3. Results and Discussions

The sounding curve describes the apparent restivity and phase values that vary with the period at each measurement point. Static shift in TDEM data is processed to reduce static effects.



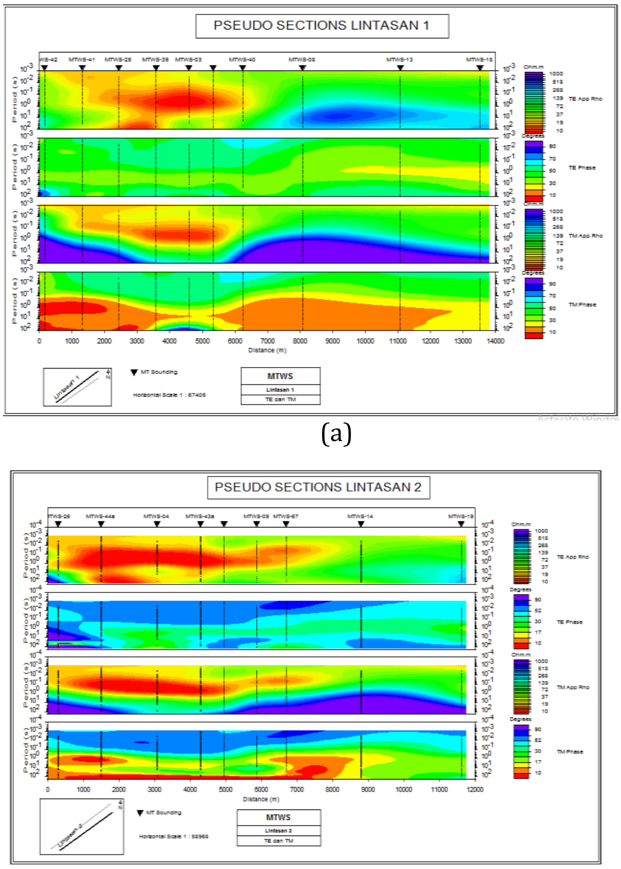
(a)

(b)

Fig. 3:(a) MTWS-41 point sounding curve (line 1) static shift correction (b) MTWS-43AA point sounding curve (line 2) static shift correction result

TDEM data were applied because it has a fairly good resolution at high frequencies and produces smaller distortions so that the data can overcome the weaknes of the MT method which are easily distorted at high frequencies because of the heterogeneity of resistivity near the surface [8]. The result of a static shift correction is better the TE curve and the TM curve. The results of the static shift correction at MTWS 41 and MTWS 43AA path can be seen in **Fig. 3** (a) and (b)**.** The curve increase in the MT curve (TE and TM curves) shows that the apparent resistivity is high. In addition, the depth value also gets higher as the period increases.

The restivity apparent value and phase to period of TE and TM modes can be described more clearly through the pseudo-section model. The pseudo-section provides an overview of the distribution of resistivity based on the color contrast produced. The pseudo-section model of each line can be seen in **Fig. 4.**



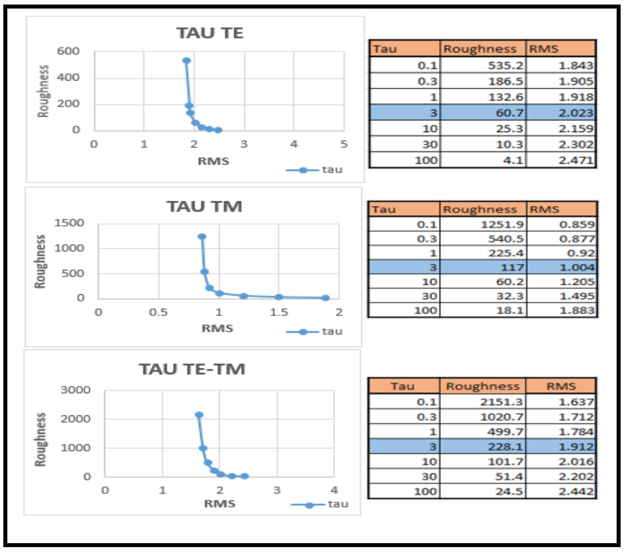
(a)

(b)

Fig. 4: (a)Pseudo-sectionline 1 (b) Pseudo-section line 2

L-Curve is used to find out the Tau value that produces the best model in each mode and path. The Tau value is an inversion parameter that regulates the relative weight between the misfit (RMS) curve and the roughness of the model [7]. L-Curve of Line 1 and Line 2 are shown in **Fig. 5** and **Fig. 6.**

Result shows the increasing Tau value correlate well to the model smoothness (roughness decreases), eventthough it is not represent the actual model (RMS increases). Tau 3 is the best know value 3 because that is located at the curvature angle of L-Curve.

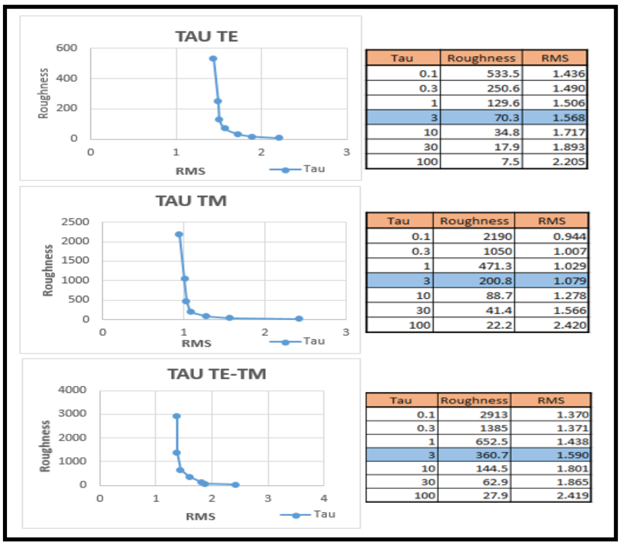


Tau	Roughness	RMS
0.1	535.2	1.843
0.3	186.5	1.905
1	132.6	1.918
3	60.7	2.023
10	25.3	2.159
30	10.3	2.302
100	4.1	2.471

Tau	Roughness	RMS
0.1	1251.9	0.859
0.3	540.5	0.877
1	225.4	0.92
3	117	1.004
10	60.2	1.205
30	32.3	1.495
100	18.1	1.883

Tau	Roughness	RMS
0.1	2151.3	1.637
0.3	1020.7	1.712
1	499.7	1.784
3	228.1	1.912
10	101.7	2.016
30	51.4	2.202
100	24.5	2.442

Fig.5: L-*Curve* Line 1



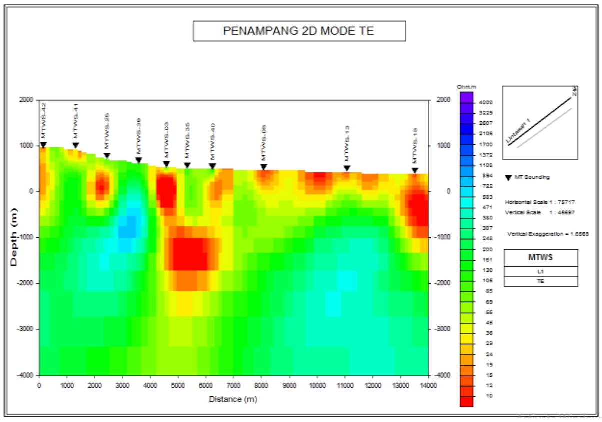
Tau	Roughness	RMS
0.1	533.5	1.436
0.3	250.6	1.490
1	129.6	1.506
3	70.3	1.568
10	34.8	1.717
30	17.9	1.893
100	7.5	2.205

Tau	Roughness	RMS
0.1	2190	0.944
0.3	1050	1.007
1	471.3	1.029
3	200.8	1.079
10	88.7	1.278
30	41.4	1.566
100	22.2	2.420

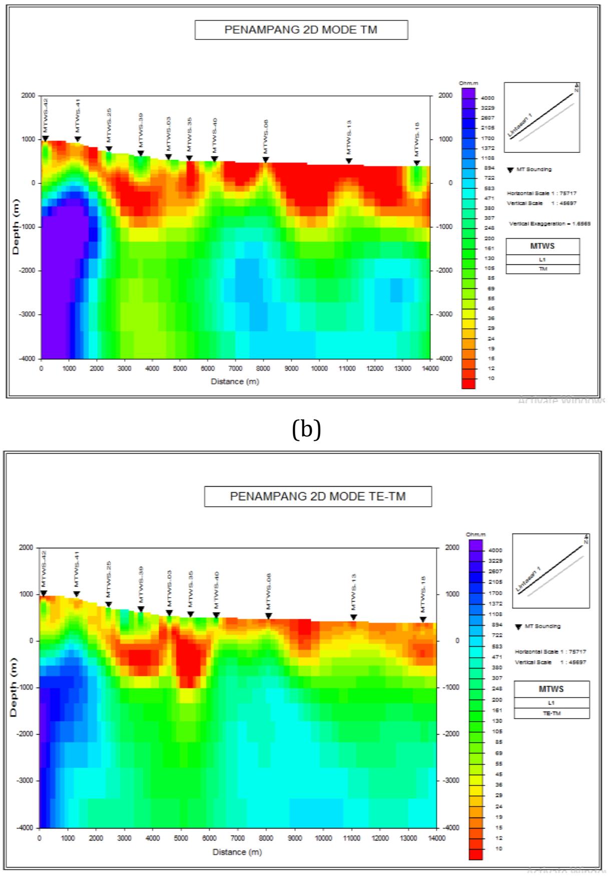
Tau	Roughness	RMS
0.1	2913	1.370
0.3	1385	1.371
1	652.5	1.438
3	360.7	1.590
10	144.5	1.801
30	62.9	1.865
100	27.9	2.419

Fig. 6: L-CurveLine 2

The angle of the L curve is the maximum curvature of the data misfit (RMS) and the level of roughness of the model, where both are balanced [9].This means that at the corner point the L curve shows a small RMS value with a roughness value that is not too high.



(a)



(b)

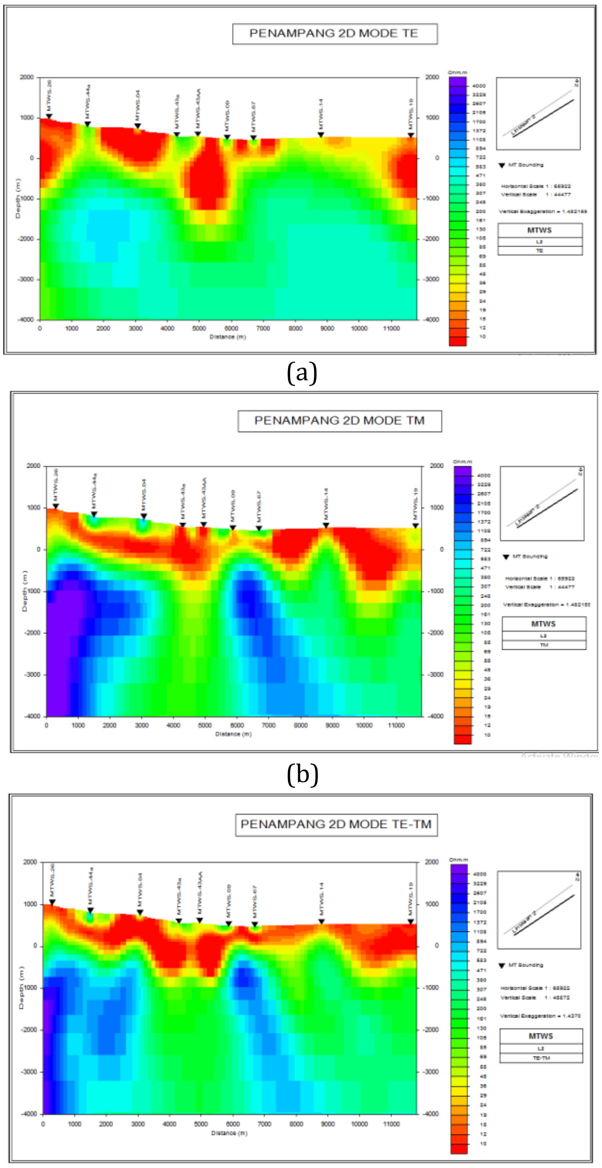
(c)

Fig. 7: 2D cross section line 1, (a) TE mode, (b) TM mode, and (c) TE-TM mode

The results modelfor Line 1 and Line 2 of TE mode are shown in **Fig.7** (a) and **Fig. 8** (a). TE mode is dominated by the distribution of low and medium resistivity. Low resistivity appear~~s~~ at shallow depth~~s~~ with a value range of less than 10Ω to a depth of 600 to 2500 m. Medium resistivity has value35-250 Ωm and most are spread evenly below the low resistivity distribution. High resistivity is only seen at some points with resistivity values that are not too high.

TE mode is dominated by low resistivity because electric current induces conductive mediummore than resistive medium. That matter result a low resistivity distribution that dominates the shallow depth, while the resistive zone almost invisible.[6] The more depth increases, the electric field will be difficult to read in TE mode because that is getting closer to the magnetic source. Induction is very sensitive with changes of magnetic field, so as deth increases, the response from the low resistivity disappears [10]. The low resistivity distribution appear laterally at shallow depth~~s~~, while below the low resistivity there is moderate resistivity which is also mostly spread laterally. As a result there is a difference in resistivity contrast that is seen betweenvertically low resistivity and medium resistivity layers.

The result model forLine 1 and Line 2 TM modes are shown in **Fig. 7** (b) and **Fig. 8** (b). In TM mode the high resistivity value is very clearly visible on the southwest side and in the middle of the line. In the southwest there is a high resistivity470-4000 Ωmwhile in the midle extending to the northeast has a value of 380-750 Ωm. The low resistivity value is also still visible in this mode, it's just that the value isn't as low as in TE mode. Medium resistivity is seen jutting down at the between MTWS-25 to MTWS-40 (Line1) and MTWS-04 to MTWS-09 (Line 2) with resistivity35-250 Ωm. That matter resulting resistivity contrast laterally at a depth of approximately 2000 meters.



(a)

(b)

(c)

Fig. 8:2D cross section of Line 2 (a) TE mode, (b) TM mode, and (c) TE-TM mode

The presence of lateral resistivity contrast in TM mode is caused by the electric current in TM mode that cross the boundary between parts that have different resistivity [11]. TM mode describes high resistivity better than low resistivity.[10]This statement is in accordance withthe things obtained in this study,very low resistivity is only obtained on the surface caused by presence of galvanic influence.The galvanic effect is one of the static effects caused by differences in topography [12].

The modeling results for modes TE-TM Line 1 and Line 2 are shown in **Fig. 7** (c) and Fig. 8 (c).Based on the modelling that the TE-TM mode generates a model that is almost similar to TM mode with a combined value with TE mode.Low resistivity obtained at a depth of 1500 to 1800 meters. Medium resistivity intended down with a range of values of 35-200 Ωm.In the southwest, resistivity has a high enough value 380-3500 meters,while in the middle to the northeast is dominated by high resistivity 380-700 Ωm at a depth of more than 2000 meters.TE-TM mode is acombination of TE mode and TM mode, so that they complement each other. This makes TE-TM mode produce the best model in the interpretation of geothermal system.

Line 1 shown in **Fig. 9** correlate well with the spring manifestations, namely APL with a temperature of 68.1^{0}C and an APS with a temperature of 44.4^{0}C. On Line 1 there is a 3 structure (dashed line) that is thought to be the controller of the "WS" geothermal system. These three structures belong to the large Sumatran fault. The existence of a fault structure is interpreted based on the presence of contrast resistivity which is then adjusted to the existing geological map.

Cap rock is interpreted by the distribution of a low resistivity value with a range of values of less than 10Ωm which is identified as alteration rock or an altered rock composed by clay minerals. Thecap rock zone is located around the appearance of APL and APS manifestations with a thickness of 500-800 meters. The manifestations of APL and APS do not have too high a temperature because it is suspected that in the course of going to the surface it is estimated that the hot fluid is mixing with surface water [13].

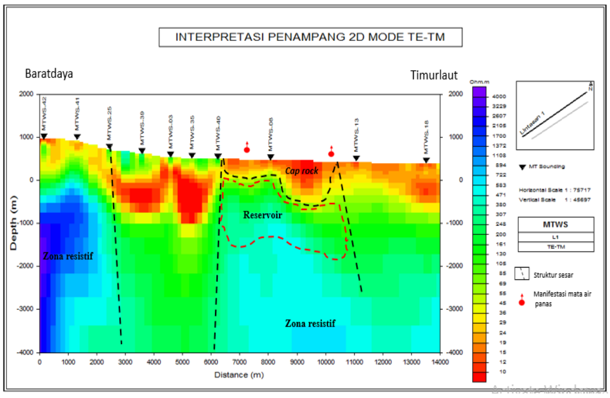


Fig. 9:Interpretation of 2D cross section of Line 1

The type of medium resistivity are scattered in the central and northeastern parts. Medium restivity in the northeast associated with sedimentary rocks. While the type of resistivity in the middle are thought to be Akarjangkang lava. Medium resistivity rocks in the middle are interpreted as reservoir zones with resistivity values of 45-380 Ωm and have an average thickness of 1500 m. The existence of a resistive zone in the southwest shows a higher resistivity value compared to the center. However, a survey of the temperature slope between the MTWS-25 to MTWS-40 did not show a significant heat anomaly.[13] Therefore, in this study It can be interpretedthat the prospect of geothermal energy is around the appearance of manifestations, which is around the zone of MTWS-30 and MTWS-13.

Line 2 shown in **Fig. 10** cuts three manifestations directly to the adjacent area, including APW 1 with a temperature of 92.5^0 C, APW 2 with temperatures of 89.3^0 C, and APW 3 with temperatures of 40.2^0 C. On this line there is also a structure (dashed line) which is thought to be the controller of the "WS" geothermal system.

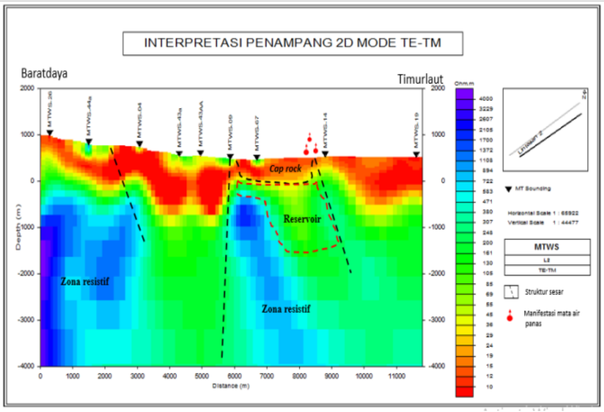


Fig.10: Interpretation of 2D cross section of Line 2

The interpretation of the geothermal system component on Line 2 is almost the same as Line 1 because of its proximity. The cap rock zone is interpreted as an altered change rock with a value range of less than 10 Ωm. Caprock on Line 2 has a thinner size than Line 1 which is around 400-500 meters. From the emergence of the three high temperature manifestations described above, it supports the location of the geothermal prospect around the manifestations discussed in Line 1.

With the same interpretation accordingto Line 1, the medium type of resistivity in the northeast is sedimentary rock while in the middle is estimated to be Akarjangkang lava. The medium resistivity distribution in the middle is thought to be a reservoir with a range of values of 40-200 Ωm and narrower than line1. The reservoir on Line 2 has a thickness of 1500 meters with a top reservoir located in depth of 700 meters.

The high resistivity zone is seen in the southwest and in the middle around the manifestation. When compared with Line 1, the high resistivity zone in the southwest tends to widen and tends to narrow in the middle part. The high resistivity zone in the western part is sedimentary rock which is overlaid by volcanic rocks and has higher resistivity value.The distribution of high resistivity in the middle part is interpreted as other volcanic lava rocks which have a lower resistivity values 380-1700 Ωm which indicate the source rock below it.

5. Conclusions

TE mode is dominated by low and mediumresistivity with a value range of less than 10Ωm and 35-250Ωm. Both resistivity produces resistivitycontrast vertically or in the direction of depth. The TM mode describes the high resistivity clearly in the southwest and the middle of the track with value more than 470 Ωm. Moderateresistity appear is in both parts produces lateral resistivity contrast. TE-TM mode is combination of TE and TM mode, but in this study the TE-TM mode is more similar to TM mode. TheTE-TM mode produces the most representa-tive model because it covers the middle values of both modes (not dominated by low or high resistivity) so that it is well used for interpretation. Geothermal system in the "WS" area consists of cap rock with a resistivity value of less than 10Ωm which is interpreted as alteration rock. The reservoir has a resistivity value of 35-380 Ωm on Line 1 and 35-200 Ωm on Line 2 and interpreted as Akarjangkang lava. The resistive zone has value more than 380 Ωm and is interpreted as a lava volcanic rock.

Acknowledgment

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References

[1] Simpson, F. dan Bahr, K, 2005, *Practical Magnetotellurics*, University Press, Cambridge.

[2] Daud, Y., "Electromagnetic Method : Success Story in Geothermal Exploration & Possibility for Hydrocarbon Exploration". Diktat Kuliah :Depok, (2010).

[3] Cherkose, B.A. and Mizunaga, M., "Resistivity Imaging of Aluto-Langano Geothermal Field Using 3-D Magnetotelluric Inversion", *J. African Earth Science* **139**, 307 (2018).

[4] Leeuwen, W.A., *Geothermal Exploration Using The Magnetotelluric Method,* Faculty of Geosciences, Netherlands, (2016).

[5] Singarimbun, A., Gaffar, Z.E., and Tofani, P., "Modelling of Reseervoir Structure by Using Magnetotelluric Method in the Area of Mt. Argopuro, East Java, Indonesia", J. Eng. Technol. Sci. **49**, 833 (2018).

[6] Unsworth, M.J., *Lecture Notes Geophysics 424*, University of Alberta, Kanada, (2008).

[7] Niasari, S.W., "Magnetotelluric Investigation of the Sipoholon Geothermal Field, Indonesia", *Disertasi*, Fachbereich Geowissens chaften der Freien Universität Berlin, (2015).

[8] Rahadinata, T., and Sugianto, A., "Survei Magnetotellurik dan TDEM Daerah Panas Bumi Way Selabung Kabupaten Oku Selatan, Provinsi Sumatera Selatan", *Jurnal PSDG*, Kelompok Penyelidik Bawah Permukaan, PSDG, (2014)

[9] Hansen, P. C, "The L-curve and Its Use in The Numerical Treatment of Inverse problems in Computational Inverse Problems in Electrocardiology", ed. P. Johnston, Advances in Computational Bioengineering, 119–142, WIT Press, (2010).

[10] Annailah, E.F., Analisis Pemodelan Inversi 2D Mode Polarisasi TE, TM dan TE-TM pada Data Magnetotellurik Daerah Panas Bumi "EFA", *Skripsi*, Jurusan Teknik Geofisika, Fakultas Teknologi Mineral, Universitas Pembangunan Nasional "Veteran", Yogyakarta, (2018).

[11] Berdichevsky, M.N. and Dmitriev, V.I., *Models and Method of Magnetotelluric*, (Springer, Verlag, Berlin, 2008).

[12] Wibowo, M.G.A., Pendekatan Inversi 1D untuk Mengurangi Efek Galvanic pada Model 2D Magnetotellurik Daerah Panas Bumi Danau Ranau, *Jurnal Geofisika Eksplorasi*, Universitas Negeri Lampung. 1, (2013).

[13] Simamarta, R.S.L. and Munandar, A., Survei Landaian Suhu Sumur WSL 1, *Jurnal PSDG*, Kelompok Penyelidik Panas Bumi, PSDG, (2015).