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Resisistivity Structures in Mt. Batur Geothermal Prospect Area in Bali Province, Indonesia

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***Abstract* — We present resistivity structure in Mt. Batur geothermal prospect area, Bali Province, Indonesia, derived from Magnetotelluric (MT) data. The study area is located in the Mt. Batur caldera, covered by pyroclastic flow and lava. The survey is set up by 40 MT stations, divided into 5 lines that is perpendicular with the main strike in the study area. In this paper, we show 2-D models of shallow and deeper crustal structure. Our overview is focused on low resistivity area (<10 Ωm) and high resistivity area (> 1000Ωm). Our study reveals two zones of low resistivity area at shallow depth which are attributed to fumaroles and steaming ground located near that area. Meanwhile, the high resistivity area at 4 km depth can be interpreted as intrusion of igneous rock.**

Keywords —Geothermal, Magnetotelluric, 2-D model, Mt. Batur; resistivity

I. INTRODUCTION

Indonesia is located within the ring of fire which caused Indonesia to have numerous of volcanoes. The presence of the volcanoes leads to the source of the geothermal energy which is used as alternative energy. This geothermal energy is environment-friendly energy that provides minimum pollution and low emission compared to other energies such as energy from oil and gas.

Mt. Batur, Kintamani, Bali, is one of the active volcanoes in Indonesia which includes in the ring of fire. Located in Kintamani Regency, this volcano is considered as one of the most active volcanoes in Bali and belongs also to Bali's tourism area. With some surface manifestation and geology information near Mt. Batur, we can assume that there is geothermal system below it.

Some physical parameters studied to image subsurface here are temperature, resistivity, density magnetization, and seismicity. Among these, resistivity method is the most successful methods for studying geothermal sites and they are referred to as direct method.

This resistivity method includes magnetotelluric (MT) method, which is sensitive to resistivity structures beneath. The MT method is a passive-surface electromagnetic geophysical technique that measures variations in the earth's natural electromagnetic field to investigate the electrical resistivity structure of the subsurface from depths to tens of kilometers [6].The method belongs to passive method in the sense that it utilizes naturally occurring geomagnetic variations as the power source. Worldwide lightning activity of frequencies from 10,000 to 1 Hz and geomagnetic micro-pulsations of frequencies from 1 to 0.001 Hz provide the majority of natural signals used by the MT method.

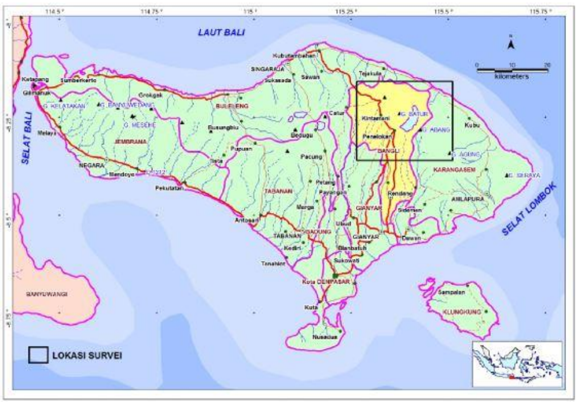

Fig. 1. The squared shape is the area of MT.Batur, Kintamani, Bali

II. SURVEY AREA

Mt. Batur is characterized by Lava Tejakula, steep sided mountains, and ridges of pillow lavas (fig. 1). It also had three times explosion so that it has three calderas. It is located at Bangli regency, Bali province. The main structure at Bali Island is fault that has strike direction mostly oriented to North West – South East with few of it has North East – South West strike direction.

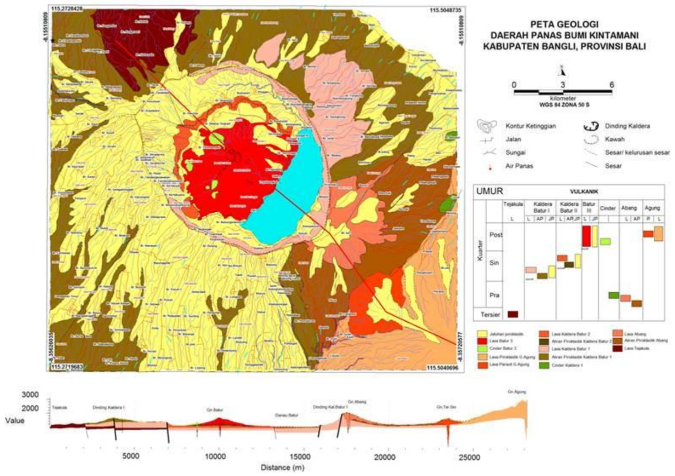

Fig. 2. Mt. Batur Geological Map [5]


Fig. 3. Steaming ground, one of the surface manifestation at the top of Mt.Batur

There are 2 groups of surface manifestation at the top of Mt batur at 2nd crater and 3rd crater. The steaming ground (fig. 3) and the metamorphic rock are located at 2nd crater while the fumarole is located at 3rd crater. The hot spring types as surface manifestation are divided by Boya Bungka Hot Spring group and Songan Hot Spring group.

III. BASIC THEORY

Magnetotelluric is one of geophysical methods that used horizontal component of magnetic field and electric field so that we can observe the vertical variation of earth's electrical conductivity [5]. The magnetic field that used by magnetotelluric method is naturally made by interaction between solar wind and earth's magnetosphere. This interaction causes an electromagnetic fluctuation at the ionosphere and induced earth. The basic concept of MT method is determined by Maxwell's equations.

A. Skin Depth

Electric and magnetic field's variations compared to depth have a limitation. This limit is called skin depth (depth penetration). Skin depth is calculated from real component of wave number (*k*):

$$k = \sqrt{i\mu_0\sigma\omega} = \sqrt{i}\sqrt{\mu_0\sigma\omega} = \frac{1+i}{\sqrt{2}}\sqrt{\mu_0\sigma\omega}$$
$$= \sqrt{\frac{\mu_0\sigma\omega}{2}} + i\sqrt{\frac{\mu_0\sigma\omega}{2}}$$
$$p(T) = \frac{1}{Re(k)} = \sqrt{\frac{2}{\mu_0\sigma\omega}} \approx 500\sqrt{\rho T} \qquad (1)$$

where p(T) is skin depth in meter, ρ is medium resistivity in Ωm and T is period in second.

B. Impedance

Impedance (*Z*) is a tensor that connecting electric and magnetic field.

$$\vec{E} = \vec{Z}\vec{H} \qquad (2)$$

Component of impedance is:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \qquad (3)$$

C. Impedance of 1D Medium and 2D Medium

In 1D medium, horizontal electromagnetic properties (Ex, Ey, and Hx, Hy) only varies against depth and doesn't have vertical electromagnetic properties.
Impedance for 1D medium described as:

$$Z_{xy} = \frac{E_x}{H_y} = \frac{i\omega\mu_0}{k}\frac{A_x\exp(-kz)+B_x\exp(+kz)}{A_x\exp(-kz)-B_x\exp(+kz)} \qquad (4)$$

$$Z_{xx} = Z_{yy} = 0$$
$$Z_{xy} = -Z_{yx} \qquad (5)$$

For 2D Medium, the horizontal properties of EM wave differ against lateral condition and depth. Therefore, Simpson and Bahr explain that there are 2 modes of polarization: Transverse Electric (TE mode) and Transverse Magnetic (TM mode). Impedance for 2D medium has a condition:

$$Z_{xx} = -Z_{yy}\text{dan}Z_{xy} \neq Z_{yx} \qquad (6)$$

IV. DATA ACQUISITION

We carried out magnetotelluric survey with 40 stations that divided by 5 lines. These lines are perpendicular to the main structure of Mt. Batur which has NW-SE orientation (fig. 5).
The focus area of MT data acquisition is at the location along the side of Batur Lake and at the top of Mt.Batur because of the location of the surface manifestation. We use 2 instruments for this survey, so that we can collect the remote data. The duration of measurement time for each MT station is about 12 until 15 hours for data recording.

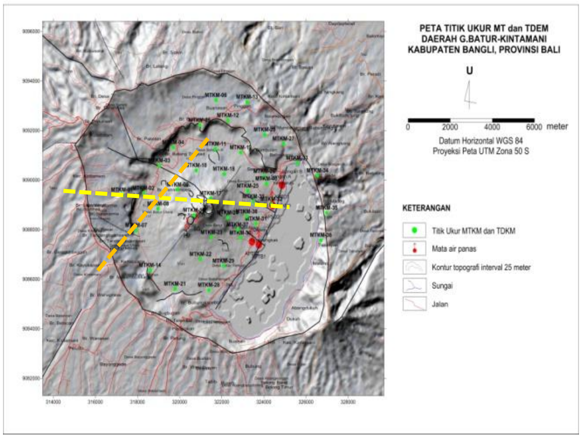

Fig. 4. Station map for MT survey at Mt. Batur, Bali. Orange line is the mark of line 1 and yellow line is the mark of line 2

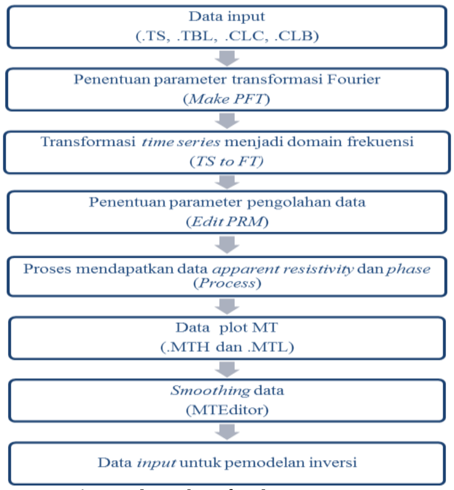

Fig. 5. Flow chart for data processing

V. RESULTS AND DISCUSSION

To get the apparent resistivity and apparent phase from the recorded data, we processed it with SSMT2000 program from Phoenix Geophysics. The field data that we get from instrument recording is categorized as time series data, so we have to transform it to frequency series data. This program's main function is the robust process. The step of data field data process on MT survey is described by fig. 5.

Result that generated from robust processing in SSMT2000 program is displayed with MTEditor program. In this program we run the smoothing process. In the smoothing process, we focused on the curve of the apparent resistivity and apparent phase. Fig. 6 shows the course of the raw MT data.

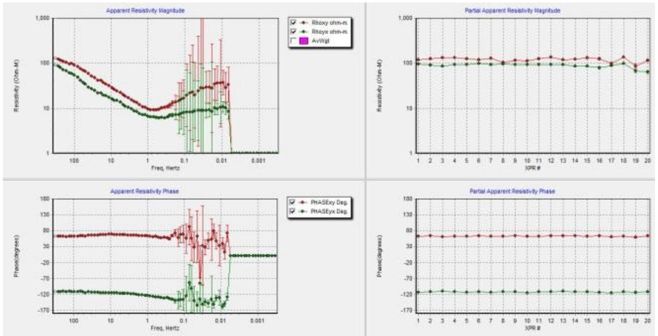

Fig. 6. Raw data from SSMT2000 displayed by MT Editor program

A. 1-D Inversion

Two 1D models were generated using Occam's inversion algorithm. The strategy of the algorithm is to find the solution agreeing with measurement that has the smallest possible roughness. This idea is familiar from the modern methods of data interpolation. There are 2 steps of 1D inversion in WinGlink software: Sounding and X-section.

In sounding, 1D Occam models were generated for each station. The iteration for each model is limited by 5 iterations. We use Occam model because it can generate more layer than Bostick model. Fig. 7 shows 1D Occam model from MTKM-09 station for 20 layers.

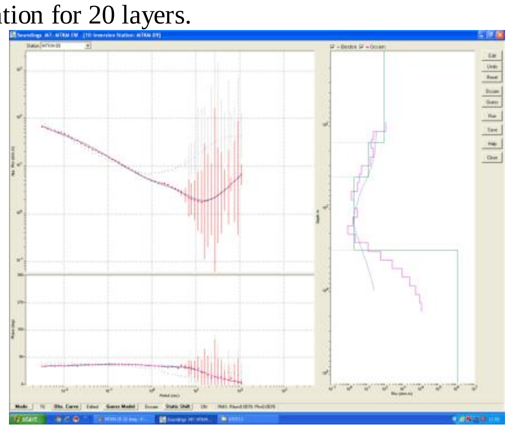

Fig. 7. 1D Inversion at Station MTKM-09

The X-section generates the section for each line of the survey area. Each 1D model that has been generated from sounding step is displayed with color scale. Fig. 8 is the 1D X-section of line 1 and fig. 9 is the 1D X-Section of line 2.

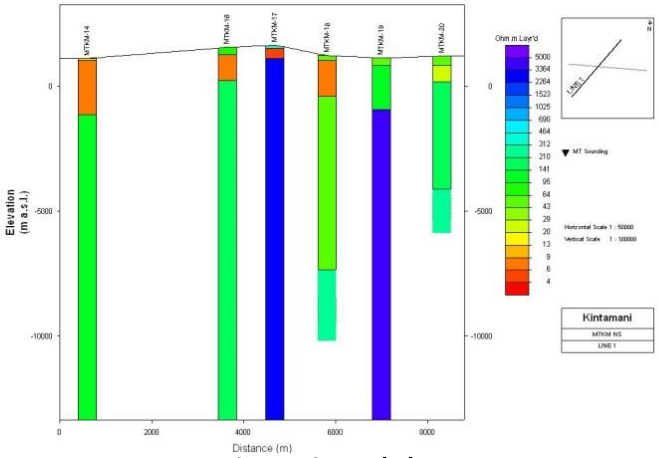

Fig. 8. 1D X-Section for line 1

From 1D inversion X-Section, we can see resistivity value below the surface for each station. In fig. 8, the low resistivity zone shown in station MTKM 14, MTKM 16. MTKM 17 and MTKM 18 have the same range. This low resistivity area may indicate an altered rock. The high resistivity area that displayed at MTKM-17 station in fig. 8 and fig. 9 is matched. Since these 2 lines are approximately perpendicular to eah other, we interpreted this high resistivity area as the intrusion of volcanic rock below Mt.Batur. From 1D model that have been generated, we can not identify the structure below the survey area.

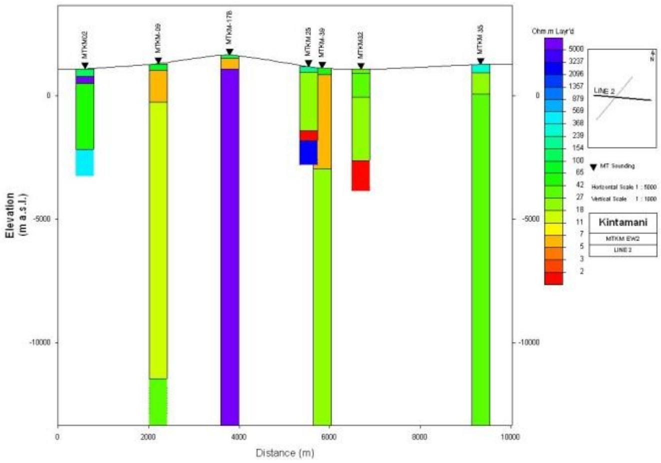

Fig. 9. 1D X-Section for line 2

B. 2-D Inversion

Two 2D models were generated with Non Linear Conjugate Gradient Algorithm (NLCG) [2]. The starting model is a homogenous model with resistivity value of 100 Ωm (fig. 10). We generated model with TE mode and TM mode, and conducted joint inversion of TE and TM mode (fig. 11-16). As we know that TE and TM mode has its own specialty for imaging resistivity value at the subsurface.

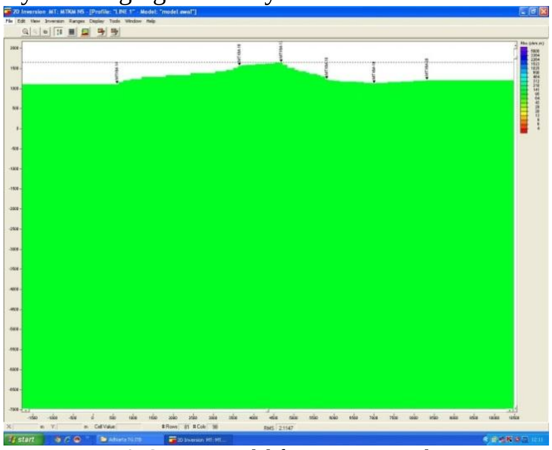
Fig. 10. Starting model for 2D Inversion line 1

The frequency limit for this inversion is 0.01 Hz because the data at the lower frequency is affected with noise. The model is made by 100 times iteration for each model.

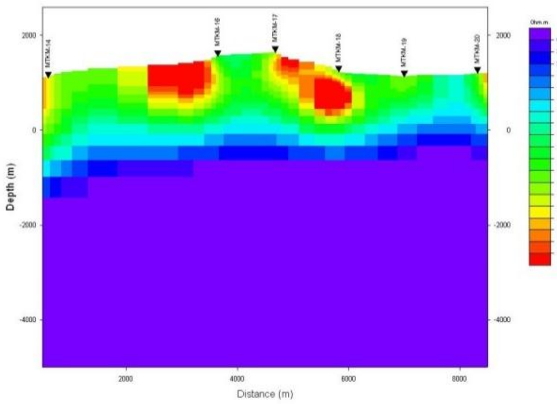

Fig. 11. 2D TE mode inversion model for line 1

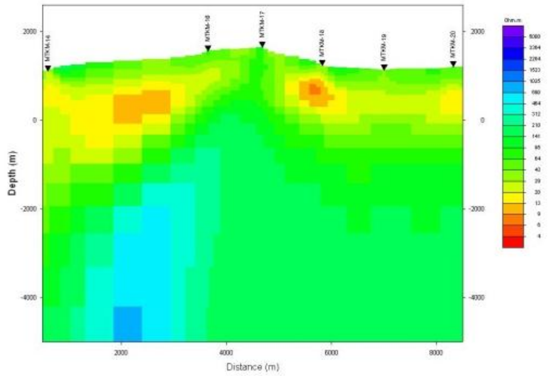

Fig. 12. 2D TM mode inversion model for line 1

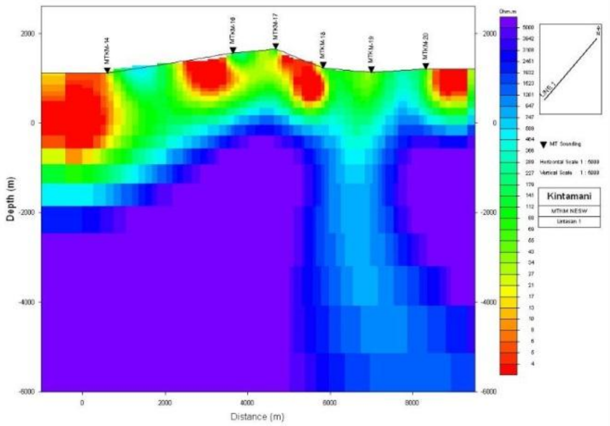

Fig. 13. 2D joint inversion TE and TM model for line 1

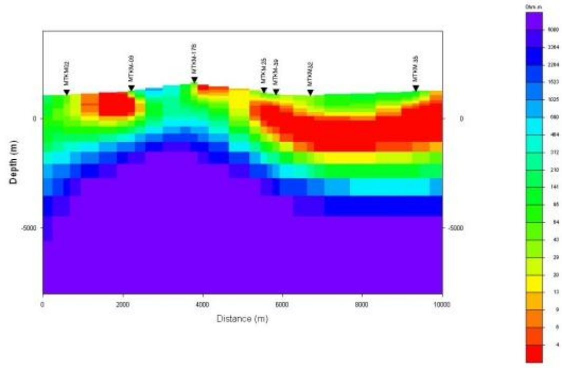

Fig. 14. 2D joint TE mode inversion model for line 2

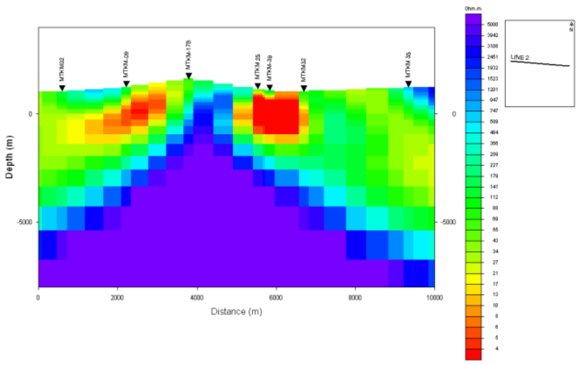

Fig. 15. 2D TM mode inversion model for line 2

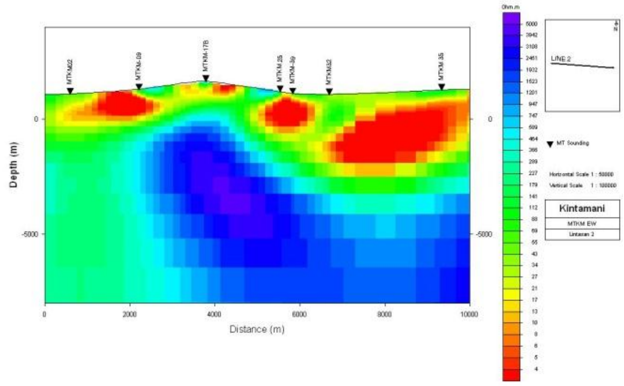

Fig. 16. 2D joint inversion TE and TM model for line 2

C. Discussion and Interpretation

In fig. 17, we made an interpretation for resistivity value at the subsurface below line 1.

We have 6 MT stations at line 1 that provide information about resistivity value at the subsurface until 5 km depth. Line 1 has a steaming ground surface manifestation at the station MTKM-16 near the top of Mt.Batur. The low resistivity area at the depth of 1000 m indicates an altered rock that been heated by the heat source below it. The low resistivity zone that appears below MTKM-16 is discontinued between MTKM-16 and MTKM-17. This anomaly denoted as a fault structure. The low resistivity zone then continued below MTKM-17 until MTKM-18 stations

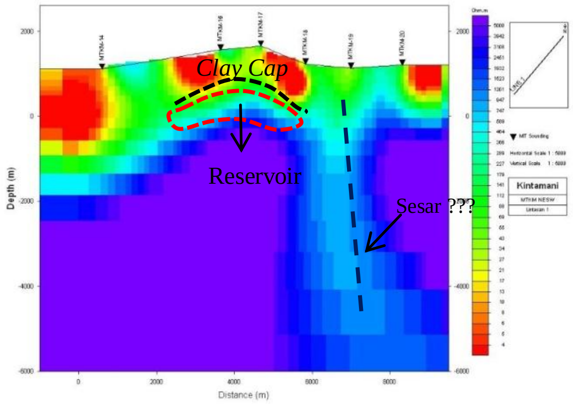

Fig. 17. Interpretation of 2D model for line 1

.The zone with resistivity value between 250 – 300 Ωm is interpreted as the reservoir of the steaming ground at the surface. The discontinued low resistivity zone below MTKM-16 until MTKM-17 stations is interpreted as a fault. This area is also interpreted as reservoir of Mt.Batur's geothermal system. The high resistivity area at depth of 2000 – 5000 m is interpreted as the basement rock of Mt.Batur. This high resistivity anomaly is discontinued below MTKM-19 station and appear again below MTKM-20 station. This discontinue area indicates a fault structure.

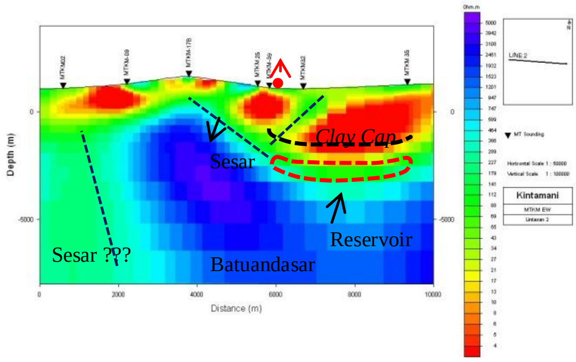

Fig. 18. Interpretation of 2D model for line 2

From the figure 18, we made an interpretation for resistivity value at the subsurface below line 2. There are 7 stations at line 2 that give information about resistivity value at the subsurface until 5 km depth. Line 2 has a Songan hot spring surface manifestation, located between the MTKM-39 and MTKM-32 station alongside of Batur Lake. The low resistivity area with resistivity value between 4 – 8Ωm at the depth of 1000 m with about 500m thickness indicates an association of altered rock that been heated by the heat source below it. This low resistivity area can be indicated as the clay cap of geothermal system at Mt.Batur. This low resistivity area is discontinued below MTKM-39 and MTKM-32 stations. The discontinued zone is associated with fault structure. The area below the low resistivity zone at the depth of 2000 m with resistivity value between 50 – 100 Ωm is associated with reservoir of the Songan hot spring. The high resistivity area at the depth of 2000 – 5000 m below the MTKM-17 station indicates the basement of Mt.Batur that can be associated with rock intrusion.

VI. CONCLUSION

The 2D models from line 1 and line 2 indicate that there is hydrothermal system below Mt.Batur. The clay cap has a resistivity value < 20 Ωm. This layer appears at the depth of 1000 m below the surface with 200 – 500 m thickness. The reservoir of Mt.Batur geothermal system has a resistivity value 50 – 200 Ωm. The top of this reservoir layer is at the depth of 1500 m with 500 m thickness. The high resistivity zone at the depth of 2000 – 5000 m with resistivity value between 1000 – 5000 Ωm indicates the basement of Mt. Batur that associated with rock intrusion. The geothermal prospect area of Mt.Batur is located at Songan Village alongside the Batur Lake. Our study also reveal two zones of low resistivity area at shallow depth which are attributed to fumaroles and steaming ground located near that area. The high resistivity area at 4 km depth can be interpreted as intrusion of igneous rock.

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