2D INVERSION AND STATIC SHIFT OF MT AND TEM DATA FOR IMAGING THE GEOTHERMAL RESOURCES OF SEULAWAH AGAM VOLCANO, INDONESIA

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ABSTRACT: In order to increase the geothermal exploration, the magnetotelluric (MT) method has been used to study the subsurface of the Seulawah Agam volcano, Aceh Province, Indonesia. Similar to all resistivity methods that are based on measuring the electric field on the surface, the MT commonly contains a static shift problem, which is caused by the heterogeneities near the surface and the different topography of the volcano. The static effect can be expressed as a vertical shift from the apparent resistivity curve. In this study, the apparent resistivity data from the 1D inversion of the Transient Electromagnetic (TEM) method were used to correct the static shift problem in the MT data. Both methods were acquired in the same site at ten stations along with a 12 km distance profile that crosses the Seulawah Agam volcano. The north-south profile of the volcano area appeared to host a geothermal system. The 1D inversion in the TEM data shows a low resistivity layer that indicated a cap rock with a thickness up to 1000 m. The area below the cap rock is estimated to be a reservoir zone while the 2D inversion of MT shows that the deep conductor below 2000 m could be the heat source for the Seulawah Agam geothermal system.

Keywords: Static shift; Magnetotelluric; Time domain electromagnetic; Geothermal exploration

1. INTRODUCTION

In Indonesia, Seulawah Agam has considerable geothermal potential for use as a power plant in Aceh Province, Indonesia. The Seulawah Agam Geothermal Working Area is estimated to have a potential of 130 MW. This considerable potential has encouraged the government to conduct exploration studies in order to accelerate the construction of power plants using renewable energies [1]. The active of the geothermal system is indicated by the appearance of reservoirs fluids that supported by the heat sources, while the hydrothermal rocks as forming geothermal systems are generally located around the reservoirs area. The alteration of the hydrothermal can be obtained by a variety of geophysical parameters, such as resistivity, passive seismic surveys, magnetic and gravity methods. However, the resistivity is the most common parameter that correlated to the geothermal permeability [2].

The resistivity method, which is specifically a magnetotelluric (MT) method, has played a dominant role in the geometric imaging of geothermal prospect location. This is due to the close relationship between the physical parameters in the resistivity of the MT method and geothermal temperature parameters [3]. Furthermore, the MT is a usually most cost-effective method for imaging the geothermal resistivity as it uses a low frequency because it can describe the relatively deep resistivity. Based on the previous research, the Magnetotelluric has been applied for determining the deep source structure of Seulawah Agam, and also the magnetic has been combined with the Very Low-Frequency (VLF-R) for the complementary study in Ie' Jue manifestation area in the volcano. The low resistivity data were very noticeable in the volcano that can be indicated as a geothermal resource [4]. However, the MT data were unable to show detailed structures in the near surface area. Thus, the combined MT and geophysics methods are needed to study the more detailed and comprehensive structures in the areas, such as cap rock, manifestations, and fractures that are usually found at shallow depths [5].

According to [6] Transient Electromagnetic (TEM) method has been widely used along with MT to observe the shallow structure on the geothermal resource, as both methods have a direct relationship with subsurface properties that characterize geothermal reservoirs, such as salinity, temperature, permeability, porosity, rock–water reactions and changes. Additionally, the MT measurements in the geothermal areas often contain a static effect. This is due to the presence of subsurface heterogeneity and significant height variations in volcanic regions [7]. Static corrections can be run by adjusting the MT curve with TEM

data, which have been measured at the same point as the MT sounding [8].

The TEM method is the same concept as the EM Induction that only measured the magnetic field [9], the data are not significantly influenced by their subsurface heterogeneity as they only measure the magnetic field without calculating the electric field running through the electrodes connected to the ground [10]. According to [11] which described the use of TEM data for static effect correction by combining the time shift to obtain the MT equivalent data. In this technique, the MT data will not be distorted at high-frequency intervals according to the depth range of the TEM method. Therefore for comprehensive results, in this study, we use the comparison of TEM and MT data to imaging the shallow and deep structure of the Seulawah Agam volcano. The aim of this research also shows the efficiency of using the TEM data acquired at the same point as the MT sounding for static shift correction.

2. GEOLOGICAL SETTING

Seulawah Agam Volcano is located in Aceh Besar District, Aceh Province. The tectonic activity in Sumatra Island formed a subduction zone due to the collision of the Indo-Australian plate in the South and the Eurasia Plate in the North. The oblique convergence between the two collisions forms a dextral slip called the Great Sumatran Fault (GSF), which extends 1900 km from Lampung to Andaman Sea [12]. According to [13] the volcanic arc along the island of Sumatra is associated with the GSF system (Fig. 1). In the northern part of Sumatra, the GSF is divided into two branches, which are namely the Aceh fault and the Seulimeuem fault. In contrast, Seulawah Agam Volcano is crossed by Seulimeuem Fault in the west [14].

The geological map of the volcano area is shown to be dominated by Lamteuba volcanic rocks. This formation consists of basaltic andesite to dacite, volcanic breccia, tuff, and agglomerates. Furthermore, Seulawah Agam Volcano has two relatively large craters, which are namely the Heutz Crater in the North and Ceumpaga Crater in the South. This volcanic activity is characterized by several traces of manifestations, such as steaming soil, fumaroles and mud. Some hot springs appear in the northwest, such as the Ie Su-uem, Ie Busuk, and Ie Ju hot springs [15].
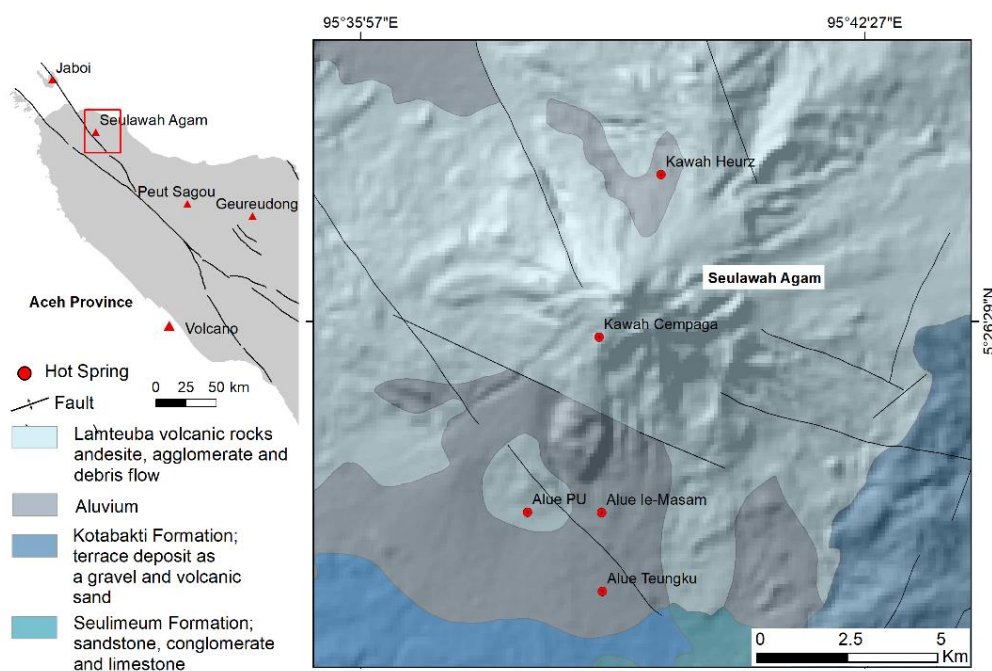

Fig.1 Geological map of Seulawah Agam, which explains the existence of the Great Sumatran fault structure. The geological strata in the study area were composed of the Lamteuba volcanic rocks. The map also shows the manifestation area in the eastern and western sides of Seulawah Agam volcano (red dot).

3. BASIC AND METHODOLOGY

In general, geothermal resources are characterized by low electrical resistivity due to the presence of fluids and conductive temperatures in interconnected pore spaces. MT applications are sufficient for studying geothermal structures. However, the data are unable to provide more details of the near surface

anomalies, such as cap rock fractures and manifestation structures. Thus, a combination of the magnetotelluric (MT) and transient electromagnetic methods (TEM) was applied to produce a high-resolution model for the deep and shallow surfaces.

3.1 Response Function

The signal sources in the magnetotelluric (MT) and TEM methods are very different. MT method uses the time variations of the natural electromagnetic field from the Earth to define the electrical conductivity, while the TEM method drives the electric current into the ground and the created magnetic field is observed at the surface. The MT method has been operated using the tensor impedance (**Z**) as a variable frequency function. This impedance connects the orthogonal components of the € electric field and (H) magnetic in the horizontal plane using the Maxwell equation to produce the half space homogeneous resistivity [16]:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \qquad (1)$$

From the impedance (1), the apparent resistivity in Ωm and phase in degrees can be possibly extracted as a transfer function. The resistivity and phase of a homogeneous half-space are given by:

$$\rho_{a=} \frac{\mu}{\omega} |Z|^2 \qquad (2)$$

$$\varphi_{a=} = tan^{-1} \left(\frac{Im\ Z}{Re\ Z} \right) \qquad (3)$$

Where ω is the angular frequency and μ is the magnetic permeability of material induction. The difference of the phase between electric (E) and magnetic (H) is equal to $\frac{\pi}{4} = 45°$ Where the phase below 45° is interpreted as a conductive zone while the phase above 45° is a resistive area [17]. All the tensor components in the MT methods are composed of real and imaginary parts. The plane wave penetration depth of the electromagnetic wave can be estimated using the following skin depth equations:

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \approx 500. \sqrt{\frac{\rho}{f}} \qquad (4)$$

where f is the frequency and ρ is the general resistivity. The equation shows that the penetration depth in the MT method is not only influenced by the frequency but also by the material's resistivity in the observation area.

Transient Electromagnetic is an active geophysical method that supplies electric currents via a transmitter, the electric is assumed as the primary field which oscillates with time. The transmission is turned off, which produces a current decay induced

below the surface and can be measured with one or more receivers above the surface in the form of a magnetic field. According to [18] the apparent resistivity generated by the TEM method is divided into two, which is namely the early and late parts. Mathematically, the equation can be written as:

$$\rho_{a-early}(t) = \frac{R^3}{3An} V_{coil} \qquad (5)$$

$$\rho_{a-late}(t) = \left(\frac{I\ R^2 An}{20\ V_{coil}} \sqrt{\frac{\mu_0^5}{\pi t^5}} \right) \qquad (6)$$

where R is the distance between the transmitter and receiver, A is the effective observation area in square meters, n is a turns number of the instrument, V_{coil} refers to the output voltage as a function of time in Volts, I_0 is the vacuum permeability in V_s/Am, I is the existing amplitude in Ampere and t is the time after the transmitter is turned off.

3.2 Data Collection

MT data were measured using MTU-5 equipment from Phoenix Geophysics while the PROTEM Receiver time domain system from Geonics was used for TEM data. To combine the results, both of the methods have been conducted in the same stations that can also use as the static correction for the MT method. A total of 10 MT and TEM stations were acquired in the area that crossing the geothermal manifestation in Seulawah Agam, which also correlated to fault structure. The length of the profile is 14 km with interval distances from 1.5 to 2.5 km, respectively. The distribution of MT and TEM stations are shown in Figure. 2. The Depth of Investigation (DOI) for the MT method is influenced not only by resistivity but also by the length of measurement time. Thus, in order to study a comprehensive geothermal resource structure, the MT was acquired in 12 hours to obtain a relatively small frequency.

The transient electromagnetic (TEM) method only measured the magnetic field components that were produced from changes in the electric field against the time taken for the electric current to be inducted into the ground, which was achieved by using the survey equipment. The TEM instrument was measured by a central loop with dimensions of 300×300 m using a square transmitter. An electric current of 10 A was used to generate a strong magnetic field around the loop. The coil loop in the center will record the magnitude of the magnetic field arising from the current induction into the material, which oscillates against the change in time.

4. RESULT AND DISCUSSION

The resources with geothermal potential are indicated by the manifestation area around the volcano. The electromagnetic methods, including the Magnetotelluric (MT) and Transient Electromagnetic (TEM) methods, are effectively used methods for studying the geothermal resource system. It should be noted that the commercial geothermal systems are associated with the presence of rocks with low resistivity and are known as cap rock. The layers with higher resistivity are located directly beneath the cap rock.

On the other hand, the presence of a conductor layer directly above the resistor is quite deceiving because even though this pattern is almost present in all geothermal reservoirs, it is also usually found in non-prospective areas. In such cases, the resistivity pattern of the model can provide the initial

information on the dimensions of the geothermal reservoir [2].

A total of 10 MT and TEM soundings were used in this interpretation. The MT and TEM methods are processed using WinGLink Version 2.20 software. The TEM data are processed by the 1D inversion method with five model parameters and resistivity values of 100 Ωm, which are used as the initial models for a homogeneous half-space. The initial RMS value of 5 can be reduced to 0.5 after the 10th iteration. The RMS defines the data between the measured and calculated values of the diagonal tensor elements, which is weighted by the variance of the measured values. Although the data in the MT method used a 2D inversion method, this inversion uses an invariant mode, which is namely the joint between the TE and TM modes. The RMS value obtained from this inversion is 4.25% with ten iterations.
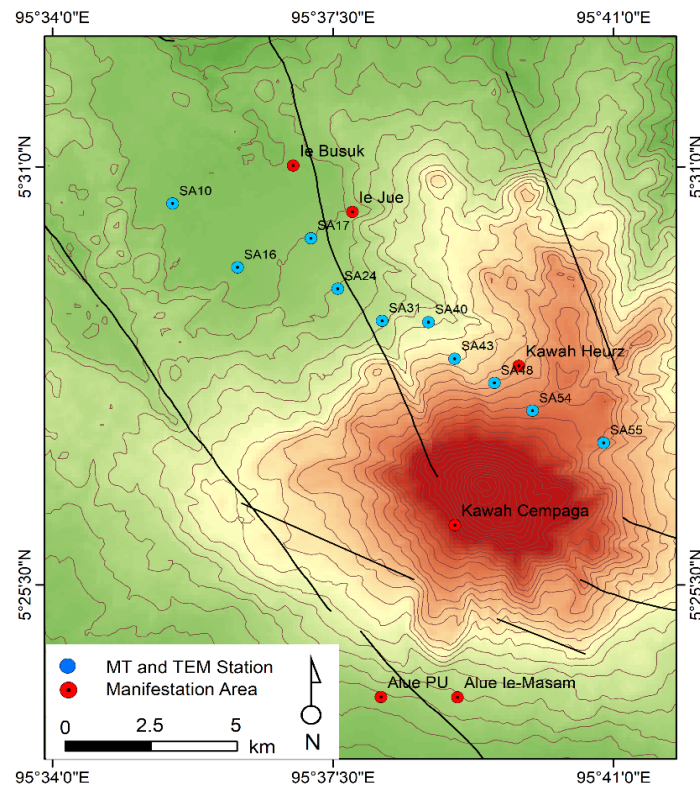

Fig. 2 Location of the MT and TEM station (blue dots) in the Seulawah Agam while red dots is represented as the manifestation area. The maps also show the different topography in the volcano as the red is a high topography and the low area is mapped by green color.

4.1 Static Shift of MT Data

Although MT is widely used in geothermal studies, one disadvantage of this method is the static shift factor that affects the anomalies near the surface. The static shift involves a shifting resistivity curve between the electric transfer (TE) and magnetic transfer (TM). This phenomenon can affect the changes of apparent resistivity in the data

obtained near the surface, which generates different resistivity values from the inversion results. Figure 3(a) shows the MT data that were obtained at the SA55 station. These data represent the response of apparent resistivity and phase in the TE (red) and TM (blue) modes to the frequency of the method. At the high frequencies of 10^2 to 10^{-1}, there is a significant difference in the curve between the two modes at the anomalies near the surface while in the

low frequencies, there is a relatively small difference between the two curves. This is due to the static shift that only occurs in the area near the surface. While in the phase data it can be seen that the response between TE and TM is not different in all frequency, this situation occurs because the static shift has no effect on the phase, but only effect on the electric field in near the surface.
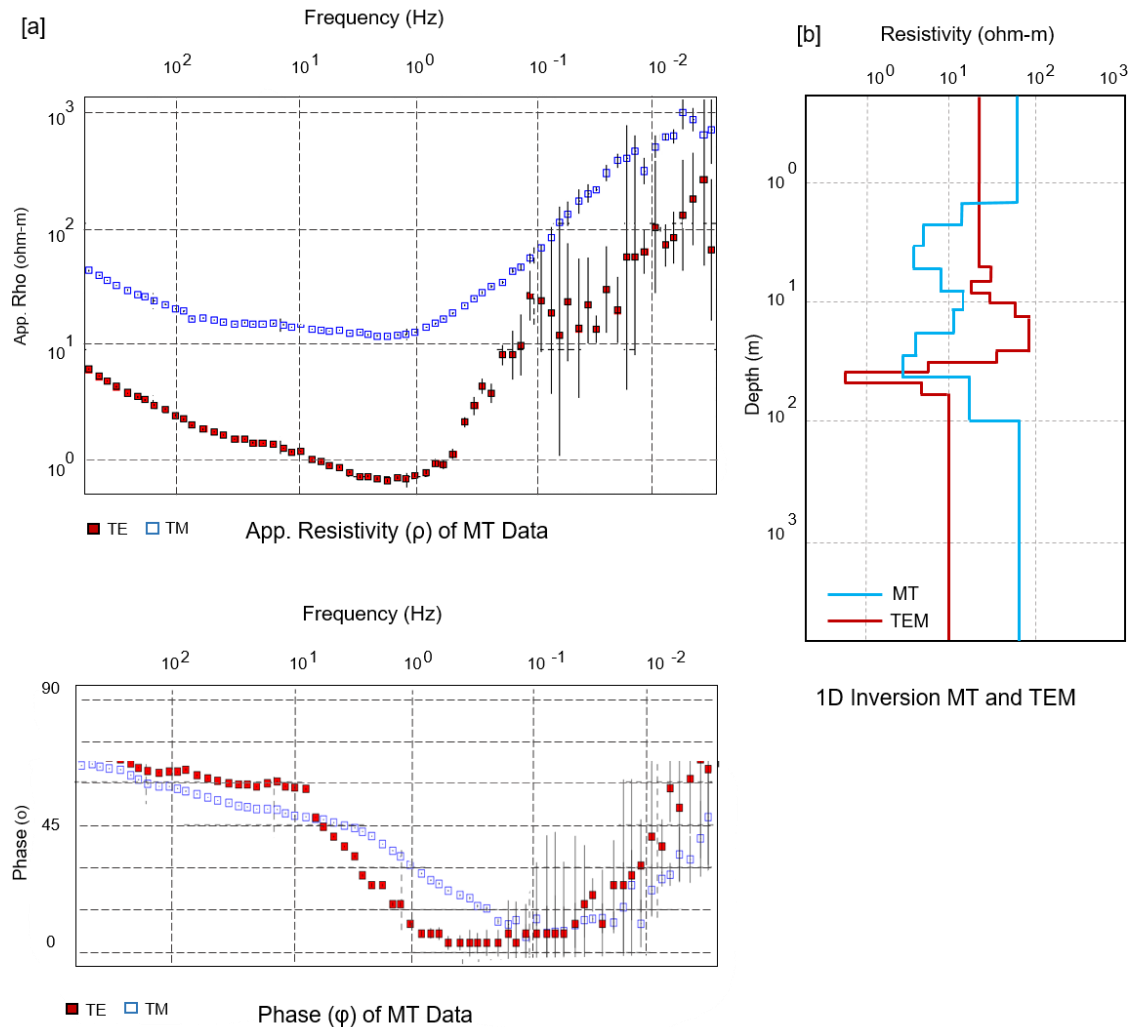

Fig.3 (a) Typical examples of the apparent resistivity and phase data obtained in SA55 station from the MT method, which shows the different apparent resistivity curves in TE and TM modes in high frequency. This indicates the static shift problem while (b) is a different result of 1D inversion of both methods. In this, the red line is an inversion response from TEM and blue is the represented MT inversion.

In addition, the results of 1D inversion from MT and TEM data in Figure (b) show different resistivity values. For example, at a depth of 300 meters, the resistivity value from the TEM data is 102 Ω while the resistivity value is 10-1 according to MT data. On the other hand, at a depth of 800 meters, the resistivity of the MT data is higher than the TEM data but overall, the patterns generated from the two data sets are relatively the same. If the RMS generated from the inversion is smaller than 3% with two iterations, this also indicates a static shift in the MT data caused by the topography of Seulawah Agam Volcano. Dissimilar to the measurement of the MT method that involves the magnetic and electric field components, the TEM method only measures the magnetic field from the decay of the electric field, which oscillates with time. Therefore, the measurement does not cause a static shift in the resistivity data even though it uses a relatively large frequency. There are several ways to conduct static corrections of the MT method, one of which involves integrating the resistivity data from the TEM and MT methods at a frequency close to the surface. This process is done by shifting the

curve of the resistivity value from the TE and TM methods to the actual TEM inversion of the 1D data.

4.2 1D Inversion of TEM Data

Seulawah Agam is an area of enhanced permeability that has geothermal manifestations, particularly in the northern part and southern part of Seulawah Agam Volcano (Fig. 2). Resistivity patterns in most geothermal systems are almost the same throughout the world where there are low permeability and low resistivity layers. A layer with higher permeability and resistivity is located beneath these layers and is known as the reservoir layer. The presence of shallow low resistivity manifestations suggests that there is a surface expression of a major up-flow zone. This can also

be used to interpret the direction of fluid flow to the surface both in the upflow and outflow areas. In this study, the subsurface image of Seulawah Agam Volcano was obtained after the inversion of TEM and MT data at the same measurement station. The deep resistivity image was obtained using the MT method while the shallow structure used the TEM method.

The penetration of the TEM method is not deep enough to determine the subsurface geological structure as the frequency used is relatively high. Therefore, TEM data is used for the static shift correction of MT data and to observe the subsurface geological structure. Furthermore, the TEM model will also be compared with the MT model. In this study, the TEM inversion data only reached 1000 m below sea level as seen in Figure 4.
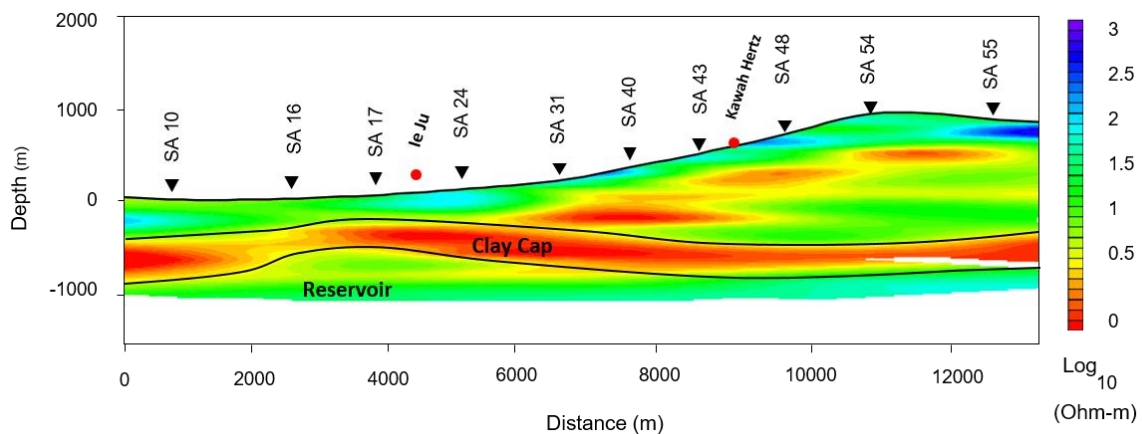

Fig.4 The 2D pseudo section that is derived from the 1D inversion of TEM data. The TEM profile was made by crossing the two geothermal manifestation areas (i.e., Ie Jue and Kawah Hertz) at the point marked by the red dot. The empty area in the figure indicates the inability of the TEM method to image the deep source of the geothermal system.

In general, there are three resistivity layers from the TEM model in this study. The first layer has a high resistivity value in the shallow zone from the surface to a depth of about 200 m. This layer is thought to be correlated to the surface deposits and Lamteuba volcanic products. The next layer is the layer at a depth of 500–1000 m, which has a low resistivity of around 2–5 Ω.m. Furthermore, this layer has a thickness of up to 300 m and extends from the bottom of the volcano to the northwest area of Seulawah Agam Volcano. This zone is thought to have clay minerals due to the alteration of rocks with geothermal fluids, which accumulate in the impermeable zones. These altered rocks are often referred to as the cap rocks. Although not all geothermal fields have a cap rock, this zone helps to determine the top reservoir zone as it is located directly beneath the cap rock, which will later be used in the initial information related to the minimum depth of the drilling point that is

subsequently used to obtain information on the reservoir zone.

The reservoir zone on the Seulawah Agam geothermal field is estimated to be located at a depth of 1000 m below sea level, which is characterized by a higher resistivity value compared to the cap rock with a rock resistivity value of around 12–45 Ω.m. Figure 4 shows that the TEM data measurement station passes two geothermal manifestations, which are namely the fumaroles in Heutz Crater close to the peak of Seulawah Agam Volcano and hot springs in the Lamteuba area northwest of the volcano peak.

However, the permeable areas where the fluid exits from the surface are not explicitly seen in the TEM model. This is likely to be due to the sensitivity in the electromagnetic method, which cannot detect permeable zones that are adjacent to the impermeable zone in the form of the cap rock layer, which has a thickness greater than the permeable zone where the fluid exits.

4.3 2D Inversion of MT Data

The penetration range of the MT method is deeper as it reached a depth of 4000 m as shown in Figure 5. However, the resolution of the inversion results near the surface is poorer compared to the TEM method despite the static correction. In general, there are three different resistivity layers in the inversion results. The top layer is the most conductive layer with a thickness of 1000–1500 m and has a resistivity value of 10–100 Ω.m.

This layer is predicted as an impermeable zone or to be composed of cap rocks containing thermal fluid that is moving to the surface. The subsurface inversion results of both the TEM and MT models are quite different. In the MT model, the permeable zone where the thermal fluid flows to the surface is clearly seen, which occurs namely where the fumaroles in the Heutz and Lamteuba Craters and Ie Ju hot springs exits the surface. This is presumably due to the wider frequency range of the MT method, which enables a wider model scope when inversion is carried out. Thus, the undetected fluid paths within 1500 m in the TEM method can be detected using the MT method. Some zones between Ie Ju and Heutz Crater indicate local

structures although there are no manifestations near the surface. The fluid reaching the surface is thought to be trapped by an impermeable zone or just exist in the form of steaming ground so that no manifestations appear on the surface. The next layer is thought to be a reservoir zone, which has an approximate resistivity value of 10–100 Ω.m with a thickness of approximately 1000 m. The top reservoir zone is predicted to be at a depth of 1000–1500 m below sea level. Similar to the cap rock zone that extends to the northwest of the study area, the reservoir zone is also predicted to be quite long.

However, only drilling can confirm whether this reservoir layer has thermal fluid for generating electricity. The last layer is the most resistive layer compared to the cap rock and reservoir layer. This heat source has a resistivity value of around 300 Ω.m. This layer is over 2500 m deep and is located directly below the Seulawah Agam Volcano and extends to the northwest of the study area. When associated with a geothermal system, this layer is predicted to be a heat source from the geothermal system in Seulawah Agam. When viewed from the resistivity model, the heat source in this area is quite large with a width of 10 km or even wider.
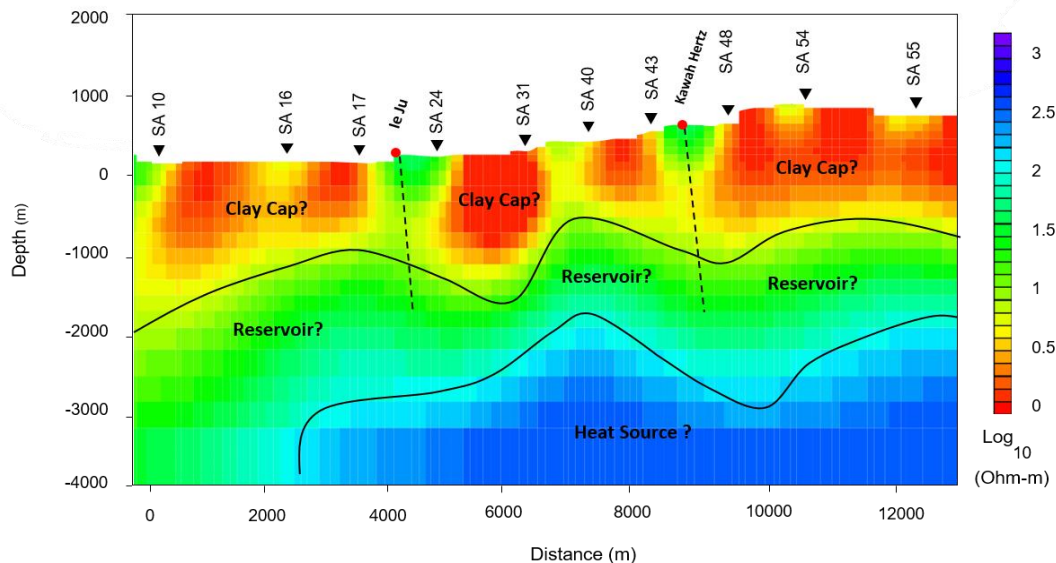

Fig.5 Resistivity section derived from 2D inversion of MT data. The black dotted line in the figure indicated the fault where the thermal fluid exits towards the surface.

5. CONCLUSION

The static shift in the MT data obtained for geothermal exploration in volcanic environments can be a significant problem. The shifts can be due to the shallow resistivity in homogeneities and topography. The former reason is the dominant factor, with the topographic effects superimposed on top of this shallow resistivity. The interpretation of MT data without static shift corrections can cause

errors in the obtained model. It is demonstrated that the inversion of MT with TEM data is an effective and consistent way to correct for the shifts.

Although, the model near the surface from the TEM method is better than that from the MT method despite the static shift correction. Furthermore, Seulawah Agam has geothermal potential as shown by the resistivity cross-sections. Clearly, the low resistivity layer occurs up to a thickness of 1000 m according to both the TEM and

MT data and is interpreted as being composed of cap rock. This zone is estimated to have a thickness of up to 1000 m. The layer below the cap rock is estimated to be a reservoir zone. The permeable pathway that is interpreted as the path of the manifestation fluid is also clearly seen in the MT model although it is not seen in the TEM model. The deep conductors below 2000 m b.s.l. could be the heat source for the Seulawah Agam geothermal system, which is located directly under Mount Seulawah Agam and extends to the northwest side of the research area.

6. ACKNOWLEDGMENTS

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