Curve splitting analysis of synthetic MT data to identify permeable zone at geothermal field “X”

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Abstract. The permeable zone is one of the important parameters in the geothermal system. Its existence is influenced by fractures or faults generated within the geothermal reservoir. Due to the continuous influence of both high temperature and pressure, reservoir rocks are stressed and tend to cause a fracture. Unfortunately, some fractures are generally not continuous to the surface, so that geological data are not able to map out the presence of this structure. While the presence of the fracture zone greatly facilitates fluid mobility in the reservoir including heat transfer from the heat source convectively. Mapping the presence of a subsurface fracture zone is not easy. The study aims to identify the existing fracture zone through curve splitting analysis of MT data (magnetotelluric). The data used here is synthetic MT data. The fracture zone is a heterogeneous zone and anisotropy for EM waves. Splitting TE and TM curves will happen when the MT wave passes through this zone. The analysis of curve splitting provides depth penetration value. Therefore, the existence of fault as the cause of curve splitting can be mapped. From the results of forward modelling, the curve splitting approach can map very well the existence of the subsurface fault. For medium/rock resistive, the deviation of its dip value is only 1.36%. When the rock medium is highly conductive the deviation of its dip value up to about 3.48%. This is due to the absorption of EM waves by the conductive layer so that it is not effective in mapping the underlying layer.

1. Introduction

The magnetotelluric method (MT) is one of the excellent geophysical methods for mapping conductive layers beneath the earth's surface. Particularly in the geothermal prospect area, the MT method is good in mapping geothermal systems because the method was usually sensitive to detect a conductive cap rock layer [1, 2]. Even though the method cannot be said to unequivocally detect the reservoir, the method can delineate the clay cap [3]. The rock layer is clay that resulted from rock alteration of the hydrothermal process. Geothermal fields are located in mountainous areas that are dominated by volcanic rocks that have unique resistivity and conductivity characteristics. The penetration of MT methods in the geothermal prospect region is greater than other methods. The method utilizes electromagnetic (EM) waves from nature derived from the ionosphere, which induces subsurface materials to obtain information about subsurface conductivity structures [4].

The propagation of electromagnetic waves has transverse electric (TE) and transverse magnetic (TM) modes. Both modes are an important role in the magnetotelluric method. Xiao said that the TE mode is a component that shows an electric field parallel to the direction of the strike, and not being able to drain current across the boundary between regions having different resistivity values [5]. While
the TM mode is a component that shows a magnetic field parallel to the direction of the strike that has the properties of an electric current that can flow over the boundary between the parts that have different resistivity.

Subsurface conditions that have different conductivity values, there will be an interesting phenomenon that separates the TE and TM curves caused by the difference in the conductivity of the rock structure [6]. The uncertainty of surface conductivity causes a drastic value in the electric field perpendicular to the strike, $E_y$ direction field referring to TM mode. This causes TM mode to have lateral sensitive change properties compared to the TE mode. In TE mode, it has a vertical magnetic field that affects the sensitivity of the subsurface conductivity. This characteristic difference that causes the separating of the TE and TM curves on vertical contact, this phenomenon is called curve splitting [7].

The permeable zone is one of the parameters calculated in the search for a geothermal reservoir [8, 9, 10]. By looking at the geological conditions of the prospect area, the permeable zones can be determined. The geological method used is only able to know the condition of structures on the surface of the earth. Find out the continuity of existing geological conditions on the surface is not easy to calculate. Using curve splitting analysis, it is expected to know the subsurface permeable zone and make a model of the permeable zone beneath the earth's surface [11].

2. Method
The curve splitting analysis is firstly done on the synthetic data model. Three different subsurface models are made to see the EM wave’s response to this splitting curve phenomenon. The first model has shaped two layers of rock that has a resistivity contrast in the form of a fault structure with a dip of $90^\circ$. While the second model with a dip on the fracture structure of $+60^\circ$ and $-60^\circ$. Both models still use rocks that have relatively high resistivity. The third model used a structure very similar to the conditions in a geothermal system. This third model consists of several resistive rocks with different values and a single layer of clay cap conductive rock that forms the cover of the reservoir layer. After analyzing the curve splitting among these models then finally, the curve analysis is implemented on the real data in the geothermal field "X".

3. Results and Discussion
In this paper here, for a technical reason, the third model only is displayed. The forward modeling creating synthetic data from h1 station until h10 station that is pulled horizontally. The determination of station line based on the cross-section that similar to a geothermal system. Resistivity determination is selected 100 $\Omega$m which is a depiction of rock that is not altered up to a weathered rock, then the clay cap that has resistivity 5 $\Omega$m with the thickness of 1500 m. In rocks that describe the reservoir has a resistivity value of 60 $\Omega$m and a thickness of 3000 m. There are basement rocks that form the structure of recharge and discharge zones that have a value of 250 $\Omega$m. This basement is on the right and left sides of the reservoir as a non-altered rock. Last is a description of source rock with a resistivity value of 1000 $\Omega$m. The heat source rock is considered as a magma body in the form of an intrusion dike from inside the earth. Figure out of the model can be seen in Figure 1.

The results of the TE and TM curve at each station are shown in Figure 2. These TE and TM curves represent the resultant response of the electric field (TE) and magnetic field (TM) of all subsurface rocks. One characteristic of the resistivity curve that reflects the geothermal reservoir area is its H type shape. Apparent resistivity again to depth is generally high, low, and high again. The variation of resistivity reflects the existence of a non-alteration rock layer, a conductive clay cap layer, and a relatively resistive reservoir layer. In Figure 2, the resistivity curves reflect this characteristic very well.
Figure 1. An ideal model of a geothermal system. The X and Y-axis represent the length of a section line (in meters) and depth (in meters), respectively.

Figure 2. Curve splitting results at station h1 – h10. Splitting the TE and TM curves occurs when the EM waves pass through a medium that has resistivity contrast.

Figure 2 shows that each station point of measurement synthetic data generated the processed TE and TM curves. At each point, there is a difference in resistivity value so that the curve splitting occurred at each MT station. The TE and TM curves are displayed in the rho app (Ohm.m) and period (second) axis. There is an interesting phenomenon, the curves in h4 to h7 have splitting twice. However, we focus on the first split only since the second split has a skin depth value incompatible with the state which can penetrate a highly conductive layer of rock structure. Further observation of X and Y-axis parameters is taken into consideration at the time of the split curve. Then the X-axis which is the period axis converted into a frequency to know the skin depth of each point for the next analysis stage. The results of the skin depth calculation of each station are shown in Table 1.
Let see qualitatively at stations h4 to h7 that below them there is a clay conductive layer. The results of the skin depth show stations h4 and h7 had a deeper value than the skin depth at stations h5 and h6. This gives an illustration that if there is a highly conductive layer below an MT station, then it will affect the station to record and obtain a deep skin depth value. The EM waves will be absorbed and attenuated by the relatively conductive layer. Clay structures are the main cause of the lowest resistivity values in geothermal systems [12].

Table 1. Skin depth calculation based on synthetic model data of Resistivity and Period.

| STATION | RESISTIVITY (Ohm.m) | PERIOD (Second) | FREQUENCY (Hz) | SKIN DEPTH (m) |
|---------|---------------------|----------------|----------------|----------------|
| h1      | 86                  | 0.249          | 4.016          | 2327.65        |
| h2      | 74.4                | 0.158          | 6.329          | 1724.58        |
| h3      | 82.1                | 0.0397         | 25.189         | 908.10         |
| h4      | 16.5                | 1.0098         | 0.990          | 2053.18        |
| h5      | 35.4                | 0.1            | 10.000         | 946.39         |
| h6      | 36.8                | 0.1            | 10.000         | 964.92         |
| h7      | 17.2                | 0.995          | 1.005          | 2080.86        |
| h8      | 82.1                | 0.0391         | 25.576         | 901.21         |
| h9      | 77.3                | 0.158          | 6.329          | 1757.87        |
| h10     | 86                  | 0.249          | 4.016          | 2327.65        |

The following phenomenon shows that the synthetic MT data at stations h1 to h3 and h8 to h10 have the same skin depth character in determining the slope. However, we here only concern with the most conductive layer. The slope value of the conductive structure can be obtained easily and correctly. The EM wave is sensitive to the conductive medium and the EM wave will be absorbed in this layer. The geothermal system generally consists of 4 main parameters: very resistive hot rock of heat source, relatively resistive reservoir, faults structure, and conductive clay cap layer. So, the phenomenon of splitting curve analysis able to detect the existence of the conductive clay layer in the geothermal system.

It is well known that the EM waves radially propagate beneath the earth's surface in the form of half a ball. The EM wave's skin depth will be calculated as a semicircle radius since the EM waves are considered to propagate through the homogeneous earth's layer. Two characteristics of curve splitting are found. Both of them occur on the structure under the clay, so it is used to determine the clay limit on the model.

The study is focused on stations h4 to h7 to determine the contact boundary contained in the model of the geothermal system. The skin depth produced at stations h4 and h7 has the same depth and as detected clay bottom layer boundary. While the stations h5 and h6 have skin depth values less than the values found as the boundary of the conductive layer. The stations h5 and h6 could not be able to detect properly the clay bottom contact boundary. The depth penetrations are shown in yellow vertical lines of Figure 3.

The described conductive layer is a clay cap layer with a slope. It has been proven in curve splitting analysis that there is a conductive cap rock layer. The lines (the vertical yellow dots lines shown in Figure 3) drawing on the skin depth is generated to see how big the angles are generated from curve splitting analysis. The dip of structure that will be a tangent line of intersecting semicircles is found. The line will be used to determine the angle generated by the propagation of the EM wave.

The result of the modeling shows that there is an angle generated in a part of h1 to h3 and part of h8 to h10 as shown in Figure 3. The dip of the real conductive structure model is 57.03°. The generating angle in the modeling is 54.91° and 55.04°. Both generated angles close to the slope angle of the
The deviation for detecting dip structure with high conductivity layer is about 3.48%.

![Figure 3](image)

**Figure 3.** Model of electromagnetic waves propagation and body contact modeling based on analysis of curve splitting.

This model is applied to real data in the geothermal prospect area "X" Mount Lawu. The results obtained indicate a curve splitting from TE-TM mode. It is suspected that the curve splitting is strongly associated with the presence of a clay cap layer at a shallow depth. Apart from causing a curve splitting, the presence of this clay cap layer unfortunately also absorbs EM waves so that the depiction of the permeable reservoir layer which is deeper in its position is noisier (see Figure 4). The indication of a geothermal reservoir in this field is quite well illustrated from the resistivity curve pattern of the MT data in the type of H-shaped. 2D modeling result of the resistivity section also shows a less clear subsurface resistivity image (see Figure 5). However, this curve splitting analysis model has been successful in detecting the presence of subsurface resistivity contrast. Unfortunately, it does not map well the permeable reservoir layer and more effort is required to increase the S/N ratio to overcome this.

![Figure 4](image)

**Figure 4.** The resulting curve splitting at the stations MTGL06, MTGL07A, MTGL04, and MTGL05 geothermal field "X".
Figure 5. Result of 2D inversion modeling of MT data for geothermal field "X".

4. Conclusion
Curve splitting analysis can be used to detect the existence of subsurface fracture structures. The method can detect the horizontal clay layer model. The result will be more accurate if the measurement is done in the resistive area. From modeling with medium to low conductivity rocks, the deviation result of structures dip is about 1.36% only. While in highly conductive areas, the deviation could reach 3.48%. The existence of subsurface conductive layers can decrease the accuracy of the measurement results. The existence of a clay cap conductive layer above the geothermal reservoir makes curve splitting analysis work not optimal. In this study, we were unable to properly map the permeable zone of the "X" field geothermal reservoir by using curve splitting analysis, because the reservoir is covered by a conductive and absorber clay cap layer.

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References
[1] Oskooi B and Ansari S M 2012 Application of Magnetotelluric method in exploration of geothermal reservoirs with an example from Iceland, *Journal of the Earth and Space Physics*, 37 (4)
[2] Singarimbun A, Gaffar E Z, and Tofani P 2017 Modeling of reservoir structure by using magnetotelluric method in the area of Mt. Argopuro, East Java, Indonesia, *Journal of Engineering and Technological Sciences*, 49(6). DOI: http://dx.doi.org/10.5614%2Fj.eng.technol.sci.2017.49.6.9
[3] Pellerin L, Johnston J M, and Hohmann G W 1996 A numerical evaluation of electromagnetic methods in geothermal exploration, *Geophysics* 61(1) 121–130
[4] Christensen A, Auken E, and Sorensen K 2006 The transient electromagnetic method, *Groundwater Geophysics*, 71 179-225.
[5] Xiao W 2004 Magnetotelluric Exploration in the Rocky Mountain Foothills, Alberta (University of Alberta)
[6] Onacha S A, Shalev E, Malin P, Arnasson K, and Palsson B 2007 Hydrothermal Fault Zone Mapping at Krafla Geothermal Field Using Seismic and Electrical Measurements, *Proceedings of INAGA Bali Seminar*
[7] Malin P 2007 Well Targeting Using Joint Geophysical Methods: New Techniques for Exploration and Modelling Proceedings of INAGA Bali Seminar

[8] Lima E, Tokita H, and Hatanaka H 2013 Reservoir Engineering in Geothermal Fields DOI: https://doi.org/10.1007/978-1-4614-5820-3_299

[9] Brehme M, Blöcher G, Cacace M, Deon F, Moeck I, Wiegand B, Kamah Y, Regenspurg S, Zimmermann G, Sauter M, and Huenges E 2016 Characterizing permeability structures in geothermal reservoirs – a case study in Lahendong Proceedings of 41st Workshop on Geothermal Reservoir Engineering Stanford University (Stanford, California, February 22-24, 2016)

[10] Vidal J, Genter A, and Chopin F 2017 Permeable fracture zones in the hard rocks of the geothermal reservoir at Rittershoffen, France. Journal of Geophysical Research: Solid Earth, 122(7) 4864-4887

[11] Daud Y, Nuğramadha W A, Heditama D M, Fahmi F, Pratama S A, and Hadi J 2015 Identification of subsurface geological structure in a geothermal system using MT imaging technology Proceeding of World Geothermal Conference (Melbourne 19-25 April 2015)

[12] Ussher G, Harvey C, and Johnstone R 2000 Understanding the resistivities observed in geothermal systems (Japan. Kyushu University)