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Identification of Subsurface Geological Structure in a Geothermal System Using MT Imaging Technology

Yunus Daud[1], Wambra Aswo[1,2], Dzil Mulki[1,2], Fikri Fahmi[1,2], Surya Aji Pratama[1,2], Julfi Hadi[3]

[1] Master Program in Geothermal Exploration, Graduate Program of Physical Science, The University of Indonesia

[2]PT. NewQuest Geotechnology, Indonesia

[3]PT. Supreme Energy, Indonesia

ydaud@sci.ui.ac.id

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ABSTRACT

Development of a geothermal resource has naturally high risks, while the highest risk is faced in the upfront stage (i.e. resource risk). Accordingly, better understanding of the subsurface condition should be achieved by integrating high quality geoscientific data to develop a geothermal conceptual model. Exploratory well targets are then determined on the basis of the conceptual model. The subsurface drilling target is actually directed to high temperature and high permeability zone. Temperature profile could be approximated by using subsurface resistivity values derived from MT data. Base of conductive zone (BOC) in a high temperature geothermal system usually correlates with temperature of about 180-200°C. The next challenge is to determine permeable zone. The permeable zone is usually associated with subsurface geological structures. Geological mapping could only figure out geological structures indicated at the surface. However, continuation of the geological structure into the subsurface is difficult to detect. Various technologies are developed to answer it. One of them is by using magnetotelluric technology. The existence of the structure can be indicated by resistivity contrast caused by the structure filled with fluid or contact with other formation which have different resistivity values. This condition will produce splitting on the curve and impedance polarization of MT data as the response of the structure. How big the contrast of the resistivity will affect the pattern of the splitting curve, and so the distance between MT stations with the location of structures will affect the frequency at which the splitting occurs. While the elongation of polar diagram could provide information on the strike direction, in which polar diagram give the response of relatively parallel or perpendicular to the strike. This paper demonstrates the ability of MT technology for delineating the subsurface geological structures using 2-D and 3-D forward modeling/simulation of synthetic MT data as well as real MT data.

1. INTRODUCTION

Exploration stage in geothermal development is a crucial and challenge stage, since it has naturally high uncertainty about the reservoir geometry, permeable zone, temperature, resource potential and fluid characteristics. The uncertainty will be more pronounced where the reservoir is deep and concealed without any indication of surface thermal manifestations. Accordingly, better understanding of the subsurface condition should be achieved by integrating high quality geoscientific data to develop a geothermal conceptual model. Exploratory well targets are then determined on the basis of the conceptual model.

There are two criteria in selecting the best drilling targets: high temperature and high permeability. High temperature zone is associated with the position of heat source, while high permeability is related to the zone of high fracturing which is associated with geological structure (i.e. fault/fracture). Subsurface temperature distribution can be assessed using subsurface MT resistivity distribution, especially the base of low resistivity (clay) layer (Ussher et al., 2000). In addition, investigation of high permeability zone is a challenge task. Even though fault structures can be identified in the surface, it is challenging to investigate those in the subsurface. Accordingly, research has been focused in how to develop a proper geophysical technology to detect the subsurface structure. One of them is MT imaging technology. The basic principle is that the fault structure can be indicated by resistivity contrast produced by conductive fluid filling the fracture zone or produced by different formation with different resistivity. The resistivity contrast causes MT curve splitting and impedance polarization.

This paper describes the ability of the MT imaging technology for detecting subsurface geological structure using 2-D and 3-D forward modeling. Moreover, the curve splitting and impedance polarization phenomena are also demonstrated by using synthetic MT data. In addition, application of this technique to the real MT data will also be presented in this paper using MT data from Muara Laboh geothermal field, Sumatera (Indonesia).

2. METHOD REVIEW

2.1 Basic Concept

Curve splitting of TE (Transverse Electric) and TM (Transverse Magnetic) mode and impedance polarization of MT data is caused by subsurface electrical discontinuity (Figure 1 and Figure 2). The physical principle governing induction at a discontinuity is conservation current. Figure 1 shows a very simple 2-D scenario with a vertical contact between two zones of different conductivity, σ_1 and σ_2 (Simpson & Bahr, 2005). The current density, (j_y), across the boundary is given by:

$$j_y = \sigma E_y \tag{1}$$

Subsurface electrical discontinuity causes discontinuity in electric field (Ey) triggering discontinuity in TM mode. Edge effect causes TM mode is more sensitive to the lateral change than TE mode. However, TE mode is associated with vertical magnetic field influencing sensitivity to the subsurface conductivity. The difference of characteristics causes splitting between TE and TM modes of the vertical contact.

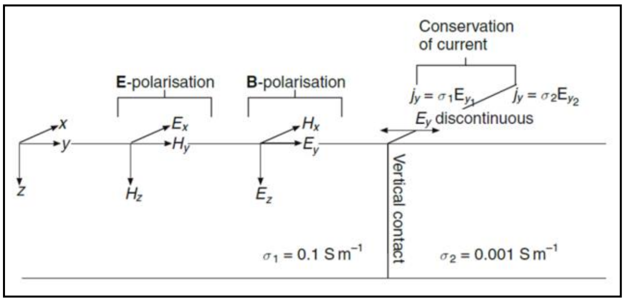

Figure 1: Simple 2-D model composed of quarter-spaces with different conductivities meeting at vertical contact. Conservation of current across the contact, where the conductivity change from σ1 and σ2, leads to the y-component of the electric field, Ey, being discontinuous (Simpson & Bahr, 2005).

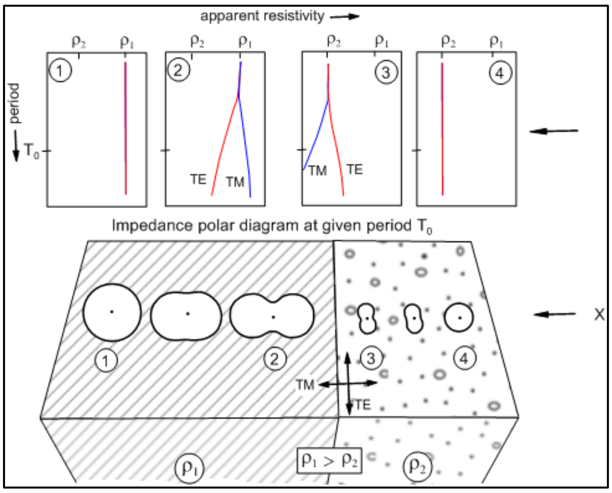

Figure 2. Curve Splitting (above) and impedance polar diagram (below) phenomena at MT station 1, 2, 3 and 4 (Vozoff, 1991).

2.1 Forward Modeling of Curve Splitting Phenomena

Splitting of MT data curve at certain frequency range usually occurs because of vertical contact in the subsurface. The following illustration explains the forward modeling process using MT2DMod-X and MT3DMod-X software developed by PT. NewQuest Geotechnology. In forward modeling, a model consists of two bodies with 300 ohm-m on one side and 10 ohm-m on the other side are in vertical contact. This vertical contact is made to have a certain slope and defined as a fault structure. Forward process is then being performed to the model so MT curve will be obtained as shown in Figure 3.

Structure located near MT stations, can cause splitting on the MT curves. The splitting pattern really depends on how much impact of the structure towards the MT data. One of the effecting factors is the distance of the structure to the MT station. From the forward modeling result we can see that the closer it is to the structure, the higher the frequency is where splitting occur.

2.2 Forward Modeling of Impedance Polar Diagram Phenomena

To determine the existence of a structure, impedance polar diagram of MT data can be analyzed by utilizing impedance data using MT3DMod-X software. Starting from a tensor impedance which is derived from measurements, and assuming 2-D conditions, several different ways have been used to find the rotation angle between measurement direction and strike. One of these is rotation the impedance Zij in steps, plot them on a polar diagram, and pick an optimum angle from the plots. An optimum angle maximizes or minimizes some combination of the Zij. These interesting diagrams, called impedance polar diagram, are usually plotted at many frequencies, because in practice the strike direction often changes with depth (Vozzof, 1991). Figure 4 illustrates an example of 3-D forward modeling of impedance polar diagram. Polar diagram of impedance (at certain frequency), and apparent resistivity, at a hundred stations on simple 3-D vertical contact model. TE and TM based on Transverse Electric (E || strike) and Tranverse Magnetic (H || strike) field polarization.

The elongation of polar diagram could provide information on the strike direction, in which polar diagram of the MT station located at the left side of the structure (conductive zone with resistivity of 10 ohm-m) give the response of relatively parallel to the strike, while the polar diagram of the MT station located at the right side of the structure (resistive zone with resistivity of 300 ohm-m) give the response of relatively perpendicular to the strike. From this simulation, it can be understood that the location of the fault structure can be detected.

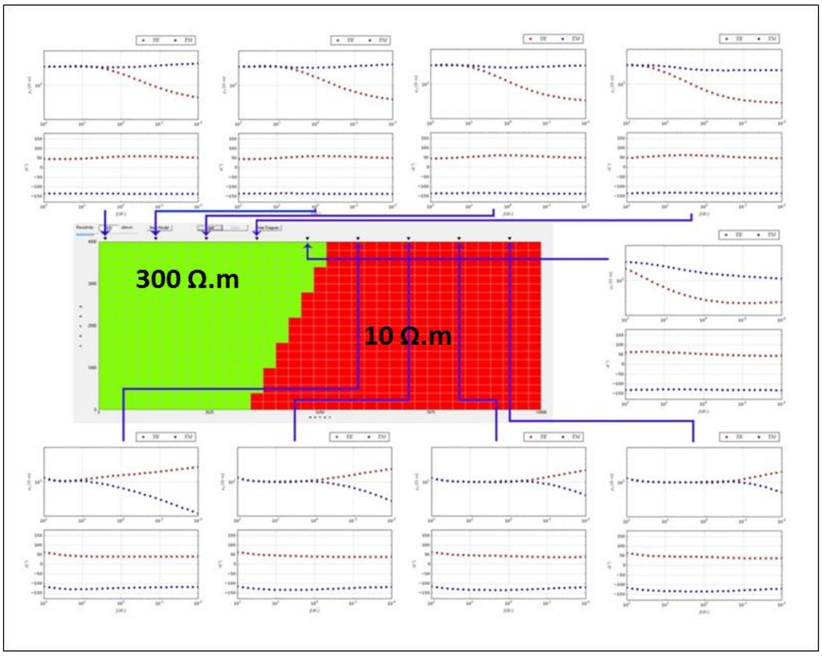

Figure 3. Forward modeling result to see effect of vertical contact structure to MT curve

Figure 4: Forward modeling result to see change of polar diagram from caused by vertical contact

3. APPLICATION OF THE MT IMAGING TECHNOLOGY

Analysis of the MT curve splitting and impedance polar diagram in identifying subsurface geological structure has been tested in Muara Laboh geothermal field in West Sumatera, Indonesia. Fault structures indicated in the surface from remote sensing data are identified using MT data. The position of the structure and MT stations are shown in the Figure 5.

3.1 Curve Splitting

Identification of curve splitting in detecting fault structure is represented with 5 MT data along Line WE (i.e. MT01, MT02, MT03, MT04 and MT05). Two MT stations (MT02 and MT03) are located close the fault 2 (crossing the Line WE), while the others are located relatively far from the fault 2. Result of the simulation shows that MT02 and MT03 experiences strong splitting (see Figure 5 (C)). While the other curves (MT01, MT04 and MT05) experiences less splitting effect or splitting effects occur in the lower frequency, since their positions are relatively far from the location of fault 2. The splitting curve occurred at MT05 data is due to its position to the location of other fault (not shown in the Figure 5 (A)).

3.2 Polar Diagram

Elongation pattern of the impedance polar diagram shows suitability with the strike of the fault structures. It is shown by the parallel elongation of the polar diagram with fault structure. On the contrary, the elongation of the polar diagram of the MT stations located between the two faults shows perpendicular with the fault strike. It means that the zone between the two faults is more resistive than the other sides from the faults.

3.2 Correlation between MT Imaging Data and Well Data

Figure 5 (D) shows the resistivity distribution derived from 3-D inversion of MT data, fault structure, well trajectory and indication of feedzone (FZ). The resistivity distribution shows a low resistivity zone at the shallow depth with the thickness varies from thinning to west gradually thickening to the east. More resistive zone can be found in the western part. Base of Conductor (BOC) which is usually associated with the top of reservoir is also shown with white dashed line. Fault structure is indicated by the contrast resistivity as shown by black dashed line. The well trajectory penetrates a permeable zone in the intersection between the indicated fault structure and BOC at depth of about 820 meter (Humaedi et al., 2013). This is shown by the feedzone (FZ) found at depth about 820 m, 1080 m and 1400 meter (Figure 5 (D)). Moreover, the temperature of the fluid produced is more than 250 ^oC. The well productivity is appoximately 20 MWe (Humaedi et al., 2013).

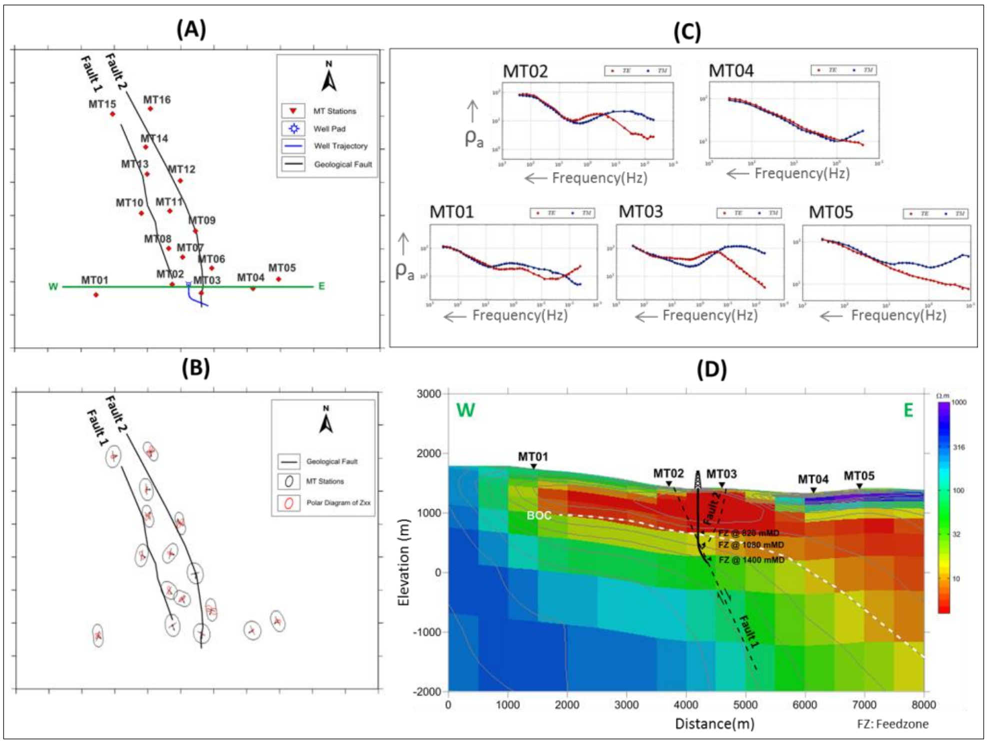

Figure 5: (A). Map of MT stations for analyzing Impedance Polar Diagram. Line WE is a line for analyzing Curve Splitting and resistivity distribution derived from 3-D inversion of MT data. (B). Impedance Polar Diagram of 16 MT data at frequency 10 Hz. (C). MT curve splitting results of MT data along Line WE. (D). Resistivity distribution derived from 3-D inversion of MT data.

4. CONCLUSION

Identification of geological structure at surface such as fault, graben and caldera rim structure can be identified using remote sensing data. However, continuation (existence) of the structure in the subsurface is challenging to discover. Many efforts have been attempted to develop a proper technology in delineating the geological structure. MT imaging technology is proposed to characterize the subsurface geological structure by identifying Curve Splitting, Impedance Polar Diagram of MT data. In addition, 3-D imaging technology can also be utilized for identifying the subsurface structure indicated by the curve splitting and impedance polar diagram. This method has been demonstrated using 3-D forward modeling simulation. Moreover, this method has also been tested using real MT data from Muara Laboh geothermal field (Indonesia) cross-checked by well data. The result showed good correlation between MT data and well data. However, further study of this method using real MT data from various geothermal area are needed to verify the reliability of this technology.

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