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RESEARCH ARTICLE

Investigation of Geological Structure Using Magnetotelluric and Gravity Data Optimization on Non Volcanic Geothermal, Bora, Centre of Sulawesi

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Abstract

The existence of geological structures is one of the important parameters in determining the permeability zone in a geothermal system. This research was conducted in a non-volcanic geothermal field, Bora, located in the province of Central Sulawesi, aiming to identify the subsurface features, especially geological structures related to permeability zones by optimizing geophysical data. Magnetotelluric (MT) 3D inversion modelling is some of the latest methods to identify geological structural patterns in geothermal systems. The results of the MT model and analysis its parameters can find variations in the distribution of subsurface resistivity, orientation of the direction of the prospect area, and indications of geological structure zones. The type and geometry of the geological structure associated with the high permeability zone can be complemented by determining the contrast of gravity values and analysis of the maximum First Horizontal Derivative (FHD) and zero of the Second Vertical Derivative (SVD). Based on the analysis of geophysical data, it is possible to identify the permeability zone associated with the main structure, namely the Palu-Koro fault, delineate the geothermal reservoir at a depth of 1500-2000 meters and determine the location of well drilling. To visualize the geothermal system comprehensively, a conceptual model is developed by integrating the geophysical model with geological and geochemical data that are correlated with each other, therefore it can assist in determining the location of production well development.

Keywords: Non-Volcanic Geothermal System, Geological Structure, 3D Inversion Magnetotelluric, Permeability

1. Introduction

The Bora geothermal field is classified as a type of non-volcanic system. It is located on one of the fault zones systems namely Palu-Koro Fault. This region's geology is composed of Pre-Tertiary metamorphic rocks, Tertiary plutonic intrusive rocks, and Quaternary sediment. Current tectonic activity is probably causing the formation of a depressed zone, which sets off a rock intrusion process that transfers heat effectively. Geothermal manifestations in Bora Village seem to be driven by hydrothermal activity in the Palu-Koro Fault zone. This fault is trending northwest to south-southeast which is in the Central Sulawesi Arm (PSDG, 2010). The permeable zone inside the geothermal reservoir can be controlled by geological features like faults. It is a difficult task to map the presence of subsurface fracture zones since some features, such as faults or fractures, are typically not connected to the surface. Therefore, this research has focused on how to optimize geophysical technologies to determine the geological structure.

The Magnetotelluric (MT) method is very efficient in assisting geothermal exploration stages, with greater penetration than other methods. The relationship between resistivity and clay mineral content allows the use of the MT resistivity cross-section to determine the conductive layer as a clay cap in the geothermal system. Although the reservoir cannot be definitively identified using this method, the bottom of the clay cap (BOC) can be distinguished (Ussher et al., 2000). Analyzing parameters is one method of improving geothermal system comprehension. By using the outcomes of the 3-dimensional inversion derived from the MT model, it was possible to analyze the splitting pattern from the MT curve, the orientation elongation of polar diagrams, as well as the delineation of subsurface structures.

In addition, the identification of geological structures from MT data can be assisted by gravity analysis. This method utilizes the measurement of the gravitational field at the earth's surface. Gravity data are analyzed using the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) techniques (Daud et al., 2019). This study was conducted to identify feature anomalies in order to find fault types and geological structures. The permeability zone should be more clearly identified by combining the results of the studies mentioned.

2. Material and Methods

2.1 Geological Setting

Sulawesi island is geologically at the intersection of the Eurasia, Indo-Australian, and Pacific tectonic plates. As a result, both volcanic and non-volcanic hosted geothermal zones are formed due to these tectonic events (Idral and Mansoer, 2015). The focus area of this study is Bora village in Sigi district, Central Sulawesi, which is located in an active tectonic environment, namely the Palu-Koro fault and has a complex geological environment with a depression zone. Hot springs with temperatures around 90.1 °C, hot ground (100.6 °C), and altered rocks are all evidence of the hydrothermal activity found in this area (PSDG, 2010). These factors, therefore, make Bora village a potential site for geothermal fields.

According to research (Wibowo et al., 2011), the stratigraphic composition of the rocks from oldest to youngest consists of schist units (Trs), Granite Genes (Trg), Filit (Kf), Salubi Granite (Tgs), Oloboju Granite (Tgo), Sediments (Qs), and Alluvium (Qal). There are four fault structures developing in the research area as shown in Fig. 1, namely the Palu-Koro Fault trending north-south, the Sidera Fault trending west-east, the Oloboju Fault trending west-east, and the Bora Fault trending northwest-southeast. There are several manifestations in Bora, that five hot springs namely Bora, Sidera, Mantikole 1 & 2 and Lompio as well as hot soil and altered rocks. The structure of the Palu-Koro fault is considered to control the emergence of the Mantikole and Lompio hot springs. The Sidera fault controls the appearance of the Sidera hot springs and the Bora Fault controls the Bora hot springs.

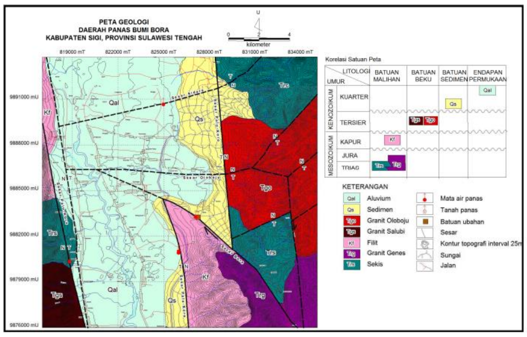

Fig. 1. Geological Map of Bora Geothermal Field (Wibowo et al., 2011)

2.2 Magnetotelluric Method

The Magnetotelluric (MT) method is a geophysical method that utilizes the principle of natural electromagnetic (EM) induction to estimate the resistivity value of subsurface rocks. Transverse electric (TE) and transverse magnetic (TM) modes describe how electromagnetic waves move through the medium (Simpson and Bahr, 2005). In the MT approach, both modes play a significant role. The TE mode, also known as the polarized electric field, describes an electric current flowing in parallel and the induction of a magnetic field perpendicular to the strike. Meanwhile, the TM mode has characteristics that are inversely proportional to the TE mode. The existence of a structure which is a heterogeneous and anisotropic zone for the EM waves can be shown by resistivity contrast in Fig. 2. The response of the structure to this scenario is splitting on the curve and impedance polarization of MT data.

2.2.1 Geological Setting

Vertical structures have a resistivity contrast that can separate components on the MT curve. Curve splitting is the term used to describe the characteristic difference that separates the TE and TM curves upon vertical contact. Due to this, TM mode exhibits lateral sensitive changing characteristics in contrast to TE mode. The sensitivity of the subsurface conductivity is impacted by the vertical magnetic field in TE mode (Daud et al., 2015; Rosid and Ghufron, 2021). The pattern of the separation curve will depend on how much resistivity contrast there is, and the extent of the separation will depend on how far the structure is from the MT station. It is expected that subsurface permeability zones connected to structural indications can be determined using curve splitting analysis (Daud et al., 2015).

2.2.2 Polar Diagram

Field observations indicate that impedance is controlled by the direction of the EM wave propagation axis as well as the spatial variation of subsurface resistivity. The dependence of impedance on the orientation of the measurement axis can be visualized on a polar diagram as shown in Fig. 2. A polar diagram uses the amplitude of the impedance tensor component on each axis. The axis configuration of a polar diagram is a good indicator of changing the dimensions of the earth's electrical structure. Meanwhile, the elongation of the polar diagram could provide information on the strike direction, in which the polar diagram gives the response relatively parallel or perpendicular to the strike (Daud et al., 2015; Vozoff, 1991).

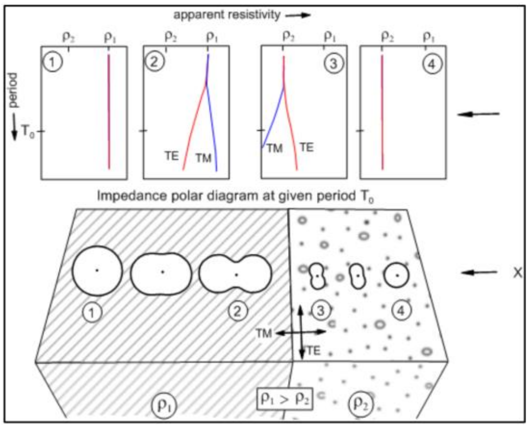

Fig. 2. Curve Splitting (above) and impedance polar diagram (below) at MT station 1, 2, 3 and 4 (Vozoff, 1991).

2.3 Gravity Method

The Geological Agency provided the gravity and magnetotelluric data utilized in 2010 (Indonesian Center for Geological Resources). The gravity method can provide information about subsurface density distribution. A Complete Bouguer Anomaly (CBA) has been produced using the gravity observation data that have been processed and corrected using the equation (1).

$$CBA = gobs - gf + FA - BC + TC \quad (1)$$

Gravity data processing will separate regional anomalies and residual anomalies from the CBA map. The residual anomaly describes the result of shallow penetration, which is obtained by using the trend surface analysis method and the first order polynomial equation (Daud et al., 2018).

Gravity data are frequently used to locate the density contrast using the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD). Geological feature anomalies are investigated to identify fault types and structural or lithological contrasts. If there is contrast on the contours of the FHD map, this indicates an anomaly as a horizontal contact with different densities which is a fault structure. Furthermore, SVD is very helpful for observing vertical contacts which can confirm the presence of structures in areas indicated by fault structures (Fig. 3).

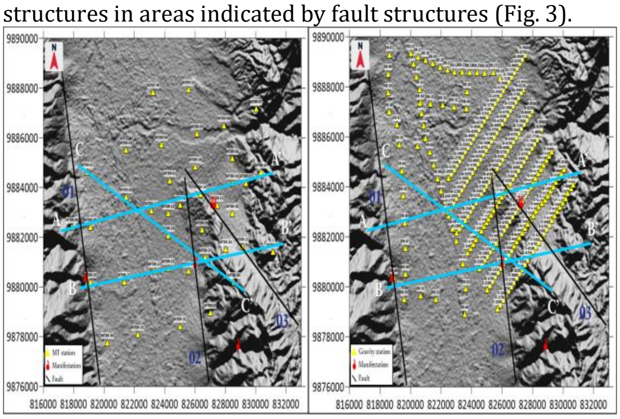

Fig. 3. Distribution of MT data (left) and Gravity data (right); line profile that will be used for structure analysis

3. Results and Discussion

The surface geological structure in the Bora geothermal area has a dominant orientation towards NW-SE and NE-SW. The structures most likely have an impact on how the local geothermal system develops. The analysis of curve splitting, polar diagrams, and 3D inversion of MT data obtained using SSMT2000 and MT3D INV-X by NewQuest Geotechnology, as well as the study of density contrast from FHD and SVD with Geosoft. These results are used to identify the surface geological structure generated from observation data. The western Palu-Koro fault zone is numbered 01, while the central part is numbered 02, and the bora fault is numbered 03.

3.1 Curve Splitting Analysis

Fig. 4 displays the result of Line A's curve splitting and 3D inversion. From the modeling result, it is possible to determine the continuation of 4 faults in the subsurface. The western Palu-Koro Fault zone is identified from the MTBR-08 curve splitting pattern. The confluence of the central Palu Koro fault zone and the Bora Fault is likely to be the basis for splitting the MTBR-13 and MTBR-14 curves.

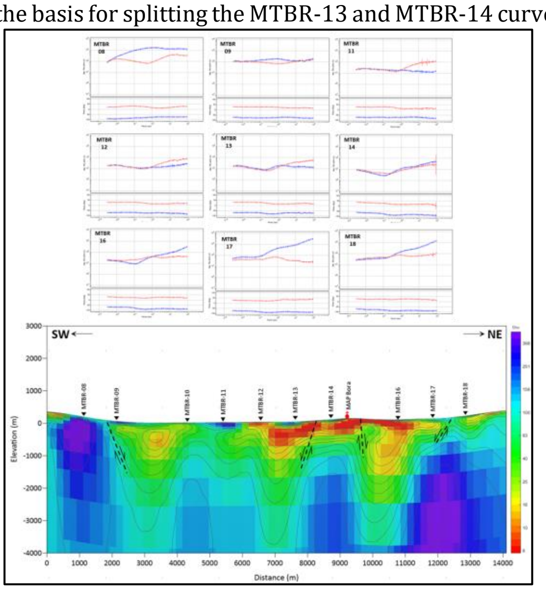

Fig. 4. Curve splitting and 3D inversion result of Line A

The presence of faults is also supported by the curve splitting on MT station (MTBR-20, MTBR-24, MTBR-25, MTBR-26) as shown in Fig. 5. At the Bora Fault zone, there is a newly identified fault in a resistive dome feature which provides supporting conditions of resistivity contrast at shallow depths. This possibility can be correlated with the existence of structures and the presence of surface manifestations around the fault zone.

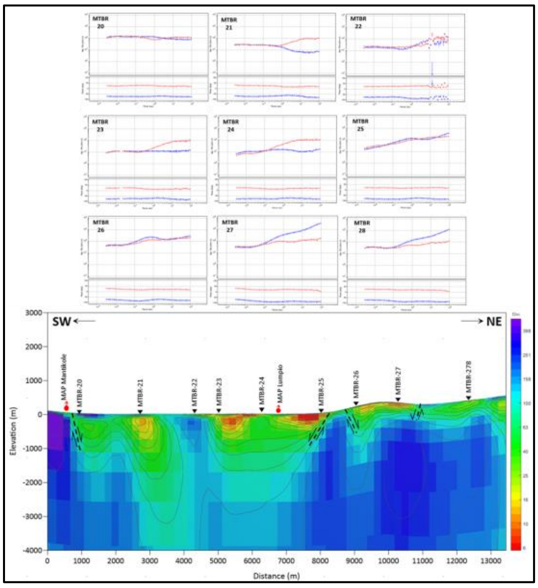

Fig. 5. Curve splitting and 3D inversion result of Line B

In Fig. 6 for line C, the existence of identified faults continues, supported by the splitting of the MTBR-11 and MTBR-25 curves. The existence of the confluence of two faults between the Bora Fault and the central zone of the Palu-Koro fault is also supported by the emergence of hot springs on the surface. From this curve splitting analysis, it is known that the permeable zone is estimated to be in the southeastern region with continuous identified faults in the three lines.

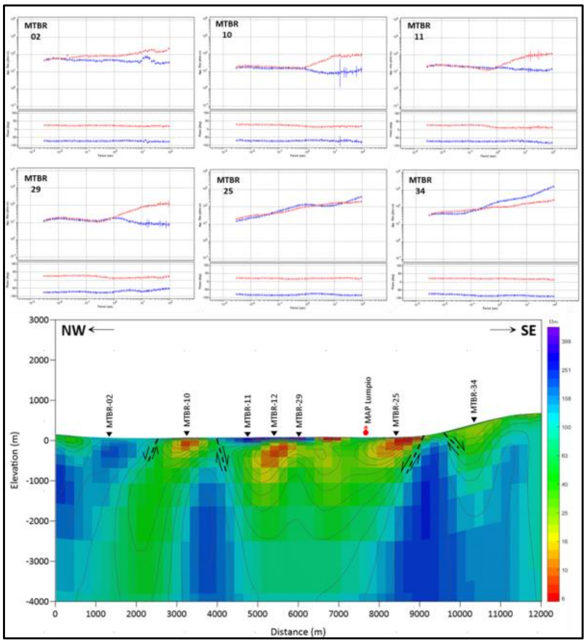

Fig. 6. Curve splitting and 3D inversion result of Line C

3.2 Polar Diagram Analysis

Polar diagrams support the analysis of 3D inversion and curve splitting results. These faults are confirmed by the elongation of the polar diagram, which is typically parallel to the fault. In contrast, the polar diagram of the MT stations that are situated between the two faults reveals an elongation that is perpendicular to the fault strike (Daud et al., 2015).

The elongation of the polar diagrams in the Bora geothermal area often follow the NE-SW and NW-SE directions. Fig. 7 shows a clear depiction of the fault structure. The elongation of the polar diagram serves as supporting information for the identified faults, such as the western and central zones of the Palu-Koro Fault, and the Bora Fault. In the zone between two faults, the polar diagram shows the elongation perpendicular to the structure. This indicates that there is a higher resistivity between the two faults compared to the other areas. It also confirms that the existence of the domes found in the MT model in Line A and Line B can be associated with the graben and horst forms of the fault.

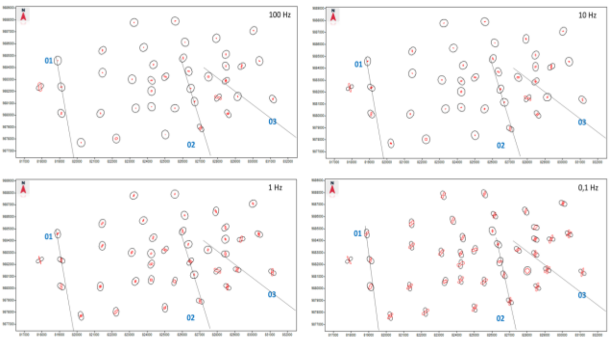

Fig. 7. Structural analysis of the polar diagram at a frequency of 100, 10, 1 and 0.1 Hz

3.3 The Gravity Anomaly

The contours of Bouguer anomaly closely match the patterns of geological fault distribution, and this indicates that the depression zone's width is decreasing from north to south. In Fig. 8, the bouguer anomaly and residual gravity anomaly are depicted. The CBA value is between -16 and 32 mGal. There is a pattern of high to low gravity anomalies moving from west to east and vice versa. Most of the residual gravity anomaly results have a contour pattern similar to CBA mapxxzc.

In general, the gravity result in the Bora geothermal field has a low gravity anomaly. Several phenomena are seen in the high gravity anomaly which appears more clearly in the western region. This anomaly partially shows its similarity with the Bouguer anomaly which implies local structural conditions. In the southern zone of the field, there is a low anomaly between -14 and 2 mGal. This could indicate the location of shallow layers like reservoir rock or a fault zone that have the same pattern as the MT analysis.

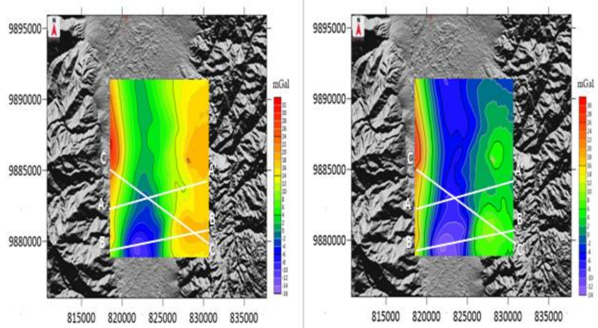

Fig. 8. Complete Bouguer Anomaly map (left) and Residual Anomaly map (right) of Bora Geothermal Field.

3.4 The Gravity Derivative Analysis

Let's see qualitatively at Fig. 9 shows the higher FHD anomaly in the western area, which has values varying between 0.009 and 0.004 mGal/m represented in blue to magenta. The high contrast in gravity values between one site and another may reveal the fault structure that actually occurred. The reverse fault shown on the geological map can be confirmed as the fault structure found and shown in the picture. The hot springs are close to fault lines which have a pattern similar to the MT model results. They are hence considered to be the discharge zone in this field.

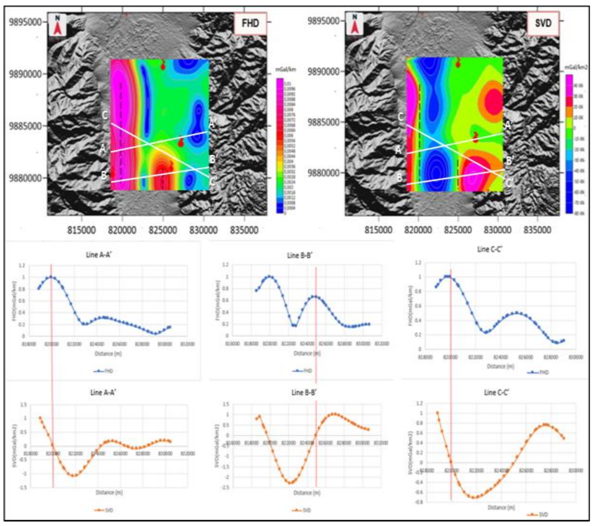

Fig. 9. First Horizontal Derivative and Second Vertical Derivative Analysis

SVD analysis is applied to find out the types of faults indicated in FHD analysis. The fault in Fig. 9 is shown with zero SVD anomaly, while the maximum and minimum anomalies have solid contours on both sides. The location of the fault on both maps will be exactly the same if the FHD and SVD contour maps align. To determine the types of faults that are detected by SVD value, if g" max is greater than g" min, the type of defect is a typical fault. Meanwhile, the value of g" max is smaller than g" min, the type of defect is a reverse fault.

Based on the analysis of existing faults, lane A and lane B show the type of reverse fault, while lane C shows the type of normal fault. The presence of structures indicates possible permeability. The fault correlation results between MT and gravity have the same pattern. Therefore, the probability of showing good permeability of the fault produced in this analysis is estimated to be a shallow fault. The potential Bora geothermal prospect area is estimated to be in the middle of the research area, at the confluence of the central zone of the Palu Koro fault and the Bora fault.

4. Conclusion

The formation of a geothermal system in the Bora field is thought to be closely related to tectonic activity which controls the emergence of geothermal manifestations. The prospect area is concentrated in the center of the research area, showing the Bora Fault and the central zone of the Palu Koro Fault which have surface hot springs. Meanwhile, the reverse fault in western zone of Palu-Koro Fault could act as a border or barrier in the Bora geothermal system. The results of the curve splitting and polar diagrams of the MT data, which shows the fault connected with the Palu-Koro fault is a good permeable zone. These are consistent with the geological structure analysis derived from the FHD and SVD analysis.

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