Magnetotelluric Signature over the Low to Moderate Temperature Geothermal System

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ABSTRACT

Of all the geothermal potentials in Indonesia, almost 41.3% are categorized as low-to-medium geothermal systems. The potential of these low-to-moderate geothermal systems has not been massively developed or even studied. The potential can occur in several geological play types, one of which is a typical fault-controlled geothermal system. The distinctive feature of this system is the occurrence of manifestations that are limited to the vicinity of the fault. The pattern of MT curves as well as the subsurface resistivity model in such a system are quite different from those of a volcanic-hosted geothermal system. The distribution and value of the resistivity anomaly may reflect the occurrence of the geothermal reservoir. This paper discusses the distinctive resistivity characteristics observed in low-to-moderate temperature fault-controlled geothermal systems.

1. INTRODUCTION

Indonesia has a number of low- to medium-temperature geothermal systems that are widely spread over 254 of the total 357 geothermal potencies. Currently, this potency has not been massively developed or even studied. Insufficient data and information regarding the potential of low-and-medium temperature resources leads to underutilization (Putriyana et al., 2022). It is important to deeply recognize the characteristics of a low- to medium-temperature system to exploit the potential benefits of these potencies.

The magnetotelluric (MT) method is the most frequently used geophysical method to reconstruct a geothermal system model (Daud, et al., 2017; Daud et al., 2019; Daud et al., 2022; Daud et al., 2023). The MT method is sensitive to the electrical resistivity signatures of the main components of the geothermal system, such as the heat source, cap rock, and geological structures that control the fluid flow (Rodriguez et al., 2021). A conceptual model of a geothermal system is produced by integrating the MT model with surface geology, geochemistry, and other geophysical data. This conceptual model is subsequently used to target deep drilling and numerical resource estimation, as well as the selection of the appropriate energy conversion technology and the projection of project economics.

The low resistivity anomaly mostly observed over geothermal systems is one of the most important exploration targets. Conductive clay produced by hydrothermal alteration is the most common cause of low resistivity in a zone above the reservoir. (Ussher et al., 2000). The formation of these hydrothermal alteration minerals is usually dependent on the temperature, permeability, pressure, fluid composition, the initial composition of the rock, and the duration of the hydrothermal activity. These factors are largely independent, but the effects of one or more of them can exert a dominant influence on the location and extent of hydrothermal alteration (Lagat, 2010). This paper describes the characteristic subsurface resistivity pattern observed from several unimpressive hydrothermal activities over low- to medium-temperature geothermal systems.

2. LOW-TO-MEDIUM GEOTHERMAL SYSTEM

There are various classifications of geothermal systems derived from many references. Reservoir temperature becomes the simplest parameter to classify the geothermal system. The selection of low-to-medium geothermal fields described in this paper is referred to the classification from Hochstein (1990) which divides the geothermal systems into three classifications based on their reservoir temperature as follows:

1. Low temperature geothermal system : < 125°C
2. Intermediate temperature geothermal system : 125-225°C
3. High temperature geothermal system : > 225°C

Geologically, the existence of low-to-medium geothermal systems can occur in many different geological settings, which can mostly be grouped as follows (referred to Hochstein & Brown, 2000):

1. System overactive and inactive volcanic arcs, i.e., hosted by volcanic rocks.
2. "Heat-sweep" systems in active rifts and at plate collision boundaries.
3. Fracture zone systems hosted by sedimentary or metamorphic rocks.

3. ALTERATION & RESISTIVITY OF ROCKS

As a result of hydrothermal activity, the rocks in a geothermal area can be altered and turned into new hydrothermal minerals. Within the temperature range of 100–150°C, rock minerals are most susceptible to hydrothermal alteration and the formation of high-surface-conductivity smectite. From 150 to 200°C, the clay changes to a less conductive mixed phase of illite and smectite (Komori et al. 2013). Smectite is not observed in rocks > 200°C, as it transitions to less conductive illite and chlorite (Essene and Peacor, 1995).

The interpretation of conductive anomalies at low- to medium-temperature geothermal systems must be made with caution. A fractured reservoir with hot fluid could have the same resistivity signature as clay-bearing rock, especially in the presence of the smectite clays common in hydrothermal alteration zones (Revil et al. 2015; Komori et al. 2013). Another challenge in evaluating conductive anomalies in low-to-medium geothermal systems is the occurrence of sediment infill, which is also represented by a low resistivity value.

4. MAGNETOTELLURIC METHODS

The MT method is a passive geophysical electromagnetic (EM) method that measures naturally occurring Earth-time-varying electromagnetic fields. Natural EM variation is recorded for several hours (about 12–16 hours) on the surface with a specific layout and produces MT time series data at each MT station. By applying the Fast Fourier Transform (FFT) and robust calculation to the MT time-series data, the impedance tensor as a function of frequency can be obtained. The MT data is usually represented as an MT curve, which consists of apparent resistivity and phase versus frequency, as shown in **Figure 1**. For a homogeneous Earth, apparent resistivity represents actual resistivity, whereas for a multi-dimensional Earth, apparent resistivity is the average resistivity represented by an equivalent uniform half-space. (Simpson & Bahr, 2005). Equations 1, 2, and 3 show the correlation of the impedance, apparent resistivity, and phase.

$$\boldsymbol{Z_{xy}} = \frac{\boldsymbol{E_x}}{H_y} \qquad (1)$$

$$\boldsymbol{\rho_{xy}} = \frac{\boldsymbol{1}}{\boldsymbol{\omega\mu}} \left|\frac{\boldsymbol{E_x}}{\boldsymbol{H_y}}\right| \qquad (2)$$

$$\boldsymbol{\emptyset_{xy}} = \boldsymbol{tan^{-1}}\,(\boldsymbol{Z_{xy}}) \qquad (3)$$

Where ω is angular frequency (ω=2πf) and μ is magnetic permeability. In the studies of the Earth, μ is usually assigned the free-space value (μ_0=4π x 10^(-7) H m^(-1)).

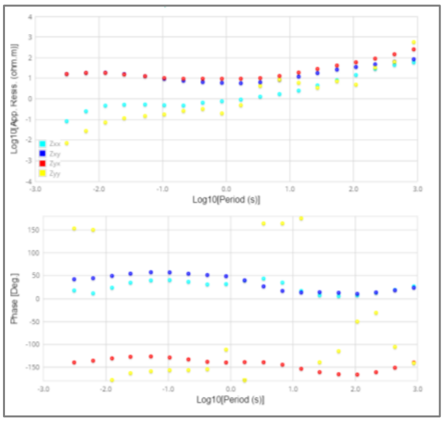

Figure 1: Apparent resistivity and phase in frequency domain.

Furthermore, to obtain a subsurface resistivity model, inversion modeling is applied to the MT data. Before that, the static shift correction is performed to correct the MT data from the static shift effect. This process is important to conduct to avoid misleading the inversion model.

In this research, the 3-D inversion process has been carried out for several MT data sets from three geothermal fields that are categorized as low- to medium-temperature geothermal systems. Several resistivity sections were then produced to analyze the subsurface resistivity pattern in each selected geothermal field.

5. RESULTS

5.1 Geothermal Field 1

Geologically, Geothermal Field 1 is situated in a depression zone. Thermal surface manifestations occur in this area, consisting of three hot springs with a temperature of 68.4–74.8°C and one warm spring with a temperature of 37.1°C. Each manifestation is controlled by geological faults, as shown in Figure 1. The estimated reservoir temperature calculated using a SiO2 geothermometer is around 148–161°C, which is categorized as a medium-temperature geothermal system. Meanwhile, using a Na-K geothermometer, the temperature of the reservoir is estimated to be around 210°C, which is situated at the boundary between medium and high-temperature geothermal systems. There are 19 existing MT stations, which are distributed around the manifestations. To delineate the subsurface resistivity, a 3-D inversion process was applied. The resistivity sections for the three lines are provided in **Figure 2**.

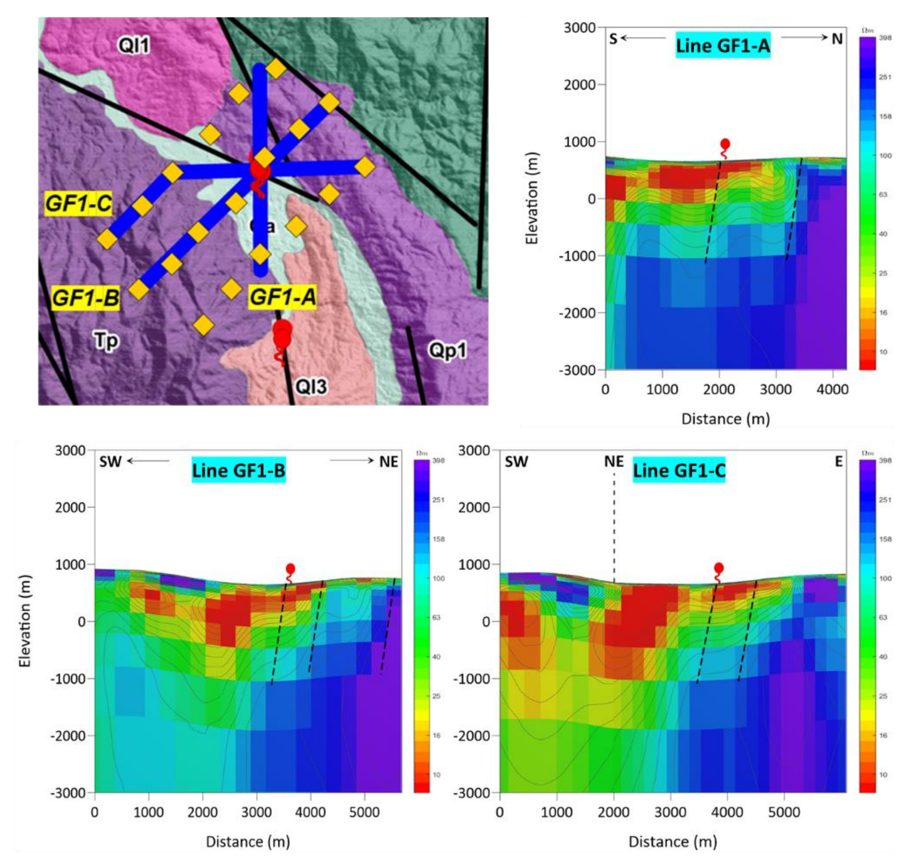

Figure 2: Subsurface resistivity model of geothermal field 1 derived from 3-D inversion.

5.2 Geothermal Field 2

Geothermal Field 2 is a typical non-volcanic geothermal system. Metamorphic and sedimentary rock products dominate the landscape. In this location, there are several important geological formations that separate the two products and influence the appearance of thermal manifestations. This location contains several surface thermal manifestations, including a hot ground with a temperature of about 100.6°C and two hot springs with temperatures of 58.1°C and 90.1°C. In addition, there are three warm springs with temperatures ranging from 37.8 to 44.3°C. Based on the Na-K geothermometer, the reservoir temperature is estimated to be around 219°C, classifying the system as a medium-temperature geothermal system. **Figure 3** shows two resistivity sections taken from the 3-D MT inversion result. A total of 39 MT stations were included for the 3-D inversion process in this area.

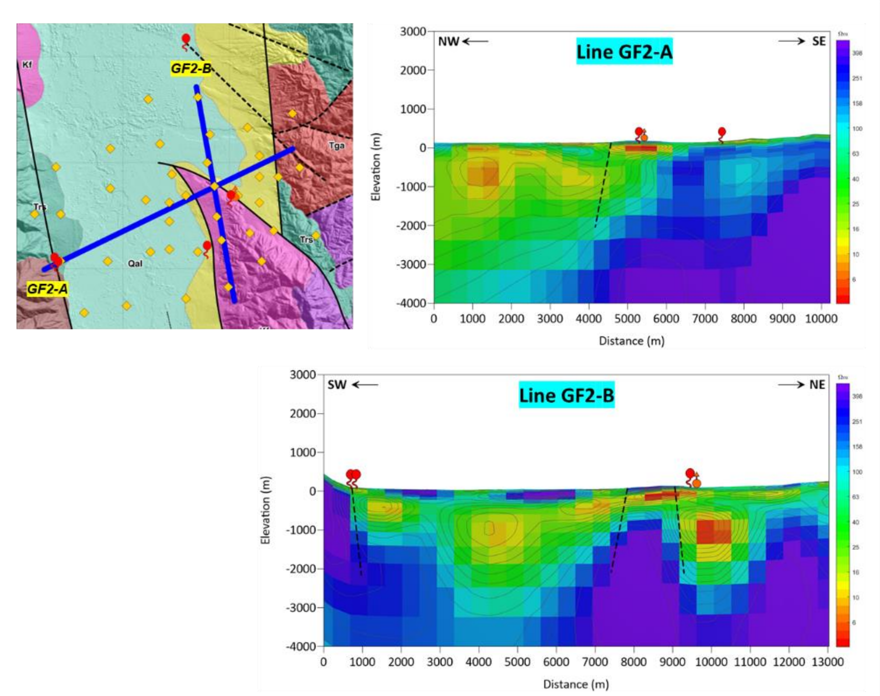

Figure 3: Subsurface resistivity model of geothermal field 2 derived from 3-D inversion.

5.3 Geothermal Field 3

Geothermal Field 3 is classified as a medium-temperature geothermal system. The reservoir temperature of the geothermal system in this location is predicted to be around 200°C, according to the Na-K geothermometer. Manifestations in this area include various hot springs and warm springs with temperatures ranging from 58-81°C to 37-39°C. Geothermal Field 3 is hosted geologically by volcanic rocks. 42 MT stations were subjected to a 3-D inversion technique. The data was then presented in two sections of resistivity, as illustrated in **Figure 4**.

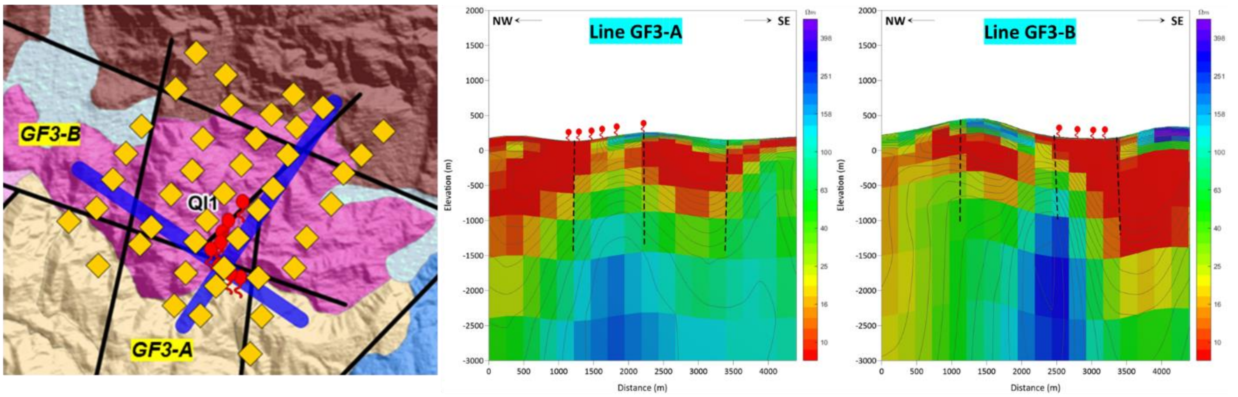

Figure 4: Subsurface resistivity model of geothermal field 3 derived from 3-D inversion.

5.4 The Signature of the Subsurface Resistivity Model

The subsurface resistivity model, as discussed in the previous chapter, can be utilized to depict the geothermal system model. The resistivity anomaly values and their distribution can be used to explain many components of the geothermal system. In a high-temperature geothermal system, for example, the existence of a clay cap is represented by a conductive anomaly with a resistivity value of 10 m that is widely dispersed over the area. Similarly, depending on the kind (magmatic or plutonic body), the existence of a heat source might be reflected by a resistive or conductive anomaly. Furthermore, the thinning and thickening of the conductive layer is usually used to define the upflow and outflow zones of a geothermal system. In addition, the upflow zone in high-temperature systems can be identified by observing the dome-shaped resistivity pattern, which is generally formed in the hottest part of the reservoir. These are prevalent patterns in the resistivity model of high-temperature geothermal systems.

The resistivity model from three low-to-medium-temperature geothermal system samples shows a slightly distinct pattern. Geothermal Field 1 and 2 have similar geological characteristics and are located inside the Graben structural complex. The horst is associated with the resistive part, while the graben is associated with conductive part. The geothermal system is most probably controlled by faults, as indicated by resistivity contact between high and low anomalies. Instead of looking for updome resistivity patterns, which are common in high-temperature volcanic systems, the presence of faults represented by resistivity contacts is the main target. Furthermore, caution is required when interpreting the existence of the base of conductor, which often correlates with temperatures ranging from 180 to 200°C in high-temperature geothermal systems. Since altered rock is not the only source of the conductive layer, the existence of sedimentary rock layers that fill the graben structure also indicates a low resistivity response.

Geological conditions in Geothermal Field 3 differ slightly from those in the preceding two fields. Despite the fact that its manifestations appear to be controlled by faults, the volcanic products found in this field may have also had a significant influence in the creation of the current geothermal system. Accordingly, the updome-shape resistivity pattern, which is common in high-temperature volcanic-hosted geothermal systems, is the main target of exploration in this field.

6. CONCLUSION

Considering many high temperature fields are owned and utilized, the development of low-medium temperature geothermal fields is one of the current challenges in Indonesia. Fields with low-medium temperatures also have a variety of geological settings, some of which are connected with inactive volcanic products while others are associated with faults that control the presence of reservoirs. Both have different resistivity patterns. For systems associated with volcanic products, updome shape resistivity patterns are still the main feature. Meanwhile, for fault-controlled geothermal systems such as those in Geothermal Fields 1 and 2, the contact resistivity between high and low anomalies is the main target.

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