Identification the geothermal system using 1-D audio-magnetotelluric inversion in Lamongan volcano field, East Java, Indonesia

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Abstract. Tiris village, Probolinggo, East Java, is one of geothermal potential areas in Indonesia. This area is located in a valley flank of Mount Lamongan and Argopuro volcanic complex. This research aimed to identify a geothermal system at Tiris area, particularly the fluid pathways. The geothermal potential can be seen from the presence of warm springs with temperature ranging 35-45°C. The warm spring locations are aligned in the same orientation with major fault structure in the area. The fault structure shows dominant northwest-southeast orientation. We used audio-magnetotelluric data in the frequency range of 10 Hz until 92 kHz. The total magnetotelluric sites are 6. From the data analysis, most of the data orientation were 2-D with geo-electrical direction north-south. We used 1-D inversion using Newton algorithm. The 1-D inversion resulted in low resistive anomaly that corresponds to Lamongan lavas. Additionally, the depth of the resistor are different between the area to the west (i.e. 75 m) and to the east (i.e. 25 m). This indicates that there is a fault around the aligned maar (e.g. Ranu Air).

1. Introduction
Indonesia is the largest archipelago in the world located between three major plates i.e. Eurasian, Pacific, and Indo-Australian plate. The collision between those plates makes Indonesia hosts 200 volcanoes that located along Sumatera, Java, and the island of eastern part of Indonesia [1]. These volcanoes provide a huge geothermal energy potential in Indonesia, which about 40% of the world’s geothermal energy, equivalent to ~29.215 MWe. However, it has been little developed. It is just about 4% of ~29.215 MWe is already installed as the source energy [2]. One of the geothermal potential in Indonesia located on Mount Lamongan which can be seen from geothermal manifestations that appear in Tiris village, Probolinggo. Tiris, which was located on the flank of Mount Lamongan, has geothermal potentials equivalent to 92 MWe from the total 1206.5 MWe in East Java [3].

Mount Lamongan (alt. 1651 m) is a basaltic stratovolcano located in the eastern spur of Java, Indonesia [4]. It lies between two large mountains, Mount Tengger to the west and Mount Argopuro to the east. Mount Lamongan is surrounded by numerous prehistoric eruptive centers comprising up to 61 cinder cones and 27 maars [5]. The lithology of Mount Lamongan consists of Lamongan lavas and
Lamongan volcanic rocks overlying Argopuro volcanic rocks. These lithologies were formed in the Quarternary period [6].

Mount Lamongan was an active volcano in East Java. It has three vents i.e. Tarub the older, Tjupu, and Lamongan itself. Lamongan was detached from other vents by a fault aligned northwest-southeast which extends to the northwest into a series of aligned maars [7] shown in figure 1.

The geothermal manifestations in Tiris area consist of warm springs and deposits of iron oxide [3]. They appear through fractures in Tancak river with northwest-southeast orientation. Hydro-geochemical studies classified the thermal water as bicarbonate water with high HCO₃ concentrations. Bicarbonate water type indicates that the appearance of hot water is an outflow process from the reservoir. Moreover, in Tiris area, there are zeolite-bearing veins, indicative of satellite boiling zones along the hydrothermal outflow zone. These veins are also indicative of deep-seated geothermal reservoirs [8]. Thus, Tiris geothermal area assumed as an outflow area with the Argopuro being the upflow area of this geothermal system.

This research conducted the primary data of audio magnetotelluric. We used 1-D inversion to imaging subsurface resistivity. Thus, the fault as part of geothermal system can be identified.

2. Materials and methods
Magnetotelluric (MT) is a passive geophysical method that measures the time-varying orthogonal horizontal electric (E) and magnetic (H) field components by utilizing electromagnetic waves for imaging the subsurface conductivity distribution [9]. Correlation between the magnetic field (H) and the electric field (E) can be described as an impedance tensor (Z) [10].

\[ E = ZH \] (1)

Electromagnetic waves are sourced from the solar wind (with frequencies <1 Hz) and lightning activity (with frequencies >1 Hz) [11]. This wave will then reach the surface of the earth and propagates down to the subsurface. The amplitude of the wave propagating to the subsurface will be attenuated by 1/e. The depth at which the amplitude is attenuated by 1/e called skin depth [12].

\[ \delta = 500 \left(\frac{T\rho_a}{\pi}\right)^{1/2} \] (2)

Figure 1. The dash line shows the fault which detached Lamongan (L) with Tarub vent (T). The fault has same orientation with aligned maars at the northwest. The black dot is lake-filled maars, meanwhile the grey one is dry maars (modified from [7]).
where $\rho_a$ is the apparent resistivity (Ωm) and $T$ is the period (s). The depth of penetration will be directly proportional to the resistivity and period [13]. The resistance layer and high period will make the wave penetrate deeper into the earth.

Resistivity is related to the characteristic impedance corresponds to homogeneous and isotropic earth. The apparent resistivity is the magnitude of the impedance as a function of the period [14].

\[
\rho_a = 1 \left( \frac{\omega \mu}{\sigma} \right)^{1/2} |Z| = 0.2T |Z|^2
\]

(3)

where $X$ and $Y$ are the real and imaginary parts of impedance [15].

The 1-D inversion is using Newton algorithm. The inversion problem can be solved by looking for a zero value of a function $\frac{\partial E}{\partial m}$ iteratively using Newton method [16]. The inversion model in the $(n+1)$ iteration can be expressed in the formula below. Where the function

\[
m_{n+1} = m_n - \left( \frac{\partial^2 E}{\partial m^2} \right)^{-1} \left( \frac{\partial E}{\partial m} \right)_{m=m_n}
\]

(5)

where $E$ is the data prediction error and $m$ is the model. The estimate of the inversion solution requires a second derivative of the data prediction error function.

This research used the audio magnetotelluric method to identify the fault as the fluid pathways. There are 6 sites on the north Mount Lamongan eastward with azimuth line N90°E. The distance between each sites is 2000 m, with the distance between AMT2 and AMT11 sites is 5000 m as exceptional. There is a site i.e. AMT8 between AMT2 and AMT11. However, the data component obtained from AMT8 differs from other sites so that the site is not included in the inversion. The data component of the AMT8 is the xy component, while at the other sites is yx which is then used for inversion. The line passed 2 faults i.e. the fault around aligned maars and the fault around warm springs. The sites and the geological features of the research area shown in figure 2.

![Figure 2. The map of the research area. The points of measurement are shown as blue dots with azimuth line N90°E. The red dots and triangle is the warm spring points and the peak of Mount Lamongan respectively. (Inset: The black square is the research area which located on the eastern of Java).](image-url)
3. Results and discussion
In this research, we used the primary data which acquired at the line northern Mount Lamongan using Stratagem, 36716-01 REV.D version. 1-D inversion was carried out to imaging the subsurface conductivity of the research area using IPI2Win software. The inverse problem is solved using variant of the Newton algorithm of the least number of layers. The period time, resistivity, and phase used for regularizing the process of the fitting error minimizing by each sites. Thus, the inverse problem is solved for each sounding curve separately shown in figure 3.

![Figure 3](image-url)

**Figure 3.** The resistivity profiles of the line measurement. The profile at the front is the magnification of the profile at the back with 100 m depth. The yellow circle shows the depth difference of low resistive anomaly. It indicates that there is a fault located in the high resistive anomaly. Meanwhile, the white circle indicates the fault too which there is an unconformity of the resistivity block.

The resistivity profile shows that there is low resistivity anomaly in the depth up to 70 m. AMT2 and AMT5 sites have a resistivity value ranging 4.65-18.6 Ωm, which means a conductive anomaly at the depth 60-75 m. At AMT11, there is a resistive structure with a resistivity value of 643 Ωm. Three sites to the east, show the existence of low resistive anomaly in the depth ranging 25-30 m. The low resistive anomaly interpreted as Lamongan lavas.

Carn [4] identified a fault in the research area which is align with the maars located in the northwest. It is the continuation fault from the peak of Mount Lamongan. The fault and the lineament of the maars have northwest-southeast orientation. This structure can be proved by the existence of a resistive structure in the resistivity profile. The resistive structure located in the zone between AMT5 and AMT11 sites.

In warm spring area, there is a fault that is oriented to the northwest-southwest as well. The fault located at the eastern research area, between AMT12 and AMT18 sites. The resistivity profile shows the depth difference between the same resistivity block. The difference indicates there is a fault there as fluid pathways. The fluid emerges to the surface as warm springs.
From the resistivity profile, it can be seen that there is an anomaly depth difference between the western and the east. The western conductive zone has a greater depth than the east. This indicates a fault, most likely related to normal fault. Despite that, we do not find the dip of the fault from the geological mapping.

4. Conclusion
In this study, it can conclude that there is two faults in the research area. It can be seen from the depth difference of the resistivity value in the resistivity profile. Both faults are part of the geothermal system of Mount Lamongan as the fluid pathways, which the fault on the east is the pathways of the warm springs. Moreover, the low resistive anomaly at the profile interpreted as Lamongan lavas.

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