

Modeling and Interpretation of Geothermal System Components Using The Magnetotelluric (MT) Method at The “X” Geothermal Field

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Abstract: In North Sulawesi Province, the Geothermal field “X” is one of the geothermal sites managed by PT Pertamina Geothermal Energy. This investigation employs the magnetotelluric (MT) technique to investigate geothermal system elements beneath the surface. The MT data are processed by adjusting the rotation angle and correcting static effects. Interpretation of data on resistivity anomalies and resistivity cross-sections reveals patterns and variations in resistivity horizontally and vertically as a function of depth. The results of the horizontal resistivity distribution indicate the presence of a dominant conductive rock layer, with localized occurrences of resistive zones in the southwestern part of the research area (1–33 Ωm). The interpretation of the resistivity cross-section based on the classification of the resistivity value consists of three rock layers: the caprock layer ($\leq 10 \Omega\text{m}$), reservoir rock layer (30–80 Ωm), and intrusive rock layer as a heat source ($\geq 100 \Omega\text{m}$).

Keywords: Geothermal field “X,” magnetotelluric (MT) method, resistivity cross-section, geothermal system components.

1. Introduction

The “X” geothermal field is geographically located in the eastern part of Indonesia (north arm of Sulawesi Island), approximately 30 km south of Manado, North Sulawesi Province (Figure 1). This area is located in a volcanic zone included in the Tondano Caldera structure, which is a large Quaternary caldera with a diameter of about $20 \times 10 \text{ km}^2$, formed by large-scale explosive eruptions (Ikhwan et al., 2025). The area lies on a row of volcanoes (V. Lengkoan, V. Kasuratan, and V. Tampusu) and a crater lake known as Lake Linau. The area lies at an altitude of 750–1200 m above sea level (Ibrahim et al., 2022).

The geothermal system in the research area remains influenced by volcanic and tectonic activity in the Sangihe Arc. The heat source is thought to be an igneous rock intrusion, which is still actively transferring heat to the environment around Lake Linau. The geothermal manifestations found around Lake Linau consist

of active and inactive types (Ibrahim et al., 2024). The presence of geothermal manifestations on the surface indicates the presence of components of the geothermal system below the Earth’s surface (Utami, 2011). Geothermal exploration at “X” began in 1973, with the first commercial operation in 2001 with a capacity of $1 \times 20 \text{ MWe}$. At present, the field continues to expand, reaching $6 \times 20 \text{ MWe}$ (Fanani et al., 2021), with an area of approximately 14 km^2 and a total of 46 installed wells (Utami et al., 2021).

Previous research on the geothermal field “X” model yielded a simple propylitic dome with a resistivity of 20–60 Ωm enclosed by a conductive clay cap of less than 10 Ωm . The peak of the dome points toward the acidic Lake Linau, which is situated approximately 500 m underground (Raharjo et al., 2010). This research aims to interpret geothermal system components such as caprock, reservoir rock, and heat source based on subsurface resistivity cross-sections in the research area.

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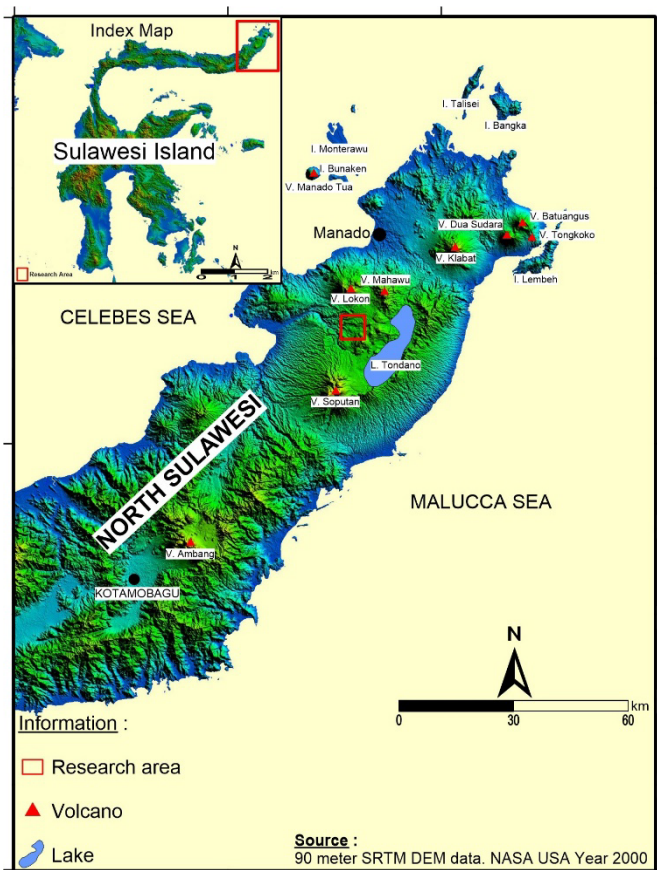


Figure 1. Map of research locations (Ibrahim et al., 2022)

2. Geology of The Research Area

The geological conditions of the research area are dominated by Tertiary (Miocene) volcanic rocks that form the bedrock composed of thick layers of hyaloclastites and lava flows with inclusions of sedimentary formations. During the late Miocene or early Pleistocene, a major eruption formed the large Lake Tondano caldera, which formed through volcanic-tectonic depression, characterized by extensive expanses of tuff rock (Ibrahim et al., 2024).

In North Sulawesi, a resurgence and intensification of volcanic activity led to the Tondano explosion, which was subsequently followed by the Pangolombian eruption during the Pliocene/Pleistocene period. The landscape today remains largely shaped by these two calderas, which have been further altered by the presence of Lake Linau and Lake Tondano (Brehme et al., 2014). Several eruption centers formed within and along the margins of the Tondano Depression, one of which produced the small Pangolombian depression. The geology was described in detail by Utami et al. (2015), as shown in Figure 2. This system consists of volcanic rocks from steep terrain. These rocks include andesitic and pyroclastic lava from the Pangolombian, Kasuratan, Lengkoan, Tampusu, and Linau eruption centers.

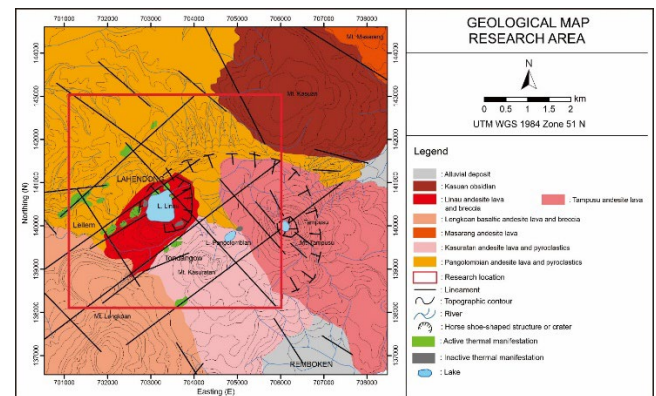


Figure 2. Geological map of the research area (Utami et al., 2015)

3. Magnetotelluric (MT) Method

Basic Principles of the Magnetotelluric (MT) Method

Magnetotellurics (MT) is a non-invasive survey method that employs a broad range of naturally occurring geomagnetic fluctuations as a source for electromagnetic induction. The magnetotelluric field waves originate from currents in the ionosphere and magnetosphere. Electromagnetic field waves propagate toward Earth through a resistive atmosphere. Magnetotelluric field waves are planar because the Earth's surface is relatively far from the source. Electromagnetic waves reaching the Earth's surface convolute and cause a magnetic field parallel to the electric field or an electric field parallel to the magnetic field (Figure 3) (Simpson & Bahr, 2005).

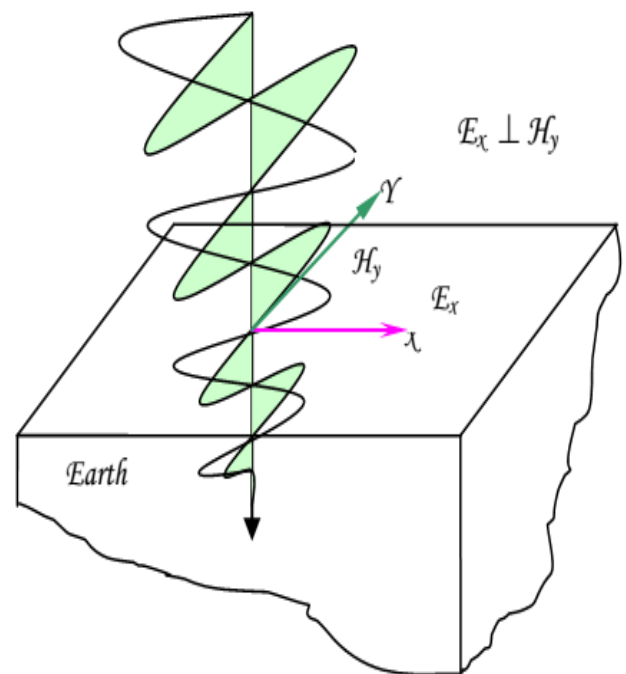


Figure 3. Electromagnetic wave propagation (Simpson & Bahr, 2005)

The magnetotelluric (MT) method provides two-component responses of electromagnetic (EM) measurements in the field at a certain frequency, where the Earth impedance tensor (Z) connects the vertical component of the magnetic field (H) with the horizontal component of the electric field (E), as shown in equation (1) below.

$$E = Z H \quad (1)$$

The electric field (E) has two components and the magnetic field (H) has two components; both are expressed in the impedance tensor using equations (2) and (3) below.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} \quad (2)$$

$$\begin{aligned} E_x &= Z_{xx}H_x + Z_{xy}H_y \\ E_y &= Z_{yx}H_x + Z_{yy}H_y \end{aligned} \quad (3)$$

For a horizontal, uniformly layered Earth, Z_{xx} and Z_{yy} are zero, and equation (3) becomes as follows.

$$\begin{aligned} E_x &= Z_{xy}H_y \\ E_y &= Z_{yx}H_x \end{aligned} \quad (4)$$

where E_x is the electric field parallel to the x-axis, E_y is the electric field parallel to the y-axis, H_x is the magnetic field parallel to the x-axis, H_y is the magnetic field parallel to the y-axis, Z_{xy} is the impedance tensor for H_y and E_x , Z_{yx} is the impedance tensor for H_x and E_y (Simpson & Bahr, 2005).

Magnetotelluric (MT) Measurement

Magnetotelluric (MT) acquisition measures the propagation amplitude of electric and magnetic fields in the time domain. In contrast, TDEM acquisition only measures the behavior of the vertical magnetic field in the time domain (Raharjo et al., 2002). In the magnetotelluric (MT) measurement method (Figure 4), two modes support the modeling and interpretation process described below.

TE (Transverse Electric)

The magnetic components occur only along the y- and z-axes, whereas the electric field components are parallel to the direction of the main structure. Electric current does not flow across the boundary between regions with different resistivity values. Therefore, the E_x component will be continuous across the y-axis plane. Similarly, the E_y component will be continuous across the y-axis plane.

TM (Transverse Magnetic)

The electric field components are present only along the y- and z-axes, whereas the magnetic field components are parallel to the direction of the main structure. In this method, conductive and static effects occur because of the heterogeneity of the medium's resistivity.

TE mode results generally yield lower resistivity values and are sensitive to vertical variations. By contrast, TM mode tends to show higher resistivity values and is more sensitive to lateral changes. TE mode is more sensitive to lateral resistivity variations (such as faults, bed boundaries, or intrusions) because the electric current flows parallel to the strike direction (the main direction of the geological structure), thus providing a more accurate response to lateral changes. Moreover, TE fields are usually more stable and reliable because the electric field is parallel to the main direction of the structure, so they often produce more accurate data. On the other hand, TM mode is more susceptible to errors in strike direction and is more easily disturbed by noise from artificial or natural magnetic fields because the electric current in TM mode must cross the resistivity boundary; the resulting response tends to be more complex and difficult to interpret (Berdichevsky & Dmitriev, 2008). The interaction of electromagnetic waves with geological structures produces electric and magnetic field responses that can be decomposed into two main modes (Table 1).

Table 1. Orientation of Electric and Magnetic Field Components in TE and TM Modes (Chave & Jones, 2012)

Mode	Electric Field Components (E)	Magnetic Field Components (H)	Aligned Direction
TE (Transverse Electric)	Parallel to strike direction (E_x)	Transverse (H_y) and vertical (H_z)	Main geological structures (e.g., faults or layering)
TM (Transverse Magnetic)	Transverse (E_y) and vertical (E_z)	Parallel to strike direction (H_x)	Geological strike direction

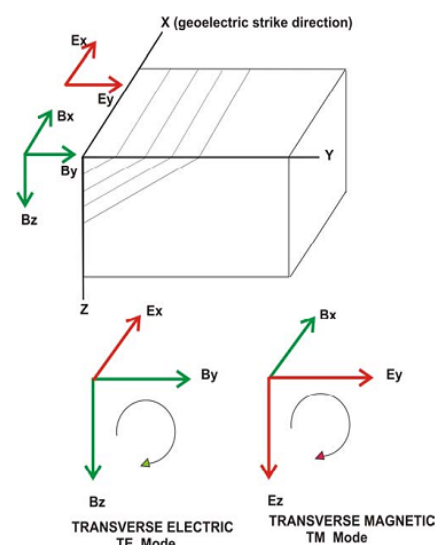


Figure 4. Configuration of TE and TM methods in the field (Xiao, 2004)

In geothermal exploration, the primary purpose of magnetotelluric (MT) is to identify subsurface geological structures and locate underground fluid reservoirs, thereby outlining potential geothermal resources (Cagniard, 1953). The magnetotelluric (MT) method is highly sensitive to the conductivity structure of the subsurface layers. The rock conductivity is influenced by physical properties, including porosity, permeability, temperature, fluid salinity, and the presence of metallic minerals. The results of magnetotelluric (MT) data processing in the research area are displayed in a two-dimensional model in the form of resistivity anomaly maps and resistivity structure cross-sections correlated with geological maps.

4. Research Methodology

The data source used in the magnetotelluric (MT) method is the result of field data measurements in the form of apparent resistivity at each measurement station in Electrical Data Interchange (EDI) format. The number of measurement stations was 28, with three cross-sectional lines covering an area of 5×5 km². Cross-section lines A – A' and B – B' run in the NE–SW direction, and cross-section line C – C' is in the NW–SE direction (Figure 5).

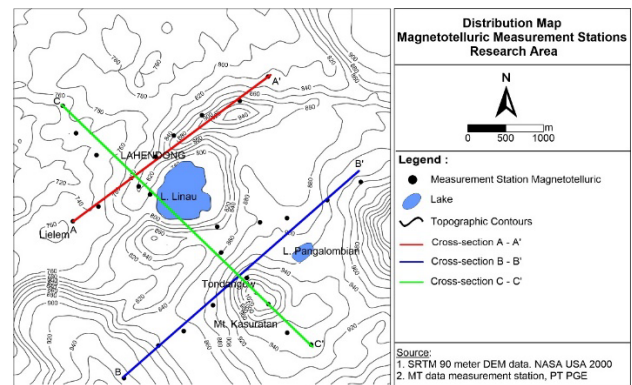


Figure 5. Map of the distribution of magnetotelluric measurement stations

The resistivity data processing stage used the 1-D MT Utilities software program that displays MT data in the form of resistivity curves ρ_{xx} , ρ_{yy} , ρ_{xy} and ρ_{yx} , displays xy and yx phases, displays peanut diagrams as 3D structural parameters, shows the rotation angle of the electric and magnetic fields, sets the rotation angle of the measurement layout, and corrects the static shift of the MT curve with TDEM (Figure 6). This research combined the results of the 1-D MT Utilities software program with Golden Software Surfer, which can produce patterns and variations in resistivity horizontally and vertically as a function of depth.

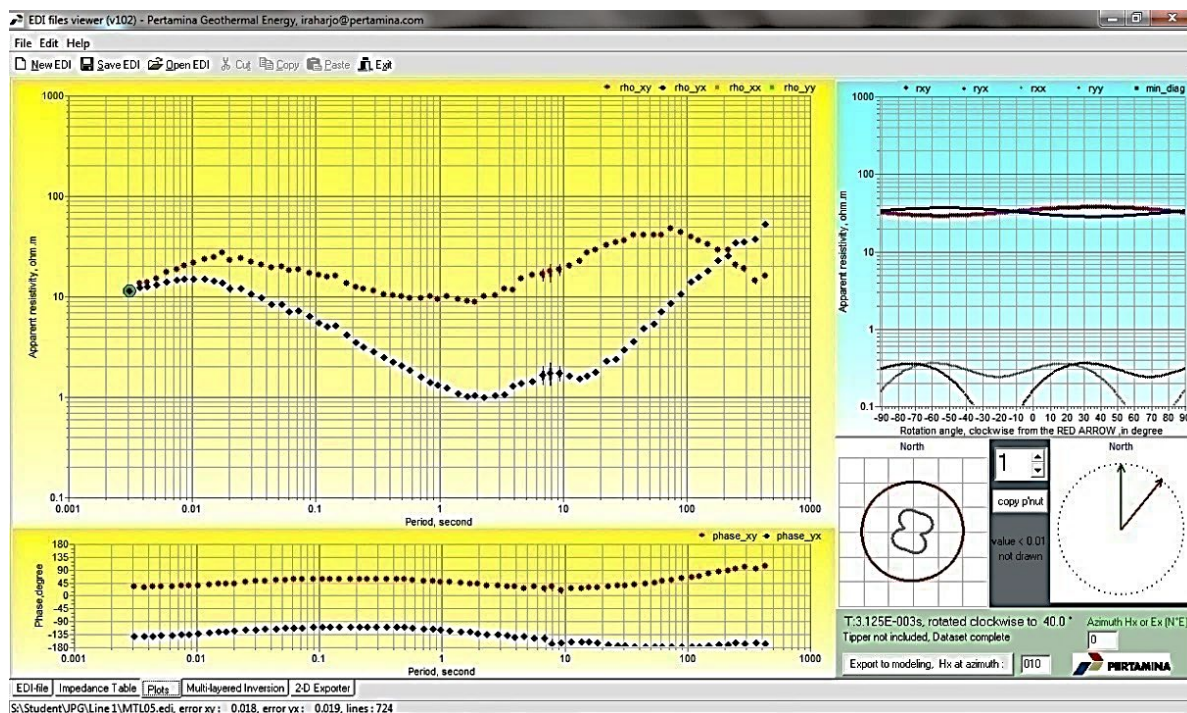


Figure 6. Data display in 1-D MT utilities software program

The researcher used the TE (Transverse Electric) mode because it has higher sensitivity to lateral resistivity variations. In geothermal exploration, this is important for identifying lateral boundaries of geological structures, such as faults, rock formation boundaries, or intrusion zones. The electric current in

TE mode flows parallel to the main direction of the geological structure (strike), producing a more accurate resistivity response to lateral changes in the subsurface. Moreover, the electric field in TE mode is generally more stable and less affected by external disturbances, improving data reliability.

5. Results and Discussion

Resistivity Anomaly Map

A resistivity anomaly map was used to map the horizontal distribution of conductive and resistive rock zones (Figure 7). The resistivity anomaly shows that the distribution of rock resistivity values spans a range of 1–33 Ωm . Resistivity values of $\leq 10 \Omega\text{m}$ are interpreted as conductive zones because they typically indicate clay-rich alteration zones containing bound water, fluid-saturated

low-permeability rocks, and layers consistent with caprocks in geothermal models. This zone lies around Lake Linau and is delineated on the resistivity anomaly map by the dotted line. Areas with rock resistivity values of 20–33 Ωm were interpreted as resistive zones, as shown on the map outside the dotted line. The overall resistivity anomaly map reveals a conductive rock zone around Lake Linau, and a resistive rock zone formed in the southwest (SW) and northeast (NE) directions.

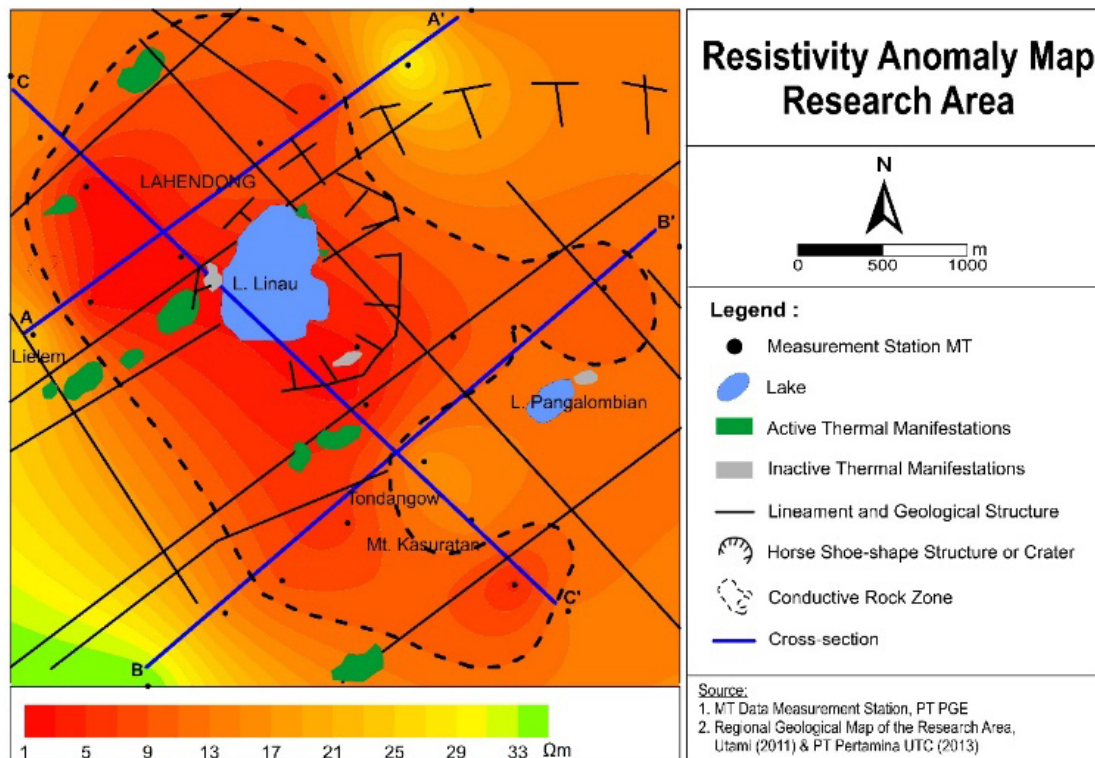


Figure 7. Resistivity anomaly map of the research area

Resistivity Structure Cross-Section

This research produced three cross-sections of resistivity structures on the resistivity anomaly with available magnetotelluric (MT) data. Supporting information for resistivity interpretation in geothermal systems was provided by Anderson et al. (2000). The cross-section of the resistivity structure is classified into three rock layers with different resistivity values, as described below.

- 1) The conductive layer, with the lowest rock resistivity value of $\leq 10 \Omega\text{m}$, was interpreted as a caprock layer. This conductive layer overlies the resistive layer at the bottom. This layer is porous and slightly permeable, if at all. Commonly located within low to intermediate temperature zones (~ 100 – 200°C), this layer functions as a hydrologically impermeable clay cap that restricts the upward movement of geothermal fluids toward the surface.
- 2) A resistive layer, with a rock resistivity of 30–80 Ωm , was interpreted as a reservoir rock layer. This layer is a permeable rock that has a higher resistivity value than that of the caprock layer. The layer typically consists of

hot rocks (200–250°C) with moderate to high porosity and permeability. It contains saline fluids, although saturation may be incomplete. Resistivity tends to increase because of a combination of reduced clay content and increased temperature and permeability.

- 3) The most resistive layer, with the highest rock resistivity value of $\geq 100 \Omega\text{m}$, was interpreted as an intrusive rock layer. This layer is impermeable rock acting as a heat source and is not affected by fluids. This layer is typically composed of intrusive igneous rocks such as granite, diorite, or andesite that have fully crystallized. These rocks are dry and impermeable, lacking free water. Despite their high temperatures, these rocks maintain high resistivity because of the absence of fluid-related electrical conductivity.

Resistivity Structure Cross-Section A – A'

Figure 8 illustrates the resistivity cross-section A–A', which reveals a caprock layer as the topmost stratum. This layer varies in thickness, ranging from approximately 600 m to 1500 m, and is shown in red on the diagram. It is continuous along the southwest

(SW) and northeast (NE) directions. The reservoir rock layer has a thickness of ± 400 to ± 1500 m (marked in green). This layer continues downward from southwest (SW) to northeast (NE). The lowest layer is an intrusive rock layer with a thickness of ± 2000 m (marked in blue). This layer appears and thickens only from measurement point 27 to measurement point 64 (relative to the southwest).

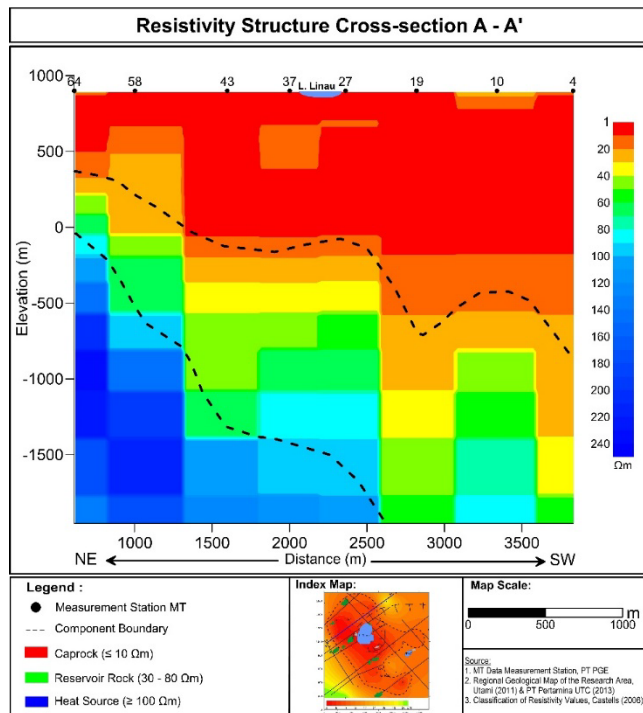


Figure 8. Resistivity structure cross-section A – A'

Resistivity Structure Cross-Section B – B'

The resistivity cross-section B–B' (Figure 9) illustrates that the topmost stratum consists of a caprock formation ranging in thickness from approximately 600 m to 1500 m (indicated in red). This layer is thick in the southwest (SW) direction and thins below measurement points 34 and 14. The thinning of this layer indicates a possible upflow zone. The reservoir rock layer has a thickness of ± 1500 m to ± 2000 m (marked in green). This layer is continuous at the bottom. There are two occurrences of the lowest layer, which is a rock intrusion layer with a thickness of ± 2000 m (marked in blue). This layer is relatively smaller than that in cross-section A.

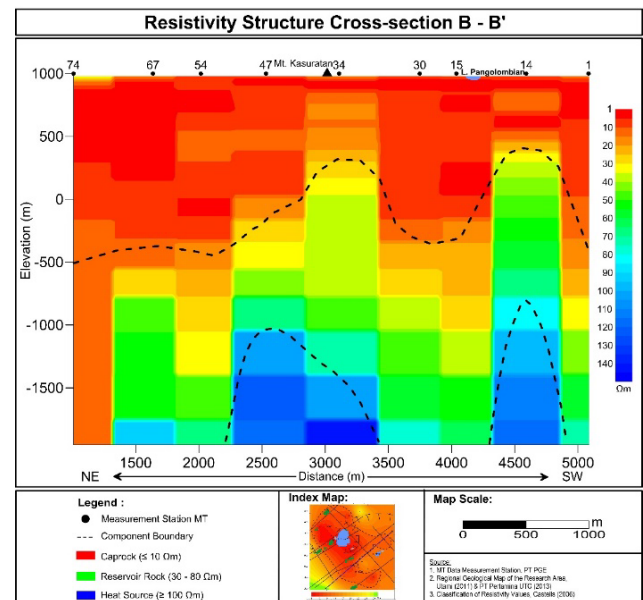


Figure 9. Resistivity structure cross-section B – B'

Resistivity Structure Cross-Section C – C'

The resistivity cross-section C–C' (Figure 10) reveals a more intricate layering structure compared with cross-sections A–A' and B–B'. The topmost stratum, identified as the caprock layer, has a variable thickness ranging from approximately 500 m to 1500 m and is depicted in red on the diagram. The layer is thick in the southeast (SE) and northwest (NW) regions. The reservoir rock layer has a thickness of ± 500 m to ± 2500 m (marked in green). This layer is continuous to the bottom of the section at measurement point 36. The lowest layer is an intrusive rock unit with a thickness of ± 500 to ± 1500 m (marked in blue).

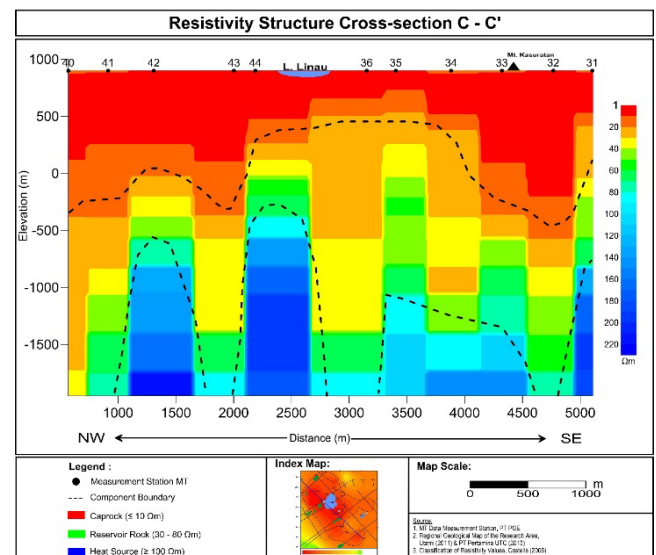


Figure 10. Resistivity structure cross-section C – C'

The efficiency of matrix decomposition techniques is typically evaluated not only by their ability to reconstruct data accurately but also by their computational efficiency. This section offers a comparative analysis of the runtime and memory consumption of Interpolative Decomposition (ID), emphasizing its practical implications in image compression tasks.

6. Conclusion

Rock resistivity values can be used to identify the role of rocks in geothermal system components, such as caprocks, reservoir rocks, and heat sources. The resistivity anomaly distribution shows a value range of 1–33 Ωm . The resistivity anomaly map reveals a conductive rock zone surrounding Lake Linau, with resistive rock formations extending in the southwest (SW) and northeast (NE) directions. Analysis of the subsurface resistivity structure cross-sections confirms the presence of three distinct rock layers, each characterized by specific resistivity values. These layers include a presumed caprock layer with resistivity $\leq 10 \Omega\text{m}$, an estimated reservoir rock layer with resistivity of 30–80 Ωm , and a suspected heat source layer with resistivity $\geq 100 \Omega\text{m}$.

The three resistivity cross-sections (A–A', B–B', and C–C') confirm the presence and distribution of these layers. The caprock layer appears thick and continuous in several directions, whereas thinning in some areas may indicate potential upflow zones. The reservoir layer lies beneath the caprock and varies in thickness. The deepest layer, interpreted as intrusive rock, suggests the likely proximity of the heat source in that area.

The caprock is located in the low to medium temperature zone ($\sim 100\text{--}200^\circ\text{C}$), is hydrologically impermeable, and inhibits fluid movement to the surface. The reservoir layer is hot rock ($200\text{--}250^\circ\text{C}$) with medium to high porosity and permeability, containing saline fluid, and its resistivity increases because of reduced clay content and increased temperature and permeability. The deepest layers consist of intrusive igneous rocks such as granite, diorite, or andesite that have crystallized completely, are dry and impermeable, and still have high resistivity despite high temperatures because they do not contain conductive fluids.

Overall, the magnetotelluric (MT) method is a powerful geophysical tool for delineating the subsurface structures critical for geothermal energy exploration and development in the "X" geothermal field.

7. Acknowledgement

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