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Integrated geophysical methods used to explore geothermal potential areas in Siogung-Ogung, North Sumatra, Indonesia

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Abstract: The manifestations of some hot springs in Siogung-Ogung, North Sumatra, Indonesia have increased speculation of likely geothermal sources. Therefore, integrated geochemical and geophysical methods were employed to identify the geothermal prospect of the area. Two-dimensional electrical resistivity and geomagnetic methods were used for the geophysical survey. The geochemical survey used three concentration measurements: geothermometer silica (SiO_2), geothermometer Na-K, and geothermometer Na-K-Ca. A Wenner Schlumberger array with a 5-meter electrode spacing was used to acquire the 2-D resistivity data, which was processed using Res2Dinv software. The geomagnetic method was performed with a proton precession magnetometer, and the data were processed using Surfer to produce the magnetic residual map. The 2-D electrical resistivity results show that the area has low resistivity values (1-700 Ωm). The resistivity values from 1 to 100 Ωm could be due to the presence of hot waters in alluvium, and the resistivity values > 400 indicate andesite rock, which can function as a hot water conductor from the source. The magnetic residual map shows geomagnetic values from 150 nT to 360 nT, which infer the potentiality of geothermal within the study area. The geochemical results show that the reservoir temperature is 572 °C. Based on the integrated results, the study area has promising geothermal potential.

Keywords: Geochemical, 2-D resistivity, geomagnetic, Siogung - Ogung North Sumatra

INTRODUCTION

Over time, the global population has experienced exponential growth, causing a corresponding rise in the consumption of fossil fuels such as coal, petroleum, and natural gas. Fossil fuels are non-renewable, and are responsible for high carbon emissions, leading to environmental degradation. Consequently, there is an increasing demand for clean and sustainable energy. Geothermal energy remains one of the cleanest, most sustainable, and alternative sources of energy (Oladele *et al*., 2022). Most of the geothermal energy in Indonesia is obtained from intermediate (basaltic andesite) to acid volcanic rock, with reservoir depths of approximately 1.5 km and high reservoir temperatures (250 °C – 370 °C) (Utami *et al*., 2018). Indonesia has approximately 40% of the globe's reserves of geothermal energy potential, at approximately 23 gigawatts (GW). North Sumatra is one of the provinces with the highest geothermal energy potential of 1857 MW (Suharmanto *et al*., 2015). Indonesia suffers from a chronic shortage of energy due to population growth, and geothermal resources has not been fully utilized. Even though the geothermal potential in North Sumatra has been explored in several areas, such as Sibayak and Sorik Marapi, identification and evaluation of other geothermal potential areas, such as Siogung-Ogung, is necessary.

The use of integrated geochemical and geophysical methods are crucial for assessing the geothermal potential of an area (Taqiuddin *et al*., 2016). Geochemical surveys involve chemical testing of water in areas with geothermal potential to determine the temperature of the geothermal reservoir based on ions present in the water. Common ions found in geothermal waters include potassium (K^+), calcium (Ca^{2+}), sodium (Na^+), mercury (Hg, several oxidation states and complexes), chlorine (Cl^-), silica (SiO_2 and complexes), sulfate (SO_4^{2-}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-). 2-D resistivity and geomagnetic surveys are also important for identifying and characterizing geothermal prospects. The 2-D resistivity method depends on the resistance to the flow of electric current in rocks beneath the Earth's surface, while the geomagnetic method is used to determine the depth and

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surface structure, and can be easily conducted at both local and regional scales. It can also identify geothermal potential in an area, providing an alternative to address the energy crisis (Santosa *et al*., 2012; Kadri & Nordiana, 2021).

GEOLOGY

Siogung - Ogung district is located on the western shore of Lake Toba, which was formed 1.3 million years ago as part of the Toba caldera complex. The last, and largest, eruption at 75 ka produced the Youngest Toba Tuff (YTT), consists of rhyolite and rhyodacite pyroclastic deposits, which cover most of the area. Samosir island, located in the middle of Lake Toba, is a newly-arisen island formed by isostatic rebound and the post-eruption recharge of the underlying magma chambers (Figure 1).

To the north of Toba, an outcrop of Middle Toba Tuff (MTT) consisting of rhyolitic can be found. Toba young tufa is a volcanic eruption product composed of rhyolite and rhyodacite lithology, produced by the Toba volcano.

METHODOLOGY

2-Dimensional electrical resistivity imaging (2-D ERI) and the geomagnetic method were the two geophysical methods employed for the study. The 2-D ERI instrumentation used in the survey consists of ABEM SAS4000, electrode selector, electrodes, the reel of cables, jumpers and 12-volt battery. Basically, the 2-D ERI involves using multiple electrodes whereby current is injected into the ground through a pair of current electrodes. The resulting potential difference is measured between a pair of current electrodes (Mohammed *et al*., 2019). The apparent resistivity ρ_a of the subsurface materials is obtained using the equation:

$$\rho_a = k\frac{V}{I}$$

V: voltage (potential difference) measured in volt
I: current measured in ampere
K: geometric factor (which depends on the array type)

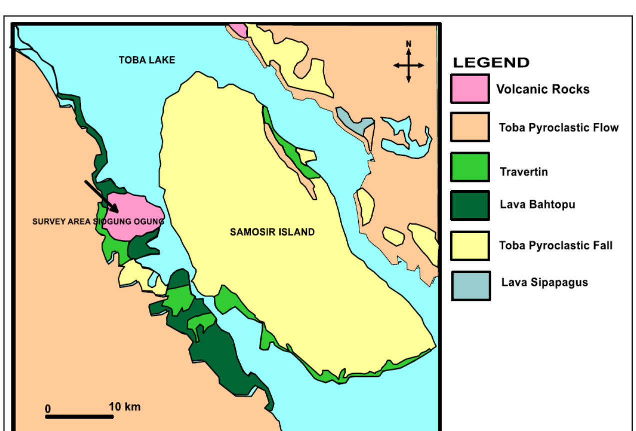

Figure 1: Geology map of Siogung - Ogung area from Barber *et al*., 2006.

Wenner Schlumberger array (Figure 2) with 5-meter electrode spacing was used for the 2-D ERI data acquisition. This is because it has high signal strength, and is moderately sensitive to both horizontal and vertical structures.

The resistivity of subsurface materials is measured through a 2-D resistivity approach. Igneous and metamorphic rock types often have high resistivity values. The resistivity values of various rocks and soil are shown in Table 1.

The geomagnetic method can be used to determine the magnetic properties of rocks below the subsurface due to the influence of magnetized rocks. The geomagnetic method is to measure the variation of the magnetic field on the subsurface. It works based on measuring small variations in the intensity of the magnetic field on the earth's surface due to differences between the properties of the magnetization of rocks in the earth's crust, thereby increasing the appearance of the geomagnetic field which is not homogeneous or called a magnetic anomaly (Santosa *et al*., 2012). The geomagnetic method used a proton precision magnetometer (Figure 3). The geomagnetic method uses geomagnetic tools to determine the subsurface structure in the geothermal area. The external and main magnetic fields need to be reduced to determine the magnitude of the magnitude field anomaly.

The water samples from four locations with surface manifestations of hot springs within the study area (Figure 4) were collected and subjected to geochemical analysis. The trilinear diagrams Cl-SO_4-HCO_3, SiO_2, and Na-K-Mg were used to determine the characteristics of the geothermal reservoir (Sobirin *et al*., 2017; Zhang *et al*., 2018).

Empirical geothermometer equations are used to estimate the temperature of geothermal reservoirs based on hot water samples (Deng *et al*., 2022). These equations are

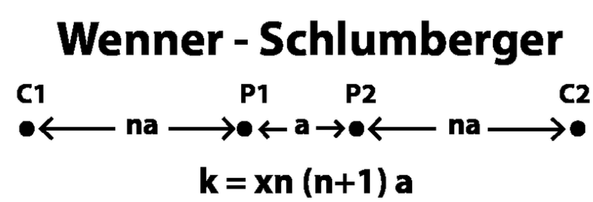

Figure 2: Wenner Schlumberger array.

Table 1: Resistivity values of rocks and soil.

Material	Resistivity (Ωm)
Alluvium	10 - 800
Sand	60 - 1000
Clay	1 - 100
Groundwater	10 - 100
Sandstone	$8 - 4 \times 10^3$
Limestone	$50 - 4 \times 10^3$
Granite	$5 \times 10^3 - 1 \times 10^6$
Andesite	$170 - 4.5 \times 10^8$

preferred because they provide more accurate temperature estimates with an error margin of less than 5% (Afandi *et al*., 2020). In the case of the Siogung-Ogung geothermal system, which is associated with volcanic activity, the Na-K and silica geothermometers are particularly effective, as they are suitable for high-temperature geothermal systems (Nicholson, 1993). Applying these geothermometers make it possible to determine the reservoir temperature by analysing the levels of Na, K, Ca, and Si in water samples. The validity of each geothermometer can be assessed by comparing the results obtained from the different equations. Equations 1, 2, and 3 can be used to calculate the Na-K, SiO_2, and Na-K-Ca geothermometers, respectively.

$$T(°C) = 855.6/[\log(Na/K)+0.8573] - 273.15 \quad (1)$$
$$T(°C) = 1533.5/[5.768-\log(SiO_2)] - 273.15 \quad (2)$$
$$T(°C) = 1647/[\log(Na/K)+[\beta(\sqrt{(Ca/Na)})+2.06] +2.47] - 273.15 \quad (3)$$

A geomagnetic survey measures the magnitude and orientation of the intensity of the geomagnetic field. The geomagnetic survey aims to identify subsurface geology-based geomagnetic anomaly fields due to the magnetic properties of underlying rocks and the geomagnetic susceptibility caused by the different magnetic values of the object (Nurgalieva & Yassonov, 2013). When a magnet is magnetized, it will have a remanence, which refers to the magnetization that remains after the outside magnetic subject is removed. This is also known as magnetic reminiscence in magnetic storage (Nurgalieva & Yassonov, 2013). Table 2 shows the overall magnetic susceptibility values in common rocks and ores. The magnetic properties of highly magnetic rocks tend to vary widely, and their magnetization is not directly proportional to the applied field.

The four hot springs in the area (HW1 – HW4) were measured for temperature and pH, and water samples taken were analyzed for cation and anion content. The three 2D resistivity lines were located as depicted on Figure 5, covering a total of 155 meters, utilizing 32 electrodes at an electrode spacing of 5 m. The geomagnetic survey area was located close to three of the hot springs (HW2, HW3 and HW4), consisting of 45 sampling locations.

Figure 3: PPM (Proton Precision Magnetometer).

Figure 4: Geothermal manifestation of Siogung - Ogung area.

RESULTS AND DISCUSSIONS

Samples were collected from four natural hot springs (HW1-HW4) with distances of 96 meters between HW1 and HW2, 87 meters between HW2 and HW3, and 26 meters between HW 3 and HW4. Concentrations of cations and anions, as well as pH and temperature measured at the site, are presented in Table 3.

The trilinear diagram (Figure 6) classification was used to determine the kind of hot water based on the relative quantity of chloride, sulfate, and bicarbonate anions in hot water. Based on the diagram, the hot water is included in the sulfate type.

The silica (SiO_2) geothermometer, Na-K geothermometer and Na-K-Ca geothermometer were used to determine the reservoir temperature in the study area. From the measurement results using the equation (1), (2) and (3), the temperature results are as tabulated in Table 4.

The silica geothermometer and Na-K-Ca geothermometer cannot be used because their temperature values only reach 112.62 °C and 157.96 °C, respectively. As the geothermometer's accuracy is limited to temperatures above 180 °C, these values cannot be used as a reference. Therefore, the only geothermometer that can be used is the Na-K-Ca geothermometer, which has a temperature of 572.71 °C.

The 2-D resistivity study at Siogung-Ogung was conducted in three lines using the Wenner-Schlumberger configuration. A total of 225 data points were obtained with a 150-meter length and 5-meter electrode spacing. The resistivity values obtained from all lines ranged from 1 to 700 Ωm.

Table 2: Susceptibility value of some rocks.

No.	Types of Rocks	Susceptibility (10^3 SI)	
		Interval	Average
1.	Dolomite	0-0.9	0.1
2.	Limestones	0-3	0.3
3.	Sandstone	0-20	0.4
4.	Quartzite	3-17	-
5.	Granite	0-50	2.5
6.	Rhyolite	0.2-35	-
7.	Andesite	-	160

Table 3: Chemical composition of Siogung - Ogung water.

No.	Parameter	Sampling location			
		HW1	HW2	HW3	HW4
1.	Potassium (K) mg/L	28.26	25.49	25.12	23.7
2.	Calcium(Ca) mg/L	64	81.8	91.1	75.0
3.	Sodium(Na) mg/L	68.65	31.6	32.6	31.0
4.	Mercury (Hg) mg/L	< 0.01	< 0.01	< 0.01	< 0.01
5.	Chlorine (Cl) mg/L	46.3	50.30	47.77	51.27
6.	Silica (SiO_2) mg/L	53.8	66.4	69.9	60.4
7.	Sulfate (SO_4) mg/L	578	675	665	667
8.	Magnesium (Mg) mg/L	73.49	59.5	64.5	49.8
9.	Bicarbonate (HCO_3) mg/L	36.46	40.50	43.69	40,57
10.	Temperature °C	72	76.5	78	77.6
11.	Potential of Hydrogen (pH)	5.6	5.6	5.7	7

Table 4: Hot water temperature measurement results.

No.	Sampel	T(SiO_2)°C	T(Na-K)°C	T(Na-K-Ca)°C
1.	Hot water 1	106.61	415.31	179.88
2.	Hot water 2	115.27	601.16	147.93
3.	Hot water 3	117.25	669.01	153.44
4.	Hot water 4	111.37	605.36	150.61
	Average	112.62	572.71	157.97

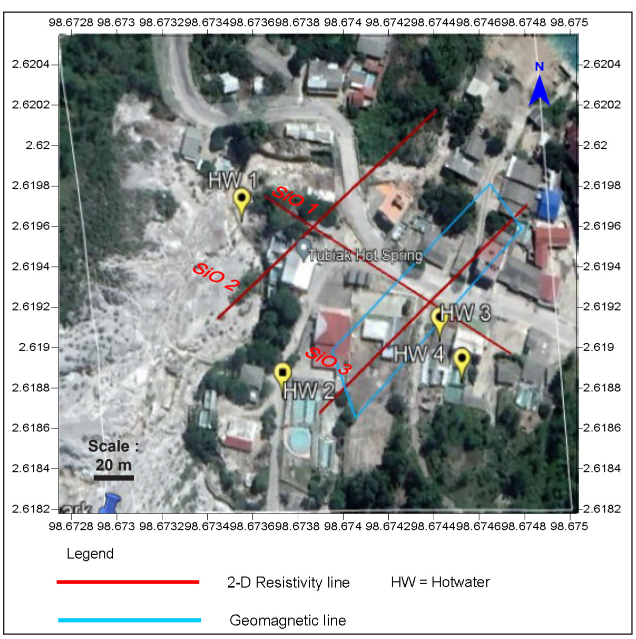

Figure 5: Siogung - Ogung survey lines.

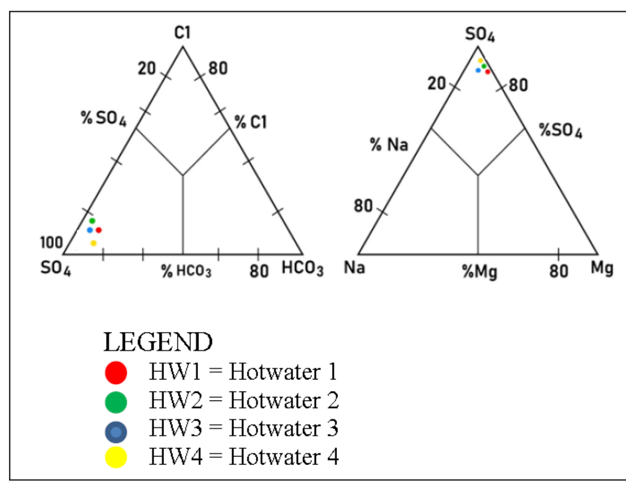

Figure 6: The triangular plots for the major cations and anions of the analyzed hot springs.

Line 1, shown in Figure 7, stretches from NW to SE and has a more than 31 meters depth. The resistivity values in Line 1 are dominated by 1 to 100 Ωm, with a few areas indicating resistivity values ranging from 200 to 400 Ωm. Only a few areas show resistivity values greater than 600. This line indicates a major low resistivity area, possibly due to hot water and high regional resistivity values (> 600). Based on the geological analysis and the analysis of resistivity values in Table 1, it can be interpreted that the area is dominated by andesite rock (Lashin *et al*., 2014).

Line 2 (Figure 8) extends from SW to NE, and the resistivity value varies from 0 Ωm to 700 Ωm. At a distance of 0 to 65 m (depth of 0 m to 22 m), the values show > 800 Ωm, indicating the presence of a heat conductor from a heat source. The resistivity value > 800 Ωm can also be found at distances of 95 m to 120 m, which can still conduct heat from a source beneath the earth. Additionally, there is a wide layer with low resistance, particularly between 1 and 100 Ωm, at a distance of 60 to 100 m (depth of 0 to 31 m). This layer is related to a hot water area or the geothermal reservoir, which is consistent with the geological analysis of this area (Elida *et al.*, 2014).

Line 3 (Figure 9) spreads from the SW to NE, and the depth of the 2-D resistivity results is 31 meters. The resistivity values of the line vary from 0 to 700 Ωm. The low resistivity value is observed at a distance of 0 to 155 meters (depth 0 to 7 m), indicating a hot water area. This observation is consistent with hot water manifestations in this area. Generally, the low-resistivity blue-colored zones within the interpreted resistivity lines indicate geothermal systems. Due to the low resistivity value near the surface, the area can be a good conductor with a thickness of 11 m (depths 6–15 m) as shown at the beginning of the resistivity line (Manyoe *et al.*, 2020).

The lines show a resistivity value range from 0 to 400 Ωm and a few locations with resistivity values from 600 to 700 Ωm, at depths of less than 7 m at 100 to 120 m. Even though the lines suggest a low resistance value in general, this may be due to the presence of hot waters in the area. It is also possible that all lines have a heat-carrying layer, or a heat-conducting conductor, and a layer with a resistance higher than 800 Ωm (Idris *et al.*, 2018). These lines resistivity

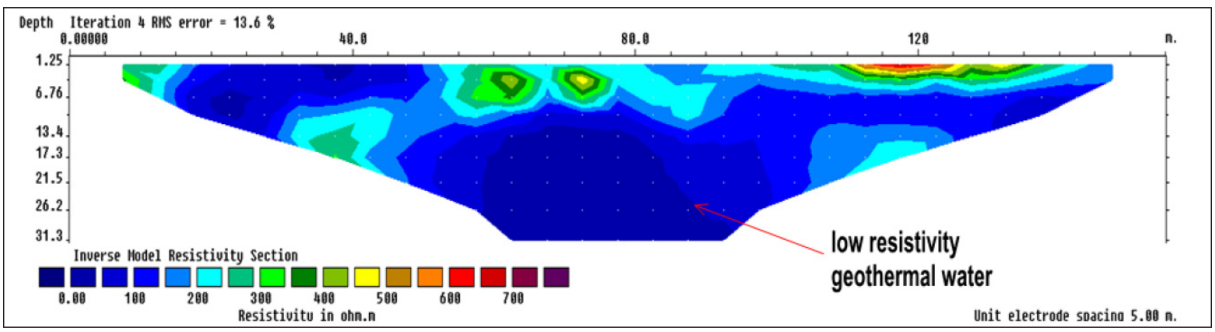

Figure 7: Line 1 of Siogung - Ogung area.

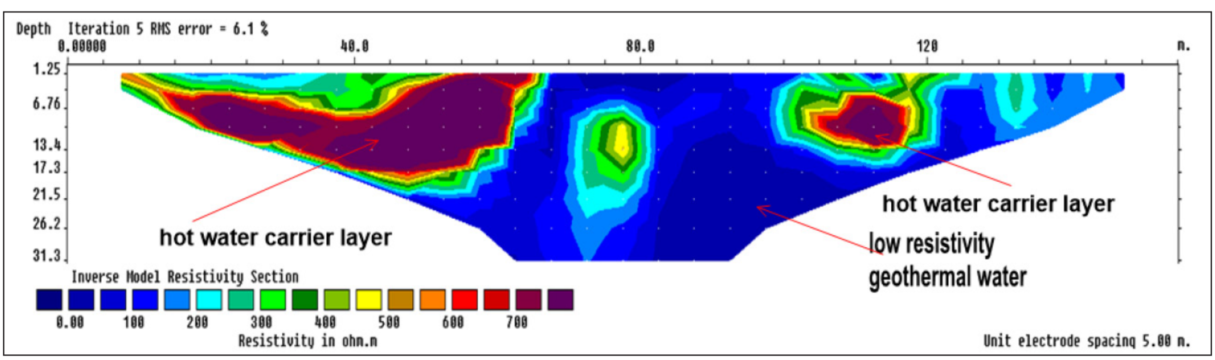

Figure 8: Line 2 of Siogung - Ogung area.

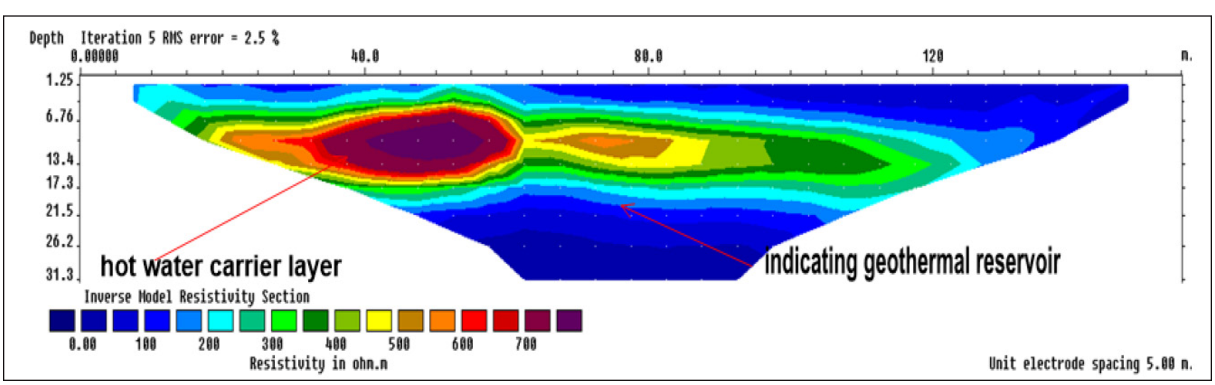

Figure 9: Line 3 of Siogung - Ogung area.

value from 0 to 100 Ωm indicate a hot reservoir (alluvium or limestone). In comparison the resistivity value > 400 Ωm can indicate a heat conductor (andesite rock).

The 2-D resistivity value in the Siogung - Ogung area is divided according to the resistivity value as shown in Table 5 below.

The geomagnetic line is close to the three hot water sources (HW2, HW3, HW3) (Figure 10). The low magnetic anomaly values range from 150 nT to 220 nT, medium magnetic anomalies range from 230 nT to 300 nT, and the high magnetic anomalies range from 320 nT to 360 nT. Based on these magnetic field anomaly value groups, the study area is mainly dominated by low magnetic field anomaly with values scattered in the middle of the study area, stretching from the north to the east direction. The magnetic field anomalies are located in the West, South, and Northeast directions. The high magnetic field anomalies are found in the study area northwest, central, and northeastern parts.

The geomagnetic susceptibility of rocks is a fundamental physical parameter in magnetic research because it indicates a rock's ability to receive magnetization from the geomagnetic field. To precisely determine of the magnetic properties of the study area, measurements of geomagnetic susceptibility were taken at each measurement point. Figure 11 shows a contour map of the obtained susceptibility values (Taqiuddin *et al*., 2016).

The geomagnetic layer with a susceptibility value of k = 0.008 is interpreted as andesite lava rock, formed by volcanic eruptions and is located at a depth of 5 to 20 meters. The susceptibility value of k = 0.004 is interpreted as pyroclastic flows located at approximately 60 to 95 meters deep. This layer acts as a rock cover zone, a barrier to geothermal water vapor loss (Suhartono, 2012). The area is also interpreted as a strongly altered rock or stone that has undergone significant changes, decreasing its magnetic value due to heating. This layer is characterized by a high ratio of secondary minerals to total minerals at each depth. The base of this layer is a reservoir zone, with geothermal host rocks and steam. The susceptibility value is interpreted as a fracture used as an outflow of geothermal steam. In some suspected areas, geothermal surface manifestations are found as fumarole craters (Oladele *et al*., 2020).

CONCLUSIONS

Geochemical, 2-D resistivity imaging, and geomagnetic surveying effectively delineate geothermal systems. The geochemical survey results suggest that the reservoir temperature in the study area is 572.71°C. The 2-D resistivity

Table 5: Resistivity value and rock type.

No.	Resistivity value (Ωm)	Rock type
1.	0 – 100	Alluvium (reservoir)
2.	> 400	Andesite rock (heat conductor)

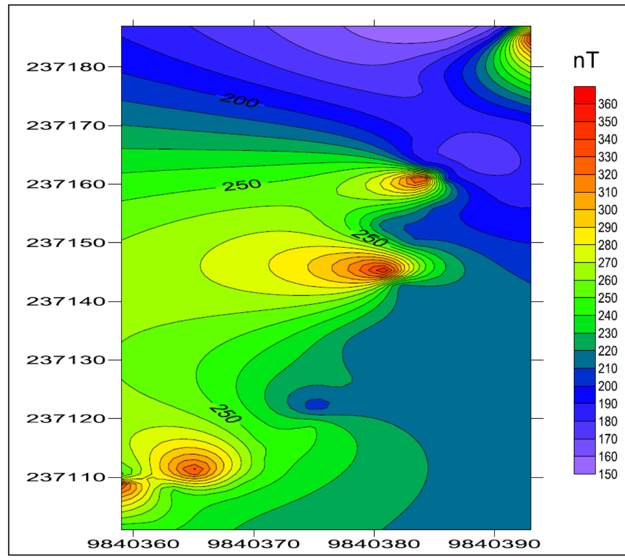

Figure 10: Magnetic anomaly contour.

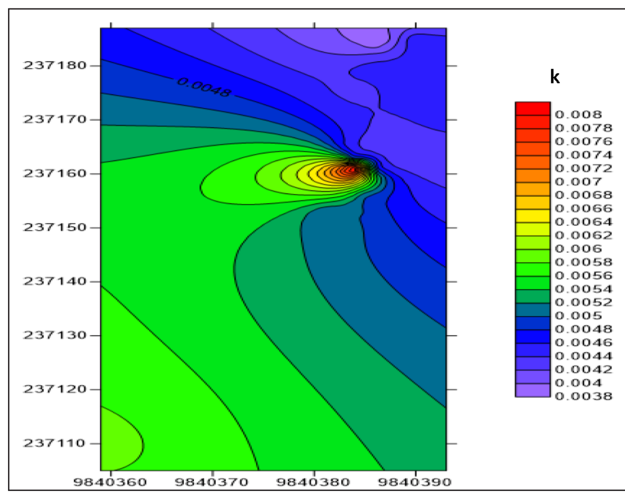

Figure 11: Susceptibility value contour.

values indicate the presence of a material that can potentially act as a carrier for geothermal fluid flow, with resistivity values ranging from > 100 Ωm to 700 Ωm (andesite rock). Low resistivity values in the 2-D resistivity imaging suggest the presence of geothermal fluid flow, which is also supported by the area high geomagnetic values (> 100 nT). The integration of these results has confirmed the presence of geothermal fluid in Siogung - Ogung. Additionally, the high geomagnetic values in the area can be attributed to the nearby volcano. The low resistivity values in deeper layers indicate increasing temperature with depth, further supporting the potential for geothermal energy in Siogung - Ogung. Therefore, the study area has a great potential for geothermal energy.

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AUTHORS CONTRIBUTION

MK - Investigation, data curation, writing original draft. NMM - Data curation, formal analysis, review and editing. MNMN - Validation, supervision, review and editing. MTZ - Conceptualization, formal analysis, methodology, software. FNR - Conceptualization, formal analysis, methodology, and software. MAM - Review and editing. SZ - Conceptualization and formal analysis.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this research or personal relationships that could have appeared to influence the work reported in this paper.

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