

Geological Structural Control on the Distribution of Rock Alteration in Ngebel Lake and Surrounding Areas, Ponorogo, Indonesia

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Abstract

The Telaga Ngebel Complex is an area with an active geothermal system. Geothermal energy is considered a promising alternative energy source for the future, especially in light of the depletion of fossil fuels. In geothermal exploration, altered rocks serve as indicators of the presence of a geothermal system. The existence of an active geothermal system is closely related to alteration zones, which are, in turn, influenced by geological structures. This study aims to identify the structural controls on the distribution of alteration zones. The methods used include literature review, field surveys, remote sensing, sampling of altered rocks, and collection and measurement of structural data. The results show that the study area has a high density of structural lineaments in the southern part of the lake, as evidenced by the intersection of several strike-slip faults. These intersections serve as pathways for hydrothermal fluids to ascend. The alteration found in these high-density areas is predominantly propylitic alteration. Other types of alteration observed include argillic alteration.

Keywords: Structure, Alteration, Ngebel, Geothermal, Propylitic, Argillic.



A. INTRODUCTION

Telaga Ngebel and its surrounding area constitute a region with an active geothermal system. Geothermal manifestations in the study area include several hot spring emergence points (Yudiantoro, 2020), which are currently utilized by the local community as hot spring baths (Figure 1).



Figure 1. Hot Spring Manifestation

Geothermal energy is a promising alternative energy solution for the future, especially considering the ongoing depletion of fossil fuels (Bakruddin W. U. et al., 2017; Sari, 2018; Khadijah, 2018; Tampubolon, 2020; Nurwahyudin, 2020; Rahmayanti, 2021; Sidik, 2022; Ahluriza, 2021; Wijayanti, 2023; Aprianto, 2023). Geothermal refers to heat concentrated from a specific energy source (Rybach, 1981 in Fajri, 2021). According to Leibowitz (1978, in Fajri, 2021), geothermal energy is a usable and economically valuable energy source near the surface. In geothermal systems, altered rocks indicate the presence of geothermal activity.

Hydrothermal alteration is a complex process involving mineralogical, chemical, and textural changes in rocks as a result of the interaction between hydrothermal fluids and the host rocks (Pirajno, 2009 in Fajri, 2021; Qodri, 2018; Mangidotua, 2018; Canavarro, 2018). Seven additional factors influence the occurrence of alteration (Corbett & Leach, 1997, in Sumotarto, 2020): (a) Temperature, (b) Chemical composition of the fluid, (c) Concentration, (d) Composition of the host rock, (e) Reaction kinetics, (f) Duration, (g) Permeability. Geological structures play a crucial role in the alteration process, as these structures serve as pathways for hydrothermal fluid migration (Hafizh T. et al., 2017). Fractures in geothermal areas can allow geothermal fluids to flow to the surface (Saptadji, 2012).

According to Pirajno (1992), alteration zones can be divided into several categories, including:

1. Potassic Zone

The presence of key minerals such as K-feldspar, biotite, magnetite, and quartz characterizes the potassic zone. This zone is located near the intrusive source and is associated with fluid temperatures of up to 300°C and high fluid salinity. Accessory minerals commonly found in this zone include albite, quartz, calcite, pyrite, and minor oxide minerals.

2. Propylitic Zone

The propylitic zone is marked by key minerals such as chlorite, epidote, and calcite. It forms at temperatures ranging from 100°C to 300°C, with neutral to alkaline fluid pH, varying salinity, and typically in low-permeability areas.

3. Argillic Zone

The argillic zone is characterized by clay minerals such as kaolinite, illite, dickite, smectite, and montmorillonite. It forms at temperatures between 100°C and 300°C, with fluid pH ranging from acidic to neutral.

4. Advanced Argillic Zone

The presence of minerals such as pyrophyllite, diaspore, andalusite, and quartz indicates the high-temperature advanced argillic zone. This zone forms at temperatures between 250°C and 350°C.

5. Silicification

This type of alteration is common and very typical in hydrothermal alteration systems. The silica minerals typically observed in Silicification include low quartz or α -quartz.

Geological structures are geological features in an area formed due to rock deformation caused by tectonic or other processes. The properties of the rocks themselves strongly influence the deformation process. Brittle rocks typically form geological structures such as joints and faults, while ductile stones tend to form folds (Djauhari, 2012). Geological structures play an essential role in the alteration process. Structures such as joints and faults act as pathways for hydrothermal fluids. As these fluids flow through the structures, they chemically and physically alter the surrounding rocks, forming alteration zones.

Tectonic plate movement significantly influences the occurrence of mineralization in a given area. This is because tectonic activity can generate geological structures as pathways for hydrothermal fluid migration. Tectonic plate movements are generally classified into convergent, divergent, and transform boundaries. Corbett & Leach (1997) categorize global convergent boundaries into two types: orthogonal convergence and oblique convergence. Among these, oblique convergence is considered more favorable for mineralization processes. This is due to the associated simple shear mechanism, which can induce dilatational structures that serve as conduits and accumulation zones for hydrothermal fluids, ultimately promoting mineralization. Such processes occur when geological structural systems develop within magmatic arc environments, enabling magma-derived fluids to intrude through existing fractures or generate new ones.

Corbett & Leach (1997) classify several dilation systems based on their tectonic settings as follows:

1. Splays and horsetails – These are structural features that control the emplacement of porphyry intrusions, typically developing along fault structures.
2. Tension fractures – These are open fractures formed as a result of strike-slip faulting and often serve as favorable sites for epithermal deposit formation.
3. Jogs – These are geological structures created by extensional forces along segmented strike-slip faults. Jogs are commonly associated with zones of mineralization.
4. Hanging wall splits – These are fault zones that occur due to normal faulting or bedding planes intersected by dipping fault surfaces.
5. Ore shoots – These refer to localized zones of increased volume or metal content (e.g., gold), formed as a result of increased dilation within vein systems.



Figure 2. Research Area

Source: Map of Google Earth (2025)

The research was conducted in Telaga Ngebel and its surroundings, Ponorogo Regency, East Java Province. Geographically, the Ngebel area is located between $7^{\circ}46'25''$ – $7^{\circ}49'13''$ South Latitude and $111^{\circ}39'7''$ – $111^{\circ}36'28''$ East Longitude. To the north, it borders Madiun Regency. An active geothermal system, with manifestations such as hot springs characterize the study area.

B. LITERATURE REVIEW

1. Regional Geology

Physiographically, the study area is part of the Ngebel Volcanic Complex, situated at an elevation of approximately 900 meters above sea level (Yudiantoro, 2023). According to van Bemmelen (1949), this location lies within the Solo Zone. The Solo Zone is dominated by Quaternary volcanic mountain ranges (Bemmelen, 1949; Hartono, 1994, in Yudiantoro, 2023) that extend from west to east.

Subsequent research conducted by Hartono et al. in 1998 concluded that two other calderas are located on the western side of the Wilis Volcanic Complex. The oldest caldera is the largest, with an estimated diameter of approximately 4 kilometers, opening toward the west, and is identified as the Jeding–Patukbanteng Caldera. Its crater walls are estimated to be located at the peaks of Mt. Manjutan (1,555 m), Mt. Kemamang (1,463 m), Mt. Patukbanteng (1,630 m), Mt. Jeding (1,612 m), Mt. Batusoko (1,396 m), and Mt. Beser (1,025 m). The second, smaller caldera is now occupied by Lake Ngebel, measuring approximately 1.5 km from north to south and 1 km from east to west. This second caldera is located further west and is younger than the Jeding–Patukbanteng caldera.

The Ponorogo area and its surroundings are part of the regional geology of the Madiun sheet (Hartono, 1992). The area generally consists of Tertiary volcanic rocks,

sedimentary rocks, Quaternary volcanic rocks, and alluvial deposits. The study area lies within the Ngebel Morphounit and the Jeding–Patukbanteng Morphounit. The Ngebel Morphounit was formed during the Early Pleistocene and is composed of volcanic breccia with pyroxene andesite, hornblende andesite, diorite, tuff, and volcanic conglomerate. The Jeding–Patukbanteng Morphounit also formed in the Early Pleistocene and is characterized by lapilli tuff interbedded with coarse tuff (Figure 3).

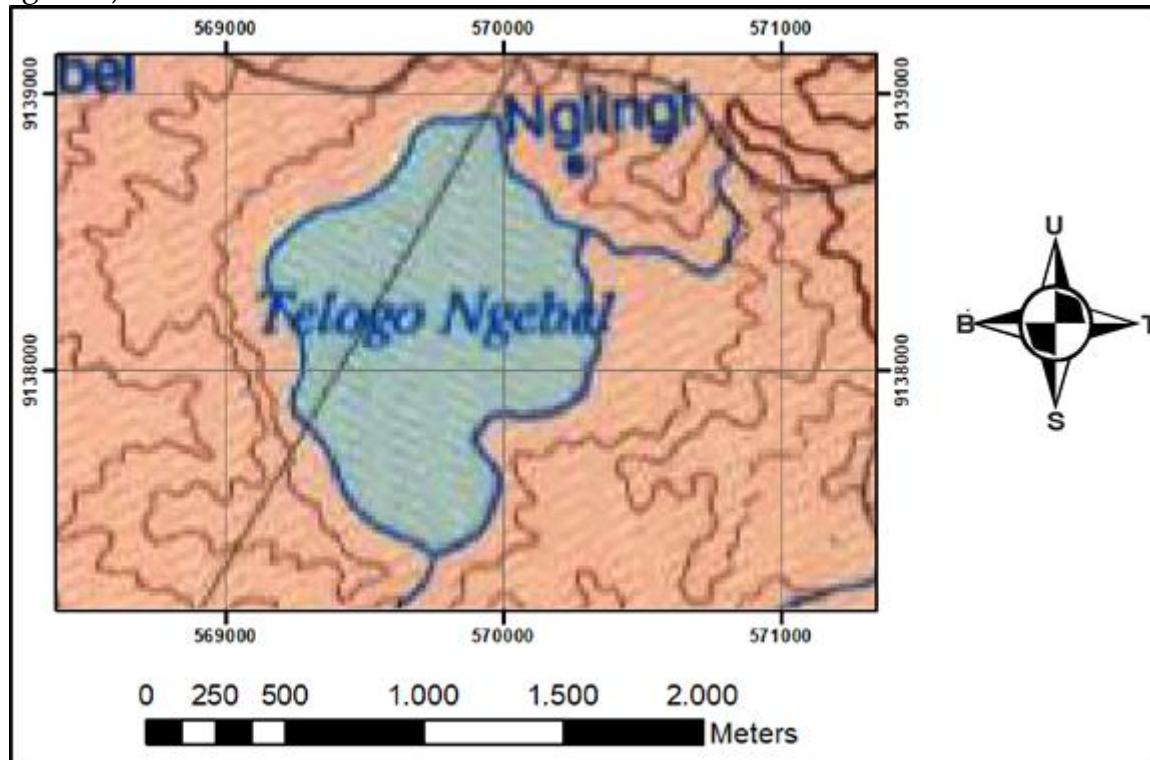


Figure 3. Geological Map of Madiun Sheet

Source: Hartono (1992)

The Ponorogo area and its surroundings are part of the regional geology of the Madiun sheet. The area generally comprises Tertiary volcanic rocks, sedimentary rocks, Quaternary volcanic rocks, and alluvial deposits. The stratigraphy of the Madiun geological sheet (Hartono et al., 1992), listed from oldest to youngest, includes:

- a. Mandalika Formation: Composed of volcanic rocks (andesite, dacite, and volcanic breccia), this formation dates to the Oligocene.
- b. Intrusive Rocks: Oligocene-aged intrusions penetrating the Mandalika Formation, causing hydrothermal alteration. These include andesite, dacite, and microdiorite, associated with the physiographic Southern Mountain Zone.
- c. Jaten Formation: Consists of sandstone and tuff with intercalations of volcanic breccia, carbonaceous siltstone, marl, and limestone. It is dated from the Early to Middle Miocene.
- d. Wuni Formation: Late Miocene to Pliocene in age, this formation comprises andesitic breccia with lower tuff intercalations and upper tuff layers with limestone beds.

- e. Wonosari Formation: Ranges from Early to Late Miocene, composed of calcarenite, limestone, conglomerate, calculative, and crystalline limestone.
- f. Kabuh Formation: Middle Pliocene in age, it consists of conglomerate, sandstone, and occasional claystone and marl interbeds. It is part of the Kendeng Zone physiography.
- g. Notopuro Formation: Composed of volcanic breccia, thick-bedded tuff, and agglomerate, it dates from the Middle to Late Pleistocene and belongs to the Kendeng Zone.
- h. Klotok Formation: Early Pleistocene formation comprising volcanic breccia, tuff, and pyroxene andesite lava.
- i. Dengean Morphounit: Formed in the Early Pleistocene, consisting of volcanic breccia with hornblende andesite clasts, tuff, and agglomerate.
- j. Ngebel Morphounit: Also from the Early Pleistocene, consisting of volcanic breccia with pyroxene and hornblende andesite clasts, diorite, tuff, and volcanic conglomerate.
- k. Tanjungsari Morphounit: Formed in the Early Pleistocene, composed of pumice lapilli tuff interbedded with coarse tuff.
- l. Jeding–Patukbanteng Morphounit: Early Pleistocene in age, consisting of pyroxene andesite lava, volcanic breccia, and interbedded tuff and pumice.
- m. Punjul Andesite Intrusion: A Middle Pleistocene intrusion into the Mandalika Formation, causing alteration associated with the Southern Mountain Zone physiography.
- n. Parang Andesite Intrusion: Also a Middle Pleistocene intrusion into the Mandalika Formation, composed of pyroxene andesite and part of the Southern Mountain Zone.
- o. Gajahmungkur Morphounit: Formed in the Middle Pleistocene, consisting of pyroxene andesite lava and minor volcanic breccia.
- p. Pawonsewu Morphounit: Middle Pleistocene in age, composed of volcanic breccia with pyroxene andesite clasts, agglomerate tuff, and pyroxene andesite lava.
- q. Sedudo Morphounit: Late Pleistocene unit composed of hornblende andesite lava and minor volcanic breccia with hornblende andesite clasts.
- r. Argokalangan Morphounit: Late Pleistocene unit composed of volcanic breccia, agglomerate, tuff, and andesitic lava.
- s. Alluvial Deposits: Holocene in age, consisting of volcanic material such as sand, gravel, silt, and pebbles.

2. Regional Tectonic

Two volcanic arcs are developed on Java Island. The Tertiary volcanic arc (Oligocene–Miocene) forms the Southern Mountain Zone, while the Quaternary volcanic arc developed since the Late Miocene.

Ongoing subduction processes significantly influence the structural development of Java Island. According to Pulunggono and Martodjojo (1994) (in Wulandari, 2023), the dominant structural patterns in Java include:

- a. The Sunda trend, oriented North-South, dated from the Early Eocene to Early Oligocene.
- b. The Meratus trend, oriented Northeast-Southwest, dating from the Late Cretaceous to Early Eocene.
- c. The Java trend is oriented West-East.

Sribudiyani et al. (2003) further stated that the main structural trends in East Java are the Meratus trend (NE-SW) and the Java trend (W-E). These tectonic settings have given rise to various regional geological structures, including joints, faults, and folds.

C. METHOD

The research activities began with a literature review aimed at understanding the geological conditions, geomorphological characteristics, and structural development of the study area. This was followed by field surveys and remote sensing to interpret lineaments within the research area. Fieldwork involved geological mapping and sampling of rocks, particularly outcrops that have undergone alteration, as well as the collection and measurement of structural data.

D. RESULTS AND DISCUSSION

1. Lineament Conditions of the Study Area

In the study area, the structural lineaments are relatively dense, particularly around the area Near Lake Ngebel and the southern part of the lake. Lineament Conditions of the Study Area.

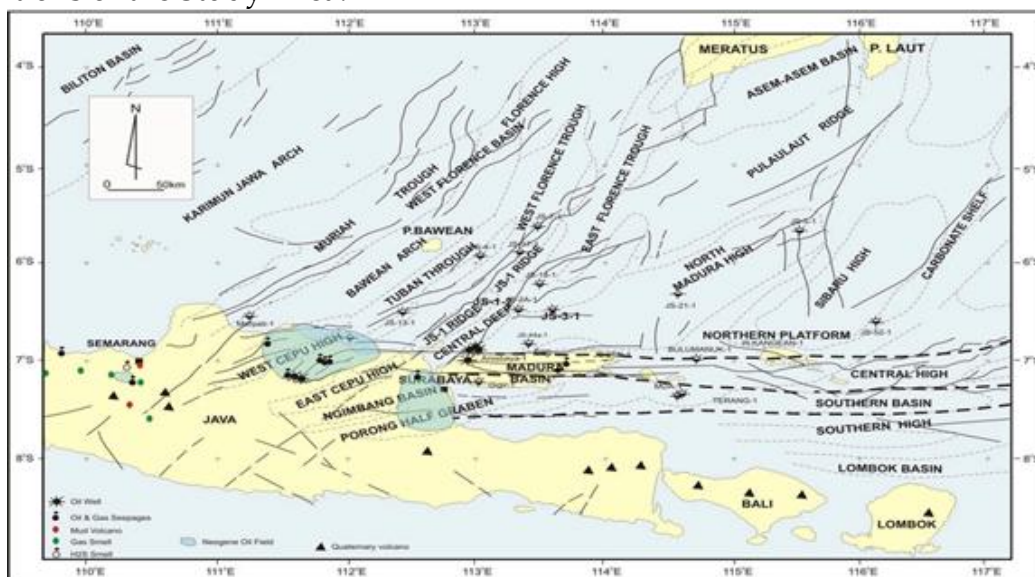


Figure 4. Structural Pattern of Java Island

Source: Sribudiyani (2003)

Lineament analysis was conducted using ArcGIS software by creating a hillshade map based on DEMNAS data. Lineaments were interpreted based on the existing valleys (Figure 5).

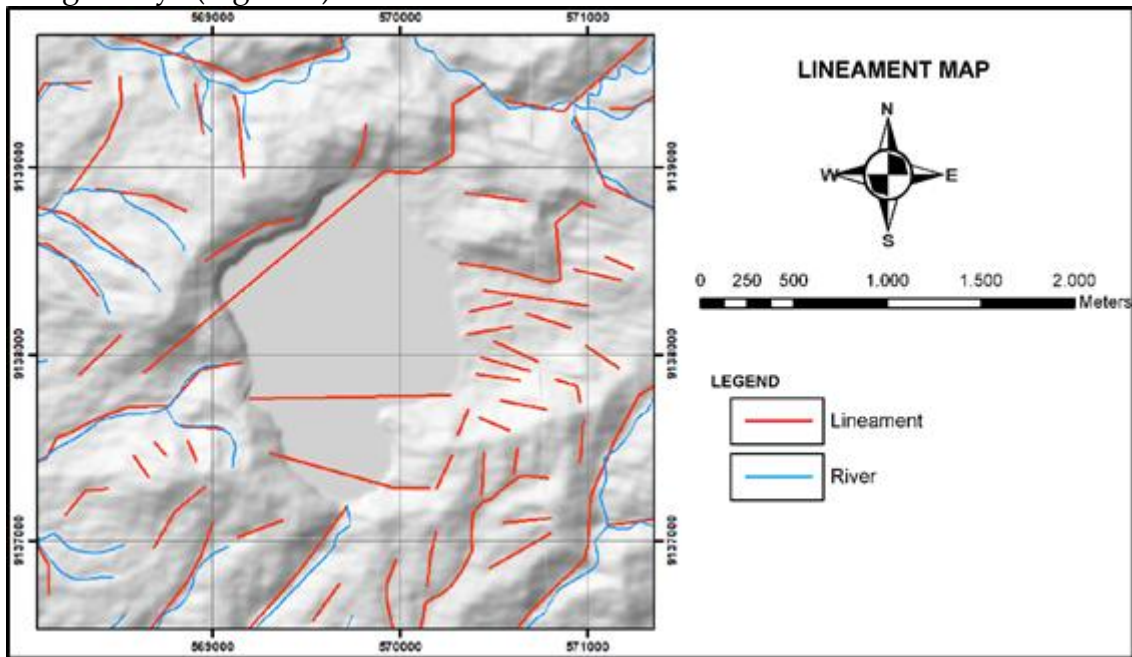


Figure 5. Lineament Map

Source: DEM: Geospatial Information Agency (2025)

These interpreted lineaments were then validated by processing their density values using a 1000-meter spatial interval, utilizing the kernel density tool in ArcGIS (Figure 6).

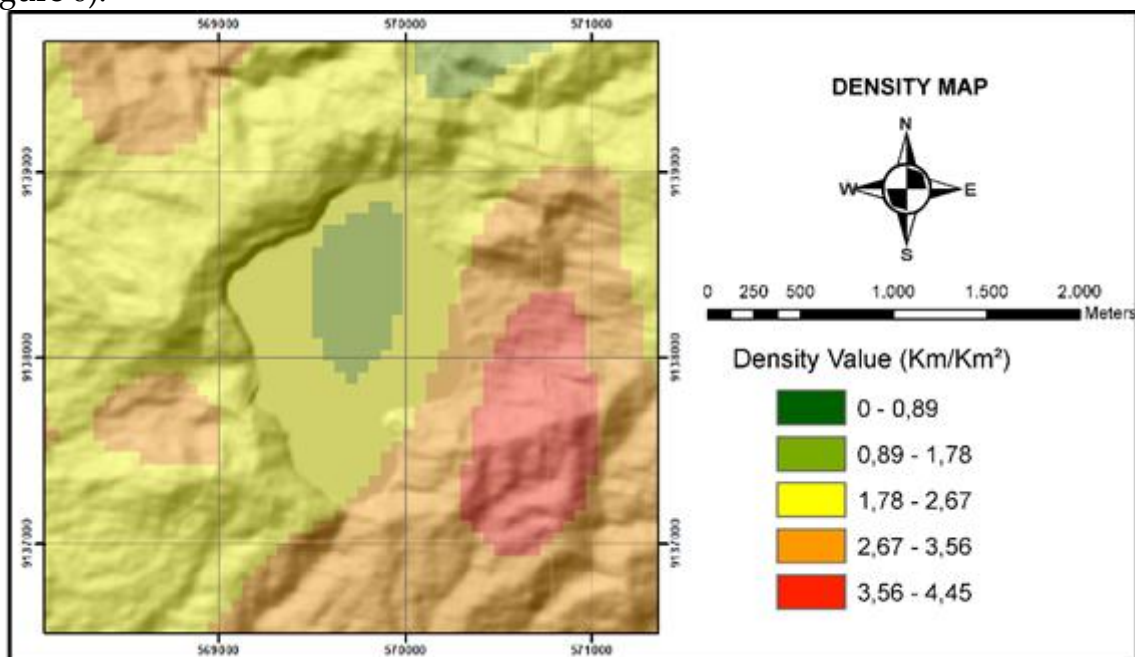


Figure 6. Lineament Density Map

Source: DEM: Geospatial Information Agency (2025)

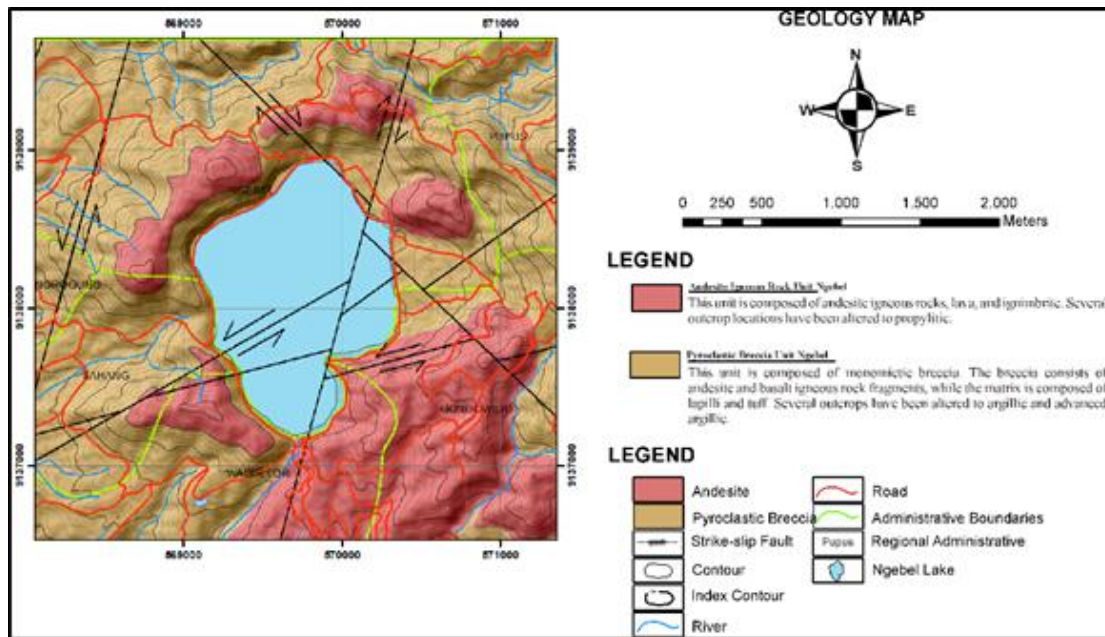


Figure 7. Geological Map

Source: DEM: Geospatial Information Agency (2025)

2. Geological Conditions of the Study Area

The geological conditions of the study area consist of two rock units. The Ngebel andesite unit (marked in red) comprises andesite rock, lava, and ignimbrite. Several outcrops of this unit have undergone alteration into the propylitic alteration zone. The Ngebel pyroclastic breccia unit (marked in pink) is composed of monomictic breccia. This breccia consists of andesite and basaltic igneous rocks as clasts. The matrix of the breccia comprises lapilli and tuff. Some outcrops of the pyroclastic breccia unit have been altered into the argillic alteration zone. Specific outcrops that have undergone argillic alteration show signs of advanced weathering.

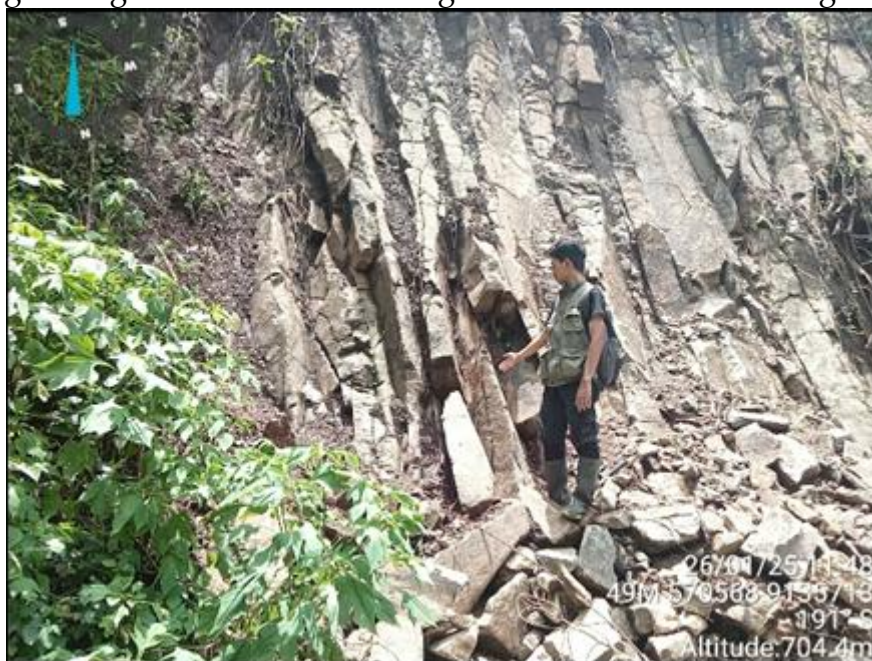


Figure 8. Outcrop of Andesite Igneous Rock

The structural development in the study area reveals the presence of several strike-slip faults. These faults align with the lineament analysis results, which were further processed into a density map. The area around the lake and its southern part is dominated by faults that intersect.



Figure 9. Outcrop of Argillic Altered Pyroclastic Breccia
Source: DEM: Geospatial Information Agency (2025)

3. Geomorphological Condition of the Study Area

Geomorphologically, the study area is composed of three morphological units: (1) Faulted Andesite Morphology, (2) Faulted Breccia Hills Morphology, and (3) Faulted Breccia Slope Morphology.

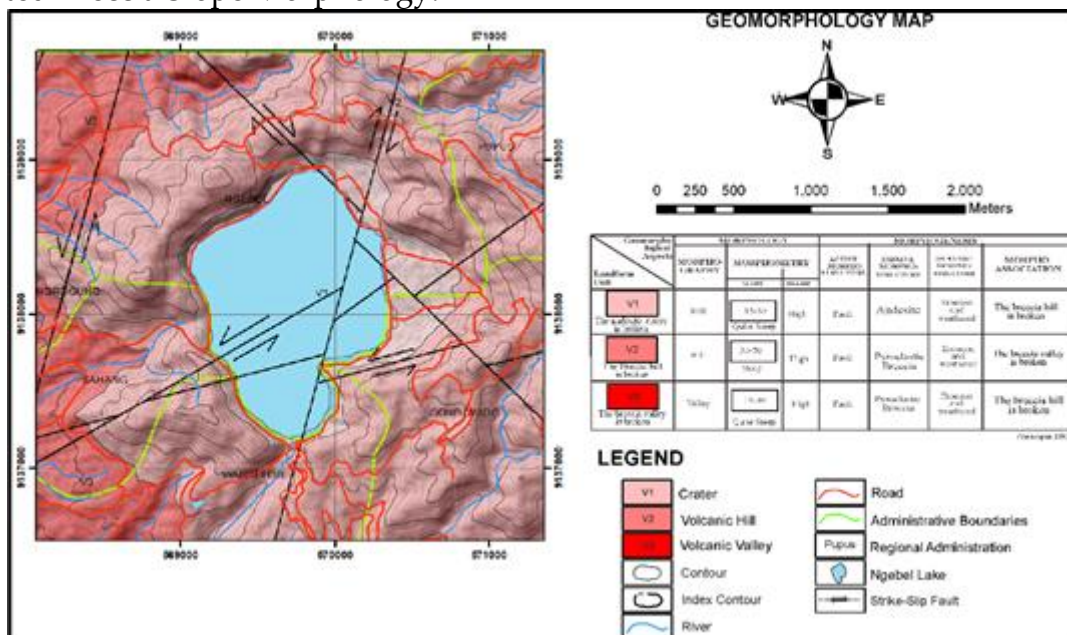


Figure 9. Geomorphological Map
Source: DEM: Geospatial Information Agency (2025)

The morphology of the faulted andesitic crater (V1) is influenced by volcanic eruptions, which were later faulted by geological structural activity in the form of strike-slip faults. This morphology is characterized by hilly terrain with a slope of 15° – 30° (moderately steep) and high relief. It has undergone weathering and erosion. This morphology is located near Lake Ngebel. The faulted breccia hills (V2) morphology is influenced by geological structural activity in the form of faults. It is characterized by hilly terrain with steep slopes ranging from 70° – 140° and high relief. This morphology is located around Lake Ngebel and has undergone erosion and weathering.



Figure 11. Landscape of Faulted Andesite Crater (V1)

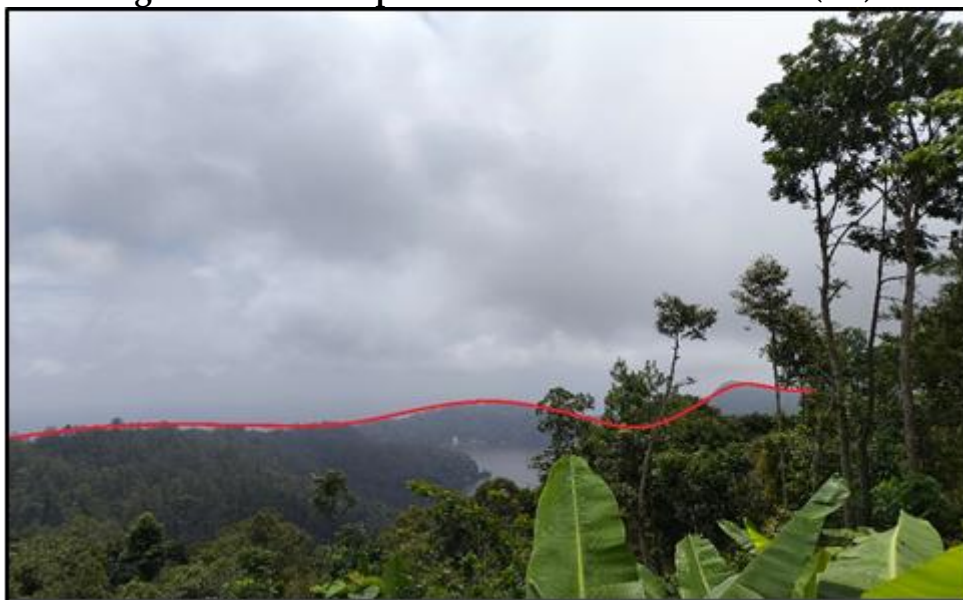


Figure 12. Landscape of Faulted Breccia Hill (V2)



Figure 13. Landscape of Faulted Breccia Slope

The morphology of the faulted breccia slope (V3) is influenced by geological structural activity in the form of faults. This morphology is characterized by sloping terrain with a slope of 15°–30° (moderately steep) and high relief. It is located west of Lake Ngebel and has undergone erosion and weathering.

4. Alteration Distribution Conditions in the Study Area

Based on the alteration mapping in the study area, two types of alteration were identified: (1) Propylitic Alteration and (2) Argillic Alteration. The distribution of propylitic alteration is found at Telaga Ngebel and to the south of the lake. The lithology undergoing propylitic alteration consists of andesite rocks and pyroclastic breccia. Megascopically, chlorite, a characteristic mineral of propylitic alteration, was observed in the outcrops that have undergone this alteration.

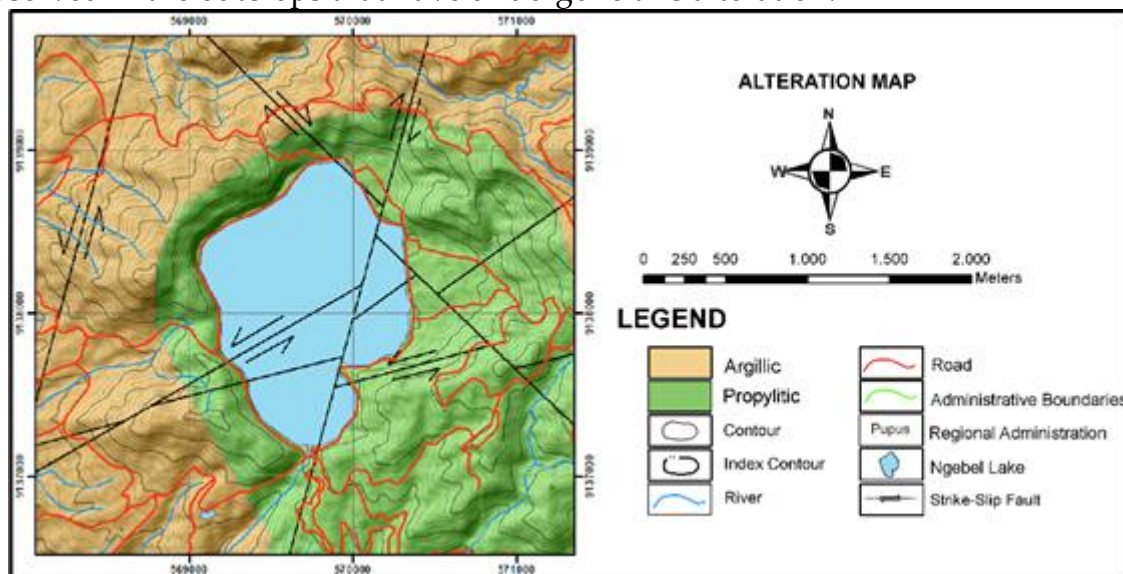


Figure 14. Alteration Distribution Map

Source: DEM: Geospatial Information Agency (2025)

Argillic alteration forms around the propylitic alteration zone. Megascopically, clay minerals, indicative of argillic alteration, were observed. The argillic alteration is widespread in pyroclastic breccia rocks. Outcrops undergoing argillic alteration show significant weathering, likely due to the alteration process. In contrast, some outcrops within the propylitic alteration zone exhibit less intense weathering than those in the argillic alteration zone.

E. CONCLUSION

Based on the lineament interpretation and confirmed by the density value processing, it was found that the structural density in the research area is higher to the south of the lake. This is further supported by the structural measurements, which show many intersecting faults at that location.

The distribution of alteration shows the presence of propylitic alteration in areas with high density. Propylitic alteration is the first alteration to form, where hydrothermal fluids rise through these faults. Chlorite minerals were found as the characteristic indicator of propylitic alteration in the megascopic view (lup). Argillic alteration forms outside the propylitic alteration zone, where it is located in areas of low density. Clay minerals are found in the argillic alteration zone.

The relationship between structural factors and the distribution of alteration in the study area shows that structures, such as faults, cause alteration to occur, as these faults serve as pathways for hydrothermal fluids. Alteration that forms in areas with dense structural zones leads to the formation of propylitic alteration zones. Hydrothermal fluids can easily rise upward in zones with high structural density. In contrast, argillic alteration zones are formed in areas with low structural density.

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