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Structural Control of the Lamteuba Geothermal System: Evidence for a Shallow Heat Source Potential

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ABSTRACT

This study aims to describe structural control on shallow geothermal systems potential in the Lamteuba paleovolcano, Aceh Besar. The methods included geological mapping, gravity anomaly analysis, and satellite imagery interpretation. The results show that geothermal manifestations, including hot springs and hydrothermal alteration zones, are spatially associated with structures related to the Seulimeum Fault, suggesting that these structures provide preferential pathways for hydrothermal fluid circulation. Petrographic analysis reveals argillic alteration acting as a cap rock around the strike-slip movement. The evidence of fissure eruption of basaltic andesite and the ratio of Vp/Vs adds more certainty of heatsource remains. Integrated analysis indicates a potential of shallow geothermal system along Seulimum Fault.

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1. INTRODUCTION

The geothermal system in Indonesia is known to be closely related to the subduction process that occurred, thus forming a series of volcanoes on the islands of Sumatra to Java with ages varying from the Tertiary to the Quaternary (Stelling et al., 2016; Ladiba et al., 2017). Lamteuba Volcano, one of the ancient volcanoes in Sumatra is known to be active at the end of the Pliocene to the Pleistocene epoch. The Subduction along Sumatra has generated extensive magmatic activity, resulting in the development of a volcanic arc that remains active today.

In addition to volcanic activity, segmentation on the island of Sumatra also occurred, marked by the emergence of the Great Sumatra Fault with several segments. The Seulimeum fault as one of

the Sumatra Fault System, is known to have shifted as far as 4 km and formed a local basin as a form of traction from the movement of the segment (Sieh & Natawidjaya, 2000).

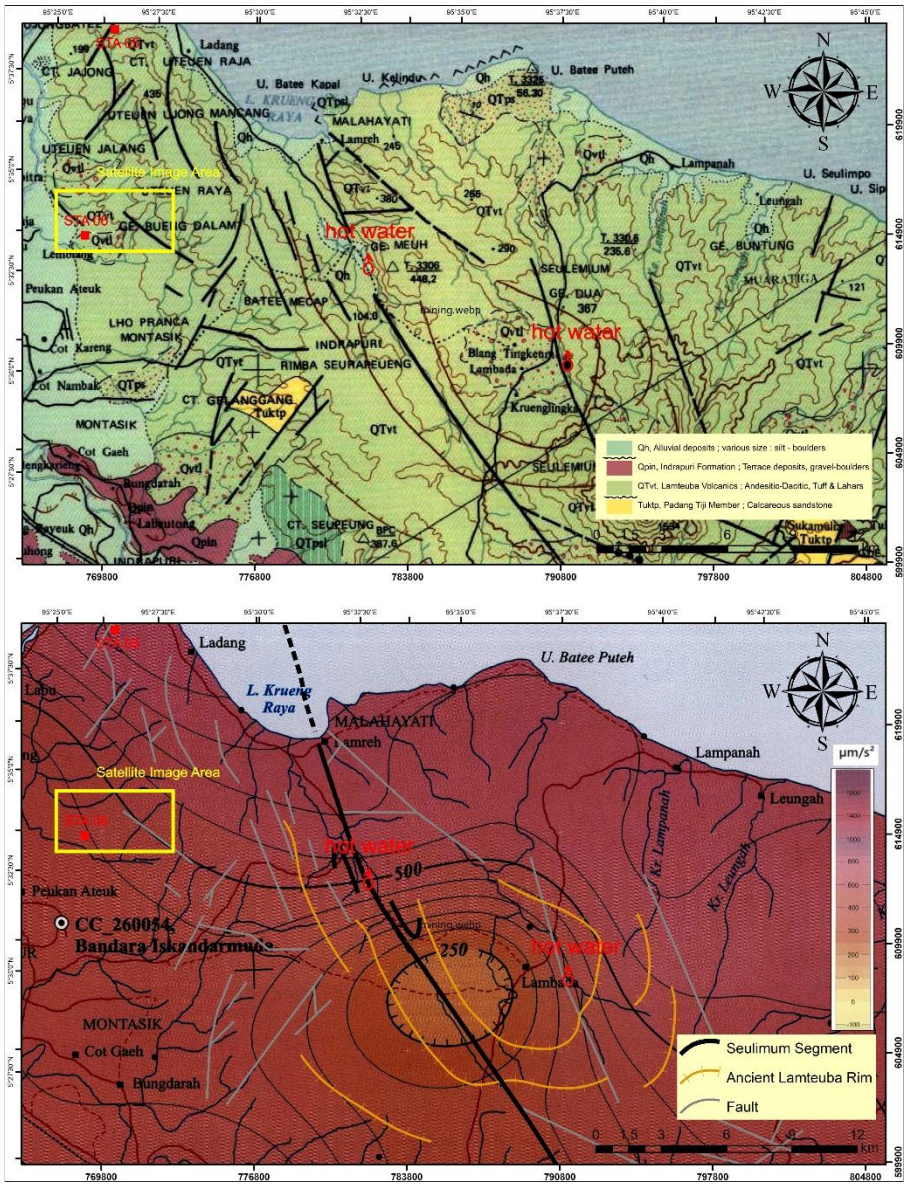


Figure 1. Geological map (above) and gravity map (below) of the research area (After Bennet et al., 1984 ; Hasyi et al., 2007)

Geologically, the Lamteuba Volcanic Formation is composed of several rock units, namely andesite to dacite volcanic rocks, pumice breccia, tuff and agglomerate, and lahar material (Bennet et al., 1984). Setiawan et al. (2023), in the latest geological mapping in the study area, also found the presence of andesitic lava rock distribution that dominates the Northeastern ridge of Banda Aceh City. The central facies of this volcano aged Plio-Pleistocene is estimated to be on the eastern side of the study area (Figure 1). Seulimeum fault (can also be named as Lamteuba Fault) activity directly influences the volcanism that occurs so that younger volcanic rocks of the Lamteuba formation are still found along the Northwest - Southeast of the study area. This complex volcanism allows the formation of new shallow thermal systems that can be developed in the future. Shallow thermal systems are generally found in rifting areas such as Alaska, Iceland, and New Zealand (Eichelberger et al., 2023).

The Geothermal systems in North Sumatra affected by subduction and associated with volcanoes in the Jaboi and Seulawah volcanoes have been extensively studied (Marwan et al., 2025,

2026). Stimac et al. (2019) also studied structurally controlled geothermal systems in the Muara Laboh geothermal field. Other previous studies have shown that the Seulimeum Fault plays an important role in controlling geothermal fluid circulation in northern Aceh (Marwan et al., 2021; Yanis et al., 2022; Marwan et al., 2025; Dharma et al., 2026). However, its influence on the Lamteuba geothermal system remains poorly understood, particularly its relationship with geothermal manifestations and a possible shallow heat source. Therefore, this study investigates the structural control of the Seulimeum Fault and evaluates geological and geophysical evidence for a possible shallow heat source beneath the Lamteuba paleovolcano. However, studies related to geothermal systems in areas with structural control at the heat source are still rare and constitute an interesting study in their own right. Shallow magma intrusions at depths of about 4-5 km are the main heat source in the geothermal system of China's Yanbajing field, where their presence is often controlled by geological structures such as faults and fractures that facilitate the migration of magma and hot fluids (Ji et al., 2000).

Previous geophysical studies in the region have demonstrated that gravity anomaly analysis, including Euler deconvolution and horizontal gradient methods, can effectively delineate subsurface structural features such as faults and fracture zones in Jaboi Volcano, Sabang (Rifqan et al., 2018). These structures are interpreted as potential pathways for fluid migration and may indicate zones associated with underlying heat sources. This study aims to investigate the structural controls of the Seulimeum Fault on geothermal manifestations and evaluate the geological and geophysical evidence for a possible shallow heat source beneath the Lamteuba volcano which is associated with the segmentation of Sumatra Island.

2. METHODS

The investigation methods generally used include literature studies, geological mapping, geophysical data analysis, and satellite imagery analysis. The geological data are collected from the field, they are geological mapping, laboratory analysis, and studio work. The geophysical method used is regional gravity data analysis of Banda Aceh and surrounding. This study integrates geological mapping, satellite imagery interpretation, and gravity anomaly analysis to investigate the structural control of the Lamteuba geothermal system. Geological mapping was conducted to identify lithological units, structural features, hydrothermal alteration, and the distribution of geothermal manifestations. Satellite imagery and DEM data were used to delineate lineaments and volcanic morphological features that may reflect fault-controlled structures. Selected geological mapping observations are presented in Table I.

Table 1. Selected field observation points.

Objectives	Longitude	Lattitude	Simple Description
STA 05	95.467	5.619	Basaltic Andesite Intrusion rocks
STA 06	95.428	5.555	Argiliceous alteration zone
Hot Water 1	95.545	5.541	Ie suum thermal bath area
Hot Water 2	95.627	5.503	Ie Jue Lamteuba area

Similar integration of remote sensing, geomorphological interpretation, and gravity data has been applied to identify structural controls in geothermal systems (Daud et al., 2018; Hofi et al., 2026). Gravity anomaly analysis was used to evaluate subsurface density variations and their possible relationship with faults, volcanic structures, and hydrothermal zones. Previous studies have demonstrated that gravity anomalies and their spatial relationships with surface geological features can provide useful constraints for identifying subsurface structures and fluid pathways in geothermal systems (Puspita et al., 2024; Satrio et al., 2026). The results from these approaches were then integrated to evaluate the relationship between the Seulimeum Fault, geothermal manifestations, and the possible shallow heat source beneath the Lamteuba paleovolcano.

Geological mapping is needed to determine geological conditions, including lithology, geological structure, geomorphology, and geothermal manifestations. These Field observations include landscape observations, macroscopic rock descriptions, and laboratory sampling. Field

outcrop observations are represented by STA 06 (Figure 2) and and the presence of intrusive rocks shown by STA 05 (Figure 6).

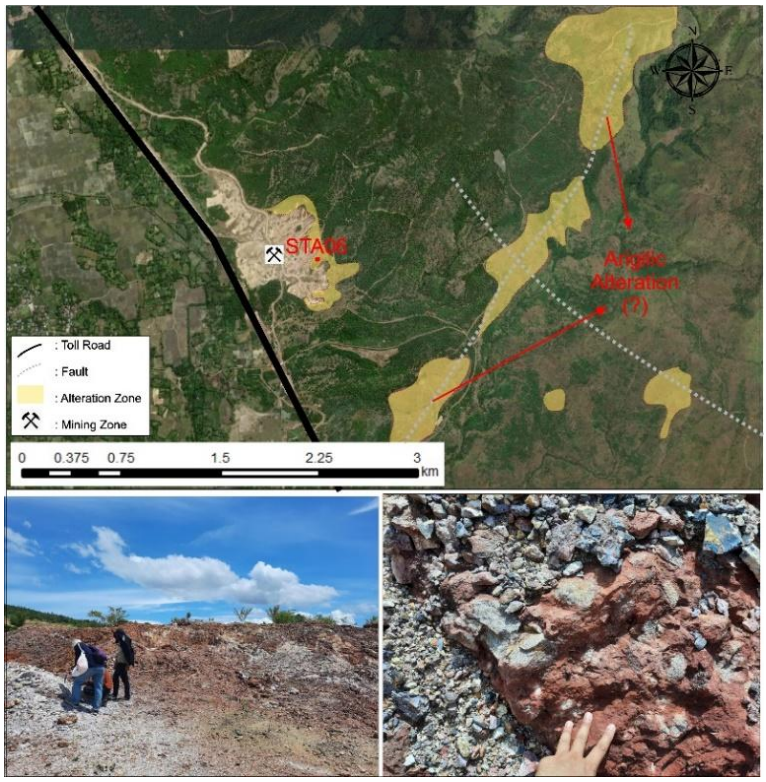


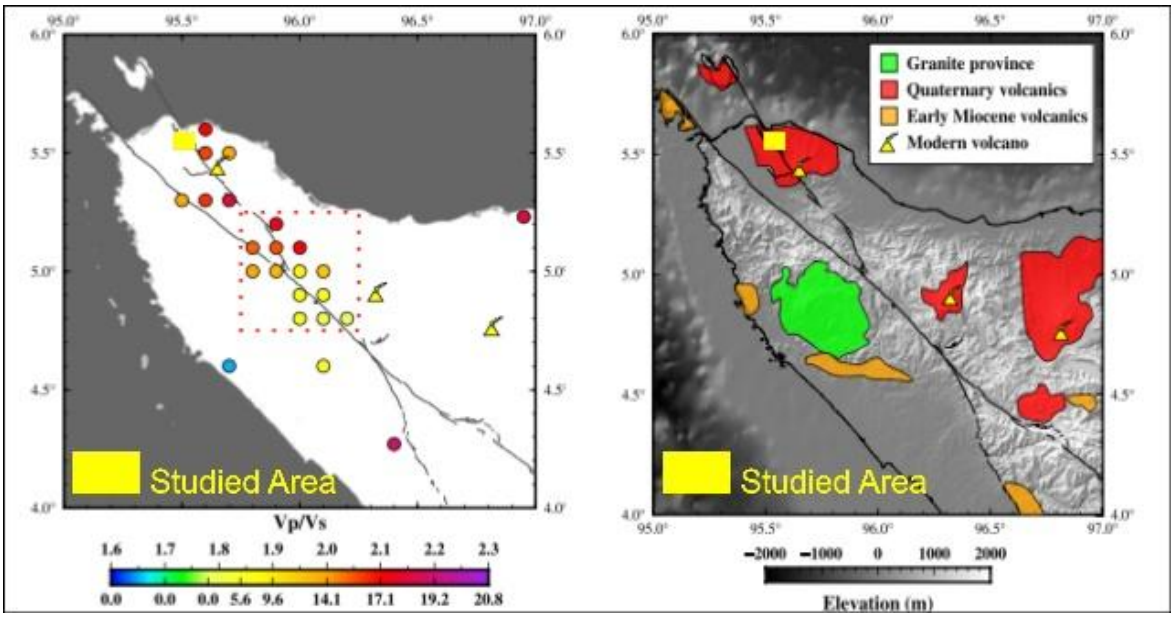
Figure 2. Satellite image analysis confirmed by field data on STA06.

Geophysical data analysis was conducted on corrected regional gravity data by analyzing anomalies in the distribution of Complete Bouguer Anomaly (CBA) data, conducted by Hasyi et al. (2007) and issued by the Bandung Geological Survey Center (PSG). The investigation area covers the central facies of the Lamteuba ancient volcano and its surroundings. Satellite image analysis was conducted on the western side of the geological study (Figure 1), with the focus of the investigation focused on areas affected by hydrothermal activities due to the Seulimeum Fault segmentation. Observations focused on the level of vegetation developing around the Seulimeum fault. Qualitative changes were observed in the density of vegetation on the surface. Rabuffi et al. (2019) also observed vegetation levels in monitoring the manifestation areas in geothermal fields as initial exploration prospects. The results of the image analysis also served as a reference for confirming field data. The image data used was Bing Maps Imagery from Microsoft and accessed in 2026.

Field observations were also conducted STA06. Rock sampling at STA06 was also conducted to characterize the types of alteration found in the field and to be compared to the others. STA05 is an observation site for andesitic intrusive rock units. This location is found on the northwest side of the ancient crater of Mount Lamteuba (Figure 5). Data collection included macroscopic descriptions of the color, texture, and structure of the rocks. The morphographic landform and slope features also been observed and validated by geological and satellite image.

3. RESULT AND DISCUSSION

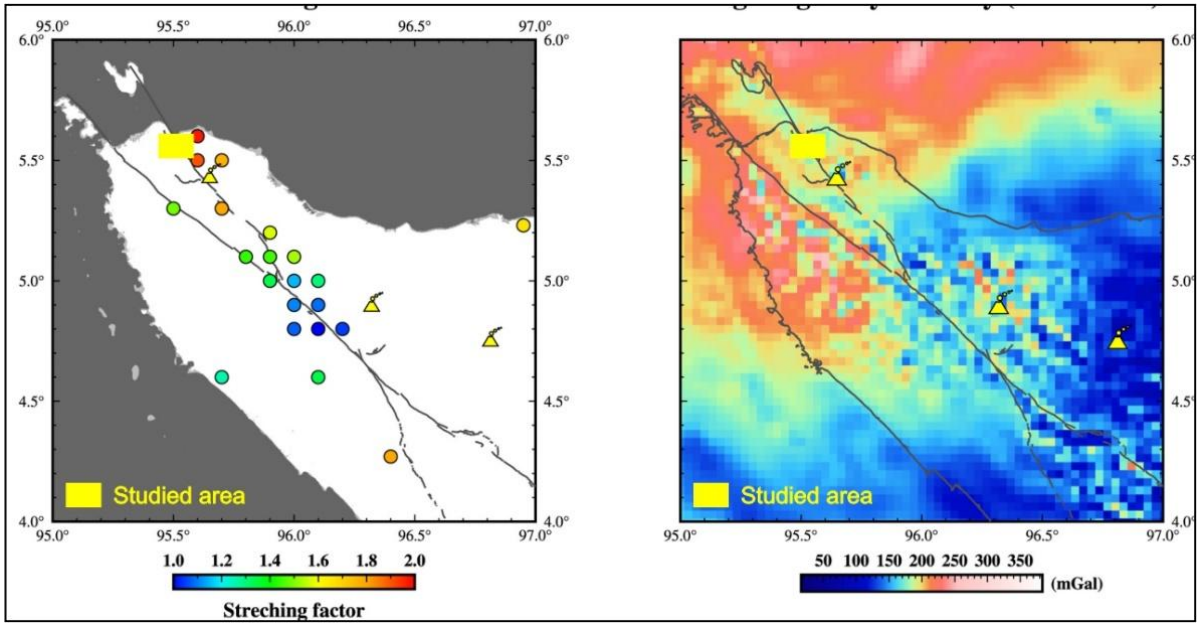
Geological mapping results show the discovery of geothermal manifestations in STA06 in the form of an alteration area on the western side of the studied area (Figure 2). This alteration zone is thought to have emerged due to hydrothermal activities in the permeability zone of a local fault with a structural trend similar to the Seulimeum Fault (NW-SE) and inferred fault by lineament of alteration area. Satellite imagery analysis shows the NNE – SSE trend thought to be due to local structures of the next phase of Seulimum Fault. In addition, other manifestations in the form of hot springs were also found associated with the presence of the Seulimeum Fault.



(a) (b)

Figure 3. Literature studies related to the potential of shallow heat sources in the research area, the ratio of compressional and tranversal wave velocity (a), the quaternary volcanics product as studied area (b) (After Feng et al., 2023).

The Literature review shows that Feng et al., in 2023, conducted a study related to subsurface conditions in the Seulimeum fault (Figure 3). The results of the investigation showed a high Vp/Vs ratio in these areas associated with Quaternary volcanoes and the Seulimeum Fault. This high ratio defines that transversal waves (Vs) have lower velocity because of liquid medium propagation (magma). Conversely, the Vp/Vs ratio was found to be lower on the western side of Aceh which covered by tertiary volcanics such Calang and Tangla Formation. These findings indicate arc migration in the magmatic system on the island of Sumatra, moved to the north and closely related to the presence of the Seulimeum Fault.



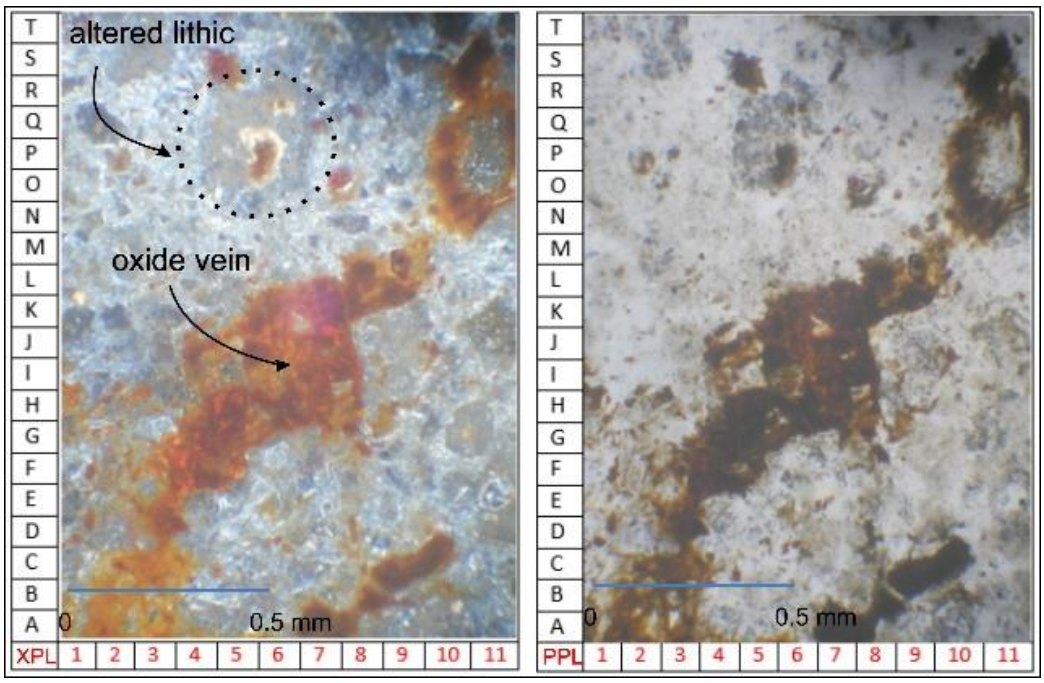
(a) (b)

Figure 4. Literature studies about magmatic potential along Seulimeum Fault based on crustal stretching factor (a), and supported by global gravity anomaly along Seulimeum Fault that show low-anomaly response due to lower density accumulation (After Feng et al., 2023).

The related study about stretching factor and regional gravity fields patterns (Figure 4) also describe the tectono-magmatic relationship along the Seulimeum Fault. The stretching factor shows high intensity in the study area that can be related to magmatism activity during quaternary period. The low gravity anomaly values observed around the Seulimeum Fault Segment suggest the presence of low-density subsurface materials, potentially associated with ductile rock deformation caused by magmatism.

Rock sampling at STA06 shows the types of alteration found in the field. The samples were located in the Lamteuba pyroclastic breccia unit, with fragments described as andesitic, dacitic, and basaltic rocks. The matrix consisted of fine to coarse sandy tuffs, filled dominantly by iron oxide cement. The level of alteration was considered high, but several types of rock fragments could still be described (Figure 2).

The results of thin section analysis indicate that the alteration found is the argillic type, with a high degree of alteration (Figure 5). The mineral composition present is dominated by clay minerals such as Kaolinite and Illite reaching 80%, Iron Oxide (15%), and lithic fragments (unidentified), amounting to 5%. In geothermal systems, the presence of argillaceous alteration can be an indication of the presence of an impermeable layer that acts as a cap rock layer. A similar area is clearly visible in the appearance of satellite imagery, dominated by the area around STA06. The area is dominated by red coloration with low vegetation.



(a) (b)

Figure 5. Photograph of a pyroclastic breccia fragment section on a cross-nicol (a) and parallel - nicol (b).

The argillic alteration observed in the Lamteuba area may represent a potential clay-rich cap rock within the geothermal system. Similar argillic alteration zones dominated by smectite and mixed-layer clay minerals have been identified above geothermal reservoirs, where their relatively low permeability can restrict vertical hydrothermal fluid circulation (Maza et al., 2018; Ardid et al., 2021).

Geological observations at STA06 show the presence of andesitic intrusive rock units with macroscopic characteristics in the form of whitish weathered color, blackish grey fresh color, porphyritic textures, and a columnar joint structures formed during fissure eruptions controlled by Seulimeum fault. Foreign rock fragments (xenoliths) in the intrusive unit are thought to originate

from older Lamteuba volcanic products and were carried and included in this young andesitic intrusive unit (Figure 5).



(a) (b)

Figure 6. Outcrop of andesitic intrusion with columnar joint structure (a), Megascopic appearance of andesitic intrusion containing xenoliths (b).

The gravity field anomalies in Figure 1 show a low- anomaly response adjacent to the center of the past Lamteuba eruption, indicated by the presence of indications of the main caldera of the ancient Lamteuba volcano. The anomaly value in the central facies is less than 250 μms-2 (Figure 1). This response is thought to originate from an old caldera system that has collapsed and filled with meteoric water and become part of the hydrothermal fluids. The strike-slip fault system in the Seulimeum Fault influences further hydrothermal fluid transport due to convection currents and also acts as a permeability zone in this geothermal system.

This strike-slip fault system also triggered changes in residual thermal conduitization trending northwest-southeast, indicated by the presence of basaltic andesite intrusive igneous rocks as products of fissure eruptions. The heat source controlled by this structure is likely distributed along the seismic segment zone and preferable to be a shallow heat source potential. This segment is also known to extend to Sabang Island and triggered the formation of the Weh Volcano.

The Lamteuba geothermal systems are typically characterized by high-temperature reservoirs, with heat supplied by shallow magmatic intrusions. The conceptual model of such systems includes a shallow heat source controlled by dextral strike-slip fault system, a permeable reservoir, fluid pathways (permeability), and a clay-rich caprock that traps the hydrothermal fluids.

Further Physical analysis such as heat dissipation between different media (rock-water) can be learned as a conceptual physics to elaborate physical properties of subsurface rocks.

4. CONCLUSION

The geothermal system in the Lamteuba area is strongly controlled by the Seulimeum strike-slip fault structure, which serves as the primary pathway for hydrothermal fluid migration. Surface manifestations of alteration and hot springs far from the central facies indicate a convection system developing at shallow depths. The presence of argillic alteration indicates a favorable capping system, while low gravity anomalies suggest the possibility of a water accumulation zone in ancient caldera system. The heat source is thought to originate from shallow magmatic intrusions remains distributed along the structural zone. The integrated geological and geophysical evidence suggests

that a potential shallow heat source may be associated with this magmatic intrusions distributed along the Seulimeum Fault zone.

Further geophysical research such as more detailed magnetotellurics (MT) and seismic survey are needed to investigate in more detail the potential existence of the shallow heat sources around the Seulimeum Fault.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

The authors declare that no Generative AI or AI-Assisted technologies were used in the writing or preparation process of this manuscript.

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