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HVSR Microtremor Analysis to Assess Subsurface Fault Characteristics and Geothermal Potential in Kepahiang

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Abstract

Kepahiang, Bengkulu, is an area with considerable geothermal potential, especially in the Air Sempiang and Babakan Bogor areas. This study aims to analyze subsurface fault characteristics and assess geothermal potential using the Horizontal-to-Vertical Spectral Ratio (HVSR) microtremor method. This passive seismic method is used to determine key geophysical parameters, including dominant frequency (f_0), amplification factor (A_0), shear wave velocity (v_s), and primary wave velocity (v_p), which are essential for characterizing subsurface geological structures and identifying geothermal reservoir zones. The results show that dominant frequency values in Kepahiang range from 1.24 Hz to 20.45 Hz, while the amplification factor varies between 1.29 and 7.22. v_s values range from 121.61 m/s to 3251.79 m/s, and v_p values range from 214.91 m/s to 6469.79 m/s. These findings suggest that the surface layer consists mainly of alluvium and hard sandy gravel, with thicknesses varying between 10 and 50 meters. The 3D subsurface model constructed from the data indicates the presence of fault-controlled geothermal manifestations, mainly influenced by the Babakan Bogor Fault and Bogor Fault. These faults facilitate the upward migration of geothermal fluids, forming surface manifestations such as hot springs, fumaroles, and altered rocks. The geothermal system in the study area is classified as a low-temperature geothermal system, mainly caused by residual magmatic heat from Kaba Mountain and Bukit Hitam Crater. This research provides important insights for geothermal energy exploration and geotourism development in Kepahiang. These findings serve as a scientific basis for future geothermal resource assessment, land use planning, and sustainable energy utilization.

Keywords: Air Sempiang; Fault; Geothermal; Microseismic.

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Introduction

Indonesia is included in the "ring of fire", where three plates meet, the Pacific, Eurasian and Indo-Australian tectonic plates. Being right below the equator between two continents and two large oceans makes for a wealth of potential natural resources such as geothermal energy (Fransiska, 2019). Indonesia's geothermal potential is currently very large, which is 40% of the total potential in the world that has been explored around 276 geothermal areas spread across 26 provinces with a total energy of 28.99 GW, but the energy developed only reaches 196 MW, or about 4% of the total energy potential. Geothermal energy is one type of renewable energy that is owned by Indonesia in a very large amount of potential (Bilondatu et al., 2021). The Kepahiang geothermal area is located in the Kepahiang and Rejang Lebong regencies, Bengkulu Province which is a high volcanic area and is on the subduction line in the magmatic arc area located in the west of Sumatra Island. Geologically, the study area generally has andesite-basaltic rock types that are closely related to magmatic activity in the hill Barisan range. The formation of rock formations in the Bukit Kaba area is influenced by tectonic activity in the direction of the Sumatra fault pattern which is southwest to northeast. Hot fluids in the Kepahiang geothermal system are bicarbonate and sulfate types in the immature water zone (Raharjo et al., 2022).

At the research location not only has geothermal potential, this location can also be made as a place that has the potential as geotourism which is quite supportive because of the hot springs in the research area. Indrayati & Setyaningsih (2017) defines geotourism as sustainable tourism with a primary focus on the evolution of the earth and its geological features that promotes environmental and cultural understanding, appreciation and conservation, and benefits local communities (Andriany et al., 2016). The scope of geotourism spans the scale of geological and geomorphological features, from mountains and coasts to smaller scales, such as the built environment and geological outcrops. It can occur in a variety of locations from natural areas to urban environments and includes geoparks and geosites, as well as buildings and monuments with geological associations. Geotourism is related to ecotourism, cultural tourism and adventure tourism but is not the same as these three types of tourism. Geotourism focuses on creating products to introduce and protect geological heritage, as well as building a community (Indrayati & Setyaningsih, 2017).

Parameters that determine the prospect area in the geothermal field are characterized by the presence of manifestations in the form of hot springs, geothermal manifestations appear due to the propagation of heat from the subsurface or the presence of fractures that can flow fluid to the surface (Ratag et al., 2022). Based on Ramadhan & Massinai (2022), the higher the surface temperature, the more likely the area has geothermal potential. The recorded surface temperature can be interpreted as the outer temperature of the object. In areas with low to moderate vegetation, the surface temperature is the temperature of the outermost layer of the soil surface, while areas with high levels of vegetation such as forests can be interpreted as the surface temperature of plants.

One of the areas that has the potential for hot springs is Babakan Bogor and Air Sempiang Village, Kepahiang Regency, Bengkulu Province. The existence of secondary permeability in the form of the Musi fault, more precisely the Bogor fault, affects the existence of geothermal manifestations in the study area. Subsurface faults are difficult to identify, one of the geophysical methods that are good enough to map subsurface conditions to determine the structure of layers and faults. This method is also a good indicator to identify fault-related structures. These faults control the hot fluids in the reservoir to flow to the surface in the form of hot springs, rock alteration, and emerging fumaroles. The Kepahiang geothermal prospect area is located 90 km northeast of Bengkulu city, which is in Bengkulu Province. The area is located on a subduction line in the western part of the Sumatra magmatic arc in the tectonic setting of western Indonesia. The volcanic activity that developed in the ring of fire of Sumatra Island, especially Mount Kaba, is responsible for the existence of geothermal systems in this area (Fahmi et al., 2015).

Previous research on hot springs in Kepahiang Regency has also been conducted by Simbolon et al. (2020). Indications of geothermal systems in this area are characterized by the appearance of manifestations such as hot water with the highest temperature of 94°C, neutral pH, solfatara and fumaroles with temperatures up to 360ºC and rock alteration around Air Sempiang, Kaba peak, and hot springs in the Sempiang and Babakan Bogor areas. Faults that were not visible in the initial seismic data can be more clearly identified in the vertical and horizontal cross sections. To show the discontinuities more clearly on the seismic cross section, this attribute combines more than two seismic traces to highlight the seismic lateral changes caused by the different geological conditions (Darma & Pujiastuti, 2021). Geological data of the Kepahiang geothermal area shows the presence of impermeable rocks with a high content of montmorillonite and kaolinite clay minerals in the alteration area around the Air Sempiang manifestation. The alteration rocks formed are argillic to advanced argillic types. The alteration appears in pyroclastic flows and lava products of the mountain. However, research in the research area focuses on Kepahiang Regency, whereas many more specific geothermal manifestations are thought to originate from Kaba Hill (Ramadhan & Massinai, 2022).

In geothermal reservoirs, hydrothermal distribution is significant. One geophysical method that is quite good at mapping subsurface conditions to determine geothermal distribution is the passive seismic method, which is microseismic (Rasimeng et al., 2024). This method aims to study the variation of secondary wave specific gravity through rock inversion in the subsurface of the earth, so as to produce a one-dimensional profile of the subsurface and is used to describe the variation of specific gravity values with depth in a multi-layered subsurface resistivity structure, this research is expected to model in 1 dimension and map the distribution of geothermal manifestations due to faults with data processing using Geopsy and HV-Inv software. This software is used because the software is freely accessible, and the data processing process does not take a long time (Purnomo, 2019).

The emergence of geothermal heat is influenced by the existence of faults that act as pathways for hot fluids from the earth to the surface. These faults are formed due to the movement of tectonic plates that cause cracks or fractures in the earth's crust, allowing heat and geothermal fluids to move upwards. This research aims to identify faults that function as the main conduit for hot fluids, which contribute to the emergence of geothermal manifestations in Air Sempiang. Focus on geothermal distribution is also needed if the government wants to develop regional geotourism, therefore, further research is needed to see the geothermal distribution and determine the type of rock in Babakan Bogor Village, Kepahiang Regency, Bengkulu Province. This study is also expected to provide recommendations for strategic steps that can be taken by the Indonesian government as a solution to geothermal energy exploration activities, based on previous efforts made by the government.

Geology Setting

Kepahiang Regency is located in the border area of the magmatic arc and the continental plate with the oceanic plate which resulted in the emergence of several geothermal manifestations on the surface in the form of solfatara, fumarole, and alteration rocks so that it becomes a geothermal energy prospect (Sihombing et al., 2024). The rock formation of the Kepahiang area is dominated by volcanic rocks so that the Kepahiang district is found in many igneous rocks because of its close proximity to volcanoes such as Kaba hill and foothills of Kaba (Firdasari, 2018). At the location of this study, geothermal manifestations in the Babakan Bogor and Air Sempiang areas that appear hot water manifestations are indicated due to the Babakan Bogor Fault and the Bogor Fault, causing geothermal manifestations in Air Sempiang (Fahmi et al., 2015). According to the geological information can be seen in the geology in Figure 1. In the alteration area around the Air Sempiang manifestation, there are rocks that have impermeable properties with a high content of montmorillonite and kaolinite type clay minerals, according to the geological data of the Kepahiang geothermal area. The alteration rocks are argillic to advanced argillic types. These host rocks are located in the area of the Sempiang fault structure that runs almost north south, where pyroclastic flows and lava products of Mount Kaba show alteration. In addition to the alteration data, the massive and not yet strongly domed Kaba product lavas are an additional potential for the cap rock (Raharjo et al., 2022). At the research location, the rock formation is dominated by the volcanic Kaba rock type.

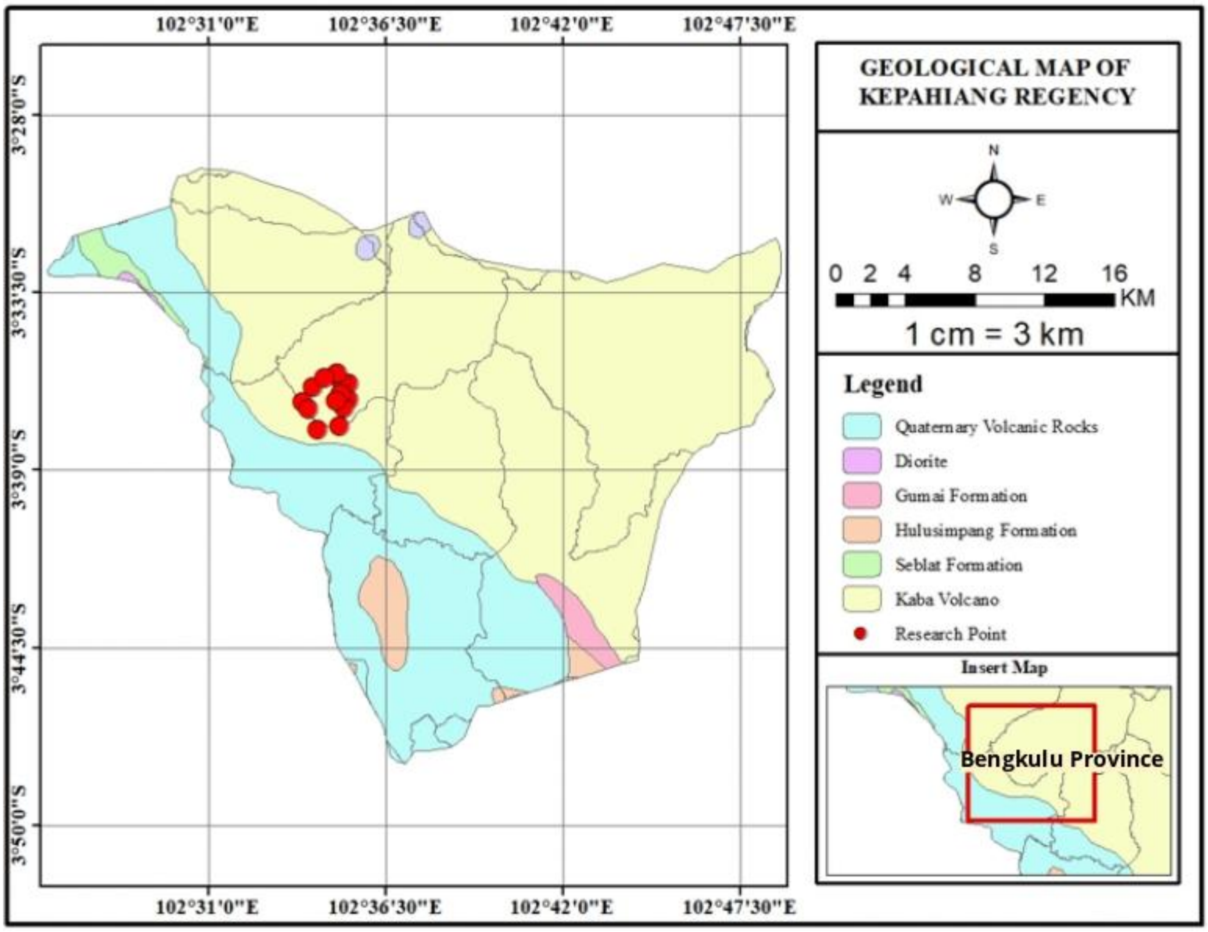

Figure 1. Geological map of Kepahiang regency.

The geology of Kepahiang hot springs clearly shows the presence of impermeable rocks with high concentrations of montmorillonite and kaolinite mineral types around the alteration zone at Air Sempiang. The altered rocks are mainly argillic to argillic rocks. This alteration is the result of pyroclastic flows and lava from Mount Kaba. These host rocks are located in the zone of the north-south trending Sempiang fault structure. The young, massive lava products of Kaba that have not been widely exposed are also classified as host rocks (Sihombing & Rustadi, 2018).

Materials and Methods

This research will be conducted in Kepahiang Regency, Bengkulu Province. In this study, 90 measurement points will be carried out which can be seen in Figure 2.

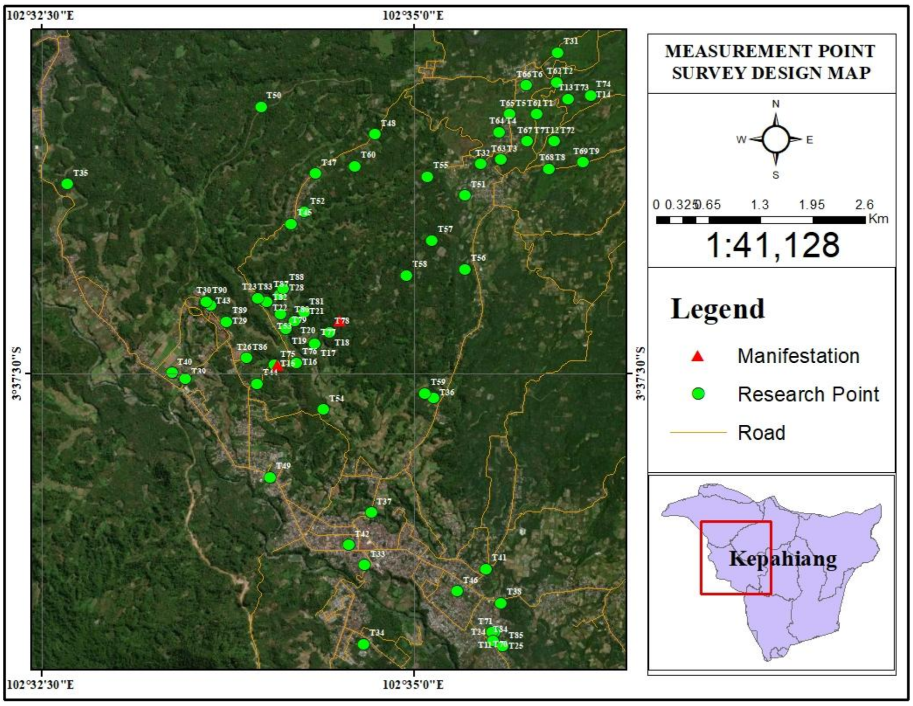

Figure 2. Map of research point location.

This research uses the microtremor method which measures very small and continuous ground vibrations sourced from various kinds of vibrations such as traffic, wind, human activity and others (Arifin et al., 2014). Research using microtremors can determine the characteristics of the soil layer based on the parameters of its dominant period and its wave amplification factor (amplification). Microtremor has a higher frequency. Microtremor recording is array based F-K method, Spacial Auto Correlation and Refraction (SPAC) microtremor and HVSR/ Nakamura methods (Arintalofa et al., 2020). Microtremor data that has obtained frequency curves and amplification values along with examples of HVSR curves as for the equation in obtaining HVSR results as follows (Arintalofa et al., 2020):

$$HVSR(f) = \frac{\sqrt{H_x^2(f)+H_y^2(f)}}{2 \cdot V(f)} \quad (1)$$

$Hx(f), Hy(f)Hy(f)$: spectral amplitude of horizontal component of microtremor at frequency ff

$V(f)$: spectral amplitude of the vertical component.

$HVSR(f)$: the value of spectral ratio at frequency ff from data processing with Geopsy software (Arintalofa et al., 2020) as shown below (Figure 3).

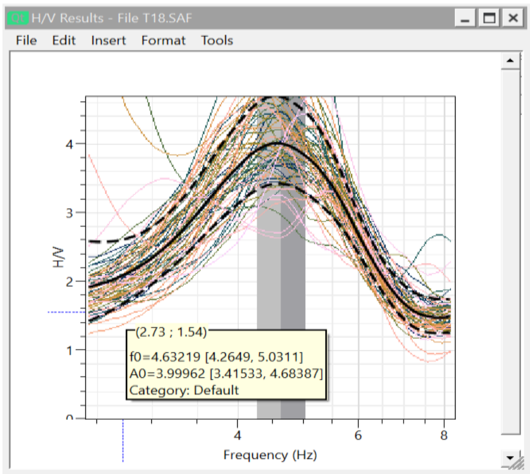

Figure 3. H/V curve graph processed using Geopsy software.

Then entered into the Hv-Inv software in the form of processed data results. The Hv-Inv application is a MATLAB-based computer application developed by Garcia-Jerez et al. (2016), which is used to analyze and model subsurface structures using the Monte Carlo (MC) principle, then analyzed using Monte Carlo simulation to get the most suitable curve. The curve is said to be suitable if the misfit value obtained is small and the H/V graph coincides. In the data processing with HV-Inv, the parameters of thickness, shear wave velocity, and rock density were obtained The Site Effect (TSITE) on the surface of a sediment layer, usually described as by comparing the amplification factors of horizontal and vertical motion at the sedimentary soil surface (Setyowati et al., 2024).

$$T_{SITE} = \frac{T_H}{T_V} \quad (2)$$

$$T_H = \frac{S_{HS}}{S_{HB}} \quad (3)$$

where SHS represents the spectrum of the horizontal motion component at the surface, and SHB represents the spectrum of the horizontal motion component at the bottom of the soil layer (Setyowati et al., 2024). Data collection in the field needs to do a literature study and also look for information related to geological data at the research site or with regard to previous research that has been done as supporting research data and make a survey design as an initial benchmark before taking field data. This microtremor data collection is based on the Site Effects Assessment Using Ambient Using Ambient Excitations (SESAME) standard. According to Bard et al. (2004), The length of the data recording process in the field will be able to provide good results if the dominant frequency (f_0) at the data collection site obtains fairly low results. So that in the field data collection, 30 minutes of data is taken for each location (Hadi et al., 2021). Microtremor is passive seismic that uses a three-component seismometer to observe spectral anomalies. The seismometer used in this research has a fairly high sensitivity, so it is very important to avoid disturbances (noise) that will be able to damage the data during recording. Before collecting data, make sure the data collection location is not close to plant roots and other disturbances that can make the data less accurate and need to pay attention to the surrounding soil must be flat (Diah et al., 2024).

Data processing is done by inputting microtremor recording data on imported signals. The data obtained is in the form of data that shows frequency, therefore it is necessary to convert the field data from the time domain to the frequency domain, then a cutting process is carried out which aims to cut noise data, after the cutting process, the data is processed with Geopsy software, to obtain HVSR curve modeling. HVSR is a geophysical method that can solve the problem of identifying the response of subsurface layers. This data processing method can produce the dominant frequency value (f_0), H/V curve, period, and peak amplification value (A_0). Furthermore, the inversion process using HV-Inv software aims to obtain the value of secondary wave velocity (v_s), primary wave velocity (v_p), and depth value (A_0) (Nurwidyanto et al., 2023). So that it can be used to identify subsurface structures in geothermal prospect areas in Kepahiang Regency.

Results and Discussion

Based on Table 1 below, which explains the range of v_s and v_p values based on depth values that apply in all locations, so this can be a reference in research locations that are dominated by volcanic rocks.

Table 1. Classification of velocity (**v_s**) and (v_p) values by depth in all areas with volcanic rocks (Kamil, 2020).

Depth (km)	v_p (km/s)	v_s (km/s)
2.0	5.80	3.46
20.0	5.80	3.46
27.0	6.50	3.85
35.0	6.50	3.85
56.0	8.04	4.48
77.0	8.04	4.49
>77.0	8.05	4.50

Dominant Frequency Value (f_0)

The f_0 value obtained from the processing results using geopsy software can be seen in Figure 4 and Table 2.

Table 2. Rock classification value based on dominant frequency value (f_0) (Yogaswara & Kuncahyani, 2024).

Soil classification Type	Type	Frequency Natural (*Hz*)	Kanai classification	Description	Measurement Point	Color
IV	I	6.667-20	Tertiary or older rocks. Consists of Hard sandy rocks, gravel and others.	The thickness of surface sediments is very thin, dominated by hard rocks.	1,2,3,4,6,7,8,9,11, 14,16,17,23,25,26, 30,31,33,34,35,38, 41,46,50,51,52,53, 54,55,56,57,58,59, 60,61,64,65,67,75, 80,81,8286,87,88,	
III	II	4.0-6.667	Tertiary or older rocks. Consists of Hard sandy rocks, gravel and others.	Surface sediment thickness falls into the medium category 5-10 m	13,18,20,21,22,28, 43,44,45,48,49,66, 72,74,77,79,83,85 89	
II	III	2.5-4.0	Alluvial rocks, with a thickness of more than 5m. Consists of sandy hard clay, loam and others.	The thickness of surface sediments is categorized as thick, about 10-30m.	10,19,24,27,29,32,36, 37,39,40,42,47,69,71, 76,78,84,90	
I	IV	< 2.5	Alluvial rocks, formed from sedimentation of deta, top soil, mud and others. Depth ≥ 30m.	Surface sediment thickness is very thick	5,12,15,62,68,70,73,	

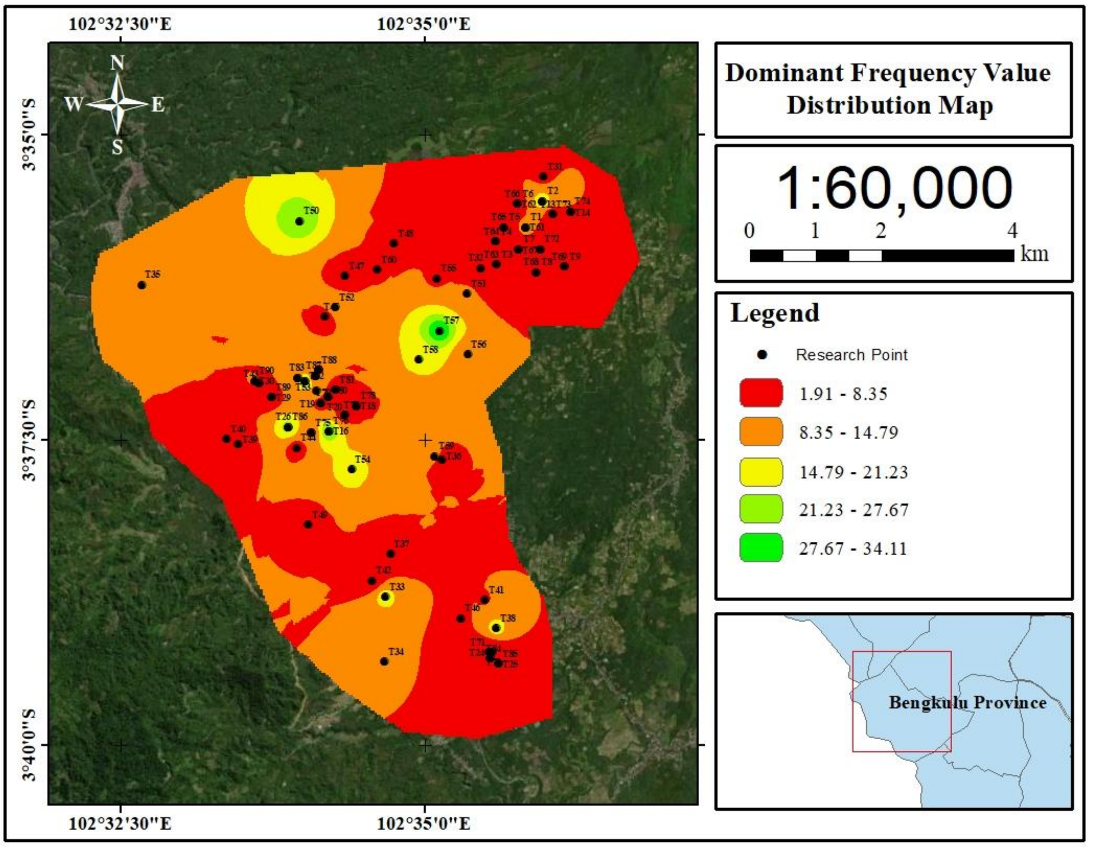

Figure 4. Rock classification value based on dominant frequency value (f_0).

Referring to the dominant frequency classification table and also the distribution map (f_0), it can be interpreted that the dominant frequency value with a large value can be said to be a fairly dense rock type while the dominant frequency value with a small value is assumed to have a fairly thick sediment layer or soft rocks such as alluvial rock types, at the research location is dominated by rocks that have a thin sediment thickness, usually consisting of igneous rocks in the form of volcanic rocks and granite. So, it can be concluded that the research location has a dense rock type because the research location is near the volcano zone.

Amplification Value (A_0)

The A_0 designation indicates the amplification of seismic waves resulting from significant differences between geological layers. Table 3 presents a classification based on the magnitude of the amplification values, as illustrated in Figure 5. The amplification value distribution map in Figure 4 shows that the Air Sempiang area, the amplitude values range from 1.29 to 7.22 times. According to Setianegara et al. (2023), amplification values are categorized into four risk levels, namely low risk ($0 < A_0 < 3$ times), medium risk (3 < A times), medium risk ($3 < A_0 < 6$ times), high risk ($6 < A_0 < 9$ times), and very high risk ($A_0 > 9$ times) (Risa et al., 2023).

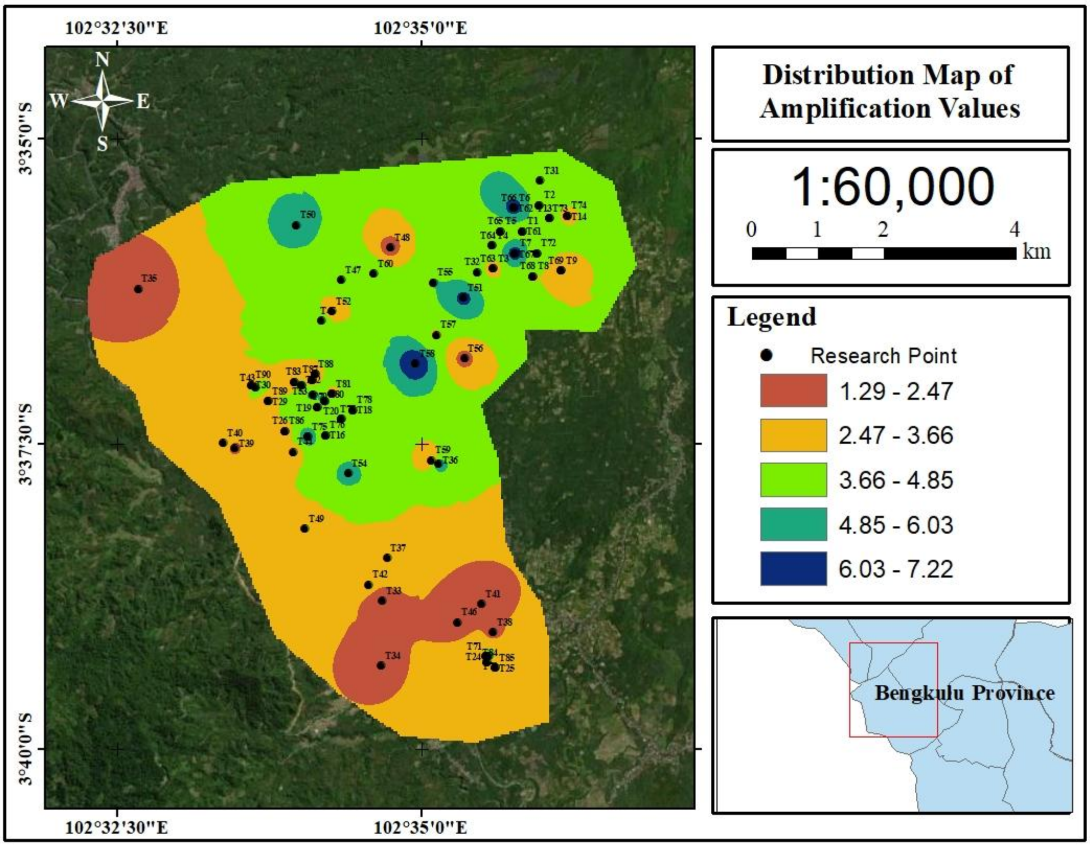

Figure 5. Distribution map of amplification values.

Based on the observations from the research table and the map of the distribution of amplification values, it can be concluded that the amplification value is inversely proportional to the dominant frequency value, so that the amplification value with a large value indicates soft rock, while the location dominated by a small amplification value is a hard rock type.

Table 3. Rock classification value based on amplification values (A_0) (Yogaswara & Kuncahyani, 2024).

Zone	Classified	Amplification Value	Measurement Point	Color
1	Low	$A_0 < 3$	4, 9, 11,12, 14, 17, 21, 24, 25, 26, 28,29, 30, 33, 34, 35, 38, 39, 40, 41, 42, 44, 46, 48, 49, 52, 56, 59, 63, 70, 73, 83, 86, 87	
2	Medium	$3 < A_0 < 6$	1, 2, 3, 5, 6, 8, 10, 13, 15, 16, 18, 19, 20, 23, 27, 31, 32, 36, 37, 43,45,47, 50, 53,54,55,57,60,61,62,64,65,67,68,69,7172, 75, 76, 77, 78, 79, 81, 82, 84, 85, 88,89,90	
3	High	$6 < A_0 < 9$	7,22,51,58,66,74,80,	
4	Very High	$A_0 > 9$	-	-

S-wave Velocity (v_s)

Softer rock materials have relatively lower values compared to harder rock materials. This is due to the fact that the shear wave velocity is directly proportional to the density of the rock. A reduction in the density of the rock in question will result in a reduction in the wave velocity value of the rock. Therefore, the v_s value is a convenient method used by researchers to interpret subsurface lithology and classify rock types based on the v_p value (Arisona et al., 2023).

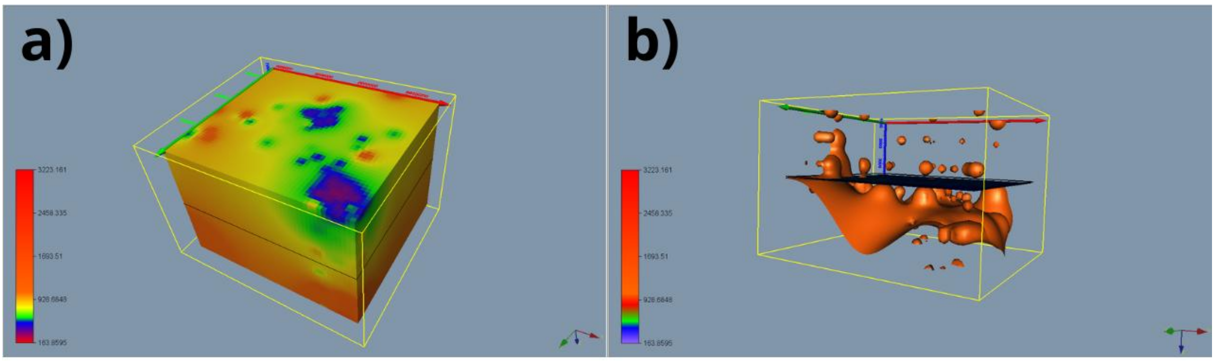

Figure 6. a) Three-dimensional modeling of (v_s) value solid rock. b) volumetric modeling of (v_s) value assumed to be solid.

Table 4. Site classification based on v_s value according to SNI (Arisona et al., 2023)

Site Classification	Shear Wave Velocity v_s (m/s)
Hard Rocks (SA)	$v_s > 1500$
Rocks (SB)	$750 < v_s < 1500$
Very dense soil and soft rock (SC)	$350 < v_s < 750$
Medium soil (SD)	$175 < v_s < 350$
Soft Soil (SE)	$v_s < 175$

It can be assumed that the large v_s value is a compact rock type with a v_s value of 1600 ≥ 3251.79 m/s which can be seen in the rock classification table based on the value based on Table 4 (Wibowo & Huda, 2020). This result is the range of values obtained from the research results, because the value range is in accordance with the research location which is dominated by volcanic rocks with a large enough v_s value. Based on rock type with v_s value classification as shown in Table 5 below.

Table 5 . Classification of v_s values by mineral type at the study site.

Material and Source	v_s (m/s)
Granite	3040
Granodiorite, Weston, Mass	3100-3200
Dunite	3790-4370
Limestone	2880-3030
Clay	500

So that the model in Figure 6 can be seen in the research location is still dominated by compact rocks.

P-wave Velocity (v_p)

P-wave propagation in the subsurface occurs through elastic media such as rock, liquid, or gas. High density values and high P-wave velocities indicate that P-waves have a high frequency. This indicates that the propagating P-waves are only affected by the variation of minerals in the subsurface (Hutami et al., 2020). The 3 (three) dimensional conceptual modeling shown in Figure 7 shows the relationship between the subsurface conditions of the study area and the occurrence of hot springs which have a layer of soil rock shown by the value of v_p ranges from 214.91 - 679.7 m/s, the v_p value between 703 − 1113.6 m/s indicates the material is alluvium, the v_p value ranges from 1120.34 – 2512.48 m/s indicates the clay layer, the v_p value is between 2517 – 3390.49 m/s in the form of sandstone layer, and the basalt material layer is indicated by the v_p value of 3393.38 – 5649.86 m/s. The clay layer is indicated as a clay cap that is impermeable so that it can withstand the flow of geothermal fluid so as not to come out to the surface, while the sand layer is thought to be a permeable layer which is where the fluid is stored (reservoir) which then through the fracture fracture zone will migrate out to the surface due to the fault Babakan Bogor and Bogor The geothermal system in the study area is classified as a low-temperature geothermal system, mainly caused by residual magmatic heat from Mount Kaba and Hitam hill crater. This research provides important insights for geothermal energy exploration and geotourism development in Kepahiang (Arintalofa et al., 2020). Classification of v_p values by mineral type can be seen in Table 6 below.

Table 6. Classification of v_p values by mineral at the study site.

Material and Source	v_p **(m/s)**
Granite	5640–5880
Granodiorite, Weston, Mass	4780–6400
Dunite	7400–8600
Limestone	4200–6060
Clay	1100–1800

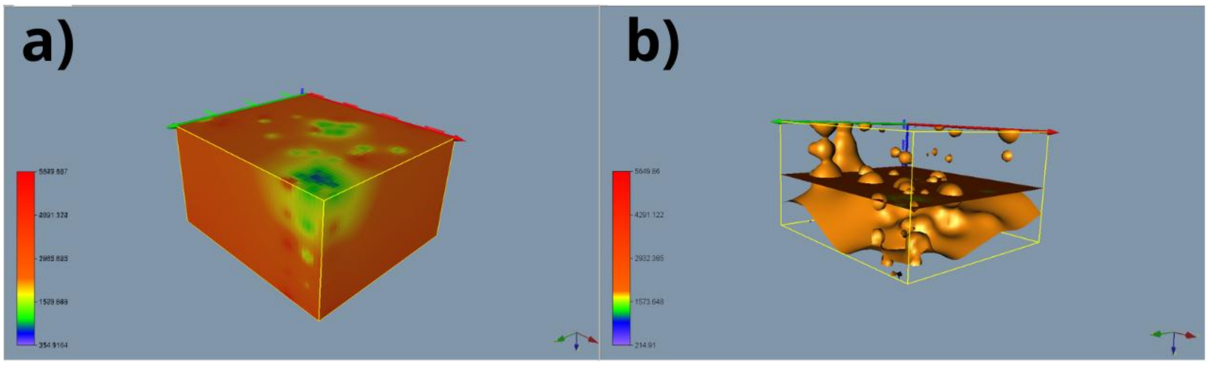

Figure 7 a) Three-dimensional modeling of the value (v_p) which is assumed to be a fault. b) volumetric modeling of the value (v_p).

Conclusion

The estimated dominant frequency parameter value (f_0) ranges from 1.24 Hz to 20.45 Hz, with an amplification value (A_0) of 1.29 to 7.22. These values are used in a statistical model to estimate the thickness of the sediment layer. The results of numerical inversion show that the shear wave velocity (v_s) ranges from 121.61 m/s to 3251.79 m/s. High v_s values indicate the presence of hard rocks below the surface, while low values indicate soft rocks. The primary wave velocity (v_p) ranges from 214.91 m/s to 6469.79 m/s. The results of 3D modeling show the vertical and horizontal distribution of v_s, which clarifies the zone of lithological change and the potential for geothermal reservoir boundaries. In the geological model identified the presence of a fault indicated by a fracture zone, which has the potential to be a path for the rise of hydrothermal fluids. The manifestation of the Air Sempiang hot springs is strongly suspected to originate from a fracture system controlled by the meeting of two main fault zones, which are the Bogor Fault and the Babakan Bogor Fault. The existence of this fault creates geological conditions that support the formation of geothermal reservoirs, both vertically (depth of the hot zone) and horizontally (lateral spread of faults and fractures). Geothermal manifestations in Air Sempiang are the result of geothermal activity triggered by active fault fractures, and the zone between the Bogor Fault and the Babakan Bogor Fault which is a potential geothermal location.

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Author Contribution

In compiling this research journal, each author is divided into several job desks. Conceptualization: Muhammad Rifqi Rabbani (MRR) contributed to the research through data **curation and investigation**, as well as preparing the original draft of the manuscript. Arif Ismul Hadi (AIH) was responsible for **formal analysis and validation of the results**, and also contributed to reviewing and editing the manuscript. Budi Harlianto (BH) supported the work by assisting in **validation and writing – review & editing**. Muchammad Farid (MF) contributed to the **validation of data processing outcomes**. Hana Raihana (HR) assisted in **writing – review and editing**, particularly through proofreading the manuscript. Arya Putra Anggi (APA) played a role in **investigation**, specifically by assisting with the **data acquisition process**.

Conflict of Interest

The authors declare that there is no conflict of interest related to this research. There is no involvement of third parties, either directly or indirectly, in the financing, implementation, analysis, or writing of this article. The entire research process was conducted independently and objectively, without any pressure or influence from any institution, organisation, or individual that could affect the results and interpretation of the data.

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