



IDENTIFICATION OF SUBSURFACE ROCKS IN GEOTHERMAL AREA OF NORTH TAPANULI USING HORIZONTAL TO VERTICAL SPECTRAL RATIO METHOD

Wita Iswari¹ and Rita Juliani¹

¹Physics Department, Faculty of Mathematics and Natural Sciences, State University of Medan

witaiswari12@gmail.com, julianiunimed@gmail.com

ABSTRACT

The research aims to identify subsurface rocks in the geothermal area of North Tapanuli using the Horizontal to Vertical Spectral Ratio (HVSr) method. The HVSr method analyzes the spectral response of microtremor waves to obtain dominant frequency parameters (f_0) and amplification factors (A_0) that can describe the depth and type of subsurface layers. Data were collected in four locations, namely Partali Toruan village, Parbubu village, Situmeang Hasundutan village, and Simasom Toruan village. The analysis results show that the f_0 values in Partali Toruan Village, Situmeang Hasundutan Village, and Simasom Toruan Village indicate the presence of breccia, andesite, and basalt bedrock in the subsurface and function as cover rock in the geothermal system. Parbubu Village produces f_0 values that indicate an alluvium sedimentary layer. The shear wave velocity (V_s) profiles obtained show a stratigraphic structure typical of volcanic areas, with a significant increase in V_s with depth indicating a transition from medium soil to hard rock.

Keywords: Rock Type, Geothermal, HVSr Method, Microtremor

INTRODUCTION

Indonesia is a country rich in natural resources, one of which is geothermal energy stored in the form of hot water or steam under certain geological conditions (Ramadhan et al., 2020). North Tapanuli Regency located in North Sumatra province is an area with geothermal potential in Indonesia, located on the Sumatra fault line, along the fault zone has a different basin structure, which causes the main tectonic structure on the island of Sumatra. The existence of the Sumatra fault makes the North Tapanuli area an area with complex geological dynamics, including plate movements, volcanic activity, and hydrothermal processes (Pratiwi et al., 2024). The Sumatra fault affects the morphology of the region, which plays a role in the formation of geothermal pathways and mineral deposits.

Geothermal activity in the North Tapanuli region can be seen from the presence of hot springs, hot springs, warm soil, and steamy land surfaces (Juliani, 2013) Geothermal systems include hydrothermal systems that involve water and rocks (Hidayati et al., 2022). Rocks in hydrothermal systems are naturally fractured rocks that contribute to porosity that causes water to flow through fissures or permeable zones. Rock porosity and seismic wave velocity can be utilized to determine the distribution of subsurface rocks. Rock elasticity characteristics affect the speed of seismic wave propagation (Sulistiani et al., 2023).

The rocks of the North Tapanuli area based on the analysis of geological maps from the geological research and development center, including the type of pematang formation

consisting of red shale, carbonaceous shale, coal, sandy siltstone, and breccia conglomerate. The North Tapanuli region has geological conditions dominated by sedimentary rocks, especially young alluvium and old alluvium. The geological formations in North Tapanuli reflect transitional conditions between the Tertiary and Quaternary periods, influenced by the eruption of Mount Toba which produced effusive liparitic rocks and created podzolic soils. The variety of rocks present has great potential to become valuable mineral resources (Nababan, 2020).

Horizontal to Vertical Spectral Ratio (HVSR) method is one of the effective geophysical methods to identify subsurface rocks by utilizing seismic waves. The HVSR method is used to analyze soil characteristics, sediment layer thickness and soil type using microtremor data with H/V curves based on the dominant frequency value (f_0) and amplification factor (A_0) (Nakamura, 1997). Microtremor is a ground vibration that reflects geological conditions that occur continuously derived from the natural frequency of soil, surface wind, topographic conditions, and human activities (Yogaswara & Kunchayani, 2024). Sorja (2018) stated that the dominant frequency is the frequency value of the rock layer that can describe the characteristics of the rock type below the ground surface.

Syah (2024) used the HVSR method to identify rock types by analyzing the ratio of horizontal and vertical components, to determine subsurface conditions and rock characteristics based on wave velocity values (Table 1).

The value of shear wave velocity (V_s) can be obtained through the value of the HVSR curve which is inverted with dinver software using the ellipticity curve method (Maulana, 2022).

Table 1. Classification of soils based on V_s values

Classification	V_s (m/s)
Hard Rocks	$V_s \geq 1500$
Rocks	$750 < V_s \leq 1500$
Very Compact Soil and Soft Rocks	$350 < V_s \leq 750$
Medium Soil	$175 < V_s \leq 350$
Soft Soil	$V_s < 175$

(Arisona et al., 2023)

The application of the HVSR method in the North Tapanuli area was carried out to

identify subsurface rocks related to geothermal systems. Information on subsurface rocks can be the basis for mapping geothermal potential in the North Tapanuli area.

RESEARCH METHODS

Place and Time of Research

The HVSR method of microtremor data collection using a Q8 digitizer portable seismograph was carried out at 4 locations in North Tapanuli Regency, namely in Tarutung sub-district, Parbubu I village and Partali Toruan village, in Sipaholon sub-district, Situmeang Hasundutan village, and in Pahae Julu sub-district, Simasom Toruan village (Figure 1). Data were collected from February 22, 2025 - March 25, 2025.

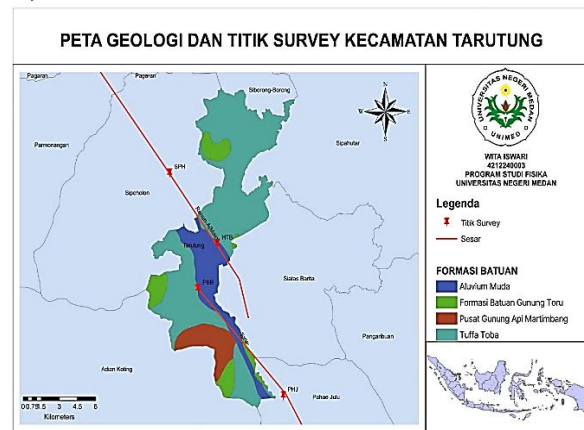


Figure 1. Geologic map of the study area

Research Tools and Materials

Research Tools

Seismograph sensor, Q-8 digitizer, seismograph connector cable, seismograph battery, laptop, global positioning system (GPS), geopsy software, dinver software, and google earth pro software.

Research Materials

Geological map sheet of North Tapanuli district

Research Procedure

The HVSR method of microtremor data collection uses a Q8 digitizer portable seismograph. The data obtained is processed using geopsy software to produce H/V curves. The microtremor data used is a seismic wave signal in the time domain with a recording duration of one hour and consists of three main components, namely North-South, East-West,

and Vertical. Disturbance (noise) of the recorded signal due to human activity vibrations needs to be avoided by selecting a stationary signal (Figure 2).

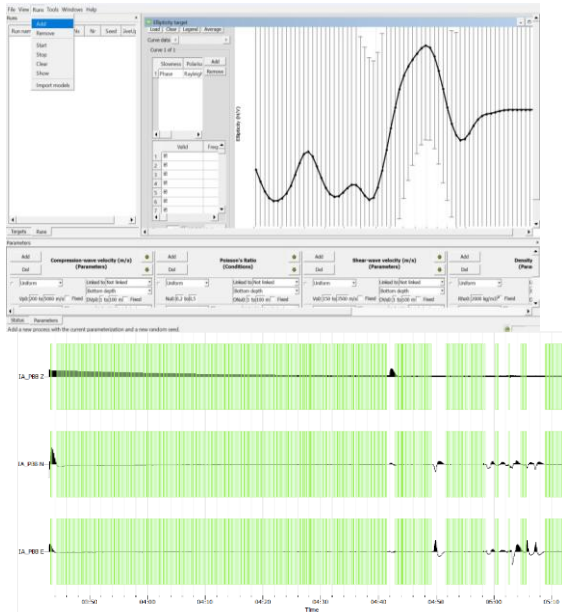


Figure 2. Seismic Wave Signal Display

Data processing uses a window width of 15 seconds, adjusted for the presence of noise in the signal. The frequency spectrum uses a signal in the range of 0.5 Hz - 20 Hz, more than 20 Hz is considered noise (Darmawan, 2023). After selecting the window and cutting the noise manually, the Horizontal to Vertical Spectral Ratio spectrum analysis is then carried out.

Amirudin (2023) states that the dominant frequency value is obtained from the first peak of the H / V curve and the amplification value is obtained from the calculation of the average H / V spectrum length. The dominant frequency is called the vertical component and the amplification is called the horizontal component so that the HVSR curve is obtained (Figure 3).

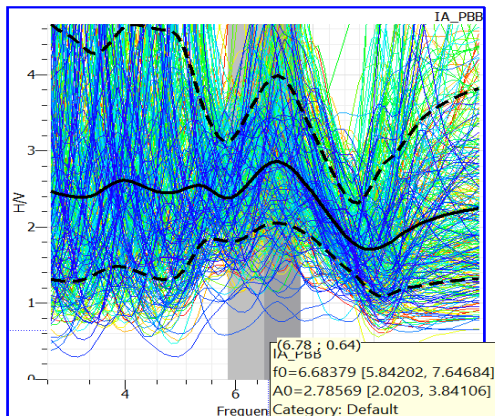


Figure 3. H/V Curve

The HVSR curve values were inverted to determine the shear wave velocity (V_s) with dinver software integrated in geopsy software using the ellipticity curve method (Figure 4).

Figure 4. HVSR Inversion Display

The ellipticity curve is a graphical representation used to analyze the polarization characteristics of rayleigh waves (Figure 5). The ellipticity curve plots the ratio of vertical to horizontal components of ground motion as a function of frequency (Sunardi et al., 2018). Rayleigh wave ellipticity is used to determine subsurface structure and indicates sensitivity to structural disturbances in low velocity subsurface sedimentary layers (Khayati et al., 2018).

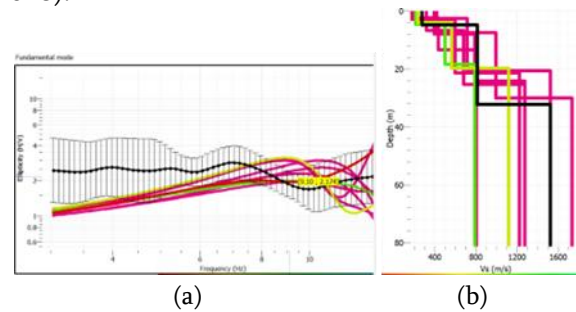


Figure 5. Ellipticity Curve (a) Fundamental Mode (b) Vs Profile

Sunardi (2018) stated that the fundamental mode (Figure 5) relates frequency (x-axis) and ellipticity (H/V ratio, y-axis). The inversion process is to match the measured ellipticity curves (black lines with error bars) with theoretical ellipticity curves generated from different velocity models (colored lines). After the inversion process, a V_s profile is obtained which shows how the shear wave velocity changes with depth. The line drawn from the V_s profile is the black line, showing the shear wave velocity profile versus depth that best fits the measured ellipticity curve data (black line with error bars on the fundamental mode graph). The other colored lines represent alternative models that may not be as accurate as the black line in matching the observed data (Daud et al., 2021).

RESULTS AND DISCUSSION

Research results

The results of the H/V curve analysis using the HVSR method produce values of the dominant frequency parameters and amplification factors. Based on the values obtained, the dominant frequency and amplification factor at the four data collection points obtained values that were close to each other (Table 3) with the H/V curve shown in (Figure 6).

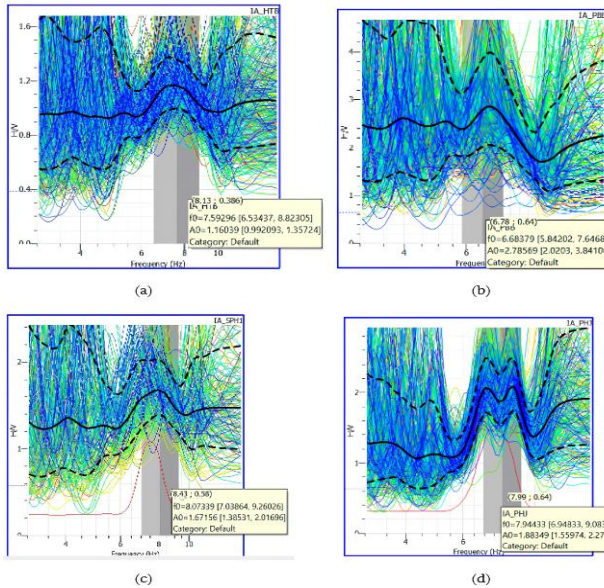


Figure 6. H/V curves (a) Partali Toruan Village, (b) Parbubu Village Site, (c) Situmeang Village Site, (d) Simasom Toruan Village Site.

The data generated from the HVSR method is interpreted in Table 2.

Table 3. Dominant Frequency and Amplification Values

Location	Dominant Frequency (Hz)	Amplification
Partali Toruan	7,59296	1,16039
Parbubu	6,68379	2,78569
Situmeang	8,07339	1,67156
Simasom Toruan	7,94433	1,88349

Maulana (2022) stated that the Ellipticity curve method integrates dominant frequency data which results in more accurate geological modeling with shear wave velocity (V_s) parameters in units (m/s) (Figure 7).

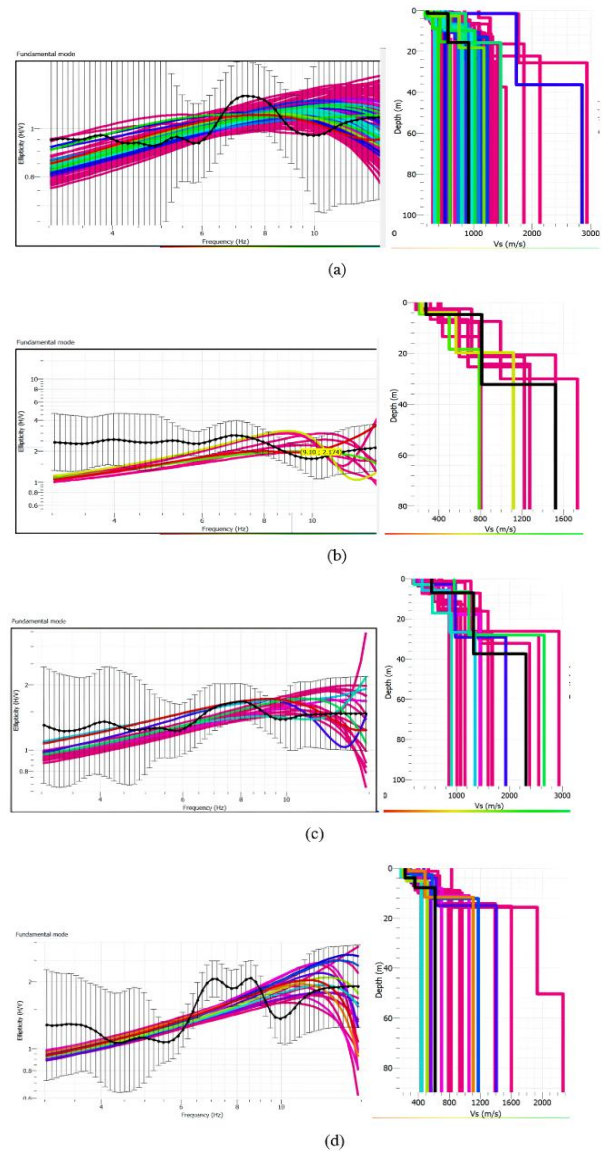


Figure 7. Ellipticity Curve (a) Partali Toruan Village, (b) Parbubu Village Site, (c) Situmeang Village Site, (d) Simasom Toruan Village Site.

The ellipticity curve produces shear wave velocity (V_s) values that are analyzed based on the layers formed on the curve, which can be seen in Table 3.

Table 3. Layer Thickness and V_s Value

Location	Thickness Layer (m)	(V_s)
Partali Toruan	1,15	226,67
	14,45	576,02
	15,55	925,37
Parbubu	4,12	278,15
	25,88	812,64
	52,12	1523,62
Situmeang	7,27	537,74
	22,73	1335,16

	65,44	2297,57
Simasom Toruan	1,78	216,76
	5,73	358,88
	24,27	622,82

Discussion

Identification of subsurface rocks in North Tapanuli district using the Horizontal to Vertical Spectral Ratio (HVSr) method obtained the dominant frequency (f_0), amplification (A_0), and shear wave velocity (V_s) values.

Dominant Frequency (f_0)

The dominant frequency is the most frequent frequency value and can be used to characterize the soil or rock layers in the surrounding area. High dominant frequency values indicate the presence of thin or hard sedimentary layers, low dominant frequency values indicate the presence of thicker or soft sediments. (Prameswari & Katriani, 2022).

The results of the H/V curve (Figure 6) of Partali Toruan area shows the dominant frequency value (f_0) of 7.59 Hz included in type IV type I describing the soil layer with hard bedrock, such as volcanic rocks, covered by very thin sediments <5 meters (Tahir et al., 2022). The Parbubu area shows a dominant frequency value (f_0) of 6.68 Hz in the boundary range of type I (igneous rock) and type II (sedimentary rock) indicating a transition zone between hard rock layers and medium sediments (Siregar & Madlazim, 2017). The Situmeang Hasundutan area shows a dominant frequency value (f_0) of 8.07 Hz, included in type IV type I, which describes a soil layer with hard bedrock, such as volcanic rock, covered by very thin sediments <5 meters (Aditya, 2021). The Simasom Toruan area shows a dominant frequency value (f_0) of 7.94 Hz included in type IV type I describing a soil layer with hard bedrock, such as volcanic rock, covered by very thin sediments (<5 meters) (Tahir et al., 2022).

Amplification (A_0)

Amplification is obtained based on the calculation of H/V averaged over the length of the spectrum. The amplification value represents the rock layer in an area that is influenced by

wave velocity and rock density. The lower the velocity and density of rocks, the greater the amplification value (Darmawan, 2023). The results of the H/V curve (Figure 6) show that the amplification value (A_0) which is included in the low category describes hard soil or rock (Demulawa & Daruwati, 2021).

Shear Wave Velocity Value (V_s)

The value of shear wave velocity (V_s) is used to determine the subsurface structure, obtained through the value of the HVSr curve which is inverted with *dinver* software using the ellipticity curve method (Maulana, 2022). The result of the ellipticity curve (Figure 7) shows:

1. Partali Toruan Village, 1 m depth with V_s 226 m/s indicates medium soil, 14 m depth with V_s 576 m/s indicates very dense soil and soft rock, 15 m depth with V_s 925 m/s indicates rock (Rahman et al., 2024).
2. Parbubu Village, 4 m depth with a value of 278 m/s indicates medium soil, 25 m depth with a V_s value of 812 m/s indicates rock, 52 m depth with a V_s value of 1523 m/s indicates a geological foundation dominated by hard rock (Hamimu et al., 2024)
3. Situmeang Hasundutan Village, 2m depth with a V_s value of 537 m/s indicates very dense soil and soft rock, 22m depth with a V_s value of 1335 m/s indicates rock, 65m depth with a V_s value of 2297 m/s indicates hard rock (Hamimu et al., 2024).
4. Simasom Toruan Village, 1m depth with a value of 216 m/s indicates medium soil, 7m depth with a V_s value of 358 m/s indicates very dense soil and soft rock. A depth of 24m with a V_s value of 622 m/s indicates very dense soil and soft rock (Arisona et al., 2023).

Amrullah (2018) stated that the thickness of the sediment layer has a relationship with the dominant frequency, amplification (A_0), and shear wave velocity (V_s).

Partali Toruan Village, Simasom Toruan Village, and Situmeang Hasundutan.

The resulting dominant frequency value (f_0) indicates the presence of hard bedrock, such

as breccia, andesite, and basalt (Hasib & Susilo, 2020). The amplification results (A_0) support the dominant frequency results with low values having high attenuation properties in hard rocks and sharp contrasts between soil and bedrock layers (Demulawa & Daruwati, 2021). The V_s results show medium to hard rock layers in line with the dominant frequency and amplification results.

The resulting correlation of dominant frequency, amplification (A_0) and shear wave velocity (V_s) values indicates that the Partali Toruan area contains shallow hard rock, covered by a thin layer of soil that is not fully compressed (Yulianto et al., 2025). Dense hard rocks such as breccia, basalt and andesite are formed by magmatic processes. Hard rocks function as overburden or structural barriers in geothermal systems (Zhao et al., 2024).

Desa Parbubu

The dominant frequency value (f_0) produced is in the boundary range of igneous rocks and sedimentary rocks indicating a transition zone between hard rock and medium sedimentary layers (Kanai, 1983 in Amrullah, 2018). The amplification result (A_0) supports the dominant frequency result with a low value indicating high damping properties in hard rock (Demulawa & Daruwati, 2021). The V_s results show medium soil layers to hard rock layers in line with the dominant frequency and amplification results.

The resulting correlation of dominant frequency, amplification (A_0), and shear wave velocity (V_s) values indicates that the Parbubu area shows sedimentary layers of alluvium and volcanic deposits, to hard layers of granite, andesite, or basalt that create ideal conditions for geothermal fluid migration pathways (Rahmawati, 2018).

The North Tapanuli region is part of an active volcanic zone on the island of Sumatra along the Bukit Barisan volcanic arc. The existence of rocks in the North Tapanuli area is strongly influenced by tectonic and volcanic activity that has been going on since the Quaternary (Pratiwi et al., 2024).

The Partali Toruan, Situmeang Hasundutan and Simasom Toruan areas show the

presence of hard volcanic rocks, such as breccia, andesite and basalt formed from volcanic activity in the past, where volcanic eruptions produce lava flows and pyroclastic material which then freezes and forms solid rock. Volcanic rocks are the result of ancient volcanic eruptions, cooling of lava forming andesite and basalt, and deposition of pyroclastic material forming volcanic breccia.

The Parbubu area shows the presence of alluvium rocks, which are loose deposits consisting of gravelly sand and sandy hard clay formed from the process of erosion, transportation, and deposition of material from higher areas. Alluvium rocks in the highlands come from weathering of volcanic rocks, due to changes in temperature, weather, chemical reactions with water and plate movements (Sulistyanawan & Harahap, 2013). Rainwater causes erosion on mountain slopes carrying material from weathering volcanic rocks flowing through fractures and accumulating in depressions to form alluvium deposits (Wahyuningrum et al., 2023).

CONCLUSIONS AND SUGGESTIONS

Conclusion

The results of the identification of subsurface rocks in the North Tapanuli geothermal area using the Horizontal to Vertical Spectral Ratio (HVSR) method show that Situmeang Hasundutan, Partali Toruan, and Simasom Toruan villages are dominated by hard volcanic rocks, such as breccia, andesite, and basalt formed from volcanic activity in the past, where volcanic eruptions produce lava flows and pyroclastic material which then freezes and forms solid rock. Volcanic rocks are the result of ancient volcanic eruptions, cooling of lava to form andesite and basalt, and deposition of pyroclastic material that forms volcanic breccia. (Sulistyanawan et al., 2013).

Parbubu I village shows the presence of alluvium rocks, which are loose deposits consisting of gravelly sand and sandy hard clay formed from the process of erosion, transportation, and deposition of material from higher areas. Alluvium rocks in the highlands come from weathering of volcanic rocks, due to

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Advice

Based on the interpretation of HVSR data, it is recommended to conduct further research by increasing the number of measurement points to obtain higher spatial resolution in mapping subsurface lithology.

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