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Hypocenter Distribution Analysis of Sinabung Volcano Eruption In 2021 Using Geiger's with Adaptive Damping (GAD) Method

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Abstract

Sinabung Volcano is located in the Karo Highlands, Karo Regency, North Sumatra, Indonesia, with a peak of 2460 meters above sea level. This volcano experienced an increase in volcanic activity in the April-October 2021 period, so it is necessary to analyse volcanic seismicity to determine the hypocenter distribution of the volcano. This study aims to determine the hypocenter distribution and classification of volcanic earthquake types based on seismogram recording data of Sinabung Volcano at four stations, namely LKW, BGR, MDD and SGR stations. The method used in this research is Geiger's method with adaptive damping (GAD) to determine the distribution of hypocenters. The results showed that the hypocenter distribution gathered below the crater centre with depths from 0.172 km to 7.139 km. The determination of the hypocenter distribution of volcanic earthquakes is expected to provide information on the depth of the earthquake to determine the movement of magma and the characteristics of events that occur during the pre-eruption process of Sinabung Volcano so that this data can be used for mitigation decision making when there is an increase in the activity of Sinabung Volcano.

Introduction

Indonesia is one of the countries with the most active volcanoes. Around 129 volcanoes and 76 volcanoes are declared very active, marked by having erupted since 1600 until now [1]. Indonesia's geographical location is on the *Ring of Fire* and is above the meeting of three major plates: the Indian-Australian, Eurasian and Pacific [2][3]. This causes Indonesia to be prone to volcanic disasters, which have caused a lot of damage and victims of the disaster [4]. One of the active volcanoes in Indonesia is Sinabung Volcano, an active stratovolcano-type volcano with an altitude of 2460 meters above sea level [5]. This volcano is in the Karo highlands, Karo Regency, North Sumatra Province. Based on historical records, this volcano has never recorded an eruption since 1600 but was active again in 2010, and the subsequent explosion occurred in 2013. The last eruption of this volcano occurred in 2021, with the ash column observed about 300 meters above the summit or 2760 meters above sea level. The ash column was marked to be grey with a thick intensity towards the east and southeast. This eruption was recorded on the seismograph with a maximum amplitude of 47 mm and a duration of 605 seconds [5].

The volcanic activity of Sinabung Volcano increased in the April-October 2021 period, characterized by volcanic earthquakes. Based on this, it is necessary to monitor volcano observations using geophysical methods [6]. Further research will provide data that will be used to analyze activity patterns and subsoil conditions to determine activity at Sinabung Volcano. Geophysical methods are often used to observe the volcano. The seismic method allows continuous observation before, during and after the eruption [4]. This method shows information about the seismicity of the volcano in the form of seismic wave recordings, which are then analyzed to obtain further information related to volcanic activity [4].

Volcanic earthquakes are earthquakes generated from volcanic activity whose visualisation is recorded by seismographs. Aiming to find out the depth of volcanic earthquakes, it is necessary to analyse the hypocenter. In this study, hypocenter analysis was carried out using *Geiger's Methods with Adaptive Damping* (GAD) [7]. The Geiger method was chosen in this study because it has a smaller RMS error, and its use is faster than the two methods above (Grid Search and Random Search). The principle of this method is to calculate the difference between observation time and calculation time [8][9]. The results of the determination of the hypocenter distribution of volcanic earthquakes are expected to provide information on the depth of the earthquake to determine the movement of magma and the characteristics of *events* that occur during the pre-eruption process of Sinabung Volcano so that the data can be used for mitigation decision making when there is an increase in activity of Sinabung Volcano. Previous research using seismic methods has been conducted in the Sinabung Volcano area to determine the location of the earthquake hypocenter for the period 2011 to 2012 [5]. In addition, another study was also conducted using the results of the relocation of the hypocenter of Sinabung Volcano with a 1-D velocity model of primary waves and secondary waves using volcanic earthquake data for January 2017.

Theory and Calculation

Hypocenter

A hypocenter is the center of an earthquake within the earth. Hypocenters can be found using seismic waves (primary and secondary waves) [5]. A hypocenter can be generated due to pressure coming from within that makes the earth's layers vibrate [10][11]. The determination of the hypocenter is one of the important earthquake parameters. In determining earthquake parameters, accuracy is needed so that it can determine good data and provide accurate information to the public [12]. One of the methods used is to determine the hypocenter of the earthquake [13][6]. The hypocenter is a representation of the place where an earthquake occurs on Earth. The projection of the hypocenter on the earth's surface is called the epicenter. Determining the location of an earthquake event (*epicenter/hypocenter*) requires the coordinates of observing stations. This realistic velocity structure model characterizes the extent of the observing station network and at least 4 P and S wave arrival time data (*tp* and *ts*) [14][15]. However, the use of P-wave arrival time data alone is not a problem if the earthquake occurs within the observing station network area [16].

Determination of the hypocenter is by time of arrival analysis. The basis for calculating the hypocenter with time difference analysis uses the following formula:

$$(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2 = (t_i - t_0)^2 {v_p}^2$$
$$(t_i - t_0)V_p = (S - P))_i k \quad (1)$$

Where:

i	: 1,2,3,...,n
X, Y, Z	: Earthquake source coordinates
$(X, Y, Z)_i$	: seismograph station coordinates
k	: distance coefficient
t_i	: wave arrival time P
t_0	: the time of occurrence of an unknown Earthquake

The distance coefficient is the constant of the Omori formula and can be found with :

$$D = \frac{V_p \times V_s}{V_p - V_s}(S - P) \text{ and } k = \frac{V_p \times V_s}{V_p - V_s} \quad (2)$$

Where V_p is the propagation speed of the P wave, V_s is the speed of propagation of S waves, D is the distance from the hypocenter (earthquake source) and $(S - P)$ is the difference in arrival time of S and P waves. In determining the hypocenter, many methods are often used, one of which is the *Geiger* method [6][7]. In addition, some parameters become references in determining the hypocenter, including location parameters and earthquake events consisting of *longitude, latitude,* depth, and time of earthquake occurrence.

***Geiger's Method with Adaptive Damping* (GAD)**

One method that is often used in determining the hypocenter is the *Geiger* method using *Geiger's Method with Adaptive Damping* (GAD) [6][17] . The *Geiger* method was first developed by *Geiger* in 1910, which aims to determine the location of the earthquake hypocenter by considering the initial model parameters. (Arimuko, 2019). The principle used by the *Geiger* method is to calculate the residual between the observation time and the calculation time. The residual equation includes.

$$r_i = r^i_{obs} - r^i_{cal} \quad (3)$$

Description:

r_i : Difference between observation time and calculation time at the *i-th* station.

r_{obs}^i : Seismic wave travelling time at the i-th station from the earthquake hypocenter.

r_{cal}^i : Calculated travel time based on the subsurface velocity model.

The calculation used in the *Geiger* method is to find the smallest residual value, which is the result of the partial derivative between the time and position of each cartesian coordinate axis and the comparison between the observed travel time and the calculated travel time.

$$r_i = \frac{\partial T}{\partial x_i}\Delta x + \frac{\partial T}{\partial y_i}\Delta y + \frac{\partial T}{\partial z_i}\Delta z + \Delta t \tag{4}$$

In simple terms, the determination of the hypocenter can be done by using the difference in the arrival times of P-waves and S-waves. The Formula Explanation is as follows:

$$(t_s - t_p) = D\,\frac{V_p - V_s}{V_p V_s} \tag{5}$$

Where:

V_s= Secondary Wave Speed

V_p= Primary Wave Speed

D= Depth (Km)[7][17]

Experimental Method

This research was conducted using the initial step of collecting seismic recording data from PVMBG. The steps to determine the hypocenter:

1. *Picking* Data

This phase explains how to select or sample P and S wave arrival times in seismographic data. This phase is carried out using the *Winchkg* application, which is *software* used to read seismogram data in **SAC format**. First, call the *Winchkg* application and select the *event* to be chosen or sampled. Then, select the station component. The component used for plotting is the Z component of the station for each *event*. When you select a feature, the amplitude of each station is displayed. The P wave is the fastest arriving wave, so it occurs first, and the S wave is the second wave that comes after the P wave. Next to the difference in arrival time is the amplitude of the P wave. It is smaller than the amplitude of the S wave.

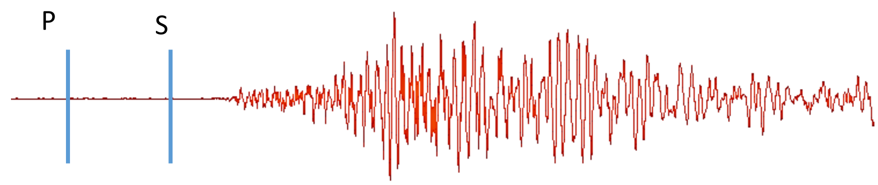

Figure 1. Showing off the data-picking process

2. Hypocenter Determination using GAD

The process of selecting the values of *tp* (p wave arrival time) *ts* (s wave arrival time) for each seismic event as a condition for determining the hypocenter. The retrieval results in the form of *tp*, and its values for each seismic event are recorded in *Notepad software*. Furthermore, data retrieval stored **in .txt format** is run by GAD (*Geiger Adaptive Damping*) software. The Sinabung Volcano GAD folder was obtained directly from PVMBG. Within this folder are four records used to enable the execution of the GAD program. The four records used include the station file (**Station.DAT**), velocity file (**Velocity.DAT**), **Arrival.DAT** file, and result file (**Result.DAT**). The process of inputting data from wave recordings in the Arrival.dat file, station coordinates in the station.dat file, and wave velocity in the speed.dat file in ASCII format (Notepad with DAT). File format) are saved. Next, you need to perform continuous GAD to obtain the source data. The obtained output results can be confirmed in the **Result.DAT** record, including the epicenter X (latitude), Y (longitude), and Z (depth) coordinates. If it is found that the error values in X, Y, and Z coordinates exceed 0.2 km, then the P and S wave selection needs to be repeated so that the actual coordinates match the GAD calculation results. The data obtained from the source distribution is then further processed by *software* to perform the slicing process and display the distribution of seismic sources from Sinabung volcanic activity. A slicing process was performed to produce a vertical section of the seismic source distribution.

After the previous volcanic event has been obtained, the next thing to do is to use GAD software. This software is used to determine the hypocenter of the volcanic event. The data used in determining the hypocenter distribution by entering data on the time of the volcanic earthquake event (year, date, hour, minute), the arrival time of P and S waves in seconds, the name of the volcano station, the polarization of P and S waves whether impulse or emergent. The results of GAD obtained the value of earthquake position and depth from the form of cartesian coordinates as well as errors from observations and calculations with the error value used is 0.04.

The determination of the exact hypocenter facilitates the discovery of the source mechanism of volcanic earthquakes as well as the magnitude of earthquake strength. Methods have been developed to determine the hypocenter, including the GAD method, inversion method, Grid Search, and Random Search. The Geiger method in determining the hypocenter of an earthquake uses software (GAD). The Geiger method was chosen in this research because it has a smaller RMS error, and its use is faster than the two methods above (Grid Search and Random Search).

The principle of this method is to calculate the difference between observation time and calculation time.

Result and Discussion

Picking volcanic earthquake *events of* Sinabung Volcano from April 2021 to October 2021 by determining the arrival time of the P and S waves shows that the earthquake *events* recorded at stations GBR (Gamber), LKW (LauKawar), SGR (Sigarang-garang), MDD (Mardinding). The number of earthquakes that occurred from April to October 2021 was 53 earthquake *events*. Volcanic earthquakes that happened in this period were more dominant, namely deep volcanic earthquakes (VA) as many as 40 earthquake *events*, with the remaining 13 earthquake *events* being shallow volcanic earthquakes (VB). The volcanic event can be seen in the table 1 below.

Table 1. Number of Volcanic Earthquake Events

No.	Month	Volcanic Earthquake (*event*)
1.	April	13
2.	May	7
3.	June	2
4.	July	11
5.	August	7
6.	September	3
7.	October	10

After analyzing the data using GAD software, the hypocenter depth value is obtained, which varies. The following are the coordinates and depth of each volcanic earthquake *event of* Sinabung Volcano:

Table 2. Coordinates of hypocentres of volcanic earthquakes of Sinabung Volcano

Event Date	Hour (WIB)	Hypocenter		
		X	Y	Z
25 April 2021	12:51	0,735	-1,799	-0,172
25 April 2021	13:43	0,323	-3,336	-0,259
25 April 2021	18:26	1,094	-0,497	-1,988
25 April 2021	23:18	0,030	-1,001	-0,700
26 April 2021	19:25	-0,120	0,661	-3,623
26 April 2021	19:45	-0,590	-0,441	-2,098
26 April 2021	23:47	0,597	-2,165	-1,875
27 April 2021	03:54	1,024	-0,982	-3,497
27 April 2021	06:54	2,148	-2,357	-0,867
27 April 2021	08:13	0,128	-1,057	-0,459
27 April 2021	08:24	0,017	-0,873	-2,195
27 April 2021	13:14	-0,677	0,374	-2,361

Table 2 shows the location of the hypocenters of the volcanic earthquakes of Sinabung Volcano. Where X represents the coordinates of the hypocenter in the x-axis, Y represents the coordinates of the hypocenter in the y-axis. And Z represents the depth. Depth is harmful because, as a reference, the location of the hypocenter is below the surface. By plotting the x-axis and y-axis coordinates, the epicenter distribution is obtained in Figure 2, which is a horizontal cross-section showing the epicenter distribution of volcanic earthquakes that occurred at Sinabung Volcano in April 2021-March 2021, along with the observing station. The flat cross-section in Figure 2 refers to the x coordinate, which is the west-east projection, and the y coordinate is the North-South projection.

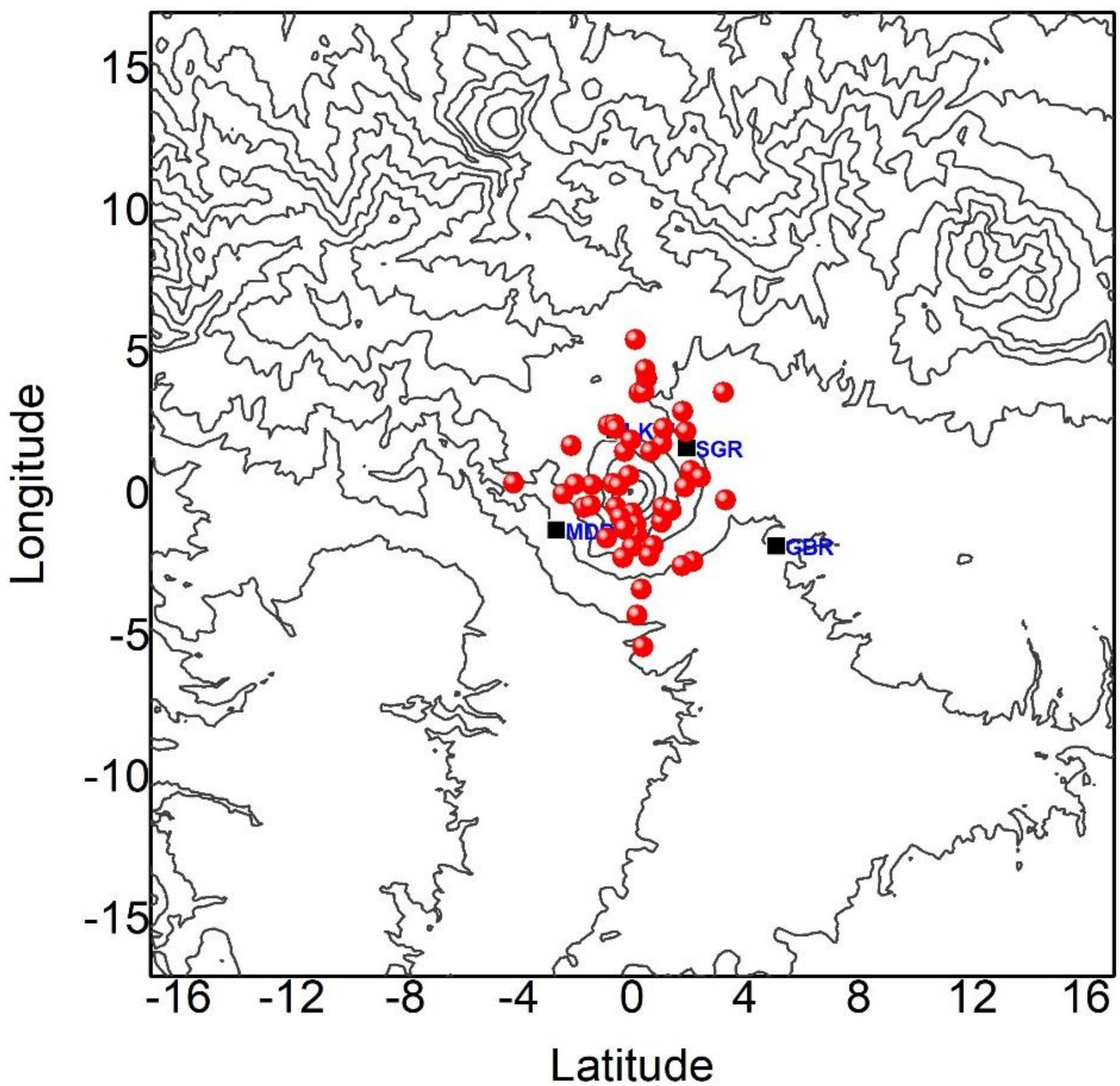

Figure 2. Epicenter distribution of Sinabung Volcano April-October 2021

Figure 2 displays a cross-section of the epicenter of the Sinabung Volcano volcanic earthquake for the period April - October 2021. The red dot in the figure shows the epicenter point, the hypocenter point projected onto the surface. The epicenter distribution of the Sinabung Volcano volcanic earthquake is located around the body of Sinabung Volcano, which is centered on the crater of Sinabung Volcano. The West-East cross-section was conducted to determine the hypocenter depth on the West to East stretch. The North-South cross section is helpful in knowing the distribution of hypocenters in the north-to-south direction.

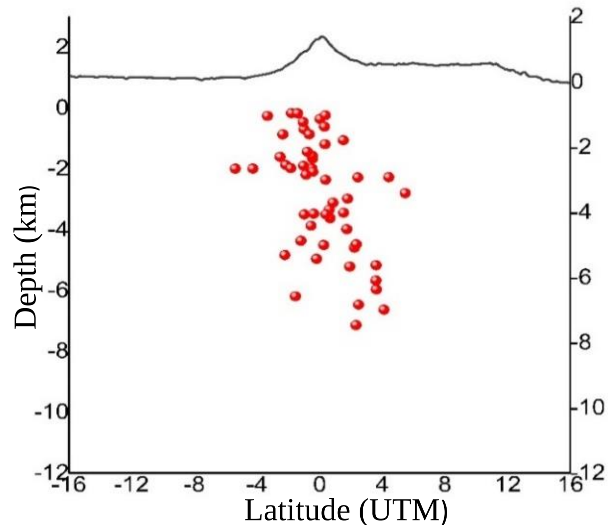

Figure 3. North-South cross-section Hypocenter Distribution (Latitude)

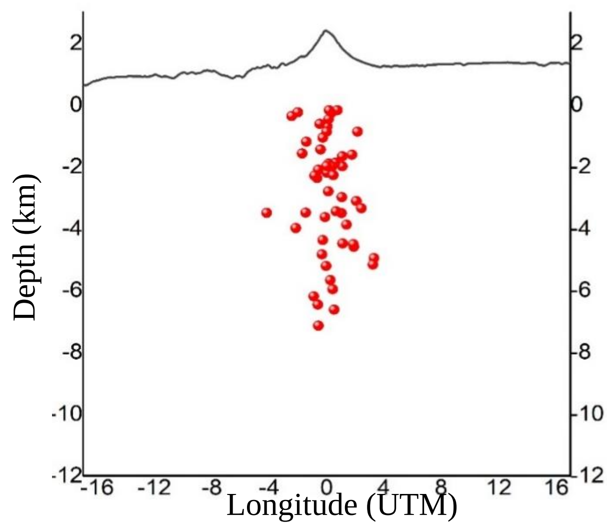

Figure 4. West-East Cross-Section Hypocenter Distribution (Longitude)

The figure of the distribution of the hypocenter of the volcanic earthquake of Sinabung Volcano shows the fluid activity from below to the surface to produce cracks that cause volcanic earthquakes. The earthquakes that occur are generally located in the active crater, where volcanic earthquakes on Sinabung Volcano are concentrated in a depth of 0.173 to 7 km. Based on the previous research the hypocenter of the eruption in the previous period (2014) was in the range of 0.1 km to 5 km [18]. Figure 3 shows that the distribution of the hypocenter is located in the body of Sinabung Volcano itself; the distribution pattern is uneven but still in the area under the volcano's crater. In Figure 4, it can be seen that the distribution of hypocenters form a vertical line, which is thought to be a conduit pipe from Sinabung Volcano. The distribution pattern of the hypocenter position of volcanic earthquakes can be seen from the development of magma migration, which is one of the causes of volcanic earthquakes. This research was conducted to reduce the impact caused by volcanic activity. This is the case when the position of the earthquake source (hypocenter) is in the right and accurate position. The distribution of hypocenters using the Geiger method which requires the average velocity of the P and S waves obtained the distribution of earthquake hypocenters spread near the center of the volcano crater, but this method has not taken into account the velocity structure of each layer below the surface of the geological conditions of the volcano [19]. Therefore, an appropriate velocity model is needed to fit the geological conditions of the volcano. The initial symptoms of a volcanic eruption are preceded by increased volcanic activity seen from the emergence of a large number of deep volcanic earthquakes followed by the recording of shallow volcanic tremors, this indicates that there is magma movement [20]. As magma and volcanic gases move closer to the surface, they cause pressure changes beneath the surface of the volcano, leading to cracks and rock ruptures. These cracks or ruptures are the source of vibration. Magma, which contains gas, gradually rises to the surface because its mass is lighter than the solid rocks around it. So it causes volcanic tremors that cause fractures in the magma wall [11][21]. In general, from the results of determining the hypocenter, the hypocenter position changes and is getting closer to the lava dome crater. This indicates that magma is moving towards the crater dome or the movement of magma to the surface. Then, the magma activity continues to rise through existing fractures and fractures that arise due to the pressure generated by magma migration to the surface. Results from the determination of the distribution of volcanic earthquake hypocenter is expected to be able to provide the depth information of the earthquake to determine the movement of magma and the characteristics of events that occur when the pre-eruption process of Sinabung Volcano so that the data can be utilized for mitigation decision making when there is an increase in activity of Mount Sinabung Volcano.

Conclusion

The hypocentral distribution of Sinabung Volcano ranges in depth from 0.172 km to 7.139 km below the surface. Earthquake depth information to determine the movement of magma and the characteristics of the event that occurred during the pre-eruption process of Mount Sinabung, so that the data can be utilized for mitigation planning when there is an increase in activity of Mount Sinabung.

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