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RESEARCH ARTICLE

The Duration Amplitude Distribution of Volcanic Tremor Recorded at Ijen Volcano, Indonesia

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□bstract This research was conducted with the aim of explaining the physical processes that occur at the source. The duration□amplitude distribution is an amplitude scaling method that can describe the process of sustained earthquake sources such as volcanic tremors. The data used in this study are seismic data from Mount Ijen for the period from January to March □□1□ and January to March □□1□. Scaling the duration amplitude distribution is done by converting the amplitude to reduced displacement □D_R□ The cumulative duration is calculated with a range of □□ 1□ cm□ which is the lowest and highest reduced displacement values. The cumulative duration plot results are then adjusted to the power law model and the exponential model. a correlation coefficient □R□□was calculated to evaluate the fit for each of these models. The results showed that the R□ exponential model was higher than the R□ power law model for all events in both □□1□ and □□1□ and there was no transition between the two models. This indicates that the source process of the Ijen volcano volcanic tremor is related to the scale□bound source process and there was no source change in either □□1□ or □□1□. However, differences in amplitude characteristics were found in □□1□ and □□1□. The volcanic tremors in □□1□ were stronger than those in □□1□, according with the reality of changing the condition of the crater lake which is stronger in □□1□. Volcanic tremors and changes in the Ijen crater lake are important for forecasting the eruption of the Ijen volcano.

Keywords□□arthquake, volcano eruption, volcanic tremor, Ijen volcano, scalling amplitude.

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Introduction

One way to understand the source process of a natural phenomenon □in this case a geophysical phenomenon such as an earthquake□is to study the scale of the relationship between the number and si□e of the phenomenon. □s in the study of earthquakes, the relationship between number and si□e is described by a power law □1□□. These results have been able to explain the process of the earthquake source as it is caused by a relatively constant stress drop and does not depend on the si□e of the earthquake □□□, material heterogeneity □□□, shear stress □□□, pore pressure and effective stress □7□and thermal gradients □8□ This number and si□e relationship can also be used for volcanic earthquakes such as volcanic tremors. However, the relationship between the number and si□e of volcanic tremors is not the same as in earthquakes because volcanic tremors are a continuous signal while earthquakes are a discrete signal □□□

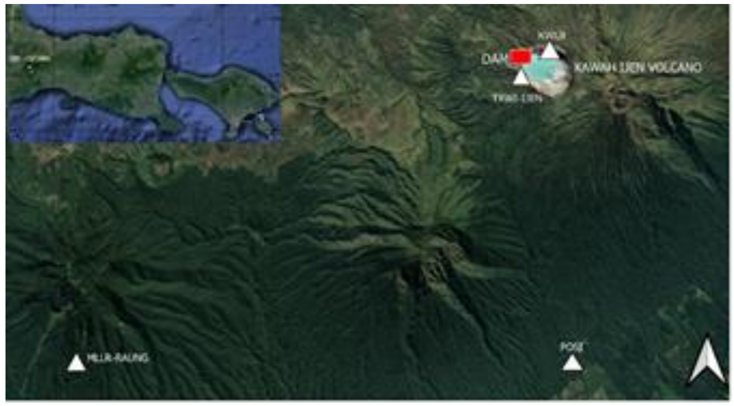

Figure 1. Ijen seismic network (KW□I, IJ□□, POSI and R□□□G) short-period sensors (MLLR and TRWI Broadband seismometer), the top left corner of the map shows the location of mountains in Indonesia, more precisely in the province of East Java which is marked with a white triangle

The scale of the relationship between the number and size of volcanic tremors is known as the duration-amplitude distribution. The scaling of this relationship is done by plotting the frequency of occurrence with the duration of the signal and the magnitude with the amplitude. Two simple models adapted to this relationship namely Power and exponential law, different source processes can be shown from the two models. The power law model can be associated with a scale invariant process where no characteristic length scale is involved, as exemplified by the earthquake magnitude-frequency scale [1□]. The exponential law model deals with scale-bound processes that can be described by variables distributed around a long-scale characteristic such as a channel filled with fluid [1□]. The basic difference between these two models can be used as a reference in determining the probable source of an earthquake (in this case, especially volcanic tremor).

The distribution of the duration-amplitude of volcanic tremor at several volcanoes in the world has been studied and found that all distribution patterns follow the exponential law model [□, 11-1□]. The exponential scaling of tremor indicates that the source of the tremor must come from a scale-bound source. which means the source has a fixed geometry but other variables change, such as the pressure variable. [□]. Changes in volcanic tremor before and during the eruption can also be observed with the amplitude scaling relation [1□]. In the Aso volcano and Popocatépetl volcano, there was a sudden change in the distribution of the duration of the amplitude of the volcanic tremor before the eruption, during the eruption and after the eruption. This condition shows that the exponential law is only found during eruptions and post-eruption, while before the eruption follows the power law. This is related to changes in the source of the volcanic tremor [1□, 1□].

Ijen volcano (□□8□ m) is a strato-type volcano located within Ijen caldera area, including in the East Java region of Indonesia (Figure 1). The surface manifestations of the ijen volcano consist of a crater lake which is the largest acidic hot water lake on Earth (V = □7 × 1□ C, and pH = □.□), and a fumarole crater [1□] which produce a large amounts of sulfur [1□]. The first magmatic eruption of Ijen volcano occurred in 1817 [17], but phreatic and geyser-like activity frequently occurred since that time [18]. In □□1□, the volcanic lake has shown signs of instability that were coupled with an increased seismicity [18]. Volcano tectonic earthquakes were recorded in large numbers followed by the appearance of a group of volcanic tremors along with changes in the condition of the crater lake. In January-March □□1□ volcanic tremor showed a maximum amplitude and its appearance coincided with an increase in temperature and volume of crater water and the continuous appearance of bubbles in the crater lake [18]. In this condition the status of the volcano was declared a crisis and lasted until the end of March □□1□. In □□1□, the Ijen volcano was declared back to normal after no volcanic tremor activity was recorded. In □□1□, a similar incident occurred again, namely the appearance of a series of tectonic volcano earthquakes, followed by a group of volcanic tremors but this was not accompanied by changes in the condition of the crater lake as in □□1□. In the following year until now this condition has not been found. Return to seismic activity ijen volcano.

In this paper, the duration-amplitude distribution of volcanic tremor record at Ijen Volcano during the crisis and after the crisis is analyzed to investigate the process of triggering the volcanic tremors of the Ijen volcano. The main issues in the article are□ □1□ the possibility of a change in distribution behavior from exponential legal behavior to power□ □□ Differences in amplitude distribution patterns during crisis and post□crisis and □□models of volcanic tremor sources that are suitable for explaining the mechanism of volcanic tremor sources of Ijen volcano according to the results of the analysis. In this paper provides an overview of the data and methodology used to calculate the duration amplitude distribution. The most likely source model to explain the volcanic tremor source process of Ijen volcano is discussed next. The results of this study can be used as an illustration of the possibility of an eruption that will occur at Ijen Volcano based on its volcanic tremor activity.

Materials and Methods

Data and Selection

The data used in this study were seismic data from the Ijen volcano for the periods January□□pril □□1□ and January□March □□1□, which had significant tremor activity. The data includes records of seismic activity of the Ijen volcano from all seismic stations around the Ijen volcano, including IJ□□, KW□I, TRWI, R□□□G, POSI □□D MLLR □Figure 1□ TRWI and MLLR are equipped with a broadband three□component sensor, while IJ□□, KW□I, R□□□G and POSI use a single□component sensor. □ll stations recording at a sampling rate of 1□□ samples/s. The data is read using seisan software assistance. Figure □ shows the recorded data from all seimsik stations around Ijen volcano on □January □□1□ at 1□.□□□1□.□□ WIB. The volcanic tremor event was selected based on the most obvious waveform appearance of at least □ seismic stations as shown in Figure □. The volcanic tremor waveform is clearly visible at IJ□□, KW□I, TRWI, R□□□G and MLLR stations. Meanwhile, the POSI station looks less clear. The selection results obtained □□ events of volcanic tremor for □□1□ and 1□ events of volcanic tremor for □□1□.

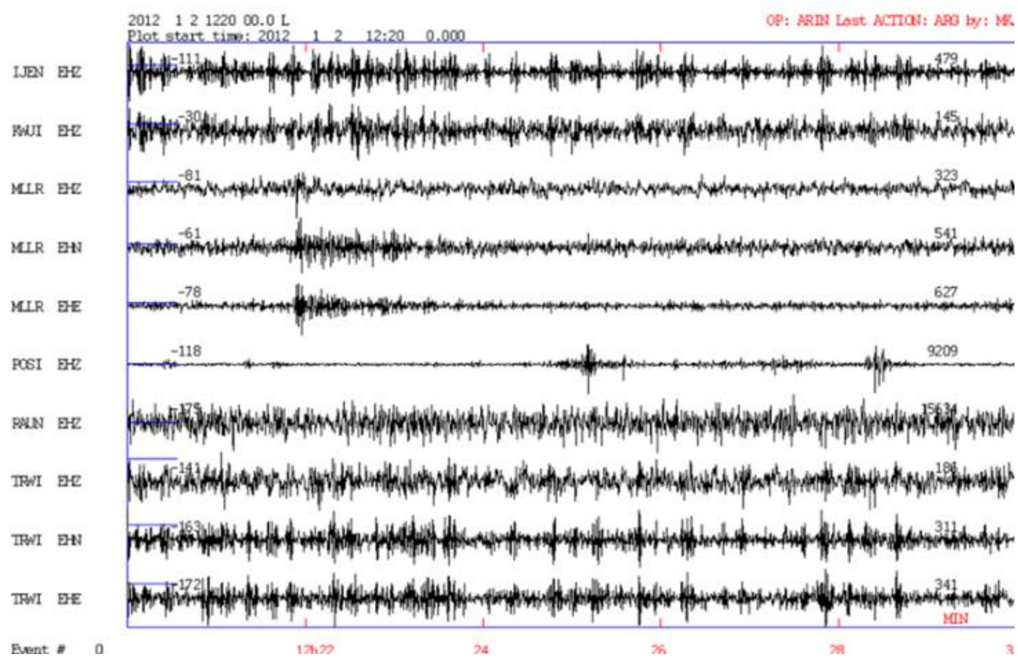

Figure 2. Record section of velocity waveforms of volcanic tremor recorded at all Ijen volcano monitoring station that occurred in 1□.□□□1□.□□ WIB on January □, □□1□ □from top to bottom□IJ□□, KW□I, MLLR, POSI, R□□□G dan TRWI□

The spectrogram of each selected tremor event is calculated to classify tremor events based on spectral which is the basic characteristic of a digital signal. In this study, it was calculated using the Short□Time Fourier Transform □STFT□method using the help of the Geopsy computer program. In this way the characteristics of the volcanic tremor of the Ijen volcano were obtained, namely monochromatic volcanic tremor with a low frequency □1.□□1.□□H□. Figure □a shows the spectrogram and seismogram of the volcanic tremor of the Ijen volcano during unrest □in □□1□□ precisely on January 1□, □□1□, □.□□□□.□□ WIB. Figure □b shows the spectrogram and seismogram of volcanic tremors after unrest □in □□1□□ precisely on 1□January □□1□ □.1□□□.□□WIB. □ bandpass filter between □.□□1□H□is applied to the signal to remove microseismic and higher frequency noise.

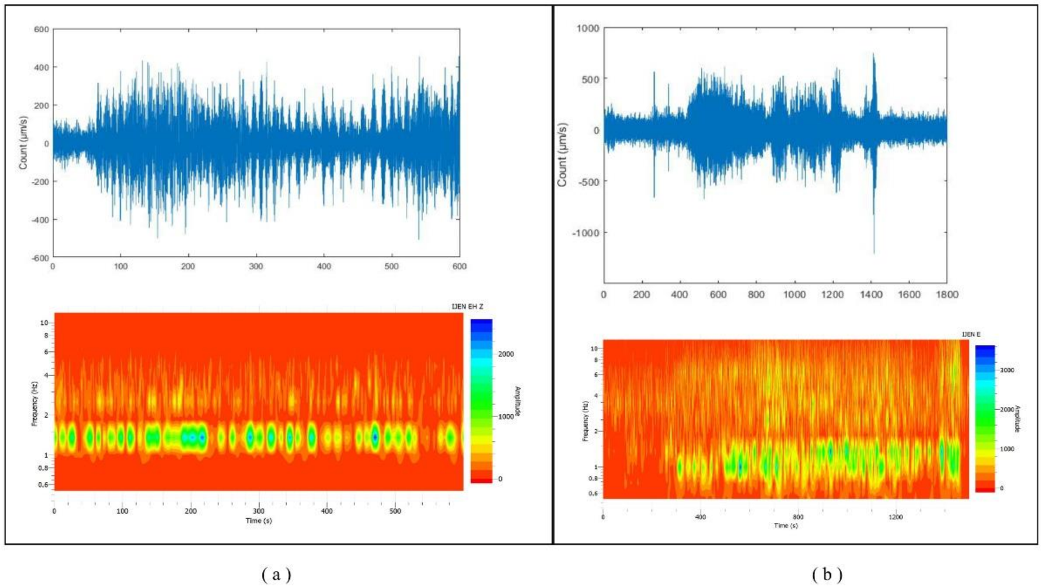

Figure 3. Vertical component velocity waveforms and corresponding spectrograms
For a) Volcanic tremor on □ january □□1□ □.□□□□.□□ WIB b) Volcanic tremor on 1□ january □□1□ □.1□□ □.□□ WIB

Apart from seismic signals from the Ijen volcano, the seismometer can also record other activities such as the footsteps of tourists from the Ijen crater or the activities of sulfur miners in the Ijen crater. To reduce this error, the volcanic tremor event used in this study was an event that was recorded with a minimum duration of 1 minute and was recorded at the MLLR station. The Ijen crater is adjacent to the Raung volcano, which in □□1□ has also increased its activity. So, there is concern that the recorded volcanic tremor event is a Raung volcanic event. To calibrate this recording, the recorded data from IJ□□ station is compared with that of R□□□G station. From all these calibrations, it was finally obtained volcanic tremor events which will be analyzed, only 1□ tremor events for □□1□ and 11 data for □□1□.

Determine the Duration-Amplitude Distribution

The envelopes of displacement waveforms are calculated and converted to reduced displacement (D_R) which is a normalized amplitude metric for volcanic tremor [1□]. In this study, reduced displacement is calculated using the equation:

$$D_R = (A/ 2\sqrt{2}) \times (r/M) \quad (1)$$

where *A* is the tremor amplitude, *r* is the distance of the station from the lava lake and *M* is the sensor magnification given by [□□]. This equation is valid for the tremor wave field which is mostly composed of body waves (according to the results of research on the volcanic wavefield tremor of the Ijen volcano). The time of onset and end of each tremor episode was estimated by considering the lowest threshold value of D_R ranging from □ to 1□ cm□. The cumulative duration in seconds is then calculated for a different set of reduced displacement values as shown in the example of Figure □. The calculation results of the cumulative duration of each tremor episode are then adjusted according to exponential law dan power law [□□]. Exponential law of the form:

$$d(D_R) = d_t e^{-\lambda DR} \quad (2)$$

where D_R is the amplitude of vibration, *d* is the duration of tremor with amplitudes larger than D_R, d_t is the total duration of the tremor and λ is the slope of the line. The inverse of the slope λ^{-1} can be called as the characteristic amplitude of the distribution and can also be taken as proportional to the geometric dimension of the tremor source. Meanwhile, power law of the form:

$$d(D_R) = d_t (D_R)^{-\gamma} \quad (3)$$

where γ is the slope of the power law line. the correlation coefficient (R^2) was calculated to evaluate the fit for each of these models.

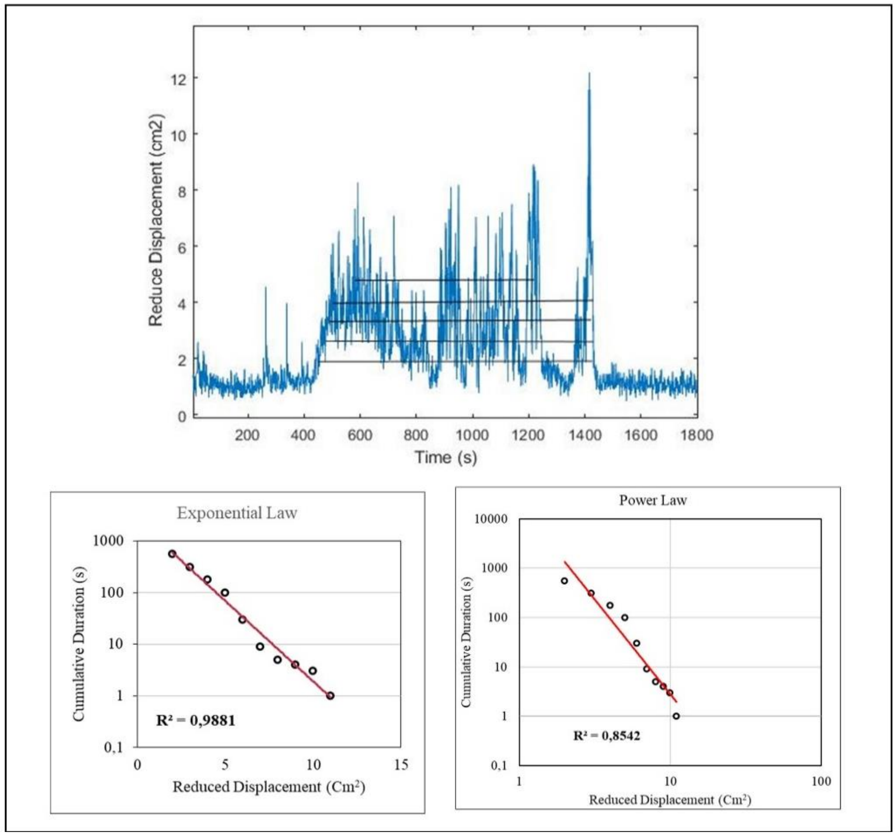

Figure 4. The determining of duration□amplitude distribution for a volcanic tremor. Cumulative duration is indicated by a black hori□ontal lines. The line that best fits the least squares is shown by the red lines.The correlation coefficient between cumulative duration and reduced displacement is shown by R□.

Results and Discussion

Duration-amplitude Distribution

The R□ exponential law and power law for the □□1□ event and the □□1□ event are shown in Figure □ where the value of the exponential correlation coefficient is marked with a blue line while the power law correlation coefficient is marked with an orange line. Based on Figure □, the value of R□ exponential law is higher than R□ power law for all volcanic tremor events in both □□1□ and □□1□. This means that all volcanic tremor events for Ijen Volcano both in □□1□ and □□1□ are better to follow the exponential law model than the power law. This precludes the possibility that rock fracturing processes may be operating at the tremor source in both □□1□ and □□1□. The results of the analysis also found no change in patternfrom exponential law to power law, which means that no change in the source process has occurred. The source process can also be seen from the relationship between the characteristic amplitude value and the lowest frequency □1□□, Figure □ shows the correlation of the two and the correlation is obtained that the greater the characteristic amplitude value, the lower the lowest frequency value. This value confirms that the source of the volcanic tremor of Mount Ijen is caused by a scale□bound source.

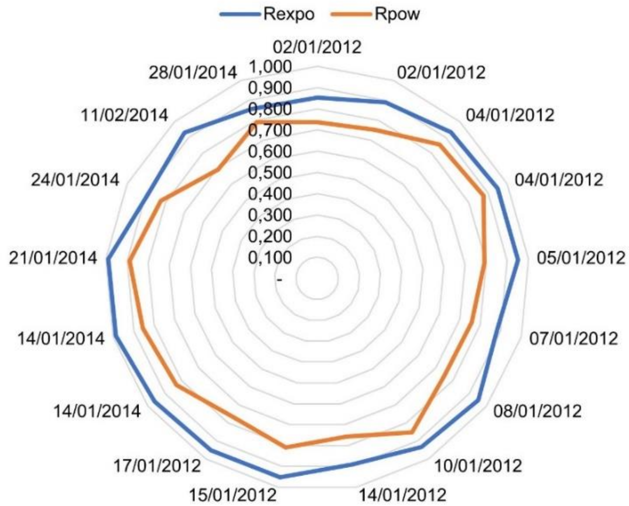

Figure 5. Plot of correlation coefficient for all event volcanic tremor of ijen volcano on □□1□ and on □□1□

Figure □ shows that the characteristic amplitude of the volcanic tremor of the Ijen volcano in □□1□ □black circle□ has a greater value than the amplitude characteristics of □□1□. This indicates that in □□1□ the volcanic tremor that occurred was stronger in energy, supported by the visual appearance in □□1□ of the emergences the tremor was followed by a change in the condition of the lake both in color, temperature, water volume and even gas bubbles which were observed on the surface of the crater lake. However, in □□1□ the change in the lake was only in the form of gas bubbles. However, the similarity in the appearance of these gas bubbles indicates that the source process in □□1□ or □□1□ came from the same source process related to these gas bubbles. The amount of energy in □□1□ is also supported by the results of the correlation between Maximum Drms and characteristic amplitude □Figure 7□. It was found that the maximum Drms yield in □□1□ was greater than the maximum Drms in □□1□, this also proves that the volcanic tremor of the Ijen volcano in □□1□ was stronger than in □□1□ even though with the same source process. So, it is possible that the source process was less strong which caused a phreatic eruption in □□1□ not to occur even though strong volcanic tremors were recorded.

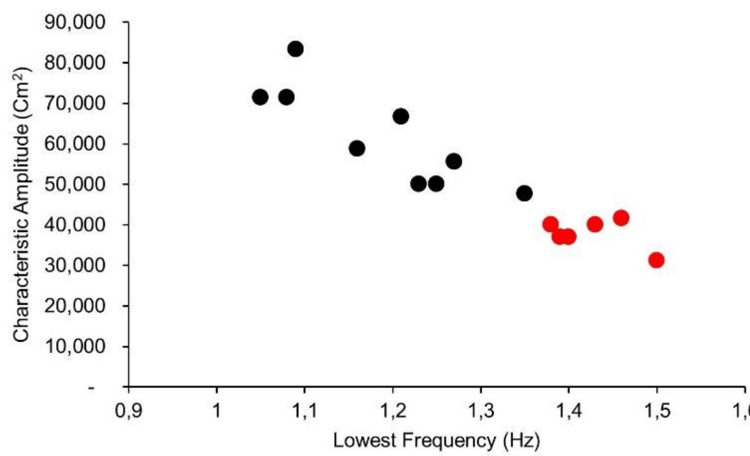

Figure 6. Plot of characteristic amplitude vs. lowest frequency for all event volcanic tremor of Ijen volcano, round red for the □□1□ event and round black for the □□1□ event

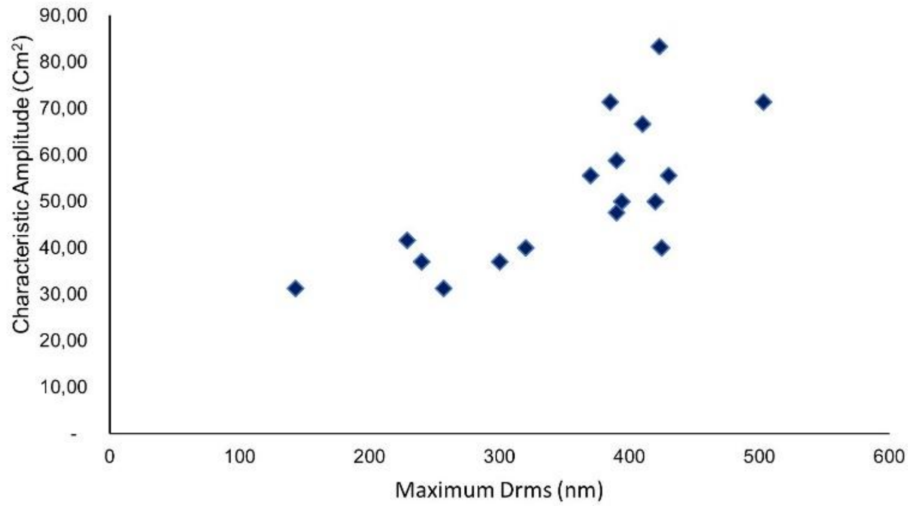

Figure 7. Plot of maximum Drms vs. characteristic amplitude for all event volcanic tremor of Ijen volcano

Discussion

Potential Source Tremor Models

The magmatic system of the Ijen volcano has a double magma chamber system with a shallow magma chamber located at a depth of □,□□□ meters while a deep magma chamber is located at a depth of □,□□□ meters □□1□. In general, the mechanism of volcanic eruptions with multiple magma chamber systems begins with the process of emptying the shallow magma chamber first. □ few moments later the empty magma chamber is filled with fluid supplied from the inner magma chamber. Filling of shallow magma chamber by deep magma chamber continues until maximum pressure is reached. when the magma pressure is maximum then the pressure will come out and an eruption will occur □□1, □□□.

This condition also occurs in the Ijen volcano, the migration process of the Ijen volcano magma is triggered by tectonic activities around the Ijen volcano which produce local tectonic earthquakes. The increasing incidence of tectonic earthquakes has disrupted the magma balance system. This imbalance results in the movement of magma or gas in the pyromagma towards the earth□s surface through the gaps or passages above it because the pressure inside the pyromagma is greater than the external load pressure. The movement of magma and gas towards the surface that occurs continues to break through the gaps so that cracks appear which cause deep volcanic earthquakes □V□□. The movement of magma that approaches the surface through the passages or gaps above it causes pressure fluctuations resulting in shallow volcanic earthquakes □VB□. Migration of magma on the shallow surface causes the opening of rock fractures or cracks and even breaking of rocks. This crack or breaking of the rock is then suspected to be the source of the emergence of volcanic tremors of the Ijen volcano □□1, □□□.

The results showed that the source process of the volcanic tremor of ijen volcano has scale□bound characteristics so that the most likely source process is rock fracture. So source models such as fluid flow□induced oscillations of magmatic fluid conduits □□□, □□□, bubble growth or collapse due to hydrothermal processes □□□, □□□, vertical expansion and conduit vibration models □□7, □8□ cannot explain the source process of volcanic tremors of Ijen volcano. The most probable source model of volcanic tremor related to the rock fracture process is the fluid fill crack model. This model is described by a square□shaped crack filled with liquid □magma or steam/gas□, the liquid flows in this crack, resonance occurs when there is maximum pressure on the wall.

This condition triggers the emergence of volcanic tremors, the model has been modeled mathematically by □□□□ and is shown to produce waves similar to the characteristics of volcanic tremors. This model depends on □a□ the geometry of the cracks□ □b□ the area and position of the pressure disturbance occurs□ □c□ boundary condition on the surface of the crack and the fluid flow inside the crack □and □d□ the dimensionless quantities called the crack stability C and the fluid□solid impedance contrast □, defined as□

$$C = \frac{b\,L}{\mu\,d},\ Z = \frac{\rho_{s}\,\alpha}{\rho_{f}\,a} \qquad (□□)$$

where *b* is the bulk modulus of the fluid, □ is the rigidity of the solid, *L* is the crack length, *d* is the crack thickness, ρ_s is the density of the solid with α its P□wave velocity and ρ_f the density of the fluid with P□wave velocity equal to *a*.

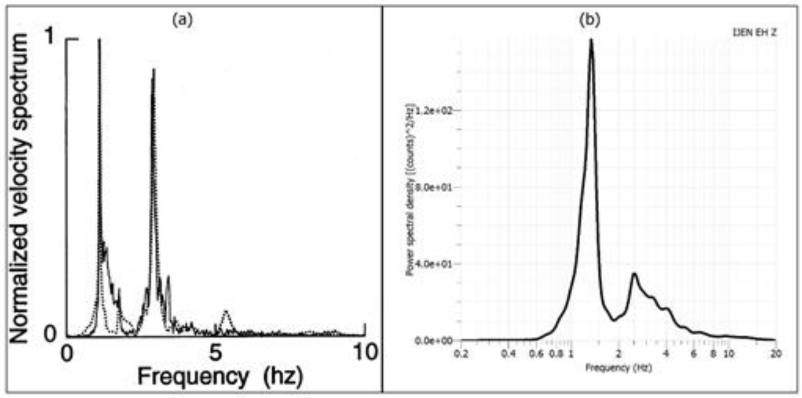

Figure 8. Spectral comparison between the results of mathematical modeling by □□□□left□and volcaniv tremor of ijen volcano on □january □□1□ □.□□□.□□ WIB □right□

For the volcanic tremor conditions of the Ijen volcano, we get the spectral tremor peaks as shown in Figure 8a with □frequency peaks in the first mode obtained at 1.□□ H□and the second mode at □.□1 H□. the results of another analysis of the location of the volcanic tremor source of the Ijen volcano □which we do not discuss in detail in this article□show that the source of the volcanic tremor leads to a depth of 1 km below the crater. We then compared the frequency mode of volcanic tremor of Ijen volcano with the results of research conducted by □□□in mathematical modelling of fluid fill cracks □Figure 8□and obtained spectral peak similarities. Based on the similarity of the spectral peaks and the depth of the source, the conditions that are most probable and in accordance with the conditions of the Ijen volcano are crack length, □8□□8□ m□crack aperture, □.□□□.□□ m□crack width, 1□□1□□ m□crack stiffness, 1□□□□□□ density ratio of fluid to rock, □.□□□.□7□sound speed of fluid, □.8□1,□ km/s□compressional wavespeed of rock, □,1 km/s. crack excitation was fitted by an impulsive pressure drop in the range □.□□□bar. Several other research results corroborate this model, such as the existence of a vertical crack at a depth of □1□□□ meters below the center of the crater with a crack length of around □□□ meters. The results of this study were obtained from an analysis of the location of the tectonic earthquake source of the Ijen volcano. both in □□1□ and □□1□ a vertical crack was found under the crater □□1, □□□. This tectonic earthquake is the trigger for the opening of fluid paths to rise to the surface □□1□so that the existence of this crack is very likely to be a source of volcanic tremor of the Ijen volcano.

Conclusions

In conclusion, the correlation coefficient of the exponential model is higher than the strength of law correlation coefficient in all volcanic tremor events of Ijen Volcano both in □□1□ and □□1□. There is also no pattern transition from exponential model to power law. These results indicate that the source of the volcanic tremor of Mount Ijen is related to a scale□bound process and does not change the source of volcanic tremor in either □□1□ or □□1□. The most suitable scale□bound source to explain the process of the source of volcanic tremor of Ijen volcano is the fluid fill crack model. this is supported by the spectral characteristics of the volcanic tremor of the Ijen volcano and the results of other studies which state that there is a crack under the center of the crater. The model for the source of the volcanic tremor of the Ijen volcano is illustrated by a square□shaped crack filled with liquid □magma or steam/gas□, liquid flows in this crack, resonance occurs when there is disturbance/maximum pressure on the wall. This condition triggered the emergence of volcanic tremors of Ijen volcano.

Conflicts of Interest

The author□s□declare□s□that there is no conflict of interest regarding the publication of this paper.

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