Characteristic of 27th September – 7th October 2017 earthquake swarms in Jailolo Volcano, West Halmahera, Indonesia, based on hypocenter and b-value

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Abstract. Halmahera is an area with active tectonics, so it has a high level of seismicity. Swarm earthquakes occurred in Jailolo from November to December 2015, and then in 2017, another earthquake swarm occurred from September to October. This earthquake is characterized by an increase in the number of earthquakes in a certain period with a relatively small magnitude, without mainshocks, and occurs in volcanic areas. This research used arrival time from P and S waves recorded at Taide Digital Seismograph (TDS) which was positioned at Ternate Geophysical Station (TNTI). We used cross-section on hypocenter to see the depth distribution using GMT and determination of b-value using ZMAP code. From the results of this study, the variation in the magnitude of the earthquake swarm obtained ranged from 0.7 to 5.0 with a depth of 7.7-12 km. Our results show a b-value of approximately 1.0 in the area near Jailolo Volcano, 1.0-1.5 in the northwest of Jailolo and 1.0-2.0 in the southeastern part of Jailolo. Based on b-value we obtained, the characteristics of the Jailolo swarm earthquake tend to be influenced by magmatic activity.

1. Introduction
Research on the earthquake swarm in Jailolo has been carried out by several previous researchers, such as Passarelli et al. [1] that study the spatio-temporal pattern of the seismic swarm around Jailolo Volcano on November 2015-February 2016, then Nugraha et al. [2] study the earthquake swarm in Jailolo that occurred on September-October 2017, by relocating the hypocenter to obtain more precise location. This study also analyzed data from the swarm earthquake in Jailolo in September-October 2017, but Nugraha et al. [2] analyzed the data by relocating the hypocenter, while we used the b-value to analyze the characteristics of the earthquake.

North Molucca and Molucca have complex tectonic regions caused by the interaction of three large plates, which consist of the Eurasian plate in the west, Indo-Australian plate in the south, Pacific plate in the east, and the micro-Mindanao plate in the north [3]. Molucca Sea was located at the confluence of three major plates in the world, known as Eurasian Plate, Philippine Sea Plate, and Australian Plate [4]. The subduction zone between the Molucca Sea plate in the east and Halmahera in the west caused a series of active volcanoes at Sangihe Arc [5]. As a result of the subduction activity between Sangihe and Halmahera, this region has a high seismicity index.

Based on the time sequence, there are three different types of earthquakes [6]. Type (1) is an earthquake with a mainshock followed by several aftershocks (decreasing magnitude and frequency of occurrence), type (2) is characterized by a slow build-up of seismicity (foreshock) leading to the type 1,
and type (3) is characterized by a gradual increase and decay of the seismicity in time without a distinct mainshock [7]. The earthquakes type graph can be seen in figure 1.

![Type I: Main shock and aftershocks](image1)

![Type II: Foreshocks, main shock and aftershocks](image2)

![Type III: Swarm](image3)

**Figure 1** Schematic graph showing the differences in earthquake types based on the time sequence [6,7].

Type (3) is also known as earthquake swarm [6,7]. This is indicated by the increase in the number of earthquakes in a certain period with relatively small magnitudes without mainshocks which generally occur in volcanic areas [6]. Type 3, or swarm, occurs in very heterogeneous materials, has a high fracture density, and highly concentrated external stresses [6,7]. Swarm earthquakes occurred in Jailolo from November to December 2015 and then in 2017, another earthquake swarm occurred from September to October. Another case of earthquake swarms also occurred in Mamasa, West Sulawesi in November 2018 [8].

![Figure 2 Tectonic and geological map of Halmahera Island.](image4)

**Figure 2** Tectonic and geological map of Halmahera Island. Bold barbed line are subduction zones and small barbed lines are thrusts. Green areas are ophiolite, emergent arc, and accreted crust. Yellow is Eurasian crust and pale yellow is submarine parts of the Eurasian continental margin. Red is Australian origin crust; pale and deep pink areas represent submarine parts of the Australian continental margin. Fine black lines are marine magnetic anomalies, and cyan areas are submarine [9,10].
Halmahera is an area with active tectonics that has a high level of seismicity. This is evidenced by the occurrence of swarm earthquakes with events reaching hundreds of earthquakes in a day. This study aims to determine the distribution of hypocenter and b-value to find the characteristics of the Jailolo swarm earthquake on September 27 - October 7, 2017.

2. Data and Method
This study used the arrival time of the P and S waves recorded on Short Periode Seismograph TDS-303 with sensor type DS-4A, that was placed at the Ternate Geophysical Station. This measurement was carried out by BMKG. This device is a single station seismograph that works as a seismic vibration processing system for monitoring earthquakes in local region. The amount of data used in this study was 941 earthquakes that occurred from 27 September to 7 October 2017, with the most earthquakes occurring on 28 September 2017, which were 275 events. The amount of data in the graph below depends on the number of signals that have been successfully analyzed. As previously explained, the earthquake swarms in Jailolo can reach hundreds of earthquakes a day, so the number of earthquakes that occur can be more than is shown in the graph below. This is also because we only select the waveforms of the P and S waves which can be clearly analyzed to determine the earthquake parameters.

![The Magnitude Value of Jailolo Swarm Earthquakes From Sept 27 - Oct 7, 2017](image)

Figure 3 Jailolo earthquakes activity graph that shows variations in magnitude recorded on September 27 to October 7, 2017.

Determination of arrival time of P and S waves was done by picking the amplitude of waveforms using software datapro.exe, which is part of the TDS 5.2 [11]. After the picking process, we obtained the earthquake parameters: origin time, magnitude, hypocenter, and depth. Determination of b-values is based on the relationship between magnitude and earthquake frequency [12-14]. In its development, the determination of these parameters was improved by using the maximum likelihood method [13-18]. This method produces a new parameter called the magnitude of completeness (Mc). Mc is a function of time for all earthquake periods used in the calculation [13-16]. After Mc is determined, the b-value can be determined. Empirically, b-value provides information of seismotectonic implications. This value can be related to regional tectonic, structural heterogeneity in the crust and stress distribution. Thermal gradients also have a relationship that is directly proportional to the b-value. Low b-value indicates an increase of stress which describes a high thermal gradient from thermal rise above the magma chamber.
or geothermal effect that still exists after volcanic activity in the past [13, 17, 18]. Scholz [19] states that the $b$-value decreases with increasing stress level. Farrel et al. [7] states that high $b$-value found in volcanic areas, the presence of dikes, and high thermal gradients. In this research, the determination of $b$-value was done using ZMAP code [20].

3. Results and Discussion

Based on the picking result of P and S wave arrival time, the earthquakes hypocenter are located at 127°10'-127°40' E and 1°10'-1°10' N with the smallest magnitude is 0.7 and the largest magnitude is 5. We use AB and CD cross-sections on the hypocenter to see the earthquake depth distribution, which is illustrated by figure 4.

![Cross section A-B and C-D](image)

**Figure 4** Cross section A-B and C-D to see the earthquake depth distribution. The dots are hypocenter. Varying sizes of the hypocenters represent differences in magnitude (between 0.7-5).

Both results of the cross section show the distribution of earthquakes depth have variation between 7.7-12 km which are included in the shallow earthquake category. Based on the distribution, the earthquakes hypocenter are located around Jailolo volcano. According to [7], earthquake swarms are common in volcanic areas. In this study, there were a fixed depth in the cross-section result, so that the analysis of the causes might be better if the hypocenter is relocated. However, research by Nugraha et al. [2] has conducted the relocation of the hypocenter, but this study did not do so because the data used in this study only consisted of waveforms recorded at one station. A map of the $b$-value distribution is shown in the figure below to study the characteristics.
Figure 5 Graph (a) shows the magnitude of completeness (Mc) while (b) shows the b-value distribution in Halmahera. The black line in figure (b) is the boundary of Halmahera Island, the red triangle shows the Jailolo volcano and the red square shows the region of earthquake concentration.

Based on the result of calculation using maximum likelihood method (figure 5), the value of Mc is 2.4 with a b-value of approximately 1.0 in the area near Jailolo Volcano. In the northwest of Jailolo, the b-value ranges between 1.0-1.5 and in the southeast of Jailolo, between 1.0-2.0. According to Farrel et al. [7], a volcanic area has typically high b-value (between the range of 1.0 to 3.0), this b-value has a depth of 7-10 km where earthquakes are generated due to magma activity, whereas Frolic and Davis [21] state that in a tectonic region, the b-value is around 1.0, and Ruhl et al. [22] state that b-values in volcanic and earthquake swarm regions are often much larger than 1.

Research by Yanuarsih et al. [23] states that the activity of the Jailolo swarm earthquake in November to December 2015 was caused by magmatic activity, this is because field observations show that there are several fractures in areas with high b-values, whereas research by Passarelli et al. [1] states that the 2015-2016 seismic swarm at the Jailolo volcano most likely originated from magmatic activity which is affected by the presence of dike. Nugraha et al. [2] interpret that the September to October 2017 swarm earthquake in Jailolo was probably related to changes in stress due to a combination of tectonic activity and deep magma activity in the area.

Based on the b-value we obtained, the characteristics of the Jailolo swarm earthquake tend to be influenced by magmatic activity, because the b-value tends to be high, which is more than 1.0. However, further research should use the relocated hypocenter data to obtain a more accurate b-value and add further deformation analysis on the crust such as analyzing the possibility of fracture caused by dike intrusion, or analyzing the possibility of magma-filled cracks push to the surface (migration of magmatic fluids).

4. Conclusions
Based on this research, the parameters of the earthquake swarms in Jailolo from September 27 to October 7, 2017, have a magnitude variation ranged from 0.7 to 5.0 with a depth of 7.7-12 km. The b-value results were obtained approximately 1 in the area near Jailolo volcano, 1.0-1.5 in the northwest Jailolo and 1.0-2.0 in the southeast Jailolo. Based on our result, the characteristics of the Jailolo swarm earthquake tend to be influenced by magmatic activity. Further analysis of deformation in the crust is needed, such as analyzing the possibility of fracture caused by dike intrusion, or analyzing the possibility of magma-filled cracks push to the surface.
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