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# Hypocenter dimension of 7.5 mw Palu earthquake using fractal approach

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**Abstract.** Research on the Palu earthquake in the period of August to October 2018 has been carried out in the Palu Koro Fault (PKF) zone with a hypocenter of 5-20 km. This study aims to determine the fractal dimensions of these earthquakes based on the relationship between logarithmic frequency and earthquake magnitude correlation introduced by Gutenberg-Richter. Statistical correlation between logarithmic frequency and earthquake magnitude was calculated using the inversion approach. Based on the calculation results obtained fractal dimension value of 1.0378, which describes the seismicity pattern at a depth of 5-20 km. It indicates that the earthquakes triggered by the movement in rupture segments which seen as points along the PKF zone.

## 1. Introduction

Sulawesi Island is located between three active tectonic plates, which are Pacific, Indo-Australian, and Eurasian. The complex geological form in this area occurs because of the continuous collision activity of the three plates. This form also contributed by the rotation process of the continental plate, island arc, and Sunda-land sea area on the southeast edge of the Eurasian plate. Sulawesi crossed by one of the major fault systems that control the Eurasian Plate in the East, the Central Sulawesi Fault System (CSFS). CSFS, as one of the primary faults in the Sulawesi region, consists of the Palu-Koro Fault (PKF) segment directed to the Northwest-Southeast and Matano Fault (MF) relative to the East-West. Also, there is a North Sulawesi Subduction (NSS) subduction zone.

Some research in this area has been carried out to illustrate the existence of major tectonic activities throughout CSFS, especially along the PKF [1]. However, Sulawesi's seismicity traces, as recorded by global seismic networks, BMKG, and other seismicity histories, show relatively low levels of shallow seismic activity in Central Sulawesi [2]. In the past 5 years the PKF shear fault movement was known to be 40 ± 50 mm / year based on the geodynamic reconstruction model of plate convergence along NSS [3–5].

An earthquake occurred in the northern area of Palu City on September 28, 2018, at 18:03 local time (10:03 UTC) with magnitude 7.5, known as the Palu earthquake, causing significant and severe damages to buildings and infrastructure. The earthquake also left around two thousand people dead and many more injured. The impact of these events is related to ground shaking, liquefaction, landslides, and tsunami.

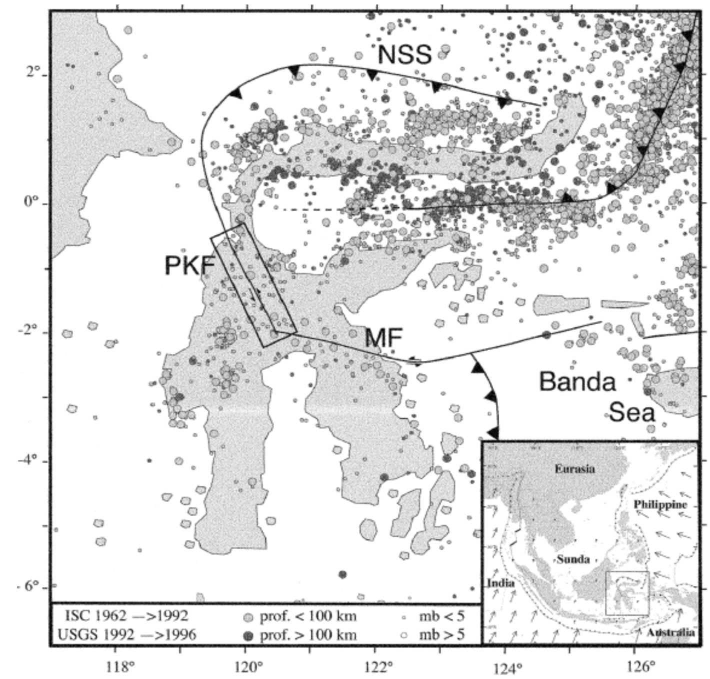


**Figure 1.** Seismicity of the Sulawesi region and the existence of PKF, MF, NSS [6].

The inset image on the lower right shows the geodynamic framework of Southeast Asia and the movement of the Indo-Australian and Philippine plates relative to the Eurasian plate. Palu earthquake occurred as a result of energy release in the strike-slip fault at shallow depth inside the Maluku micro sea plate. Based on the focal mechanism, the Palu earthquake shows that trigger earthquakes occur on the left and right sides of the PKF. In addition, there was a horizontal displacement in the PKF rupture zone after the 2018 Palu earthquake [7]. Sub-pixel correlation method [8–10] was applied to two images obtained at different times and corrected orthogonally so that it was possible to detect homologous points by the correlation method (theoretical sensitivity is1/10 pixel).

The regional seismicity distribution is often considered clustered so that the seismicity pattern is not a Poisson [11]. The strength of an earthquake can be estimated using a magnitude scale. Magnitude generally depends on earthquake frequency so that it can involve fractal techniques to understand the characteristics of the earthquake area. Moreover, the temporal behavior of seismicity affects fractal segmentation. [12–15] develop fractal methodologies for tectonic and seismic activities. Various tectonic processes are directly related to the surface topography on the earth. Earthquakes are also corresponding to each other with fractal statistics, and seismicity is classic examples from complex phenomena that can be measured using the concept of fractals [14,16].

This study aims to determine the fractal dimensions of the hypocenter location from a series of earthquakes that occurred in this region in the period from August to October 2018. The steps in this study include; (i) inventory of earthquakes in the period August to October 2018 based on data obtained from USGS, (ii) selection of earthquake epicenter areas based on the PKF zone (iii) selection of earthquake hypocenter depth (≤20km.) (iv) and calculation fractal dimension of hypocenter dimensions of the earthquake.

## 2. Methodology

### *2.1. Sulawesi earthquake history*

Shifting points throughout the fault area will always be associated with large earthquakes like what happened with the Palu earthquake. Still, crustal deformation is more complex and is usually associated with relatively extensive deformation zones. However, although crustal deformation seems complex, it still adheres to fractal statistics and can be applied to all tectonic deformation zones. From 1923 to 2019, there were 119 earthquakes with magnitudes of ≥6 Mw based on USGS seismicity catalogue data.

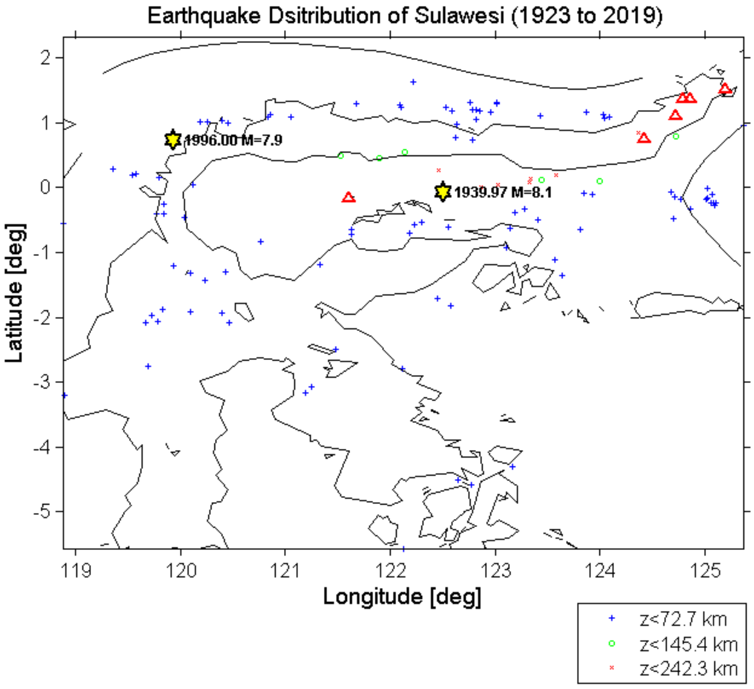


**Figure 2.** History of the Sulawesi seismicity with a magnitude ≥6 Mw (source: USGS) .

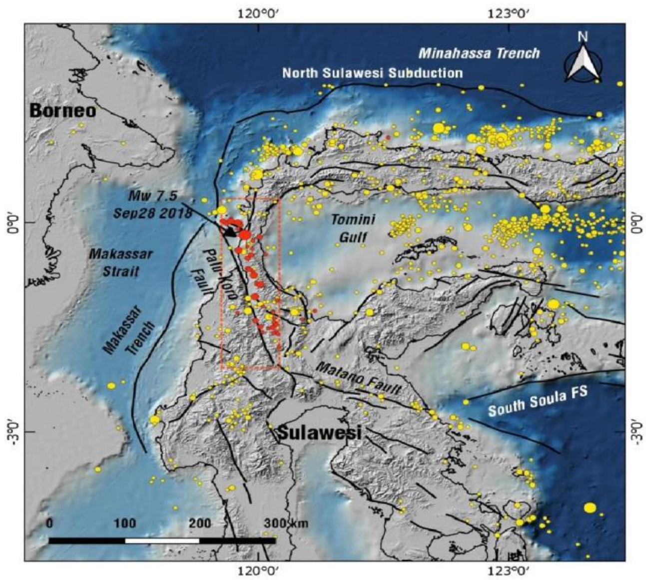


**Figure 3.** Tectonic setting and seismicity of Sulawesi, Indonesia [7].

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The main active structures and faults showed in the red zone area, which is the PKF zone associated with the 7.5 Mw earthquake in September 2018. The yellow circle point is the location of the earthquake source with a strength of >5 Mw in the period 1970-2018 recorded on IRIS, while the red dot is the epicenter of the earthquake trail as a series of 7.5 Mw earthquakes [7].

The history of seismicity in the PKF zone cannot be separated from the fact that PKF is a horizontal fault with a movement of about 35 ± 8mm per year. This situation indicates that the region has a high tectonic activity, which causes the fracture zone [17]. Moreover, The Palu earthquake on September 28, 2018, occurred due to PKF movement in the form of strike-slip faulting at a shallow depth that occurred on the inside of the Molucca microplate as part of the Sunda tectonic plate based on mapping data on the co-seismic displacement.

### *2.2. Mw Palu earthquake in 2018*

The Palu earthquake occurred on 28 September 2018, with a magnitude of 7.5 Mw. Figure (4) shows the epicenter distribution of seismic data period August to October 2018 from the USGS, where a preliminary earthquake preceded by the main earthquake and followed by aftershocks.

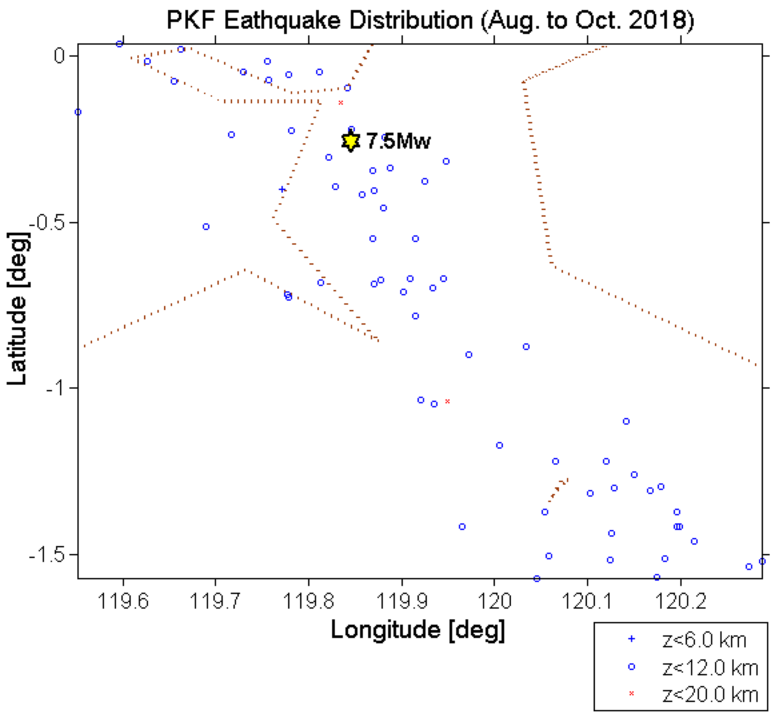


**Figure 4.** Distribution of the Palu earthquake hypocenter from August to October 2018, depth of 5-20 km along the PKF zone (Source: USGS).

The indicate major earthquakes that occurred on September 28, 2018. The depth of the earthquake's hypocenter is 5-20 km, so that it can be considered as a shallow earthquake. The earthquake was still in a horizontal plane of rock along the PKF zone.

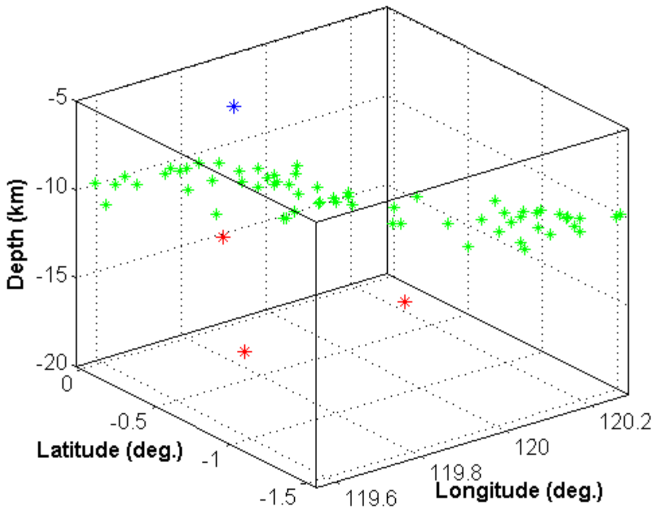


**Figure 5.** Distribution of the Palu earthquake hypocenter from August to October 2018.

### *2.3. Fractal seismology*

Mandelbrot developed and applied the concept of fractals widely in the fields of geology and geophysics based on preexisting fractals theory. The mathematically fractal theory is a series of construction events/opportunities that stated in the following equation [18],

$$N_i = \frac{C}{r_i^D} \quad (1)$$

Where $N_i$ is the number of objects (fragments) with linear dimensions $r_i$, proportionality constanta C, and fractal dimensions D. Fractal dimensions can be integers and in this case equivalent to the Euclidean dimension, where the Euclidean dimension value of a point is zero, the line segment is 1, the segment plane is 2 and cube is 3. In general, fractal dimensions are not integers but fractional dimensions.

Gutenberg and Richter introduce various statistical correlations to show the connection between the frequency of earthquakes with magnitude, but the most commonly accepted is the following log-linear relationship,

$$log\,log\,(N) = -bm + log\,log\,(a) \quad (2)$$

where $b$ and $a$ are constanta and $N$ is the number of earthquake events.

Equation (2) is a Gutenberg-Richter equation, which is the number of earthquake events at a specific time interval that depends on constanta a. Magnitude ($m$) is the empirical value of the earthquake intensity. This can be related to the total energy in the seismic waves produced by the earthquake, $E_s$, by using their relations,

$$log\,log\,(E_s) = 1.44m + 5.24 \quad (3)$$

where $E_s$ in Joule.

The moment of an earthquake can be connected based on magnitude as,

$$log\,log\,(M) = cm + d \quad (4)$$

where *c* dan *d* are constanta.

Kanamori and Anderson have established a theoretical basis for the value of *c=1.5* [19–21] consider that equation (4) can be applied by taking the values of *c* = *1.5* and *d* = *9.1* (*M* in joules). The empirical equation is currently applied using surface waves with periods (50-200 seconds) and is used to get the moment magnitude value. Fractal dimensions was describes based on the distribution of seismicity as [22],

$$D = \frac{3b}{c} \tag{5}$$

And based on theoretical relation *c=1.5* then obtained,

$$D = 2b \tag{6}$$

Thus, the fractal dimension of seismicity activity is twice the *b-value*. The empirical frequency-magnitude relation given in (2) is fully equivalent to the fractal distribution.

## 3. Result and Discussion

This research objective is to identify the Palu earthquake hypocenter fractal dimensions before the main earthquake (foreshock), during the main earthquake (mainshock) and after the main earthquake (aftershock). Based on geological and seismological investigations, fault surfaces display mechanically heterogeneous properties at all scales [23,24]. This type of heterogeneity is related to differences in rock type and geometry in the fault plane so that it impacts on the characteristics of seismic sequences, preliminary earthquakes (foreshock) and particular aftershocks (aftershock) [25]. Heterogeneity factors can explain the fractal distribution and earthquake classification, which are quantified using fractal dimensions [26].

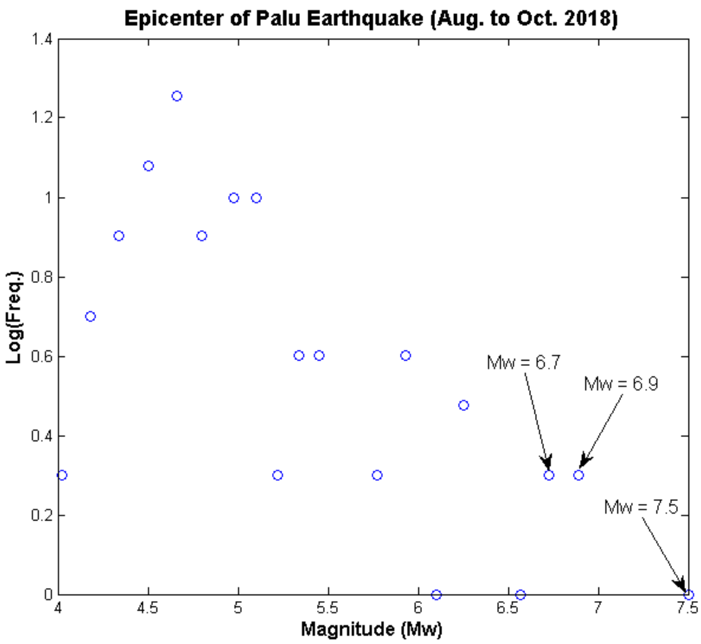


**Figure 6.** Palu earthquake logarithmic frequency from August to October 2018.

The arrows in Fig 6. indicate the main earthquake of Palu with magnitude 7.5 and two aftershocks with magnitude 6.9 and 6.7 that occurred on September 28, 2018.

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**Table 1.** Series of earthquakes that occurred on 28 September 2018 (Source; USGS).

| Month | Da y | Hours | Lat. (deg.) | Long. (deg.) | Depth (km) | Mw | Energy ($10^{15}$ Joule) |
|---|---|---|---|---|---|---|---|
| 9 | 28 | 7:00:00 | -0.4009 | 119.7705 | 5 | 6.1 | 1,929.87 |
| 9 | 28 | 7:03:18 | -0.2102 | 120.0175 | 10 | 6.3 | 4,669.97 |
| 9 | 28 | 7:28:38 | -0.3749 | 119.925 | 10 | 5.5 | 42.283 |
| 9 | 28 | 8:24:58 | -0.3464 | 119.8682 | 10 | 5.8 | 277.603 |
| **9** | **28** | **10:02:45** | **-0.2559** | **119.8462** | **20** | **7.5** | **7,647,642.72** |
| 9 | 28 | 10:14:20 | -0.0175 | 119.7549 | 10 | 6.9 | 201,295.59 |
| 9 | 28 | 10:16:49 | -0.8748 | 120.0342 | 10 | 6.7 | 78,560.50 |
| 9 | 28 | 10:25:05 | -1.0465 | 119.9346 | 10 | 6.9 | 201,295.59 |
| 9 | 28 | 10:26:11 | -1.1072 | 119.4677 | 10 | 6.1 | 1,822.57 |
| 9 | 28 | 10:39:03 | -0.6847 | 119.8697 | 10 | 6.3 | 4,669.97 |
| 9 | 28 | 10:47:44 | -0.5499 | 119.8689 | 10 | 5.9 | 711.302 |
| 9 | 28 | 10:49:04 | -1.5194 | 120.2872 | 10 | 5.5 | 42.283 |
| 9 | 28 | 10:50:25 | -0.7806 | 119.9147 | 10 | 6.6 | 30,660.15 |
| 9 | 28 | 11:06:51 | -1.5037 | 120.0576 | 10 | 5.9 | 711.302 |
| 9 | 28 | 12:27:33 | -0.4574 | 119.8805 | 10 | 5.9 | 711.302 |
| 9 | 28 | 13:10:27 | -0.0491 | 119.8111 | 10 | 5.5 | 42.283 |
| 9 | 28 | 13:35:31 | 0.0587 | 119.6831 | 10 | 6.7 | 78,560.50 |
| 9 | 28 | 13:39:44 | -1.4136 | 119.9655 | 10 | 5.9 | 711.302 |
| 9 | 28 | 14:26:01 | 0.0819 | 119.549 | 10 | 6.3 | 4,669.97 |
| 9 | 28 | 15:28:13 | -0.699 | 119.934 | 10 | 5.5 | 42.283 |
| 9 | 28 | 15:35:42 | -1.3217 | 119.7951 | 10 | 5.6 | 108,341 |

Table 1. shows the number of earthquakes that happened in the PKF zone on September 28, 2018, with a hypocenter range from 5 to 20 km. The main earthquake with magnitude 7.5 occurred and followed by aftershocks. The results of the energy calculation from the main shock are 7.65 x $10^{21}$ joules.

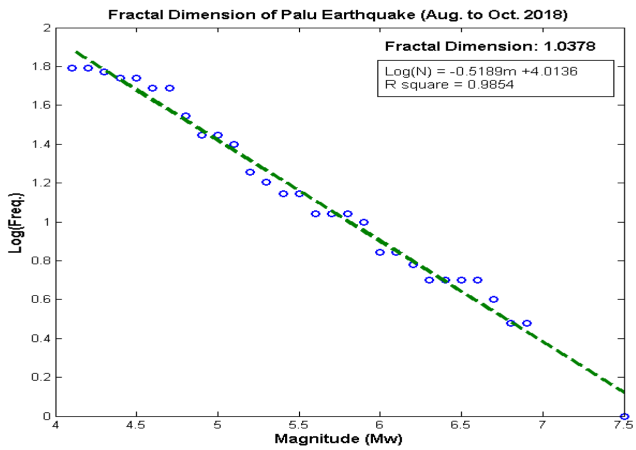


**Figure 7.** Fractal dimension of Palu earthquake from August to October 2018.

Based on the calculation from a series of earthquake events before and after the main earthquake in Palu with a magnitude of 7.5 and a depth of 5-20 km, provide a fractal dimension value of 1.0378. It means that all of earthquake hypocenter occurs by the interconnected single line fracture. This process is only possible if a movement in the fracture zone triggers the earthquake hypocenter. The fracture lines are a series of fracture point that are interconnected and there are still in the 5-20 km depth range.

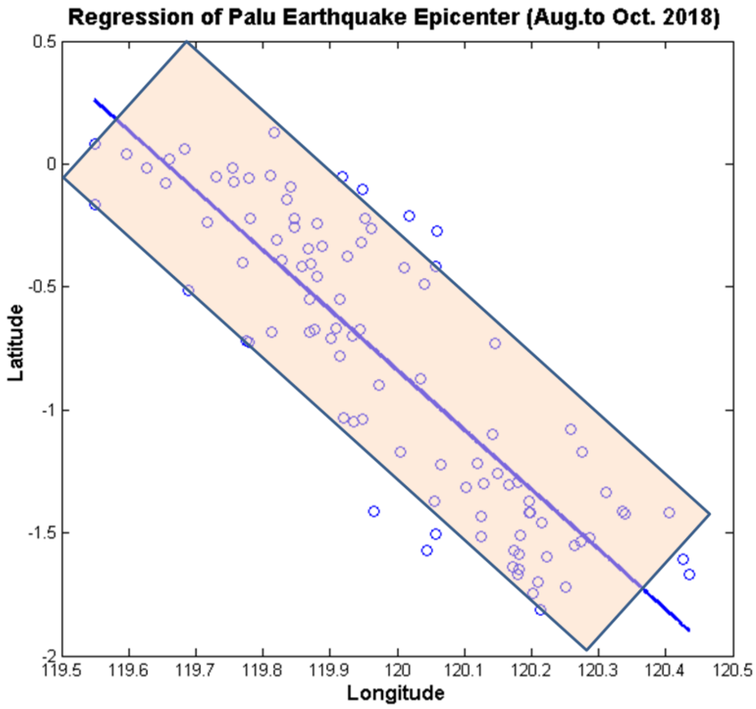


**Figure 8.** Estimated of line fracture of the Palu earthquake in August to October 2018.

There are two segments of the earthquake distribution of each upper and lower segment in the PKF zone. The results of the epicenter linearization of the PKF zone in that period are shown in Figure (8), indicate the pattern of seismicity in the Southeast - Northwest direction that was estimated as rupture line segments along the PKF zone.

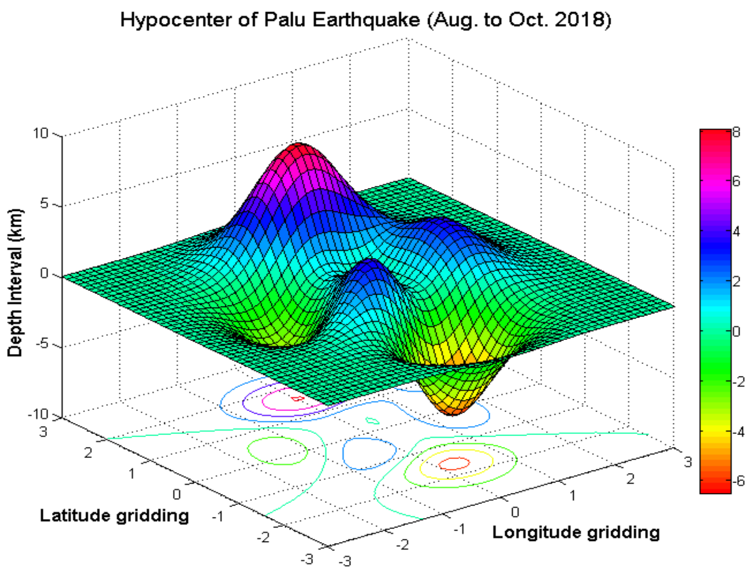


**Figure 9.** Hypocenter configuration of the Palu earthquake from August to October 2018.

From the configuration plotting of the earthquake hypocenter position (Figure 9) also shows the hypocenter distribution pattern estimated as rupture segments that develop with a depth interval from 5-20 km in the PKF zone. This study was strengthened by Socquet et. al., who reported that the damage to the southern city of Palu was very linear and following the geological conditions at the surface and concluded that the Palu earthquake might destroy the segment [27].

The results of this study are also consistent with Sentinel-2 satellite optical imaging studies that describe the rupture level before and after the 2018 Palu earthquake, in the form of (i) detailed traces of PKF rupture areas in the southern region (Palu segment), (ii) more deformation patterns complex in the northern part of the rupture zone (iii) The mechanism of the epicenter shows that rupture occurs in the horizontal plane to the left of the PKF zone [7].

In addition, the results of the calculation of *log(a)* in the curve of Figure (7) are 4.0136, so that the value of *a* is 10.318 x $10^3$ for every three months. This result means that an earthquake with a scale of 7.0 Mw will be release at 2 to 3 times every year in the 5-20 km depth range along the PKF.

## 4. Conclusion

Based on the results of the analysis in this study it can be concluded several things include,

1. The most dominant range of earthquake magnitude in this area is indicated by *a*-value is 4.0136, and the *b*-value results of 0.5189 indicate a high level of stress on PKF and a high chance of occurrence of bigger earthquakes in the future.
2. The fractal dimension of 1.0378, it means that all of earthquake hypocentre occurs by the interconnected single line fracture. This process is only possible if a movement in the fracture zone triggers the earthquake hypocentre.
3. Base on a-value, an earthquake with a scale of 7.0 Mw will be release at 2 to 3 times every year in the 5 to 20 km depth range along the PKF.

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