INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Fractal Dimension Analysis and Earthquake Repeated Period Estimation in the Southern Part of Sumatra Subduction Zone (Bengkulu-Lampung-Sunda Segment)

Syamsurijal Rasimeng[1,2], Masdar Helmi[3], Tugiyono[1], and Suharno[4]

[1]Department of Geophysic Engineering, Faculty of Engineering, University of Lampung, Indonesia
[2]Doctoral Programme of Environmental Sciences, University of Lampung, Indonesia
[3]Department of Civil Engineering, Faculty of Engineering, University of Lampung, Indonesia
[4]Post Graduate Programme of Environmental Sciences, University of Lampung, Indonesia

Corresponding author: syamsurijal.rasimeng@eng.unila.ac.id

Manuscript received: June, 1, 2020; revised: August, 21, 2021;
approved: May, 14, 2022; available online: October, 24, 2022

Abstract - An earthquake seismicity parameter study has been conducted in the southern part of the Sumatra Subduction Zone (SSZ) for the period of 1919 to 2019 with a hypocentre depth of 120 km and magnitude of ≥4Mw. The researched area is divided into three segments, Bengkulu, Lampung, and Sunda segments, respectively. This study aims to evaluate the seismicity parameters in the form of *a*-value, *b*-value, fractal dimension, and probabilities of earthquake recurrence period. Frequency-magnitude correlation statistical approach introduced by Gutenberg-Richter was used to calculate the seismicity parameters based on catalogue data obtained from USGS. An *a*-value variation of 5.11±1.84 to 5.85±2.46 obtained indicates the most dominant seismic intensity. *b*-value of 0.69±0,.17 to 0.83±0.35 correlates with high-stress levels, the level of spatial heterogeneity on the SFZ, and the probabilities of bigger earthquakes in the future. The calculation of fractal dimension of 1.4±0.33 to 1.7±0.71 indicates an earthquake distribution pattern was caused by a single fracture zone along the southern part of SSZ. The fracture zone is located on the left and right sides of the southern part of SSZ, which may not have been connected. In addition, the calculation result of earthquake recurrence period with magnitude ≥6.5Mw indicates that there will be an 5 - 6 earthquake event in the Bengkulu segment, 2 - 3 event in the Lampung segment, and 1 - 2 event in the Sunda segment, while the probabilities of an earthquake with magnitude ≥7.5Mw along the southern part of SSZ is 1 - 2 times.

Keywords: fractal, earthquake, a -value, b-value, SSZ, hypocentre

---

How to cite this article:
Rasimeng, S., Helmi, M., Tugiyono, and Suharno, 2022. Fractal Dimension Analysis and Earthquake Repeated Period Estimation in the Southern Part of Sumatra Subduction Zone (Bengkulu-Lampung-Sunda Segment). *Indonesian Journal on Geoscience*, 9 (3), p.383-394. DOI: 10.17014/ijog.9.3.383-394

Introduction

Background

Various tectonic processes become one of the main factors in the geomorphological patterns on the earth surface, such as fracture and fault. The earthquake, as one of the effects of the tectonic process, becomes a particular concern because of the substantial and great danger posed. Indonesia is one of the countries that has the highest levels of earthquake vulnerability. Therefore, studies on earthquake hazards are very much needed in Indonesia, especially in densely populated areas. This is evidenced by the large number of earthquake damage data in several regions in Indonesia. Most of the destructive earthquakes in Sumatra are dominated by earthquakes with thrust mechanisms that occur due to the subduction process and strike-slip mechanisms, such as the Sumatra Subduction Zone (SSZ) and Sumatra Fault Zone (SFZ) (Triyoso *et al.*, 2021).

Earthquakes as complex phenomena can also be measured using the concept of fractals (Luginbuhl *et al.*, 2018). Based on the plate tectonic theory, crustal deformation occurs at plate boundaries, and becomes the centre of ocean plate widening, subduction zones, and fault transformation. Displacement and transformation of the fault in the subduction zone will produce disruption in the form of shocks as a form of energy release. However, crustal deformation is more complex and is usually associated with relatively more extensive deformation zones.

The 2000 Bengkulu earthquake, the 2004 Aceh earthquake, the 2005 Nias earthquake, the 2007 West Sumatra earthquake, the 2007 Bengkulu earthquake, and the 2019 Lampung earthquake potentially become a series of the precursor activity to a much bigger one in the southern area, between the Lampung Strait and the South Sunda Strait. The earthquakes that occurred in this region have ruined many lives and property. The high seismic activity in the southern part of SSZ is shown in the Figure 1. The distribution of regional seismicity is often considered clustered, so that the seismic pattern is not a Poisson distribution (Natale *et al.*, 1988).

The strength of an earthquake can be estimated using a magnitude scale. Magnitude generally depends on earthquake frequency, so it can involve fractal techniques to understand the characteristics of the earthquake area. Also, the temporal behaviour of seismicity is related to fractal geometrical clustering (Smalley *et al.*, 1987). King (1983) and Turcotte (1986a, 1986b) developed fractal methodologies for tectonic and seismic activities. Various tectonic processes are directly related to the shape of the surface topography on the earth. Seismicity is classic examples of complex phenomena that can be measured using the concept of fractals (Turcotte, 1986a, 1986b; Luginbuhl *et al.*, 2018).

This study aims to determine the fractal dimension of the hypocentre from a series of earthquakes that occurred in the southern part of SSZ from 1919 to 2019. The partition of the segment in the southern part of SSZ is based on the relative direc-

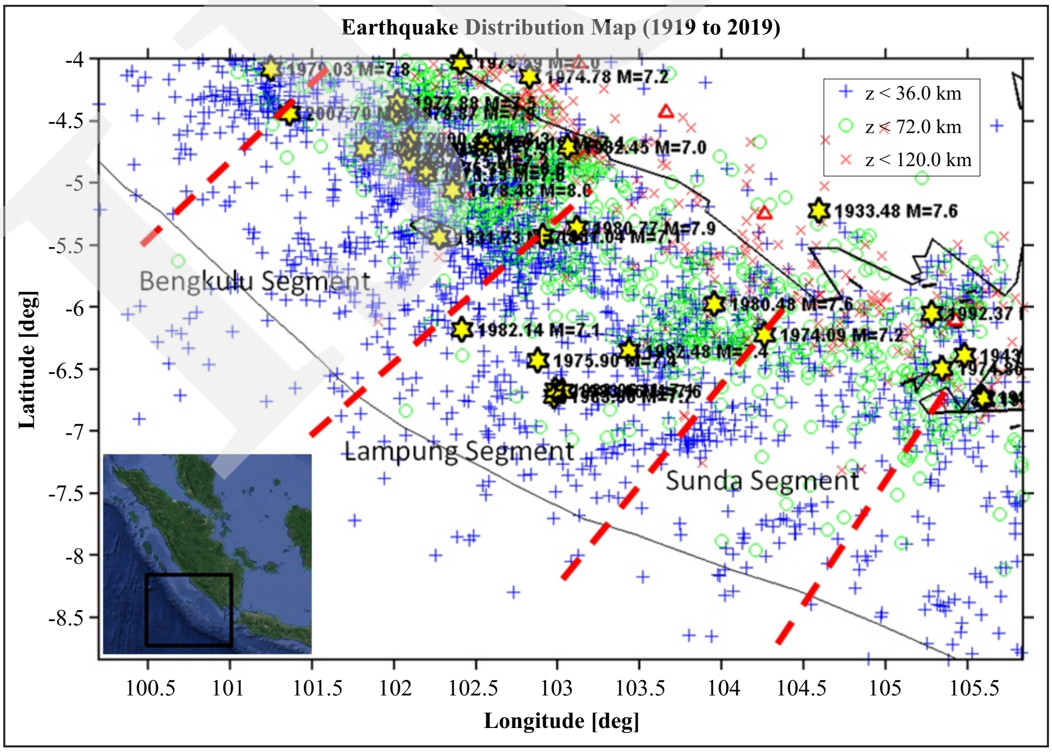

Figure 1. Historical seismicity of the southern part of SSZ (source: USGS).

tion of the subduction zone, where the Bengkulu segment has a relative direction from the north azimuth of 102°; the Lampung segment with a relative direction of 113°; and the Sunda segment that has a relative direction of 123°. The steps in this study include: (i) inventory of earthquakes in the period of 1919 to 2019 based on data obtained from the USGS, (ii) selection of earthquake epicentre areas based on segment zones, (iii) selection of earthquake hypocentre depths (<120 km), (iv) calculation of *a*-value and *b*-value, (v) calculation of fractal dimensions, and (vi) estimation of future earthquake recurrence period.

METHODS AND MATERIALS

Fractal Theory

Mandelbrot (1967) developed and applied the concept of fractals widely in the fields of geology and geophysics based on pre-existing fractals. The mathematical fractal theory is a series of construction events that can be quantized according to the following equation:

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

where:
N_i is the number of objects (fragments) with linear dimensions r_i,
C is constant of proportionality, and
D is the fractal dimension.

The fractal dimension can be an integer (Figure 2), in this case equivalent to the Euclidean dimension, where the Euclidean dimension of a point is zero. The line, plane, and cube segment are valued by 1, 2, and 3 respectively. In general, the fractal dimension is not an integer but a fractional dimension.

The zero-order is a line segment in a length unit (Turcotte, 1986b). (a) and (b) are line segments valued by one unit length (zero-order), (c) and (d) fractal dimension segment line of 1, (e) and (f) show line segments with fractal dimension of 0,6309 and 0.6309 respectively (Turcotte, 1998).

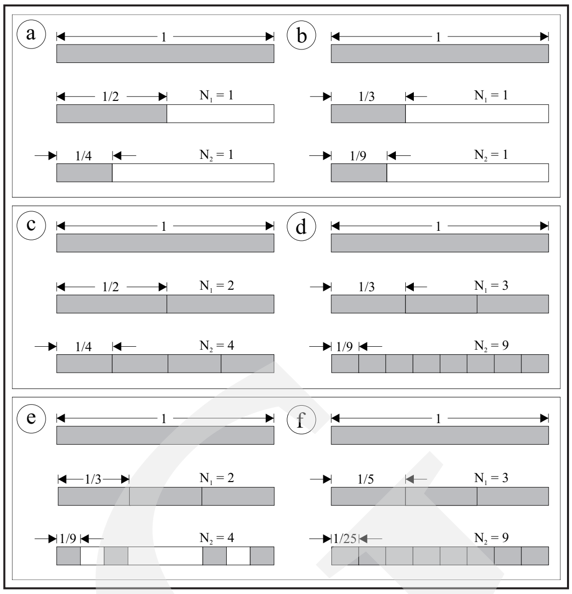

Figure 2. Illustration of six 1D fractal constructions (Turcotte, 1998).

The fractal dimension *D* can be calculated based on the following equation,

$$\mathrm{D} = \frac{\ln\,(N_{i+1}/N_i)}{\ln\,(r_i/r_{i+1})} = \frac{\log(N_{i+1}/N_i)}{\log(r_i/r_{i+1})} \quad \text{.........................} \quad (2)$$

where:
ln is *e* based logarithm, and
log is 10 based logarithm.

The concept of fractal geometry applied to line segments can also be applied to a plane or area segments. Fractal dimensions in the case of plane can be described as Figure 3.

Six initial steps of the construction on fractal geometry concept is shown in Figure 3. (a) only one square is maintained (fractal dimension of 1); (b) fractal dimension of 0,6; (c) the remaining planes will be lines (fractal dimension of 1); (d) only the central square is deleted (fractal dimension of 1,9); (e) shows the value of the Euclidean dimension of an area because when all blocks are maintained it will produce units of area (fractal dimension of 2) (Turcotte, 1998).

The construction can be designed to produce fractal dimensions between 0 and 2. The application of 1D and 2D such as Figures 2 and 3 can be expanded into 3D shapes like the two models in Figure 4.

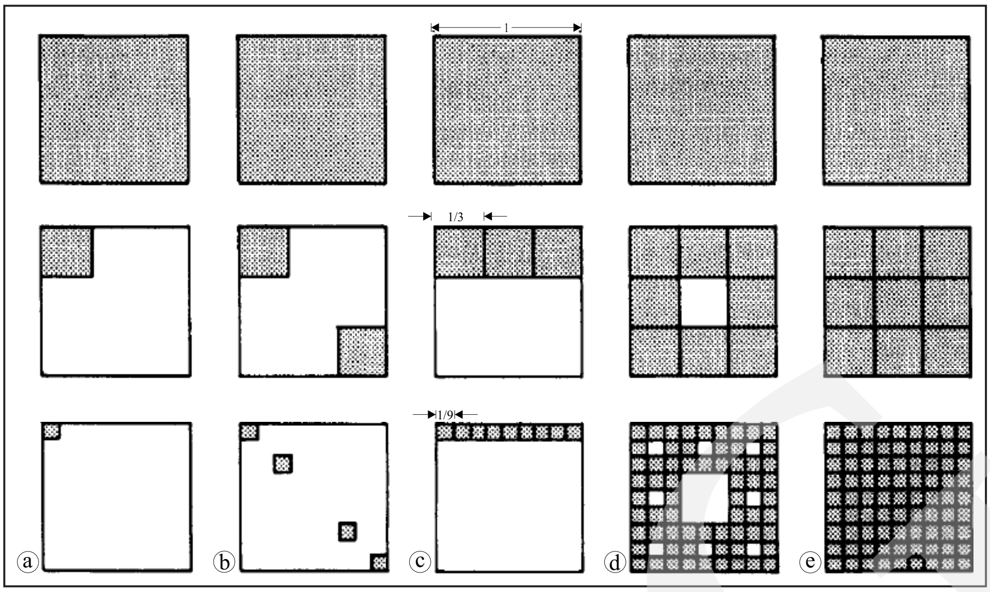

Figure 3. Fractal geometrical concept in a simple plane (Turcotte, 1998).

Figure 4 (a) is a solid cube with a fractal dimension of 2,7, while (b) is a solid cube with a fractal of 2,6 (Turcotte, 1998). Repeated constructions can be designed to produce fractal dimensions between 0 and 3. The models given above illustrate how geometrical construction can provide non-integer and non-Euclidean dimensions, but not in continuous structure. One model of continuous fractal construction is the Koch triangle which is illustrated in Figure 4.

Figure 4 (a) zero-order in equilateral triangle with r_o of *3* and N_o of 3, (b) first order equilateral triangle with side length r_1 of *1/3* placed in the middle of each side. Now there are 12 sides. So, N_1 is 12, (c) construction of the second order by placing an equilateral triangle r_2 of *1/9* in the middle of each side, and N_2 becomes 48. Based on equation (2), a fractal dimension of 1,3 was obtained (Turcotte, 1998).

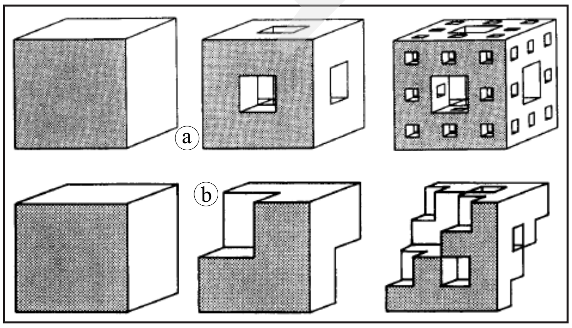

Figure 4. Fractal dimensional concept in 3D (Turcotte 1998).

From the basic concept of the one and two dimensions of fractal dimension, this can proceed to unlimited construction and mathematically written as:

$$P_i = r_i N_i \quad \text{..} \quad (3)$$

The fractal P_i parameter calculation is based on the length of the sides in the *i-th* sequence and *N* as the number of sides. Equation (3) is substituted into Equation (1) and obtained:

$$P_i = \frac{C}{r_i^{D-1}} \quad \text{...} \quad (4)$$

The application of fractal dimension calculation in the Koch triangle case is described as:

$$D = 1 + \frac{\log (P_{i+1} / P_i)}{\log (r_i / r_{i+1})} \quad \text{.................................} \quad (5)$$

Seismicity History of the Southern Sumatra Subduction Zone

The history of the earthquake in these two provinces is not new. On January 29, 1833, a massive 8,9Mw earthquake occurred in Bengkulu. On

June 4, 2000, an 8,3Mw earthquake occurred in the Bengkulu offshore which killed eighty-five people and seriously injured more than six hundred people. In September 2007, another series of earthquakes shook Bengkulu, first occurring on September 12, 2007 with a magnitude of 8,4 and hypocentre depth of 30 km. The first significant aftershock (7,9Mw) occurred on September 13, 2007, with a hypocentre depth of 10 km. The 2007 earthquake killed twenty-six people and caused damage to buildings and infrastructure. From September 12, to October 24, 2007, there were 109 aftershocks, nine of them with ≥6Mw and > 4Mw aftershocks (Zen *et al.*, 2008).

In the western part of Indonesia, the tectonic style manifests itself as a tectonic subduction zone, an oblique subduction underneath Sumatra with a small subduction angle. The Sumatra Fault Zone (SFZ) is a result of the stress distribution in this subduction zone (Figure 1). This subduction zone cuts through the entire length of Sumatra west coast (1,6 km). SSZ is a right-lateral strike-slip fault which is divided into 11-13 segments (Zen *et al.*, 2008). The SSZ segment at the southern end is located on offshore Lampung and intersects the Java Trench in the south of West Java.

This research objective is to determinate the dimension of earthquake in the southern part of the SSZ, which can be divide into Bengkulu segments, Lampung segments, and Sunda segments. The approach used is based on fractal dimension calculations. The steps taken in this study include; (i) earthquake inventory based on seismicity data obtained from USGS (≥4Mw), (ii) earthquake epicentre segmentation (Bengkulu-Lampung-Sunda segment), and (iii) calculation of fractal hypocentre and fractal dimensions.

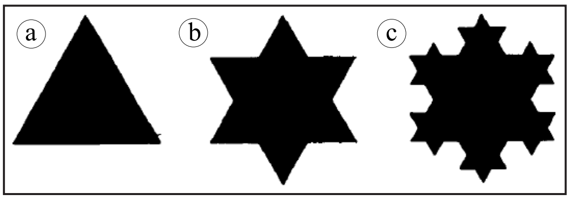

Figure 5. Fractal construction on continuous structure (Turcotte, 1998).

The minimum earthquake magnitude value is 4Mw which is considered the least hazardous earthquake according to Schwartz and Coppersmith (1984) and Kramer (1996).

Results and Analyses

USGS earthquake catalogue data along the Bengkulu-Lampung-Sunda SSZ segment from 1919 to October 2019 were used, with a total of 2010 ≥4Mw earthquake events and maximum hypocentre depth of 120 km. The entire event of each segment consists of: (i) Bengkulu segment with 1174 earthquake events, (ii) 629 events in Lampung segment, and (iii) Sunda segment with 207 events. Figure 6 shows the earthquake frequency in each segment based on the magnitude value.

The seismicity history of the studied area is shown in Figure 7, indicating the number of earthquake events per year, where earthquake events reached more than 400 in 2000 (see Figure 7a). Figure 7b shows more than 700 events with hypocentre depth at 30 km. While from distribution, more than 200 seismicity events during this period is an earthquake with a magnitude of around 5Mw (see Figure 7c).

By applying the Gutenberg and Richter approach (Gutenberg and Richter, 1945) in the form of a statistical correlation, this correlates the frequency of earthquakes with the following magnitude:

$$\mathrm{Log}\,(N) = -bm + \log(\alpha) \qquad (6)$$

where:
b and a are constants, and
N is the number of earthquake events, resulting in the relationship of b-values and constants a.

Magnitude (m) is an empirical value of an earthquake size. It can be related to the total energy in the seismic waves produced by the earthquake. A curve, as shown in Figure 8, was obtained based on the results of the subduction segment statistical correlation in this studied area.

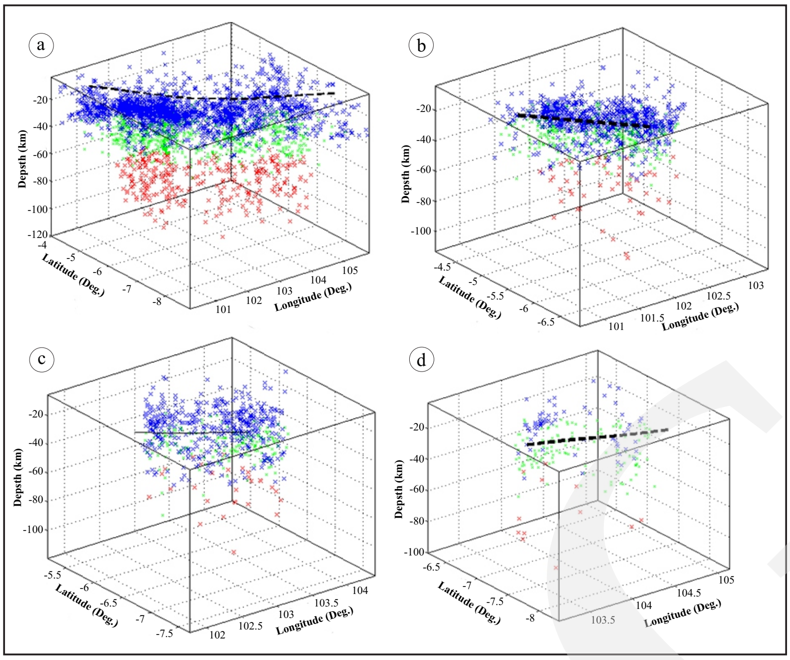

Figure 6. Distribution of earthquake hypocentre; (a) southern part of SSZ segment, (b) Bengkulu segment, (c) Lampung segment, and (d) Sunda segment.

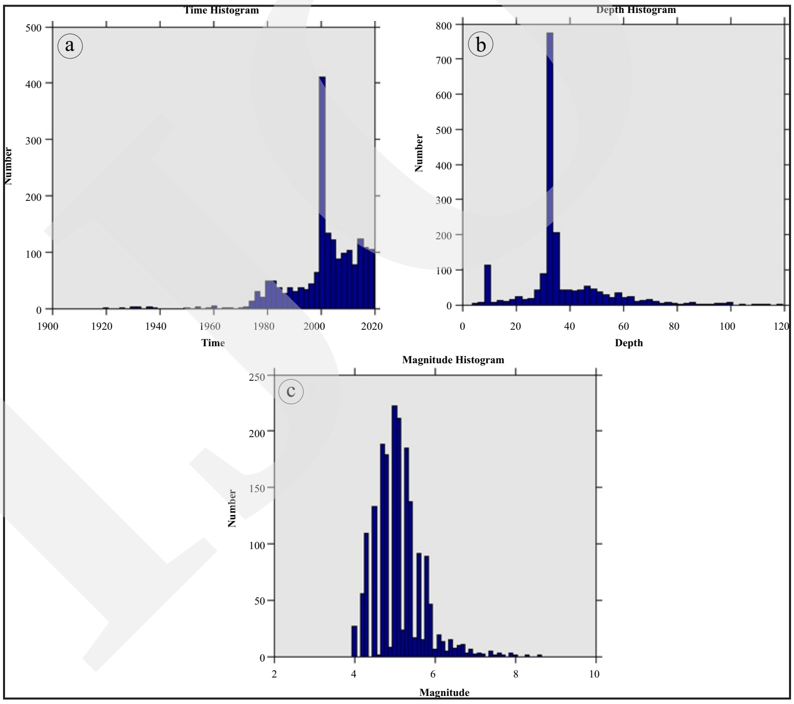

Figure 7. Historical seismicity of the southern part of SSZ from 1919 to 2019 with the magnitude of ≥4; (a) Bengkulu segment, (b) Lampung segment, and (c) Sunda segment.

In theory, *a* logarithmic is defined as seismicity values of earthquakes that most often occur in an area (Figure 9): the higher the value, the more frequent earthquakes with a magnitude of *a*. The *a*-value of 5,81±1,51 was obtained based on the calculation in the southern part of SSZ indicating the distributions of earthquakes with a magnitude of 5,81±1,51. Variations in *a*-value

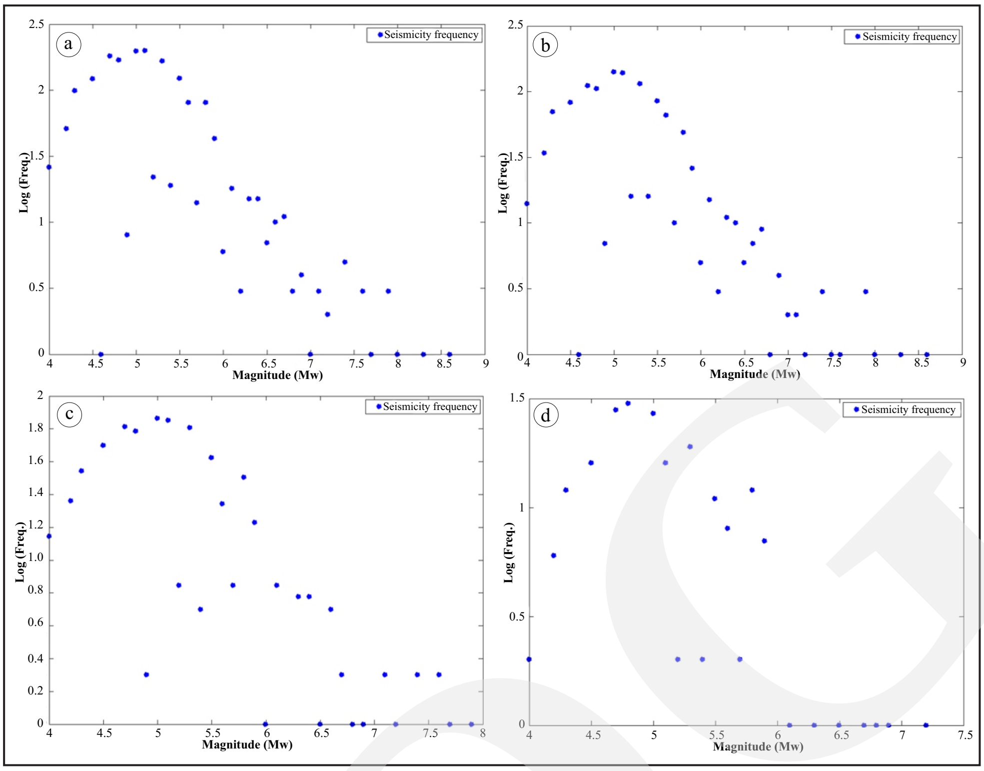

Figure 8. Frequency of magnitude even at; (a) southern part of SSZ, (b) Bengkulu segment, (c) Lampung segment, and (d) Sunda segment.

of around 5,11±1,84 to 5,85±2,46 are obtained if the zones are divided into different segments. The highest *a*-value occurred in the Lampung segment of 5,85±2,46.

A comprehensive study of the spatial mapping of the frequency distribution was also carried out for all zones. Variations for the *b*-value were obtained at intervals of 0,69±0,17 to 0,83±0,35 using weighted inversion calculations. Experts concluded that *b*-value varied systematically and were estimated to be around 1 (Schorlemmer *et al.*, 2004). In addition, several other experts pointed out that *b*-value varied significantly in some fault zones (Wesnousky and Scholz, 1983). Many experts stated that *b*-value depended on the tectonic character and stress level or material structure of a region. Variations of the *b*-value in a region are related to the heterogeneity of the structure and the stress distribution of that region (Scholz, 1968; Hatzidimitriou *et al.,* 1985; Tsapanos, 1990).

From that relationship, regions with significant heterogeneity correlate with high *b*-value. A high-stress correlation with a relatively low *b*-value indicates that there will be giant earthquakes in the segment with a low *b*-value the following year (Singh, 2016). So, the three segments in this study indicate that the Sunda segment is likely to produce an enormous earthquake in the future. In addition, the results of this study are consistent with Montuori *et al*. (2010), also having observed a low *b*-value anomaly in the northwest of the Wadati-Benioff Zone at a depth of more than 40 km. This observation is in accordance with the conceptual model that has been found previously, that the distribution of fluids in the shallow part of the subduction zone depends on the permeability of the geological terrance of the overlying plate.

Ketthong and Pailoplee (2012) investigated The Sumatra-Andaman Subduction Zone (SASZ) temporal seismicity with *b*-value focusing on seismicity data before and after the declustering process. It obtained a *b*-value of 0,56-0,79 before the 8Mw earthquake at six locations. In fact, Batte and Rümpker (2019) clearly suggests a low *b*-value observation [0.65 ± 0.03 to 0.88 ± 0.05],

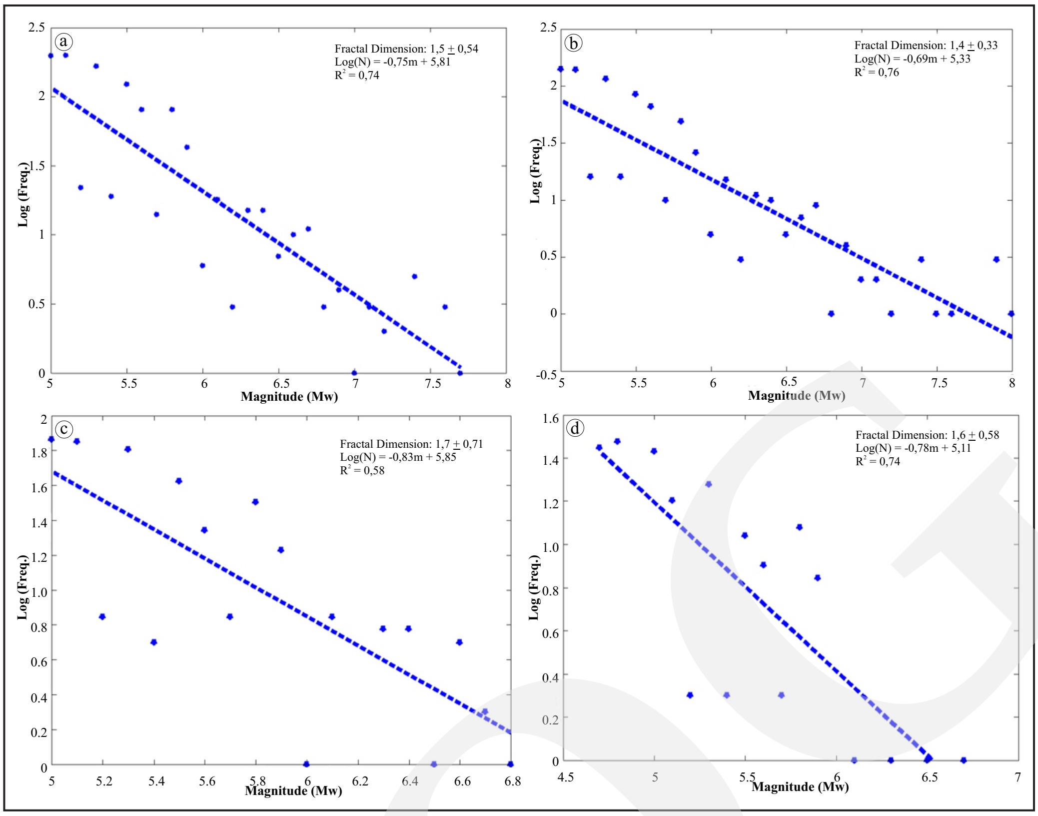

Figure 9. Fractal dimension in each earthquake; (a) southern part of SSZ, (b) Bengkulu segment, (c) Lampung segment, and (d) Sunda segment.

which is associated with the presence of a higher friction region along the fault plane, where it becomes locked. He interpreted these low values as a sign indicating increased stress levels associated with the homogeneity of the material in the crust. The results of other researcher observations related to *b*-value in some earthquake events are:

a. $b \leq 1{,}6$ global seismicity,
   $b \sim 1{,}0$ for latitude $\geq 40^o$,
   $b \sim 1{,}6$ whereas latitude $\leq 40^o$ (Mogi, 1967),
b. $0{,}8 \leq b \leq 1{,}2$ global seismicity (McNally, 1989),
c. $0{,}6 \leq b \leq 1{,}6$ Central America seismicity (Monterroso and Kulhánek, 2003),
d. $0{,}6 \leq b \leq 2{,}6$ mining tremors, Zinkgruvan, Sweden (Nuannin *et al*., 2002).

The calculation of the b-value by nonparametric method which was developed based on the data-based concept, revealed that the b-value was low in the pre-mainshock near the mainshock source region, and this was relatively in accordance with the mainshock rupture area (Jiang *et al*., 2021). The decrease in *b*-value during aftershocks implies that *b*-value could be an indicator of a state of stress. Thus, it can be seen that there is a close relationship between the b-value and the dimensions of the hypocentre distribution. Therefore, the characteristics of the b-value distribution indicate that the best way to study the heterogeneous pattern of *b*-values is by not separating the space and time dimensions. Nuannin *et al.* (2005) obtained a *b*-value variation of 0,71-1,21 based on 624 earthquakes in the Andaman-Nicobar Islands region over a five-year period prior to the giant shock on December 26, 2004. The temporal variation indicates a significant decrease in *b*-value that coincided with the occurrence of two major shocks (Ms≥7,0) towards the end of 2002 and 9,0Mw before the devastating earthquake off the coast of Sumatra NW on December 26, 2004. In addition, to calculate the dimension of the hypocentre Kanamori and Anderson (1975) introduced the theoretical basis for the *c* of 1,5. So, Kanamori and Stewart (1978), Hanks and Kanamori (1979) apply these values to calculate earthquake moments based on magnitude values as:

$$\log (M) = cm + d \qquad (7)$$

where:
d of 9,1 is a constant.

In certain regions, the number of *N* earthquakes in a time from fracture zone generally has a large distribution, so the fractal dimension *D* of seismicity is distributed as (Mandelbrot, 1983):

$$D = 1 \; \frac{3b}{c} \qquad (8)$$

Based on theoretical relation *c=1.5*,

$$D = 2b \qquad (9)$$

The fractal dimension of whole seismic activity is only twice the *b*-value. The empirical frequency-magnitude relation given in Equation (6) correlates with the fractal distribution (Aki, 1981). The results of calculating the hypocentre fractal dimensions in the three segments in this studied area have values between 1,4±0,33 and 1,7±0,71. Fractal dimension analysis shows that the pattern of seismicity is caused by a single fracture zone along the southern part of SSZ. In the fractal dimension, the fracture zones are located on the left and right of SSZ, which may not have been connected. The lowest fractal dimension is in the Bengkulu segment (1,4±0,33), so it has the potential to produce high seismic intensity in the future. This is based on the comparison of Lampung and Sunda fractal dimensions segment of 1.7±0,71 and 1.6±0,58 respectively. Comparing the results obtained by other researchers, for example Ketthong and Pailoplee (2012) who calculated the dimensions of the SASZ fractal almost reached 2.0, this means that the pattern of spreading earthquake events in the SASZ region spreads in areas or fields that are interconnected. The *b*-value may be greater, because the study is in a very broad regional review.

In addition, the results of the calculation of the earthquake recurrence period using equation (6) with a magnitude ≥6,5mW indicate that an earthquake will occur 5-6 times in the Bengkulu segment, 2-3 times in the Lampung segment, and 1-2 times in the Sunda segment, while the chance of an earthquake with magnitude ≥7,5Mw along the southern part of SSZ is 1-2 times. This calculation is in accordance with what was done by Pailoplee (2017) which obtained the magnitude of the earthquake magnitude in the SSZ region capable of reaching 7.0Mw within the next 30-50 years using a logarithmic of correlation function approach.

Frequency-magnitude correlation statistics for the 1904 to 1980 earthquakes have been carried out by Abe (1981) and Purcaru and Berckhemer (1982) for the period of 1920-1979. The results provided by (Abe, 1981) support the systematic reduction of large earthquake correlation curves, while the results provided by Purcaru and Berckhemer (1982) support direct extrapolation of correlation curves with more massive earthquakes. Pacheco *et al.* (1992) have considered the extrapolation problem in detail and supported the systematic reduction of large earthquakes.

DISCUSSION AND CONCLUSIONS

Based on the results of the analysis, it can be concluded that the most dominant range of earthquake magnitude in this area is indicated by *a*-value variation of 5,11±1,84 to 5,85±2,46. Meanwhile, the *b*-value results of 0,69±0,17 to 0,83±0,35 indicate a high level of stress on the southern part of SSZ and a high chance of occurrence of bigger earthquakes in the future. The fractal dimension of 1,4±0,33 to 1,7±0,71 indicating the seismicity distribution pattern is caused by a single fracture zone along the southern part of SSZ, with fracture patterns located on the left and right on the southern part of SSZ that may not have been connected. Lastly, the calculation result of earthquake recurrence period with magnitude ≥6,5Mw indicates that there will be an earthquake 5-6 occurrences in the Bengkulu segment, 2-3 in the Lampung segment, and 1-2 in the Sunda segment, while the chance of an earthquake with magnitude ≥7,5Mw along the southern part of SSZ are 1-2 occurrences.

Acknowledgment

The authors express their gratitude to the Director General of Higher Education, Ministry of National Education, Indonesia, for the *Penelitian Hibah Pascasarjana* decentralization grant of the University of Lampung in 2019, under the Research and Community Service Institute (LP2M). Special appreciation is also delivered to the Department of Geophysical Engineering, Faculty of Engineering, the University of Lampung for providing the 130-SMHR Strong Motion High-Resolution Recorder provides accurate data and related information about seismic events. The authors also thank the USGS for the open-source earthquake data event so that this research can be carried out. Last but not least, their gratitude to reviewers who have provided corrections to improve this paper

References

Abe, K., 1981. Magnitudes of Large Shallow Earthquakes from 1904 to 1980. *Physics of the Earth and Planetary Interiors,* 27 (1), p.72-92. DOI: 10.1016/0031-9201(81)90088-1.

Aki, K., 1981. A Probabilistic Synthesis of Precursory Phenomena. *Maurice Ewing Series* 4, p.566-574.

Batte, A.G. and Rümpker, G., 2019. Spatial Mapping of B-Value Heterogeneity beneath the Rwenzori Region, Albertine Rift: Evidence of Magmatic Intrusions. *Journal of Volcanology and Geothermal Research* 381, p.238-345. DOI: 10.1016/j.jvolgeores.2019.05.015.

Gutenberg, B. and Richter, C.F., 1944. Frequency of Earthquakes in California. *Bulletin of the Seismological Society of America* 34 (4). DOI: 10.1785/BSSA0340040185.

Hanks, T.C. and Kanamori, H., 1979. A Moment Magnitude Scale. *Journal of Geophysical Research,* 84 (B5), p.2348-2350. DOI: 10.1029/JB084iB05p02348.

Hatzidimitriou, P.M., Papadimitriou, E.E., Mountrakis, D.M., and Papazachos, B.C., 1985. The Seismic Parameter of the Frequency-Magnitude Relation and Its Association with the Geological Zones in the Area of Greece. *Tectonophysics,* 120 (12), p.141-151. DOI: 10.1016/0040-1951(85)90092-7.

Jiang, C., Han, L., Long, F., Lai, G., Yin, F., Bi, J., and Si. Z., 2021. Spatiotemporal Heterogeneity of b Values Revealed by a Data-Driven Approach for the 17 June 2019 Ms6.0 Changning Earthquake Sequence, Sichuan, China. *Natural Hazards and Earth System Sciences,* 21 (7), p.2233-2244. DOI: 10.5194/nhess-21-2233-2021.

Kanamori, H. and Anderson, D.L., 1975. Theoretical Bases of Some Empirical Relations in Seismology. *Bulletin of the Seismological Society of America,* 65 (5), p.1073-1095.

Kanamori, H. and Stewart, G.S., 1978. Seismological Aspects of the Guatemala Earthquake of February 4, 1976. *Journal of Geophysical Research: Solid Earth,* 83 (B7), p.3427-3434. DOI: 10.1029/jb083ib07p03427.

Ketthong, T. and Pailoplee, S., 2012. Frequency-Magnitude Distribution and Fractal Dimension of the Seismicity along the Sumatra-Andaman Subduction Zone: A Temporal Comparison Bulletin of Earth Sciences of Thailand. *Bulletin of Earth Sciences of Thailand,* 8 (1), p.12-23. DOI: 10.1186/s40623-015-0269-0

King, G., 1983. The Accommodation of Large Strains in the Upper Lithosphere of the Earth and Other Solids by Self-Similar Fault Systems: The Geometrical Origin of b-Value. *Pure and Applied Geophysics,* 121 (5/6), p.761-815. DOI: 10.1007/BF02590182.

Kramer, S.L., 1996. *Geotechnical Earthquake Engineering*. New Jersey: Prentice Hall, Inc.,pp.

Luginbuhl, M., Rundle, J.B., and Turcotte, D.L., 2018. Statistical Physics Models for Aftershocks and Induced Seismicity. *Philosophical Transactions of the Royal Society,* A377 (20170397). DOI: 10.1098/rsta.2017.0397.

Mandelbrot, B.B., 1967. How Long Is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension. *Science,* 156 (3775), p.636-638. DOI: 10.1126/science.156.3775.636.

Mandelbrot, B.B., 1983. *The Fractal Geometry of Nature*. New York: W.H. Freeman and Company.

McNally, K.C., 1989. Earthquakes and Seismicity. *In*: James, D.E., (ed.), *The Encyclopedia of Solid Earth Geophysics*, p.308-315.

Mogi, K., 1967. Earthquakes and Fractures. *Tectonophysics* 5 (1), p.35-55. DOI: 10.1016/0040-1951(67)90043-1.

Monterroso, D.A. and Kulhánek, O., 2003. Spatial Variations of B-Values in the Subduction Zone of Central America. *Geofisica Internacional,* 42 (4), p.575-587. DOI: 10.22201/igeof.00167169p.2003.42.4.312.

Montuori, C., Falcone, G., Murru, M., Thurber, C., Reyners, M., and Eberhart-Phillips, D., 2010. Crustal Heterogeneity Highlighted by Spatial B-Value Map in the Wellington Region of New Zealand. *Geophysical Journal International,* 183 (1), p.451-460. DOI: 10.1111/j.1365-246X.2010.04750.x.

Natale, G.D., Musmeci, F., and Zollo, A., 1988. A Linear Intensity Model to Investigate the Causal Relation Between Calabrian and North-Aegean Earthquake Sequences. *Geophysical Journal,* 95 (2), p.285-293. DOI: 10.1111/j.1365-246X.1988.tb00467.x.

Nuannin, P., Kulhanek, O., and Persson. L., 2005. Spatial and Temporal b Value Anomalies, *Proceedings of the Devastating of Coast of NW Sumatra Earthquake of December 26, 2004. Geophysical Research Letters,* 32 (11), p.1-4. DOI: 10.1029/2005GL022679.

Nuannin, P., Kulhanek, O., Persson, L., and Tillman, K., 2002. Forecasting of Increased Seismicity in the Zingruvan Mine, Sweden, by Using Temporal Variations of b-Values. *Acta Montana,* 21 (125), p.13-5.

Pacheco, J., Scholz, C.H., and Sykes, L.R., 1992. Changes in Frequency Size Distribution from Small to Large Earthquakes. *Nature,* 355, p.71-73. DOI: 10.1038/355071a0

Pailoplee, S., 2017. Probabilities of Earthquake Occurrences along the Sumatra-Andaman Subduction Zone. *De Gruyter,* 9 (1), p.53‑60. DOI: 10.1515/geo-2017-0004.

Purcaru, G. and Berckhemer, H., 1982. Quantitative Relations of Seismic Source Parameters and a Classification of Earthquakes. *Tectonophysics,* 84 (1), p.57-128. DOI: 10.1016/0040-1951(82)90154-8.

Scholz, C.H., 1968. The Frequency-Magnitude Relation of Microfracturing in Rock and Its Relation to Earthquakes. *Bulletin of the Seismological Society of America,* 58 (1), p.399-415. DOI: 10.1785/bssa0580010399.

Schorlemmer, D., Wiemer, S., and Wyss, M., 2004. Earthquake Statistics at Parkfield: Stationarity of b Values. *Journal of Geophysical Research,* 109 (12), p.1-17. DOI: 10.1029/2004JB003234.

Schwartz, D.P. and Coppersmith, K.J., 1984. Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Fault Zones (USA). *Journal of Geophysical Research,* 89 (B7), p.5681-5698. DOI: 10.1029/JB089iB07p05681.

Singh, C., 2016. Spatial Variation of Seismic B-Values across the NW Himalaya. *Geomatics, Natural Hazards and Risk,* 7 (2), p.522-530. DOI: 10.1080/19475705.2014.941951.

Smalley, R.F., Chatelain, J.L., Turcotte, D.L., and Prevot, R., 1987. A Fractal Approach to the Clustering of Earthquakes: Application to the Seismicity of the New-Hebrides. *Bulletin of the Seismological Society of America,* 77 (4), p.1368-1381.

Triyoso, W., Suwondo, A., and Naibaho, Z.Y.X., 2021. Earthquake Potential Hazard Analysis of Palembang City. *Indonesian Journal on Geoscience,* 18 (1), p.1-9. DOI: 10.17014/ijog.8.1.1-9.

Tsapanos, T.M., 1990. B-Values of Two Tectonic Parts in the Circum-Pacific Belt. *Pure and Applied Geophysics PAGEOPH,* 134 (2), p.229-242. DOI: 10.1007/BF00876999.

Turcotte, D.L., 1986a. A Fractal Model for Crustal Deformation. *Tectonophysics,* 132 (13), p.261-269. DOI: 10.1016/0040-1951(86)90036-3.

Turcotte, D.L., 1986b. Fractals and Fragmentation. *Journal of Geophysical Research,* 91 (B2), p.1921-1926.

Turcotte, D.L., 1998. *Fractals and Chaos in Geology and Geophysics, Second Edition*. Cambridge University Press, 414pp.

Wesnousky, S.G. and Scholz, C.H., 1983. Earthquake Frequency Distribution and Mechanics of Faulting. *Geophysical Prospecting,* 88 (B11), p.9331-9340. DOI; 10.1029/jb088ib11p09331

Zen, M.T., Wira, F., and Andriansya, 2008. The Enigmatic Bengkulu Earthquake of 2007. *International Conference on Earthguake Engineering and Disaster Mitigation*. Jakarta.