# SEISMIC RATE CHANGES ANALYSIS BASED ON THE SPASIAL DISTRIBUTION SEISMOTECTONICS IN THE SOUTHERN SUMATRA REGION

**Nora Florentina Simalango, Syafriani*, Letmi Dwiridal, Zulhendra**

*Department of Physics, Faculty of Mathematics and Natural Science, Universitas Negeri Padang, Jl. Prof. Dr.Hamka Air Tawar, Padang, 25131, Indonesia*

*email: Syafriani@fmipa.unp.ac.id

***ABSTRACT***

The southern Sumatra region experiences high seismic activity, often resulting in large earthquakes that cause significant losses. Before such earthquakes, a phenomenon known as seismic quiescence a decrease in seismic activity commonly occurs. This phenomenon can be analyzed through changes in seismic rates using the spatial distribution of Z-values. This study investigates the occurrence of seismic quiescence before major earthquakes and examines changes in seismic rates in southern Sumatra. Used secondary earthquake data from the United States Geological Survey (USGS) for 1973–2023 were analyzed, focusing on the region between 2.050°S–5.885°S and 101.030°E–106.611°E. The study centered on three significant earthquakes: the 2000 (7.9 Mw), 2001 (7.4 Mw), and 2007 (8.4 Mw) events. Seismic rate changes were analyzed using the Z-value method, dividing the region into grids to calculate and spatially distribute Z-values. Results showed seismic quiescence before the 2000 (±16 years), 2001 (±13 years), and 2007 (±17 years) earthquakes in Bengkulu. Additionally, similar phenomena were observed in Bengkulu and Lampung before 2023, suggesting the potential for future significant earthquakes in the region. These findings highlight seismic quiescence as a precursor to major seismic events.

**Keywords:** *Earthquake; Seismic Quiescence; Seismic Rate Changes; Z-value*

## INTRODUCTION

Indonesia is a country that is often hit by natural disasters, including earthquakes. Geographically, Indonesia is located at the meeting point of three large tectonic plates (triple junction plate): the Indo-Australian Plate in the south, the Pacific Plate in the east, and the Eurasian Plate in the north. The interaction between these three large plates creates a subduction zone, which causes high seismic activity and places Indonesia in a very active tectonic zone (Suwandi, 2022).

One of the areas in Indonesia that is prone to earthquake events is the Sumatra Island region, especially southern Sumatra. The western part of Sumatra Island is known as the Mediterranean earthquake track and on land Sumatra Island raises the Great Sumatra Fault which stretches along Bukit Barisan and stretches from Aceh, North Sumatra, West Sumatra to Lampung Bay, so that the southern Sumatra region has a high level of seismicity threatened by earthquake natural disasters (Sari et al., 2020).

Southern Sumatra region includes Bengkulu, Lampung, Bangka Belitung and South Sumatra. Southern Sumatra can be morphologically divided into three parts, namely lowland units in the East and Northeast, mountainous units in the Central and Southwest, undulating hilly units in the Central and slightly in the South. In the southern part of Sumatra, there have been many significant earthquakes that have caused damage, loss of life and casualties. One of them is the Bengkulu earthquake that occurred on 4 June 2000 with a magnitude of 7.3 and on 12 September 2007 with a magnitude of 7.9. These major earthquakes have claimed many lives, property and destroyed public facilities (Hadi et al., 2010). In addition to Bengkulu, major earthquakes also occurred around western Lampung such as the 1933 and 1994 earthquakes had a magnitude of about 6 on the Richter Scale and in Panjang Bandar Lampung 1913 had a magnitude of about 7 on the Richter Scale, with a depth of 20-40 km (Suharno, 2012).

Earthquakes are seismic vibrations that occur due to the rupture or shifting of rocks in an area of the earth's crust. These vibrations propagate through the ground in the form of seismic waves, so that people on the surface of the earth can feel them, and this phenomenon is known as an earthquake (Pristanto, 2010). Based on the "Elastic Rebound Theory", earthquakes occur in areas that are deformed, where the deformation is caused by stress and strain in the earth's layers (Linda et al., 2019).

Earthquake precursors are initial symptoms or signs that appear before a major earthquake, used to predict earthquakes. Earthquake precursors occur before the main earthquake and can be classified into two phenomena: seismic and non-seismic phenomena. Seismic phenomena include seismic silence (seismic gap), reduction (seismic quiescence), and increased seismic activity, as well as changes in seismic wave velocity (Nurdiyanto et al., 2010).

The earthquake precursor parameter to be observed in this study is the phenomenon of reduced seismic activity, commonly refered to as seismic quiescence. Seismic quiescence describes a significant decrease in earthquake activity, where this phenomenon is usually studied to predict earthquakes and see the seismic activity that precedes the occurrence of significant and damaging earthquakes (Syaputri, 2022). Seismic quiescence precursor is one of the precursors that can be observed from seismic rate changes using the standard deviation Z.

The phenomenon of decreased seismic activity (seismic quiescence) can be investigated by examining variations in seismic rate changes. This analysis can be conducted using the spatial distribution of seismotectonic features, notably employing the z-value method (Simamora & Namigo, 2016). Seismotectonics is a subfield of seismology focused on earthquakes, plate tectonics, and fault presence within a region. It involves three key parameters: a-value, b-value, and z-value. The b-value is a statistical metric that characterizes the local stress conditions within rock formations. The a-value represents the level of seismicity in a given area, while the z-value is used to investigate the phenomenon of seismic quiescence (Yulianda et al., 2017).

Z-value is one of the statistical parameters used to analyze changes in seismic rates. Where a positive Z-value indicates a decrease in seismic rates and a negative Z-value indicates an increase or rise in seismic rates. A decrease in the average seismicity level several years before a strong earthquake is suspected to be a precursor to an earthquake (Katsumata, 2011).

The seismicity phenomenon can be seen by using the Long-term Average (LTA) function which is very suitable for z-value measurement. This LTA function aims to make the anomalies obtained statistically unbiased (Wiemer, 2001). The curve of LTA can be seen in Figure 1.

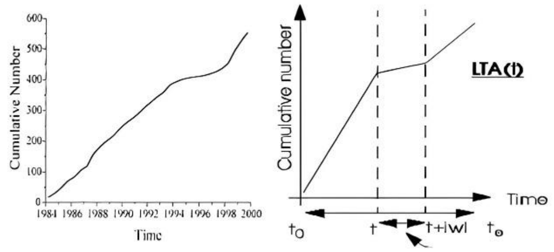



**Figure. 1**. Curve Long Term Average (LTA) (Wiemer, 2001)

According to the LTA curve above, z-value compares the deviation of average seismic activity in a specific region and time frame from the overall average seismicity for that area. Its purpose is to assess the likelihood of an anomalously low seismicity period occurring prior to significant seismic events near the epicenter (Wiemer, 2001).

Seismic quiescence is defined as a reduction in the average seismicity rate, compared to the previous rate within the same volume of the Earth's crust. The degree of reduction in seismicity rate is expressed by the z-value (Wyss & Martirosyan, 1998). The z-method will compare the average seismicity level in a particular region during a certain period with the overall average seismicity level in the region. The purpose of the z-method is to detect possible anomalies in the form of periods of low seismicity before a large earthquake (Wyss et al., 2004). Several researchers have conducted seismic rate change analysis in various regions of Sumatra, including West Sumatra (Yulianda et al., 2017), Northern Sumatra (Zakiyah & Syafriani, 2021), and Padang (Syaputri, 2022) . The results of these studies indicate the presence of seismic quiescence several years before major earthquake occur.

## METHODS

The data utilized in this study are sourced from the United States Geological Survey (USGS) catalog, covering the period from 1973 to 2023 within the region defined by coordinates 2.050°S - 5.885°S and 101.030°E - 106.611°E. The data used includes magnitudes $3.0 \leq M < 8.4$ with depths $D \leq 300$ km and is processed using the ZMAP6 program. ZMAP is a GUI-based software designed to assist seismologists in analyzed seismicity parameters. The study area defined by the coordinates is divided into several grids with a size of 0.1 × 0.1. In each of the divided grids, the seismotectonic parameter z-value will be calculated. Before the z-value is calculated, the earthquake data obtained from USGS is first declustered using the Reasenberg declustering method to remove foreshocks and aftershocks. The z-value calculation is conducted using the z-value method with the following formula:

$$z(t) = \frac{(R_{bg} - R_w)}{\sqrt{\frac{S_{bg}}{n_{bg}} + \frac{S_w}{n_w}}} \quad (1)$$

Where $z(t)$ is the z-value variation over time, $R_{bg}$ is the mean rate in background period, $R_w$ is the mean rate in window period, $S_{bg}$ and $S_w$ are the standard deviation in this period, and $n_{bg}$ and $n_w$ are the number of samples.

Data obtained from the United States Geological Survey (USGS) catalogue for the period 1973 to 2023 were downloaded and transferred into the Excel program. The data obtained were then edited and organized according to the format used with ZMAP provisions, namely longitude, latitude, year, month, date, magnitude, depth, hour and minute. Incomplete data will be banned and valid power will be saved in "Dat" format. The aim is to make it easier to plot and analyse the data used in ZMAP.

The research location map for the southern part of Sumatra can be seen in Figure 2.

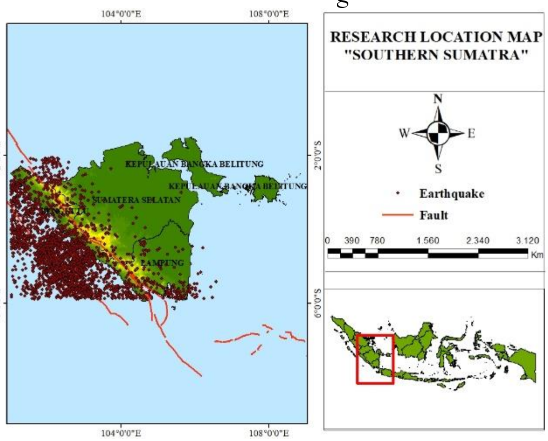



**Figure. 2.** Map of Research Locations in Southern Sumatra Region

Figure 2 shows the research area used, namely in the southern part of Sumatra and its surroundings which are at coordinates 2.050°S-5.885°S and 101.030°E-106.611°E. The earthquake data used has a magnitude of 8.5 ≥ M ≥ 3.0, with a depth of D ≤ 300 km.

This research was conducted in several phases. The first phase involved creating a map of earthquake seismicity distribution for the period from 1980 to 2023. The second phase entailed plotting the cumulative number curve of earthquake events against the z-value, based on the Long-Term Average (LTA) function (see Figure 1). This cumulative curve represents earthquake events as a function of time. The third phase focused on determining the z-value. Prior to calculating the z-value, earthquake data obtained from the USGS were first processed using the Reasenberg Decustering method to exclude foreshocks and aftershocks. Z-value can be calculated using equation 1.

## RESULTS AND DISCUSSION

Earthquake data from the USGS earthquake catalogue with a period of 1973 - 2023, 2832 earthquake events were obtained. After the declustering process, 416 secondary earthquake events were found. This left 2504 earthquake data that could be used. Figure 2 is the seismicity distribution map of the Southern Sumatra region.

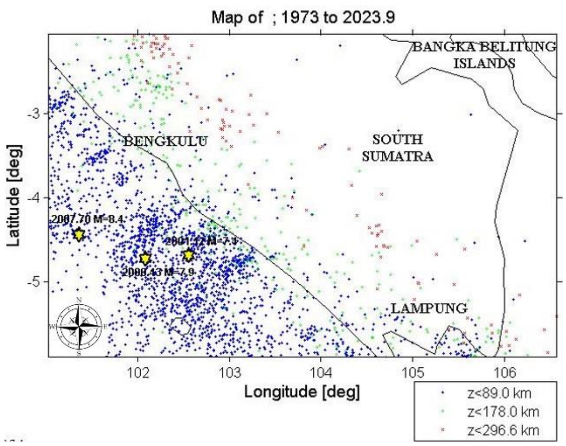
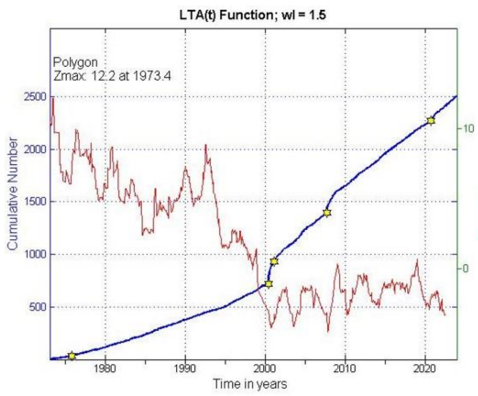


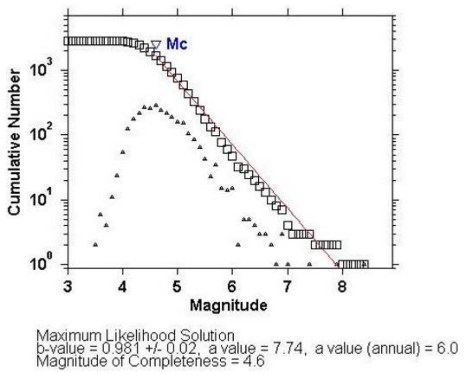

**Figure. 3.** Seismicity distribution map of the Southern Sumatra region for the period 1973-2023

The southern region of Sumatra has experienced frequent earthquakes from 1973 to 2023 as shown in figure 3. The figure highlights three earthquake events with magnitudes greater than 7.0. Earthquakes with depths less than 89.0 km are indicated in blue, those with depths less than 178.0 km are shown in green, and earthquakes with depths less than 296.6 km are depicted in red.

The magnitude frequency distribution depicts the correlation between earthquake magnitude and the frequency of their occurrences. This magnitude-frequency relationship can be seen in Figure 4 using the ZMAP software.




(a)




(b)

**Figure. 4**. Curve (a) Cumulative Number (b) Magnitude of complements analysis

The cumulative number graph shown in Figure 4a, represents the cumulative number of earthquakes over time using the LTA curve, which covers the period 1973-2023 or 50 years with a total of 2504 earthquake events. In the curve from 1973 to 2000, before the 2000 earthquake, the number of earthquakes was less than 800. After the 2000 earthquake, followed by the 2001 earthquake, the number of earthquakes increased again in 2002, but the increase was not very significant. The magnitude-frequency distribution graph in Figure 4b shows that as the magnitude value increases, the occurrence of earthquakes becomes less frequent. The magnitude of completeness (MC) for this study is determined to be 4.6. Therefore, earthquake data with magnitudes less than 4.6 are not used in this analysis (Hisyam et al., 2024).

The distribution of z-values for the southern part of Sumatra, particularly related to the 2000 earthquake with a magnitude of 7.9 SR, is shown in Figure 5.

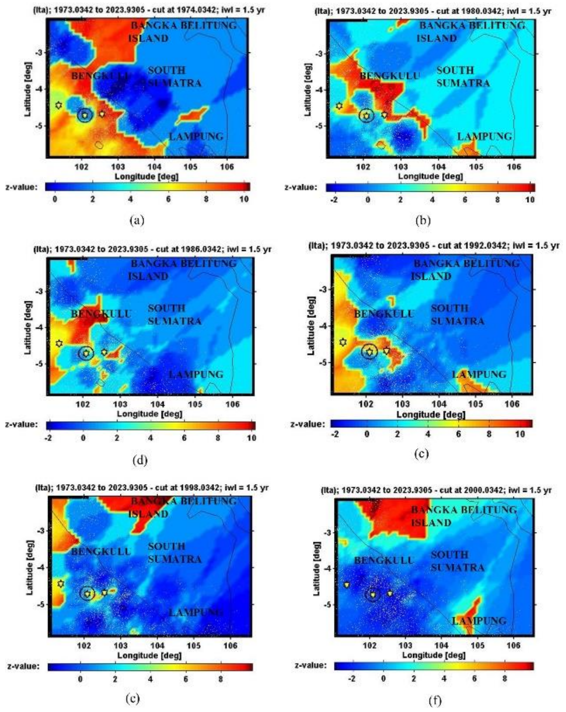



**Figure. 5.** The spatial distribution z-value before the 2000 earthquake event (magnitude 7.9 SR) with iwl 1.5 years is illustrated as follows: (a) cut at 1974.0342 (b) cut at 1980.0342 (c) cut at 1986.0342 (d) cut at 1992.0342 (e) cut at 1998.0342 (f) cut at 2000.0342

The distribution of z-values preceding the 2000 earthquake is illustrated across several time intervals, each spanning 1.5 years, beginning with the period starting in 1974.0342. Figures 5b, 5d, and 5e reveal a phenomenon of seismic quiescence occurred before the 2000 earthquake. This phenomenon indicates the accumulation of energy in the area where the seismic quiescence occurs. This accumulated energy will be released in the form of a sudden significant earthquake, such as the 2000 earthquake with a magnitude of 7.9. Seismic quiescence from the 2000 southern Sumatra earthquake (7.9 SR) lasted for approximately ±16 years.

The distribution of z-values for the southern region of Sumatra, specifically related to the 2001 earthquake with a magnitude of 7.4 SR, is shown in Figure 6.

 ISSN: 2502-2016

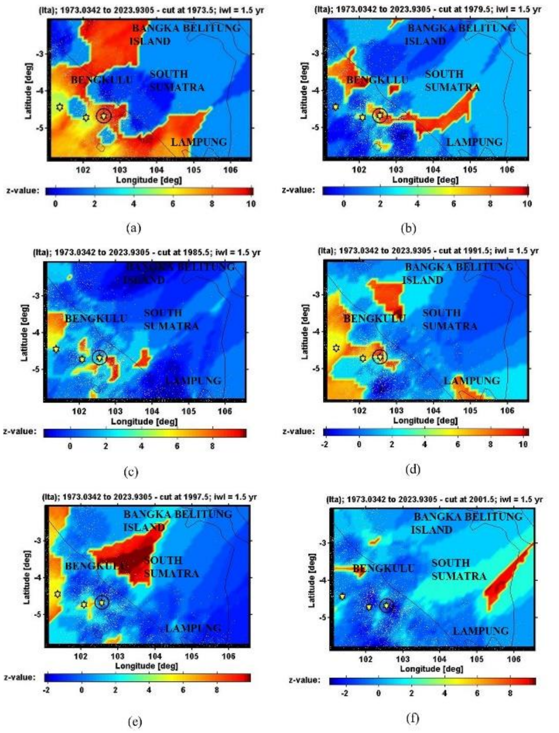



**Figure. 6**. The spatial distribution z-value before the 2001 earthquake event (magnitudo7.4 SR) with iwl 1.5 years is illustrated as follows: (a) cut at 1973.5 (b) cut at 1979.5 (c) cut at 1985.5 (d) cut at 1991.5 (e) cut at 1997.5 (f) cut at 2001.5

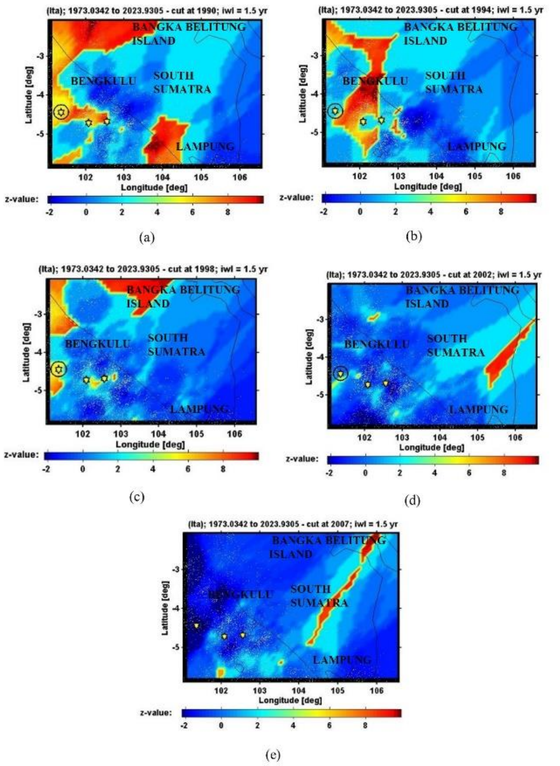



**Figure. 7.** The spatial distribution z-value before the 2007 earthquake event (magnitude 8.4 SR) with iwl 1.5 years is illustrated as follows: (a) cut at 1990 (b) cut at 1994 (c) cut at 1998 (d) cut at 2002 (e) cut at 2007

The z-value distribution is presented in several time intervals, starting with the period beginning in 1973.5, each using an iwl 1.5 years. Figures 6a to 6d illustrate the period of seismic quiescence activity before the 2001 earthquake. Initially, there was little seismic activity, localized over a small area and gradually expanding, indicating an accumulation of energy that was eventually released as a significant earthquake. Seismic quiescence from the 2001 southern Sumatra earthquake (7.4 SR) lasted for approximately ±13 years.

The distribution of z-values for the southern part of Sumatra in the area of the 2007 earthquake with a magnitude of 8.4 SR is shown in Figure 8.

The z-value distribution is plotted across several time periods, beginning from the 1990 intercept with intervals of 1.5 years. Figure 7 demonstrates that a period of seismic quiescence lasted 8 years, from the 1990 intercept until the 1998 intercept, preceding the major 2007 earthquake. In 2002, there was a notable increase in seismic activity in the third zone, leading up to the 2007 earthquake. Seismic quiescence from the 2007 earthquake (8.4) in southern Sumatra lasted for approximately ± 17 years.

The spatial distribution of z-scores in the Southern Sumatra region at the beginning of 2023 is shown in Figure 8.

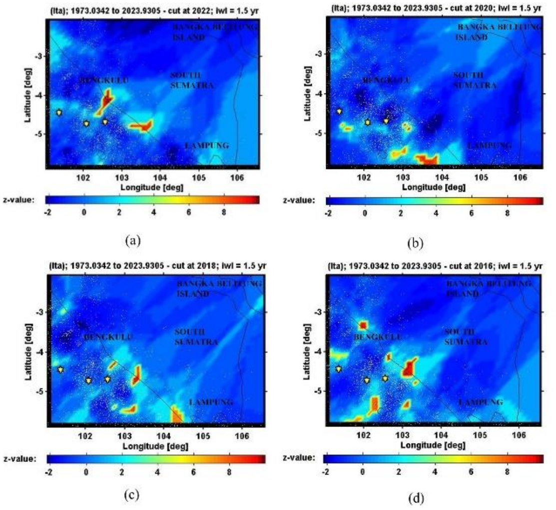



**Figure. 8**. The spatial distribution of z-value in Southern Sumatra with 1.5 years iwl (a) cut at 2022 (b) cut at 2020 (c) cut at 2018 (d) cut at 2016.

The spatial distribution of z-value in early 2023, shown in figure 8, indicates experienced a decrease in seismic activity. The seismic quiescence phenomenon is seismic activity that precedes a significant earthquake(Katsumata, 2011)(Mogi, 1981). Before a large earthquake occurs, there has been seismic activity around the epicenter of the large earthquake. After a seismic quiescence, it is usually followed by an increase in seismicity as a preliminary earthquake (Mogi, 1981). A decline in average seismicity in the years leading up to a major earthquake should be regarded as a potential precursor to a moderate magnitude earthquake (Sunardi et al., 2013).

A reduction in seismic activity is marked by a positive z-value, signifying an energy buildup within the region. This energy accumulation occurs while the pressure on the rock remains below its elastic threshold. Eventually, this stored energy is released as earthquakes (Don et al., 2006). An increase in seismic activity is indicated by a negative z-value, reflecting a release of energy within the region. When seismic activity rises, the pressure on the rock surpasses its maximum resistance, leading to a gradual release of energy. Areas that exhibit a rapid surge in seismic activity signify a sudden and large-scale release of substantial energy.

The analysis of seismic rate changes in the southern Sumatra region is based on the temporal distribution of earthquake events from 1973 to 2023, as shown in Figure 9. In the period 1973-1999, there were around 700 earthquake events recorded in a span of 27 years. Furthermore, in the period 2000-2010, the number of earthquake events increased significantly with around 1,000 events in a span of 10 years. While in the period 2011-2023, there were around 800 events in a span of 12 years. From these data, it can be concluded that the seismic rate changes in the southern Sumatra region has increased significantly from the period 1973-1999 to the period 2000-2010. Although there was a slight decrease in the rate in the period 2011-2023, the frequency of earthquake events was still higher than in the initial period.

Based on the spatial distribution of Z-values, changes in seismicity rates were observed in southern Sumatra over the period 1973–2023. These changes were particularly evident before and after major earthquakes in 2000, 2001, and 2007, where positive Z-values were recorded prior to these events and negative Z-values afterward. Positive Z-values indicate a decline in seismic activity, a phenomenon known as seismic quiescence. During this period, the seismicity rate decreased, suggesting reduced seismic activity in southern Sumatra, which contributed to stress accumulation. Following the major earthquakes, negative Z-values were observed, signifying an increase in seismic activity. The major earthquakes in 2000, 2001, and 2007 were the result of energy accumulation during the seismic quiescence period. During this phase, tectonic stress was significantly accumulated without being released through smaller earthquakes, leading to the release of all accumulated energy in a single large event. The rise in seismic activity following these major earthquakes reflects the release of substantial energy, often accompanied by aftershocks as a response to changes in stress conditions within the fault zone after the mainshock. Consequently, the seismicity rate experienced a significant surge, breaking the preceding period of quiescence.

## CONCLUSION

In the southern Sumatra region during the period 1973-2023, there were 3 significant earthquake events, namely 2000 (7.9 SR), 2001 (7.4 SR) and 2007 (8.4 SR). These three earthquake events were preceded by the seismic quiescence phenomenon. Seismic quiescence in the 2000 earthquake (7.9 SR) lasted ±16 years, the 2001 earthquake (7.4 SR) lasted ±13 years and the 2007 earthquake (8.4 SR) lasted ±17 years. The southern Sumatra region before 2023 also had seismic quiescence around Bengkulu. Seismic rate changes in the southern Sumatra region were seen throughout the period 1973-2023 in the 2000, 2001, and 2007 earthquake events, which were marked by positive z-values before major earthquakes and negative z-values after major earthquakes. Positive z-values indicate a decrease in seismic activity that usually occurs quite a long time before a major earthquake occurs. Negative z-values indicate an increase in seismic activity that occurs after a major earthquake occurs. In the period 1973-1999, around 700 earthquakes were recorded in a span of 27 years. Furthermore, in the period 2000-2010, the number of earthquake events increased significantly with around 1,000 events in a span of 10 years. While in the period 2011-2023, around 800 events occurred in a span of 12 years.

## ACKNOWLEDGMENT

The author would like to thank Wyss and Wiemer for developing the ZMAP6 program code, which helped in the data processing stage of this research. The author also extends gratitude to the operators of USGS-NEIC for providing access to their earthquake catalog.

## REFERENCES

Don, L., Leet, F., & Suparnyakir, W. (2006). Gempa bumi: penjelasan ilmiah & sederhana: proses, tanda-tanda akan terjadinya, serta antisipasi dampak. *(No Title)*.

Hadi, A. I., Suhendra, S. dan, & Efiyandi, E. (2010). Studi Analisis Parameter Gempa Bengkulu Berdasarkan Data Single-Station dan Multi-Station serta Pola Sebarannya. *Berkala Fisika*, *13*(4), 105–112.

Hisyam, F., Susilo, A., Anshori, M., & Hasan, M. F. R. (2024). Spatio-Temporal Variation Seismicity Pattern in East Java Between 2002 and 2022 Based on the b-value and Seismic Quiescence z-value. *Trends in Sciences*, *21*(4). https://doi.org/10.48048/tis.2024.7608

Katsumata, K. (2011). A long-term seismic quiescence started 23 years before the 2011 off the Pacific coast of Tohoku Earthquake (M = 9.0). *Earth, Planets and Space*, *63*(7), 709–712. https://doi.org/10.5047/eps.2011.06.033

Linda, L., Ihsan, N., & Palloan, P. (2019). Analisis distribusi spasial dan temporal seismotektonik berdasarkan nilai b-value dengan menggunakan metode likelihood di Pulau Jawa. *Jurnal Sains Dan Pendidikan Fisika*, *8*(3), 269–278.

Mogi, K. (1981). Earthquake prediction program in Japan. *Earthquake Prediction: An International Review*, *4*, 635–666.

Nurdiyanto, B., Sunardi, B., Harsa, H., Ngadmanto, D., Susilanto, P., & Rohadi, S. (2010). Integrasi Pengamatan Parameter Geofisika dalam usaha Prediktabilitas Gempabumi. *Laporan Akhir Program Intensif Kementrian Negara Riset Dan Teknologi*.

Pristanto, A. I. (2010). Upaya Peningkatan Pemahaman Masyarakat tentang Mitigasi Bencana Gempa Bumi di Desa Tirtomartani Kecamatan Kalasan Kabupaten Sleman Provinsi Daerah Istimewa Yogyakarta. *Universitas Negeri Yogyakarta*. https://eprints.uny.ac.id/494/

Sari, D., Khairina, F., & Daniarsyad, G. (2020). Relokasi Hiposenter Gempabumi Menggunakan Metode Modified Joint Hypocenter Determination (Mjhd) Untuk Analisis Zona Subduksi Sumatera Bagian Selatan. *JGE (Jurnal Geofisika Eksplorasi)*, *4*(1), 88–104. https://doi.org/10.23960/jge.v4i1.9

Simamora, J. T., & Namigo, E. L. (2016). Pemetaan Magnitude of Completeness (Mc) untuk Gempa Sumatera. *Jurnal Fisika Unand*, *5*(2), 179–186. https://doi.org/10.25077/jfu.5.2.179-186.2016

Suharno. (2012). *Resiko Gempa Bumi di Provinsi Lampung*. *April*, 1–10.

Sunardi, B., Sulastri, & Jimmi, N. (2013). Analisis Periodesitas dan Perubahan Tingkat Kegempaan Wilayah Jawa Barat Berbasis Statistik. *In Conference Paper*, *March 2016*, 67–77.

Suwandi, H. K. (2022). *Analisis Percepatan Tanah Maksimum dengan Menggunakan Beberapa Pendekatan Empiris di Wilayah Nusa Tenggara Timur (Ntt)*. 1–60.

Syaputri, R. (2022). *Analisis Prekursor Seismic Quiescence Sebelum Gempabumi M= 7, 6 SR 30 September 2009 Padang Berdasarkan Distribusi Spasial Seismotektonik*. Universitas Negeri Padang.

Wiemer, S. (2001). A software package to analyze seismicity: ZMAP. *Seismological Research Letters*, *72*(3), 373–382. https://doi.org/10.1785/gssrl.72.3.373

Wyss, M., & Martirosyan, A. H. (1998). Seismic quiescence before the M7, 1988, Spitak earthquake, Armenia. *Geophysical Journal International*, *134*(2), 329–340. https://doi.org/10.1046/j.1365-246X.1998.00543.x

Wyss, M., Sobolev, G., & Clippard, J. D. (2004). Seismic quiescence precursors to two M7 earthquakes on Sakhalin Island, measured by two methods. *Earth, Planets and Space*, *56*(8), 725–740. https://doi.org/10.1186/BF03353081

Yulianda, W., Syafriani, & Sabarani, A. Z. (2017). Analisis Perubahan Laju Seismik (Seismic Rate Changes) berdasarkan Distribusi Spasial Seismotektonik Wilayah Sumatera Barat. *Pillar of Physics*, *9*, 49–56.

Zakiyah, V. F., & Syafriani, S. (2021). Seismic Rate Change Analysis Based on Spatial Distribution of Seismotectonics in Northern Sumatra. *Pillar of Physics*, *14*(2), 75–82. https://doi.org/10.24036/12157171074