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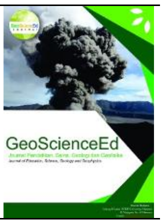

Analysis of Seismic Rate Change Based on Spatial Distribution of Seismotectonics and Deformation Extension in West Nusa Tenggara

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Abstract: The purpose of this study to determine the changes in seismic rate observed from the seismic quiescence phenomenon and extent of deformation. The seismic rate change method is z-value spatial distribution. And the deformation area method is the formulation of Utsu and Seki for the M7.0 earthquake on August 5, 2018 with the input magnitude surface. This research uses data from the USGS website for the period 1983-2023. In this study, there are three research focus zones, namely the 2009 (M6.6), 2018 (M7.0) and 2018 (M6.9) earthquakes. Using the z-value spatial distribution method, the region is divided into several grids. The z-value is calculated on each grid and describes the seismic rate change. This phenomenon can be seen based on the seismic rate change that has been obtained. The results obtained, in the first zone there was an increase in seismic activity before the 2009 earthquake, the second zone and the third zone there was a seismic quiescence phenomenon that preceded the 2018 earthquake. Based on the spatial distribution of z-value the beginning of 2023, there is a phenomenon of decreased seismic activity in some areas of West Nusa Tenggara. And there was a deformation of 1.091,44 km^2 in the M7.0 earthquake on August 5, 2018. This should be suspected to be the beginning of earthquake symptoms in the future**.**

Keywords: Earthquake; Seismic Quiescence, Seismic Rate Change, Z-Value, Deformation Area

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Introduction

An earthquake is a shaking of the earth's surface caused by the sudden movement of rock plates in the earth's crust caused by the movement of tectonic plates (Sunarjo et al., 2010). Earthquakes are one of the natural phenomena that often occur in Indonesia, including the West Nusa Tenggara region. This is because West Nusa Tenggara is located in the eastern Sunda arc region which stretches from the Sunda Strait to the east to Sumba Island. The seismicity level in West Nusa Tenggara is quite dense because it is influenced by the subduction activity of the Indo-Australian plate in the south and the Flores back arc thrust fault in the north (PuSGeN, 2017).

Seismic activity can be seen from the frequency-magnitude distribution (FMD) relationship by analyzing the b-value seismotectonic parameters that describe local tectonic stress conditions and the a-value that describes earthquake activity (Syafriani et al., 2018). The Equation (1) illustrates the connection between an earthquake's magnitude and its frequency as described by Gutenberg and Richter:

$$logN(M) = a - bM \qquad ....(1)$$

Where N is the cumulative number of earthquakes with magnitudes greater than M and a and b are constants. The condition of the region affected by the number of seismic events is represented by the a-value and the local tectonic stress condition of the rock is represented by the b-value (Katsuma, 2011). The constant a depends on the region and the level of seismic activity or frequency of earthquakes occurring, while the constant b describes the degree of rock fragility. Higher

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values of b indicate that earthquakes with larger magnitudes occur less frequently than earthquakes with smaller magnitudes. Lower values of b indicate that large earthquakes occur more frequently relative to small earthquakes. This relationship is crucial in seismic research because it clarifies the connection between the frequency of earthquakes in a specific area over a certain period and their magnitude (Isa et al., 2014).

West Nusa Tenggara is located on the subduction zone to the south and the Flores back arc thrust fault to the north, and there are horizontal faults in the form of the Lombok fault to the west, the Sumbawa fault to the east, the Teluk Panas fault to the south of West Sumbawa and the Sape fault to the east of Sumbawa Island. This geological condition causes West Nusa Tenggara to experience frequent earthquakes (Silver et al., 1986). History records that the West Nusa Tenggara region has experienced several devastating earthquakes that have caused casualties, including the Lombok earthquake on November 2, 1954 with a magnitude of 6.7 SR, the Sumbawa earthquake on August 19, 1977 with a magnitude of 7.0 SR, the Lombok earthquake on May 30, 1979 with a magnitude of 6, 1 SR, the Sumbawa earthquake on March 11, 1982 with a magnitude of 6.5 SR, the Dompu earthquake on January 23, 2003 with a magnitude of 5.0 SR, the Lombok earthquake on January 1, 2004 with a magnitude of 6.1 SR, the Lombok earthquake on November 25, 2007 with a magnitude of 6.7 SR, and the Lombok earthquake on June 22, 2013 with a magnitude of 5.0 SR. 0, the January 1, 2004 Lombok earthquake with a magnitude of 6.1, the November 25, 2007 Lombok earthquake with a magnitude of 6.7, and the June 22, 2013 Lombok earthquake with a magnitude of 5. 3, the Dombo earthquake on August 1, 2016 with a magnitude of 5.6, the North Lombok earthquake on July 29, 2018 with a magnitude of 6.4, and the Lombok earthquake and tsunami on August 5, 2018 with a magnitude of 7.0 and a tsunami height of 10-13 cm (Setiyono et al., 2019).

To reduce the effects of major earthquakes, it's essential to monitor precursors in regions prone to significant seismic activity. Analyzing the seismic quiescence phenomenon helps identify signs that precede a large earthquake. Seismic quiescence refers to a noticeable reduction in the number of earthquakes or seismic energy in an active region over a specific time period (Wyss, et al., 2004).

The variation in the number of earthquakes or seismic energy in a seismically active area over a given time period is referred to as the seismic rate change. Where this change depends on the stress and strain of the rock in a region that is directly related to stress or pore pressure, the aim is to observe stress changes caused by coulomb failure or changes in the level of previous earthquakes (Wiemer, 2001). Seismotectonic parameters of earthquakes can indicate the level of rock vulnerability in a region. Fragile rocks, which release energy through small earthquakes, have less stored energy. In contrast, robust rocks accumulate significant amounts of energy over extended periods. When this energy exceeds the rocks' capacity to withstand pressure, it results in large-magnitude earthquakes. If the accumulated energy is released, the number of earthquakes will rise, with their magnitude being measurable by the magnitude. The connection between earthquake energy and magnitude is illustrated in Equation (2) (Gutenberg & Richter, 1942):

$$Log\ E = 5.8 + 2.4\ Mb \qquad \text{……….(2)}$$

Or Equation (3) :

$$Log\ E = 11.8 + 1.5\ Ms \qquad \text{……….(3)}$$

Where E is the energy released by the earthquake in ergs. Mb is the body magnitude and Ms is the surface magnitude.

Before the occurrence of a major earthquake, there is usually a pre-earthquake. One of the parameters that can be used to observe this phenomenon is seismic data. This is because seismic data is distributed in seismically active areas and is used to observe seismicity patterns before a large earthquake occurs. This data provides the necessary information to determine the level of early warning related to the observation of earthquake precursors. Seismic data is obtained at the depth of the earth's crust where the earthquake occurred. By using seismicity patterns, research on earthquake prediction becomes a good earthquake precursor to study at this time (Wyss & Habermann, 1988).

The phenomenon of seismic quietness is observed by looking at the z-value in a region (Zakiyah et al., 2021). He aim is to detect possible anomalous periods of low seismicity prior to a large earthquake. A positive z-value indicates a decrease in seismic activity and a negative z-value indicates an increase in average seismicity over the selected interval (Ozturk, 2015).

Alongside analyzing seismic quiescence, it's important to evaluate the extent of deformation caused by major earthquakes to pinpoint affected areas and assess earthquake potential. Deformation refers to the changes in the earth's shape, structure, and composition resulting from energy release during tectonic movements in the crust. The Utsu and Seki (1954) model is employed to analyze deformation magnitude due to its high accuracy, ease of use, and effectiveness with limited earthquake data, and it is applicable for earthquakes with magnitudes >5 (Nemati, 2014).

To analyze changes in earthquake rates, the z value in the study area can be assessed to identify potential anomalies of reduced seismicity before the main shock occurs near the epicenter. A positive z value suggests a decrease in seismic activity, whereas a negative z value points to an increase in activity. A decline in seismic activity prior to a significant earthquake is suspected to be indicative of the seismic quiescence phenomenon (Sukrungsri & Pailoplee, 2016). Generally, seismic quiescence phenomena occur in the vicinity of a major earthquake several years before a large magnitude earthquake (Sunardi et al., 2013).

The seismic quiescence phenomena is closely relate to deformation. Deformation is a change in the shape, formation and structure of the earth that occurs due to the release of energy by tectonic movements in the earth's crust. Calculating the z-value in the West Nusa Tenggara region will reveal variations in seismicity rates and identify the seismic quiescence phenomena that occurs before a major earthquake. By knowing the precursors and extent of earthquake deformation areas, the possibility of significant earthquakes occurring in the future can be estimated. Apart from that, we can also predict areas that have the potential to experience significant earthquakes. This can be used to minimize the impact caused by earthquakes.

Method

The earthquake data utilized were obtained from the United States Geological Survey (USGS) website, covering the period from 1983 to 2023. The study area is situated between coordinates 8°10' - 9°5' N and 115°46' - 119°5' E. The data include earthquakes with magnitudes ranging from 9 ≥ M ≥ 3, classified by magnitude body type. The data were analyzed using the ZMAP V 6.0 software (Wyss et al., 2001).

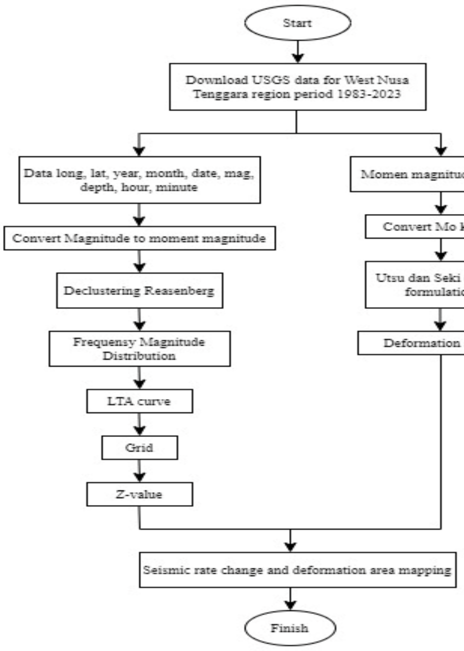


Figure 1. Data Processing Techniques for Seismic Rate Change and Deformation Area

Magnitude data is converted to moment magnitude. After conversion, the data were organized according to the ZMAP format, namely long, lat, year, month, date, magnitude, depth, hour, and minute. The compiled data was then entered into the ZMAP software and a declustering process was performed using Reasenberg declustering (1985). This process aims to separate the main earthquake from the foreshock and aftershock. The ZMAP software will display the seismicity distribution map for the West Nusa Tenggara region for the period 1983-2023. Furthermore, the process is carried out to see the frequency distribution of magnitude in the z-tool menu to see the values of a and b. And on the z-tool menu, select the time series analysis menu to display the LTA curve.

Seismic rate changes are analyzed through the z-value distribution method. The region is divided into grids with a spacing of 0.1 x 0.1, each containing 100 earthquake events. The z-value is computed using the specified Equation (4):

$$z(t) = \frac{(R_{bg} - R_w)}{\sqrt{\frac{S_{bg}}{n_{bg}} + \frac{S_w}{n_w}}} \qquad \text{..........(4)}$$

Here, Rbg represents the average seismic level across all data except for the selected time period, while Rw is the average seismic level for the chosen time period. Sbg indicates the variation over the entire period, and Sw reflects the variation for the selected period. ng and nw denote the number of events in the total and selected datasets, respectively.

The z-value is calculated based on the number of selected earthquakes in each grid using \(N_{ZMAP} \). The time frame from Ts_{start} and T_{end} is divided into $N_{\Delta t}$ short time (ST) windows, each with a width of $N_{\Delta t}$ is Δt. The background seismicity level is determined using Equation (5).

$$R_{bg} = \frac{1}{n_{bg}}\left(\sum_{i-1}^{N1} ni + \sum_{i=n2+1}^{N\Delta t} ni\right) ni = 1, \dots, N\Delta t$$
……(5)

Here, ni represents the number of earthquake data points within the short time (ST) window, and n_{bg} in Equation (1) is equivalent to $N_1 + N_{\Delta t} - N_2$, where N_2 is the number of events in the last ST window before transitioning to the long-term (LT) window. The LT window has a width of Δt. The seismicity level R_w in the LT window is determined using Equation (6).

$$R_w = \frac{1}{nw}\sum_{i=N1+1}^{N2} ni \qquad \text{……….(6)}$$

Where $nw = \Delta T/\Delta t$ the seismicity level R_w is then compared with R_{bg} using Equation (1). The variations S_{bg} and S_w are calculated with the following Equations (7a).

$$S_{bg} = \frac{1}{n_{bg}}\left\{\sum_{i=1}^{N1}\left(ni + R_{bg}\right)^2 + \sum_{i=N1+1}^{N\Delta t}\left(ni - R_{bg}\right)^2\right\}$$
……….(7a)

And Equation (7b):

$$S_w = \frac{1}{n_w}\left\{\sum_{i=N1+1}^{N2}(ni - R_w)^2\right\} \qquad \text{……….(7b)}$$

A positive z-value indicates a decrease in the average seismicity level during a selected interval compared to the average seismicity level of the entire dataset. Conversely, a negative z-value signifies an increase in the average seismicity level during the selected interval. The greater the z-value, the more pronounced the observed difference (Yulianda et al., 2017).

Deformation is a change in the shape, formation and structure of the earth that occurs due to the release of energy by tectonic movements within the earth's crust. Empirical calculations to obtain the extent of earthquake deformation areas use input data in the form of Ms (Surface magnitude) of the main earthquake. Therefore, it is necessary to convert the magnitude of the main earthquake data Mw (Moment Magnitude) into Ms (Surface Magnitude) using the Equation (8) (Kanamori & Anderson, 1975):

$$M_W = \left(\frac{\log Mo}{1.5}\right) - 10.73 \qquad \text{……….(8)}$$

Empirically, the relationship between seismic moment and surface magnitude can be seen from Equation (9):

$$Log\ Mo = 1.5\, M_s + 16.1 \qquad \text{……….(9)}$$

Where Mo is the seismic moment, Mw is the moment magnitude and Ms is the surface magnitude.

Then, to determine the extent of the deformation area of the fault plane surface after rupture, using the empirical formula introduced by Utsu and Seki (1954) with the input magnitude surface, can be seen in Equation (10) (Utsu & Seki, 1954):

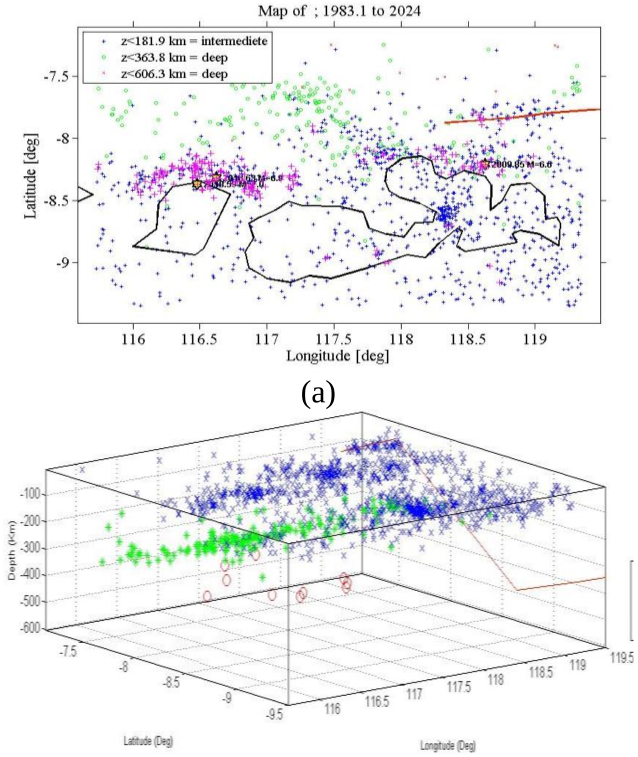
$$Log\ A = 1.02\, M_s + 6.0 \qquad \text{……….(10)}$$

where A is the deformation area (cm^2) and Ms is the Surface Magnitude of the main earthquake.

The seismotectonic parameter b-value is related to the extent of deformation in an area. A low b-value is linked with high stress levels and indicates that energy is being accumulated, which can potentially be released as a major earthquake, leading to broader deformation in the region. The impact of seismicity rates and b-value distribution is influenced by the active fault segments and stress changes. A reduction in seismic quiescence suggests either a lack of oriented faults or a decrease in earthquake frequency in the area. This affects the seismotectonic parameter z-value, which can help explain in the seismic rate changes (Westerhaus et al., 2002).

Result and Discussion

A total of up to 1503 earthquake events from the period 1983-2023 can be analyzed. The magnitudes of these earthquakes range from 9 ≥ M ≥ 3 SR. Figure 2 below shows the seismicity distribution map for the West Nusa Tenggara region.



(a)

(b)

Figure 2. Regional Seismicity (a) Seismic Distribution Map of West Nusa Tenggara (b) Three-Dimensional Variation of Latitude and Longitude with Depth

According to Figure 2(a), the data shows a high frequency of earthquakes during this period, with a predominance of medium-sized quakes. Figure 2(b) highlights different earthquake D < 181.9 km are shown in blue, a depth of D < 368.8 km in green, and depth of D < 606.3 km in red. As depicted in Figure 2, the West Nusa Tenggara region frequently experiences earthquakes in the Flores back-arc thrust fault zone to the north. Earthquakes with depths of ≤ 300 km are classified as moderate, while those with depths greater than >300 km are categorized as deep.

The frequency of earthquake events in the West Nusa Tenggara region is illustrated by a cumulative curve, as shown in Fig. 3. This curve displays the total number of earthquakes over time based on the data. The frequency-magnitude relationship highlights how earthquake magnitude correlates with the number of occurrences. The frequency-magnitude distribution curve for the West Nusa Tenggara region is also depicted in Figure 3.

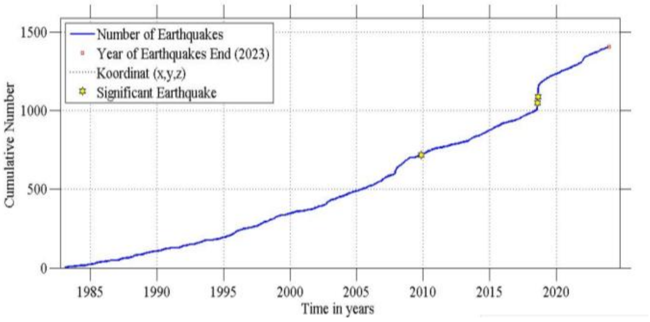


Figure 3. Cumulative Number Curve

As seen in Figure 3, the incidence of earthquakes is increasing from year to year. It can be seen in the curve in 1983-2023 before the 2009 earthquake the number of earthquakes that occurred was less than 800 earthquake events. The number of earthquake events increased from 2010 to 2018.

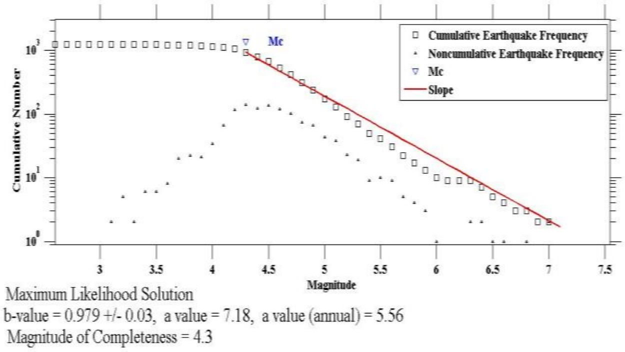
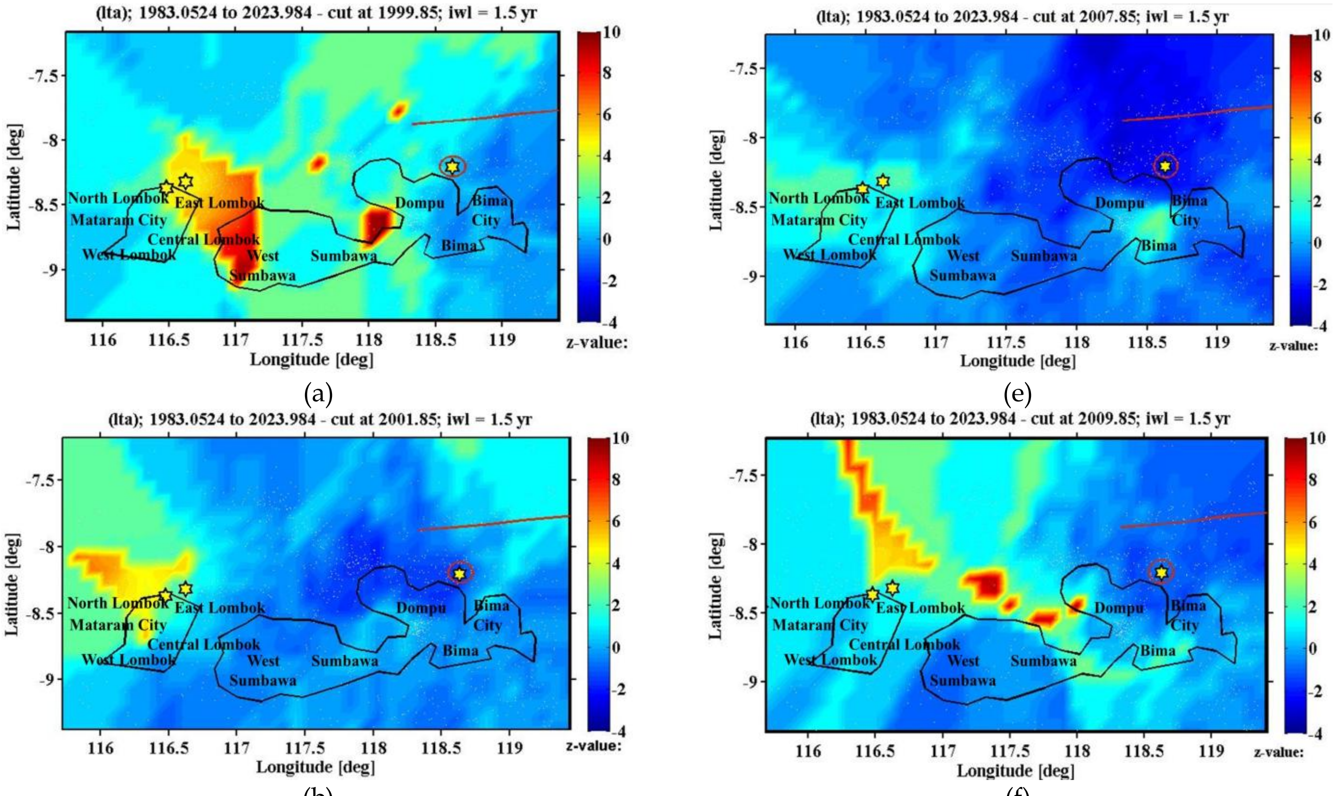


Figure 4. Magnitude Frequency Distribution

Figure 4 presents the regional distribution curve, which shows that the completeness magnitude (Mc) for this area is 4.3 based on the data. This suggests that the earthquake data catalog reliably records earthquakes with a minimum magnitude of 4.3. The b-value for the West Nusa Tenggara region was calculated to be 0.979, with an error margin of approximately 0.03, and the a-value was 7.18, with an annual a-value of 5.56.

The spatial distribution of z-values in the West Nusa Tenggara region prior to the 2009 earthquake with a magnitude of 6.6 SR is illustrated in Figure 5.



(a)

(e)

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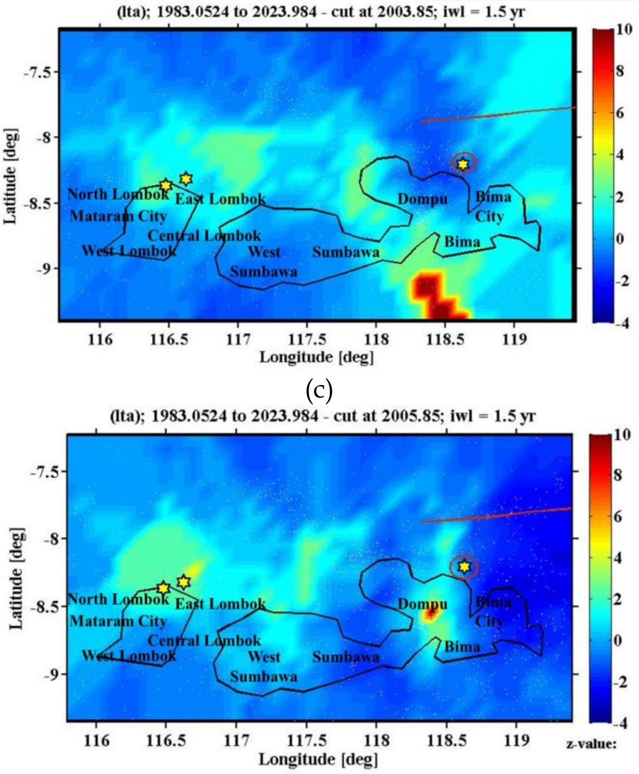


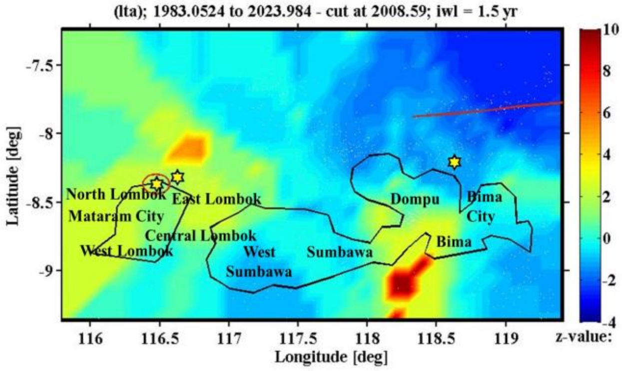
(c)

(d)

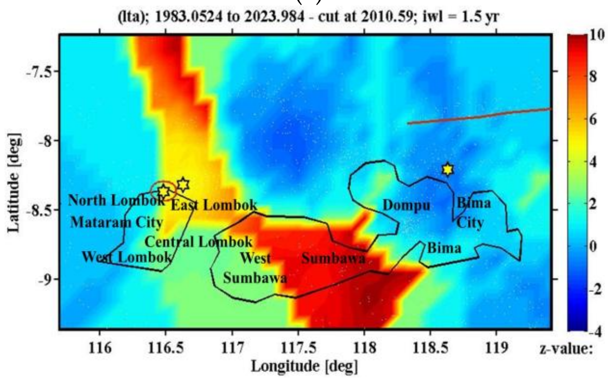
Figure 5. Spatial Distribution of Z-Values before the 2009 Earthquake Event (6.6 SR) with iwl = 1.5 Years (a) Cut at 1999,85 (b) Cut at 2001,85 (c) Cut at 2003,85 (d) Cut at 2005,85 (e) Cut at 2007,85 (f) Cut at 2009,85

Figure 5 illustrates the z-value distribution for the West Nusa Tenggara region prior to the 2009 earthquake with a magnitude of 6.6. The data reveal an increase in seismic activity, marked by a negative z-value near the mainshock. Specifically, there was a notable drop-in seismic activity around 1999.85, followed by a rise in activity from 2001.85 to 2009.85. This increase is attributed to the significant 2009 earthquake, which had a magnitude of 6.6 and is associated with a negative z-value, indicating heightened seismic activity. A negative z-value reflects increased seismic activity, suggesting that accumulated energy was released as earthquakes. Conversely, a positive z-value signifies reduced seismic activity, indicating energy accumulation in the study area.

Figure 6 displays the z-value distribution in the West Nusa Tenggara region before the 2018.5 earthquake with a magnitude of 7.0 SR.



(a)



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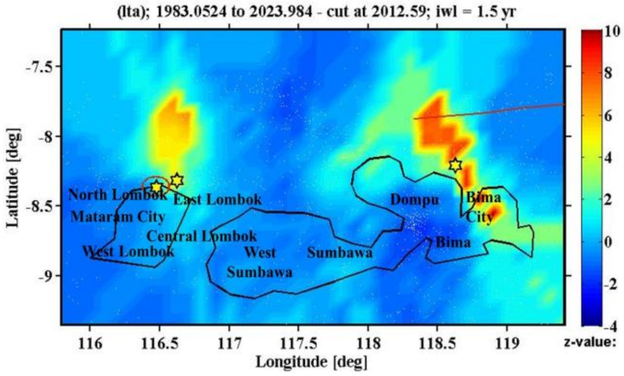

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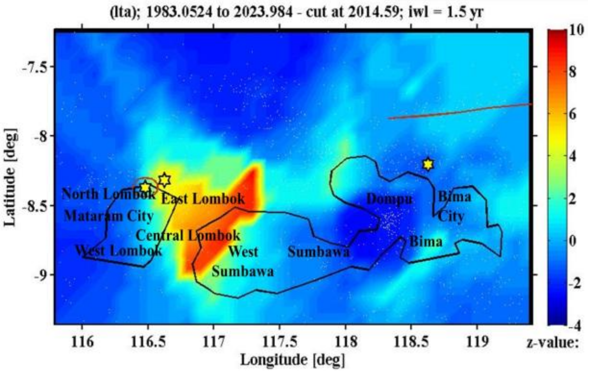

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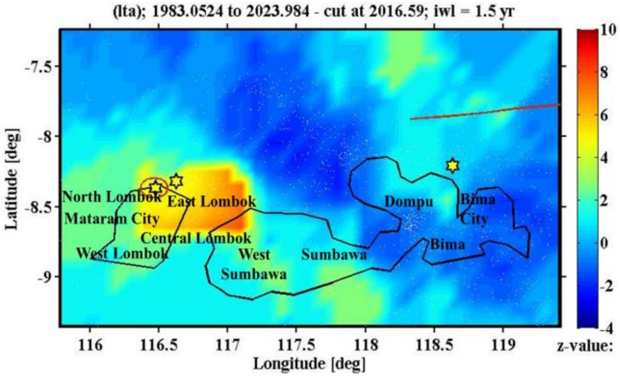

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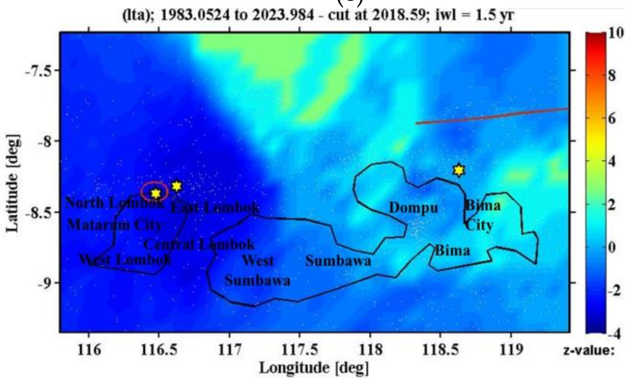
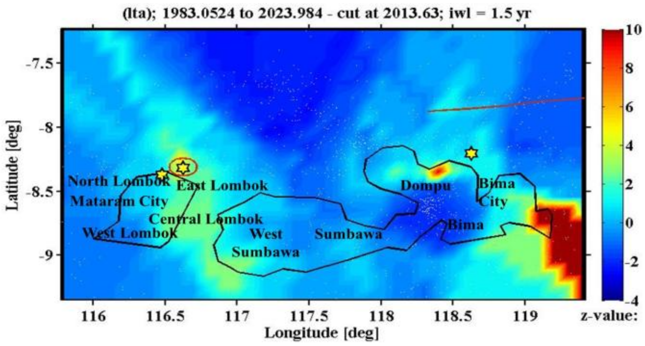


(f)

Figure 6. Spatial Distribution of Z-Values before the 2018 Earthquake Event (7 SR) with iwl=1.5 Years (a) Cut at 2008,59 (b) Cut at 2010,59 (c) Cut at 2012,59(d) Cut at 2014,59 (e) Cut at 2016,59 (f) Cut at 2018,59

Figure 6 shows the z-value distribution for the West Nusa Tenggara region prior to the 2018 earthquake with a magnitude of 7.0. There is a seismic quiescence phenomenon that precedes it. Based on Fig. 6. the seismic quiescence phenomenon occurs at the cut at 2008.59 to 2016.59. The time slice cut at 2018.59 saw an increase in seismic activity, because there was a significant earthquake in 2018 with a magnitude of 7 SR, which is marked by a negative z-value on the map marked with a bluish color.

Figure 7 displays the z-value distribution for the West Nusa Tenggara region prior to the 2018.6 earthquake with a magnitude of 6.9 SR.



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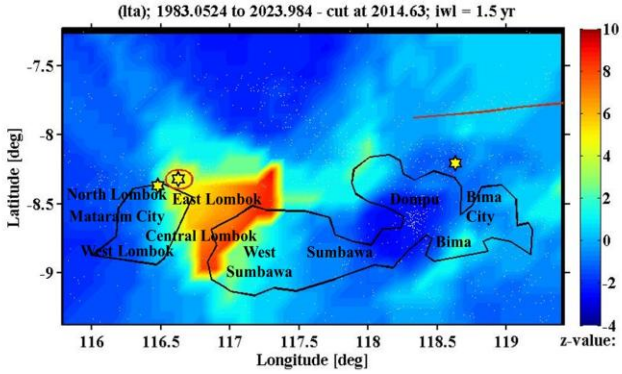

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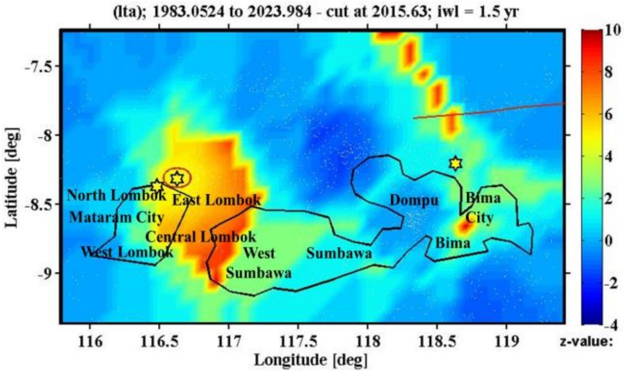

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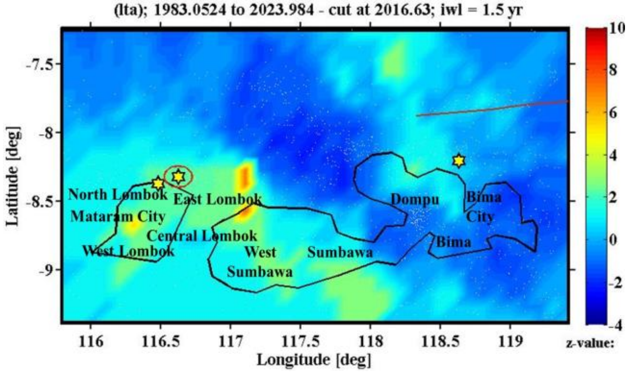

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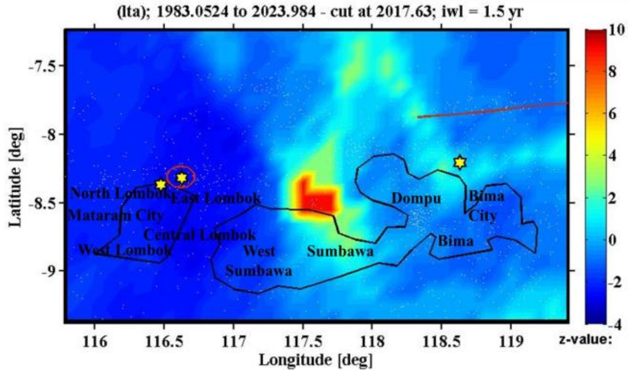

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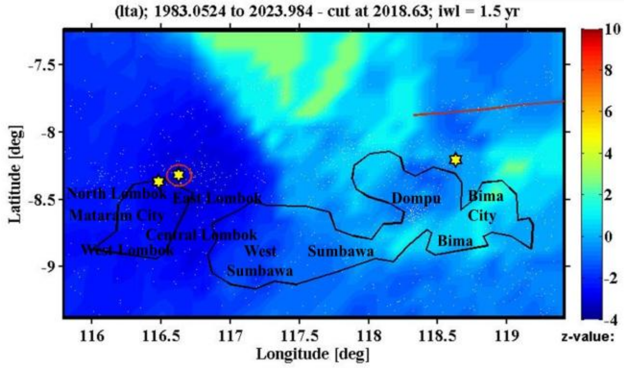
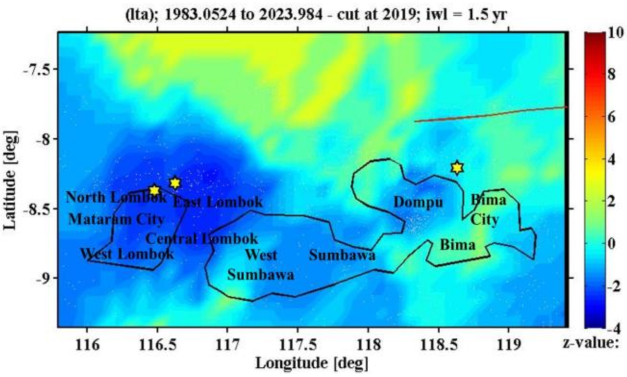


(f)

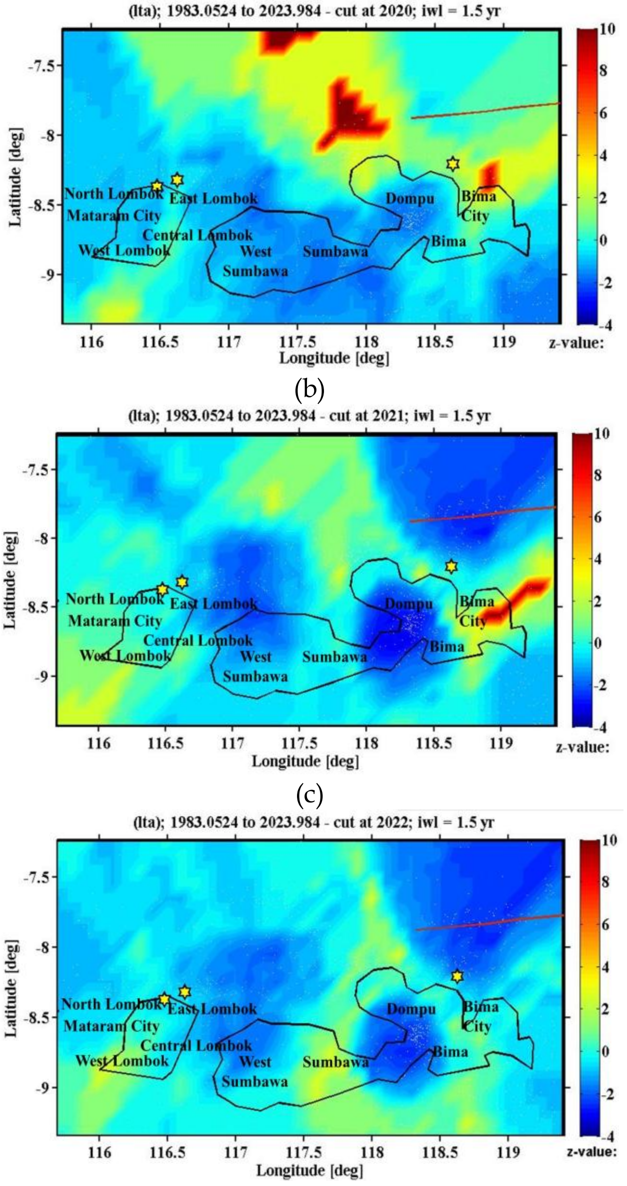
Figure 7. Spatial Distribution of Z-Values before the 2018 Earthquake Event (6.9 SR) with iwl =1.5 Years (a) Cut at 2013,63 (b) Cut at 2014,63 (c) Cut at 2015,63 (d) Cut at 2016,63 (e) Cut at 2017,63 (f) Cut at 2018,63

Figure 7 illustrates the z-value distribution for the West Nusa Tenggara region before the 2018 earthquake. The data reveal a seismic quiescence phenomenon preceding the 2018 earthquake. Prior to the 2018 event with a magnitude of 6.9, there was also a major earthquake with a magnitude of 7 earlier in the same year. According to Katsuma (2011), when two significant earthquakes occur close together, their seismic quiescence anomalies can merge into a single anomaly. Figure 7 shows that before 2018, there was a noticeable decrease in seismic activity in the West Nusa Tenggara region. The anomaly observed before the 2018 earthquake with a magnitude of 7 SR is similar to the anomaly recorded before the 6.9 SR earthquake. There was an increase in seismic activity around 2017 and 2018, which can be attributed to the significant earthquake in 2018, indicating that previously accumulated energy was released as large magnitude earthquakes.

Figure 8 illustrates the spatial distribution of z-values in the West Nusa Tenggara region at the start of 2023.



(a)



(b)

(c)

(d)

Figure 8. Spatial Distribution of Z-Value in West Nusa Tenggara region with iwl =1.5 Years (a) Cut at 2019 (b) Cut at 2020 (c) Cut at 2021 (d) Cut at 2022

Figure 8 provides an overview of the z-value distribution in the West Nusa Tenggara region. It shows that at the start of 2019, 2020, 2021, and 2022, certain areas in West Nusa Tenggara experienced a seismic quiescence phenomenon. This phenomenon was observed in the marine areas around Bima, Sumbawa, and Lombok Island. This shows that there are several areas in West Nusa Tenggara that should be suspected of significant earthquakes in the future.

From the earthquake data obtained from the USGS, the Mw value of the main earthquake was 7.0 in the West Nusa Tenggara region in 2018. The Mw price obtained was then substituted into the Ms (Magnitude surface) equation and obtained a Ms value of 6.9. After obtaining the Ms value, then substitute the Ms value into the deformation area equation. So that a deformation area of 1,091,44 km^2 is obtained from the epicenter point in the West Nusa Tenggara region in 2018. Figure 9. is a map of the deformation area.

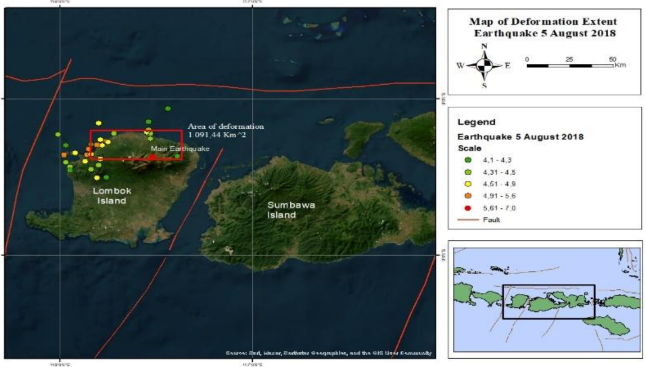


Figure 9. Map of Deformation Area of August 5, 2018 Earthquake

Based on the formulation of Utsu and Seki 1954, the value of the deformation area in the North Lombok, West Nusa Tenggara earthquake on August 5, 2024 is 1,091.44 km^2 from the epicenter point with a magnitude of 7.0. This earthquake was centered on land north of Mount Rinjani. Lombok Island is flanked by the subducting Australian plate in the south and the Flores fault in the north. The Flores fault extends west-east from the north of Bali Island to the north of Nusa Tenggara. As a result of the pressure exerted by the subduction of the Australian plate south of Lombok Island, the long-established Flores fault reactivates, i.e., there is a sudden movement that causes earthquakes.

A positive z-value signifies a reduction in seismic activity within an area, indicating energy accumulation. When energy accumulates, it means that the stress within the rock has not yet surpassed its capacity, preventing the release of accumulated energy. In contrast, a negative z-value points to an increase in seismic activity, signaling an energy release in the region. This occurs when the stress in the rock exceeds its capacity, causing fractures. Consequently, the area experiences heightened seismic activity as the stored energy is gradually released. A significant increase in seismic activity reflects a large-scale, sudden release of energy.

Changes in the number of earthquakes or energy levels in seismically active areas over time are referred to as seismic rate changes. The results indicate noticeable variations in seismic rates both before and after major earthquakes in 2009 and 2018. Prior to a major earthquake, a period of seismic quiescence typically occurs, characterized by reduced seismic activity in the vicinity of the impending earthquake. This calm period is due to stress and strain in the area not exceeding the rock's capacity. When a major earthquake does occur, it releases the accumulated energy as seismic events, with the magnitude reflecting the amount of energy released. Post-earthquake, the area experiences heightened seismic activity as the released energy is substantial, resulting in a negative z-value.

Seismic rate changes are typically accompanied by an expansion of deformation around the main earthquake zone. There is a direct correlation between the magnitude of an earthquake and the extent of the deformation. Larger deformation areas indicate a higher potential for changes in the seismic rate. This is because deformation in the Earth's crust can lead to an accumulation of energy, which is eventually released through an earthquake. Thus, as the magnitude increases, so does the length, width, and overall area of the deformation, resulting in a greater increase in seismic rate changes along the fault plane.

Conclusion

The seismicity of the West Nusa Tenggara region for the period 1983-2023 shows that Nusa Tenggara has a high level of seismic activity. Based on the research that has been done, the results were obtained for the distribution of z values in three focus zones of the research area in West Nusa Tenggara. In the first zone, there was an increase in seismic activity before the 2009 earthquake. The second and third zones before the significant earthquake were preceded by the seismic quiescence phenomenon. In early 2023, the general distribution of z-values in the West Nusa Tenggara region showed a reduction in seismic activity in several areas. And based on calculations using the empirical formulation of Utsu and Seki (1954) for the M7.0 earthquake that occurred on August 5, 2018, the deformation area (A) was 1,091.44 km^2. This can be suspected as an early sign of an earthquake in the future.

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