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Statistical Analysis of Seismicity in West Sumatra (2015–2025) and Aftershock Decay of the 2009 Padang Earthquake Using Gutenberg–Richter and Omori–Utsu Laws

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Abstract

Previous studies on seismicity in West Sumatra have generally focused either on frequency–magnitude distribution or aftershock decay separately, with limited integration of updated earthquake catalogs and combined statistical approaches. This study examines the seismicity of West Sumatra using the Gutenberg–Richter (GR) law and the Omori–Utsu aftershock decay model for the 30 September 2009 Padang earthquake. Earthquake catalogs from the United States Geological Survey (USGS) covering the last ten years and the aftershock sequence of the 2009 event were analyzed. The GR law was applied through cumulative frequency–magnitude distributions to estimate the *a*- and *b-values*, which represent seismic activity level and magnitude distribution. The Omori–Utsu model was used to determine the decay parameter *p* and the initial aftershock activity constant *K*. The results show a strong linear frequency–magnitude relationship with a relatively high *b-value*, indicating dominant small- to moderate-magnitude earthquakes and high seismicity. Aftershock activity follows the Omori–Utsu decay pattern with a moderately slow decay rate. These results emphasize the influence of subduction zone dynamics and provide important implications for earthquake hazard mitigation in West Sumatra. These results provide updated seismic parameters for West Sumatra, support regional seismic hazard modeling, and contribute to refining empirical parameter estimation for the Sunda subduction setting.

INTRODUCTION

Indonesia is one of the regions with the highest seismicity levels in the world due to its location at the convergence of three active tectonic plates, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate [1], [2]. The complex interactions among these plates trigger intense tectonic activity, including the development of active subduction zones and dynamically evolving onshore fault systems. This condition makes Sumatra Island, particularly the West Sumatra region, highly susceptible to earthquake occurrences with a high level of seismic hazard [3].

West Sumatra Province is located directly along the convergent boundary between the Eurasian Plate and the Indo-Australian Plate and is therefore dominated by the presence of an active subduction zone formed through plate collision and subduction mechanism [4]. This tectonic configuration generates various earthquake sources, both those associated with the subduction zone (megathrust) and active onshore fault systems. Consequently, seismic activity in this region is intense and has the potential to generate large-magnitude earthquakes [5]. The distribution of seismicity, active fault systems, and plate boundaries in the Sumatra region is generally illustrated in Figure 1 [6].

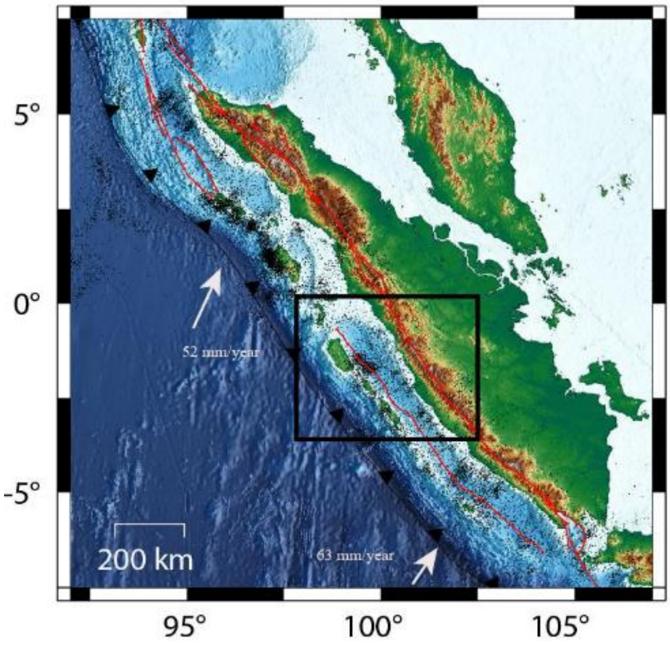

Figure 1. Tectonic processes occurring in the Sumatra subduction zone

One of the most significant seismic events in West Sumatra was the Padang earthquake on 30 September 2009, with a magnitude of Mw 7.6 and a focal depth of approximately 80 km [7]. This event was recorded as the strongest earthquake ever to strike Padang City and caused widespread damage [8]. However, this earthquake was not directly associated with the main energy release along the Sumatra megathrust at the convergent boundary between the Indo-Australian and Eurasian plates [9]. This indicates that tectonic energy accumulation along the Mentawai/West Sumatra megathrust segment has not been fully released, suggesting that the potential for future large earthquakes capable of triggering tsunamis remains.

Earthquake activity generates seismic waves or signals that can be recorded by seismographic instruments and analyzed either automatically or manually to obtain various earthquake parameters, such as origin time, magnitude, epicenter location, and hypocentral depth [10]. Analysis of these parameters enables the application of statistical seismology to quantitatively characterize the seismicity of a region. Statistical seismicity studies in West Sumatra indicate an a-value of 5.28 and a b-value of 0.65, reflecting a moderate level of seismicity with a tendency toward high rock stress accumulation [11]. The physical meaning of seismic parameters is important in statistical seismology. The b-value in the Gutenberg–Richter law is commonly related to the regional stress state and crustal heterogeneity, where high b-values generally indicate dominant small earthquakes and more heterogeneous stress conditions, whereas low b-values may reflect higher stress accumulation. Meanwhile, the p-value in the Omori–Utsu law represents the rate of aftershock decay and can be interpreted as an indicator of post-seismic stress relaxation. Lower p-values suggest slower aftershock decay and more gradual redistribution of stress, which may also reflect viscoelastic adjustment following a major earthquake.

Despite numerous studies on seismicity in West Sumatra, several limitations remain. Previous research has generally analyzed the Gutenberg–Richter frequency–magnitude relationship or the Omori–Utsu aftershock decay separately, resulting in a fragmented understanding of regional seismic behavior. In addition, reported b-values and aftershock decay parameters (p-values) often show variability due to differences in data selection, magnitude completeness, and observation periods, leading to inconsistencies in the interpretation of seismic hazard. Furthermore, studies utilizing updated earthquake catalogs in the last decade are still limited, and comprehensive analyses integrating both Gutenberg–Richter and Omori–Utsu approaches within a single regional framework remain scarce. Therefore, a re-evaluation of seismicity using recent data, combined with a unified statistical approach, is necessary to provide a more consistent and up-to-date characterization of earthquake behavior in West Sumatra, particularly in the context of post-2009 Padang earthquake conditions.

Furthermore, the decay characteristics of aftershocks in West Sumatra generally follow the Omori–Utsu law, with variations in aftershock duration and intensity reflecting differences in earthquake source mechanisms and local tectonic conditions [12]. Therefore, this study aims to estimate updated seismic parameters of West Sumatra using the Gutenberg–Richter and Omori–Utsu approaches. Specifically, the study is intended to: (1) estimate the updated a-value and b-value to characterize the level and magnitude distribution of regional seismicity during the 2015–2025 period; (2) evaluate the statistical stability of regional seismicity through the frequency–magnitude relationship; and (3) compare the background seismicity of West Sumatra with the aftershock decay characteristics of the 30 September 2009 Padang earthquake through the estimation of the Omori–Utsu decay parameter. Through these objectives, this study seeks to provide a more integrated statistical interpretation of seismicity in West Sumatra in relation to stress heterogeneity and post-seismic relaxation [13], [14].

RESEARCH METHODS

Gutenberg–Richter Law Analysis

The analysis of regional seismicity levels was conducted using the Gutenberg–Richter (GR) law, which describes the relationship between earthquake occurrence frequency and magnitude through the frequency–magnitude distribution [15], [16], [17], [18]. This relationship is expressed as:

$$log_{10} N(m) = a - bM \tag{1}$$

where $N(M \geq m)$represents the cumulative number of earthquakes with magnitudes greater than or equal to m. The *a-value* represents the seismicity level of the region, while the *b-value* indicates the relative proportion between small- and large-magnitude earthquakes.

The data used in this study consist of an earthquake catalog for the West Sumatra region covering the period 2015–2025, obtained from the United States Geological Survey (USGS). The analysis was performed by calculating the cumulative frequency–magnitude distribution for each magnitude interval and subsequently transforming it into the logarithmic domain to obtain a linear relationship between $\log_{10} N$ and magnitude M.

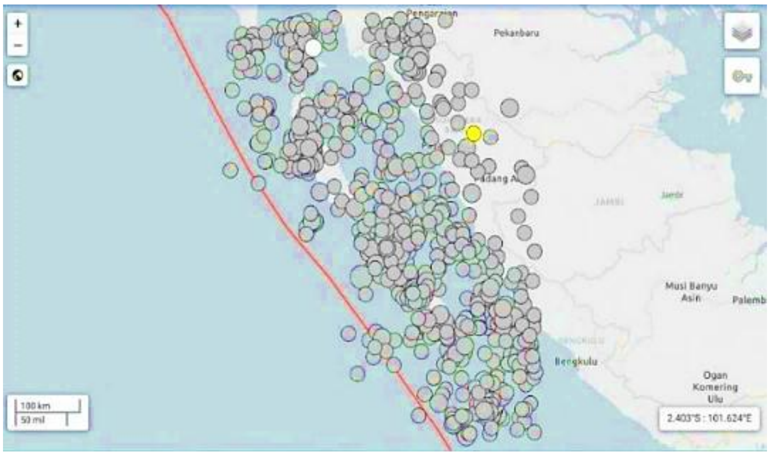

Figure 2. Earthquake distribution map of West Sumatra for the period 2015–2025

The estimation of seismicity parameters was carried out using the Maximum Likelihood Estimation (MLE) method and linear regression to improve the stability of the estimates, particularly for catalogs with a wide magnitude range. The *b-value* was calculated using the following equation:

$$b = \frac{1}{\ln(10)\,[\bar{M} - (M_c - \Delta M/2)]} \tag{2}$$

where $\bar{M}$ is the mean magnitude of earthquakes with $M \geq M_c$, M_c is the magnitude of completeness, and $\Delta M = 0.1$. Subsequently, the *a-value* was determined using the equation:

$$a = \log N + \log(b \ln 10) + bM_c \qquad (3)$$

where N denotes the total number of earthquake events with magnitudes $M \geq M_c$.

The determination of the magnitude of completeness (M_c) was conducted carefully, as it directly affects the accuracy of the estimated *b-value* and *a-value*. Errors in determining M_c may lead to bias in seismicity parameters and influence the interpretation of regional seismicity levels [11].

Omori Law Analysis

The decay of aftershock activity was analyzed using the Omori–Utsu law, which describes the relationship between aftershock occurrence frequency and time elapsed since the mainshock [19], [20], [21]. This relationship is expressed as:

$$n(t) = \frac{a}{(t+c)^b} \qquad (4)$$

where $n(t)$ is the number of aftershocks at time t, parameter a represents the initial level of aftershock activity, parameter b (or p) indicates the decay rate of seismic activity, and parameter c is a small time constant introduced to avoid singularity at $t = 0$ [22].

This analysis was applied to the aftershock sequence following the Padang earthquake of 30 September 2009. Aftershock data were obtained from the USGS catalog. The analysis procedure began by calculating the time difference between each aftershock event and the mainshock. The data were then grouped into logarithmic time intervals to reduce data sparsity at longer observation times. The number of aftershocks in each interval was subsequently plotted against time to identify the decay pattern of seismic activity.

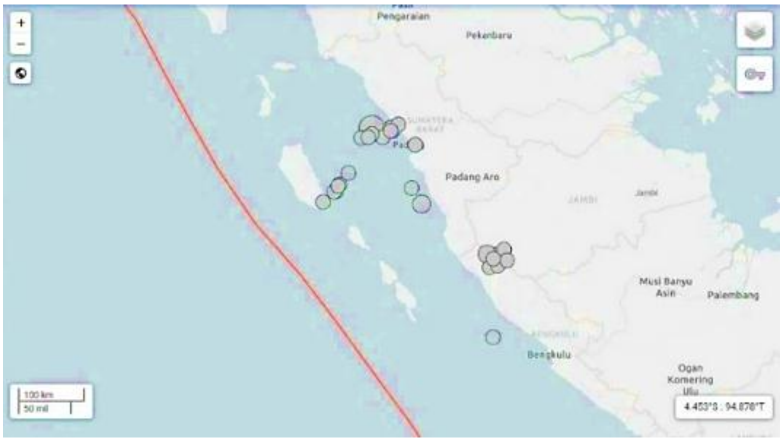

Figure 3. Earthquake distribution map of the Padang earthquake on 30 September 2009

The Omori–Utsu parameters (a, b, and c) were estimated using nonlinear curve fitting with the Levenberg–Marquardt algorithm. To support parameter evaluation, the Omori–Utsu equation was transformed into a logarithmic form as follows:

$$log\ N(t) = log\ a - b\ log(t + c) \qquad (5)$$

The parameter $p(b)$ was used to evaluate the decay rate of aftershock activity, while parameters a and c provide information on the initial conditions and temporal characteristics of seismic activity following the mainshock. Model validation was performed through curve-fitting analysis against observational data and error evaluation to ensure that the obtained parameters reliably represent aftershock behavior.

RESULTS AND DISCUSSION

Gutenberg–Richter Law Analysis for West Sumatra

Based on the seismicity data of the West Sumatra region, the Gutenberg–Richter (GR) law analysis was conducted using the cumulative frequency distribution of earthquake occurrences with respect to magnitude. The data are presented in the form of a frequency–magnitude table in Table 1, which includes magnitude classes (M), the number of earthquake events in each magnitude class (N), cumulative earthquake frequency, and the corresponding values of $log_{10} N$ derived from the cumulative frequency. The use of cumulative frequency and logarithmic transformation aims to facilitate the identification of a linear relationship between magnitude and earthquake occurrence frequency, as formulated in the GR law.

Table 1. Cumulative frequency distribution of earthquake occurrences by magnitude in the West Sumatra region

M (mb)	N	M(mw)	$\log_{10}$ N (≈)
4	220	5,16	2,342423
4,2	164	5,24	2,214844
4,4	159	5,32	2,201397
4,6	98	5,4	1,991226
4,8	65	5,48	1,812913
5	50	5,57	1,69897
5,2	30	5,66	1,477121
5,4	13	5,75	1,113943
5,6	11	5,84	1,041393
5,8	7	5,93	0,845098
6	4	6,03	0,60206
6,2	2	6,13	0,30103

The results presented in Table 1 indicate that the value of $\log_{10} N$ decreases consistently with increasing earthquake magnitude. This pattern demonstrates that small-magnitude earthquakes occur at a much higher frequency than large-magnitude events. This relationship is visualized in the frequency–magnitude distribution graph shown in Figure 4, where magnitude is plotted on the horizontal axis and $\log_{10} N$ on the vertical axis. The graph exhibits a clear downward linear trend, reflecting the statistical characteristics of seismicity in West Sumatra and its strong conformity with the Gutenberg–Richter theory.

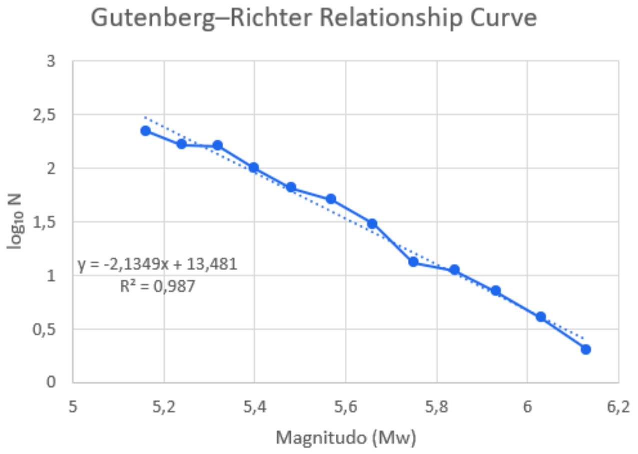

Figure 4. Frequency–magnitude curve for the West Sumatra region.

Linear regression analysis of the data in Figure 4 yields the equation $\log_{10} N = 13.481 - 2.1349\, M$ with a coefficient of determination of $R^2 = 0.987$. The R^2 value, which is very close to unity, indicates an excellent level of agreement between the observed data and the GR model. This result suggests that the frequency–magnitude relationship of earthquakes in the West Sumatra region can be represented very reliably by the GR law. It further implies that the seismogenic processes in the study area are characterized by a statistically stable (stationary) seismic regime within the analyzed magnitude range.

The slope of the regression line, corresponding to the *b-value* of $b = 2.1349$, indicates a strong dominance of small- to moderate-magnitude earthquakes relative to large-magnitude events. When compared with the classical Gutenberg–Richter reference value, which generally reports *b-values* close to 1 (approximately b ≈ 0.8 – 1.0), for global earthquake frequency–magnitude distributions [15], The slope of the regression line, corresponding to the *b-value* of $b = 2.1349$, indicates a strong dominance of small- to moderate-magnitude earthquakes relative to large-magnitude events. When compared with the classical Gutenberg–Richter reference value, which generally reports *b-values* close to 1 ((approximately b ≈ 0.8 – 1.0), for global earthquake frequency–magnitude distributions [23]. rom a seismotectonic perspective, this condition reflects intense stress fragmentation in West Sumatra due to the interaction between the subduction zone and active fault systems [24], [25]. Nevertheless, a high *b-value* does not eliminate the potential for large earthquakes, as long-term stress accumulation may still occur on specific tectonic segments. Therefore, despite the relatively lower frequency of large earthquakes, the seismic hazard level in West Sumatra remains significant and must be considered in disaster mitigation efforts [11].

Meanwhile, the intercept of the regression line, represented by an *a-value* of $\alpha = 13{,}481$ reflects a very high absolute level of seismic activity in the West Sumatra region. This value indicates a large total number of earthquake events during the observation period, which is consistent with the highly active tectonic setting of West Sumatra due to the interaction between the Indo-Australian and Eurasian plates and the presence of the Sumatra Fault system. The high *a-value* signifies intense seismicity, in line with high crustal deformation rates and continuous stress accumulation.

From a disaster mitigation perspective, the combination of a very high *a-value* and a *b-value* of 2.1349 emphasizes that seismic risk in West Sumatra is primarily controlled by the high frequency of small- to moderate-magnitude earthquakes. Repeated earthquake occurrences can lead to cumulative damage to buildings and infrastructure, particularly if structures are not designed according to earthquake-resistant standards. Therefore, the results of this GR law analysis provide a strong scientific basis for the development of seismic hazard maps, risk-based spatial planning, and the strengthening of mitigation policies and earthquake-resistant building regulations in the West Sumatra region.

Beyond its statistical meaning, the relatively high b-value obtained in this study may also reflect the physical characteristics of the stress regime in West Sumatra. A high b-value is commonly associated with a more heterogeneous fault system and fragmented stress release, in which accumulated tectonic stress is accommodated through numerous small- to moderate-sized fracture events rather than being concentrated in a few large ruptures. In the context of West Sumatra, this condition may be related to the complex interaction between the Sunda subduction zone, the Mentawai forearc region, and the Sumatra Fault system. Such tectonic complexity may produce spatially variable stress conditions and fault heterogeneity, which favor distributed seismic release. In addition, variations in plate coupling along the subduction interface may also contribute to this pattern, because non-uniform coupling can cause some segments to accumulate stress more effectively while others release strain through more frequent smaller earthquakes. Therefore, the observed magnitude distribution may reflect not only high seismicity, but also the fragmented and heterogeneous character of the regional stress field.

Omori–Utsu Law Analysis of the 2009 Padang Earthquake

The analysis of aftershock activity following the 30 September 2009 Padang earthquake was carried out by applying the Omori–Utsu law to estimate the decay rate of aftershock occurrences over time. The data used consist of the daily number of aftershocks during the first 12 days after the mainshock, as presented in Table 2.

Table 2. Omori law calculation data for aftershock activity following the 30 September 2009 Padang earthquake

Day (t)	Number of Aftershocks per Day n(t)	t+c	log10(t+c)	log10(n)
1	6	2	0,301029996	0,77815125
2	4	3	0,477121255	0,602059991
3	1	4	0,602059991	0
4	1	5	0,698970004	0
5	1	6	0,77815125	0
6	1	7	0,84509804	0
7	1	8	0,903089987	0
8	1	9	0,954242509	0
9	2	10	1	0,301029996
10	1	11	1,041392685	0
11	1	12	1,079181246	0
12	1	13	1,113943352	0

In this table, the time variable t represents the number of days after the mainshock, while the daily aftershock count $n(t)$ reflects the level of daily seismic activity. For quantitative analysis, the data were transformed into logarithmic form, namely $\log_{10}(t+c)$ and $\log_{10}(n(t))$, with the parameter $c = 1$. The choice of this value aims to avoid mathematical singularity at $t = 0$ and represents a common approach in aftershock studies in the Sumatra region.

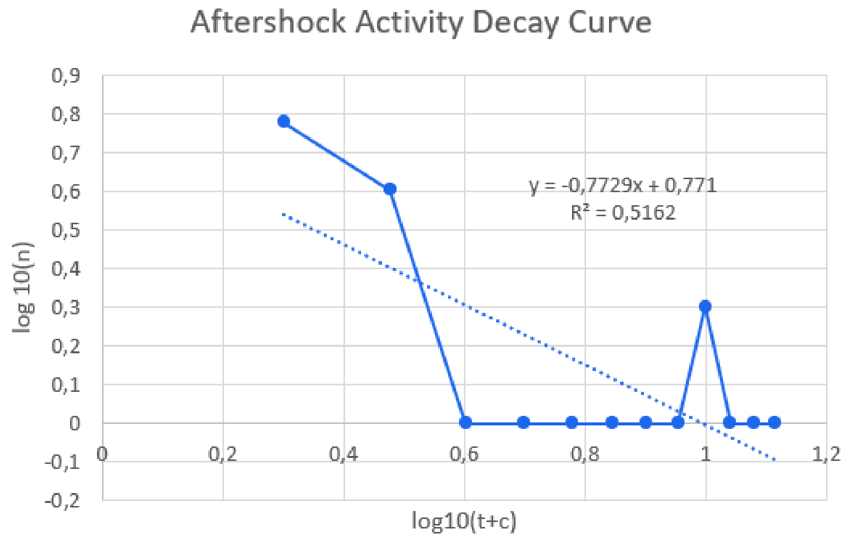

Figure 5. Decay of aftershock activity following the 30 September 2009 Padang earthquake based on the Omori law

The graph in Figure 5 illustrates the relationship between $\log_{10}(t+c)$ on the horizontal axis and $\log_{10}(n(t))$ on the vertical axis. Each data point represents the level of aftershock activity on a specific day following the mainshock. The observed pattern shows a general decreasing trend in $\log_{10}(n(t))$ with increasing time, indicating that the frequency of aftershock occurrences decreases progressively from day to day. Although local fluctuations are observed on several days, particularly during the intermediate observation period, the overall trend clearly reflects a decay pattern.

The logarithmic transformation of the aftershock data results in a linear relationship between $\log(t+c)$ and $\log(n)$, which was subsequently analyzed using linear regression. The regression analysis yields the equation $y = -0.7729x + 0.771\, y$ resulting in a decay parameter of $p = 0.7729$ and an initial activity constant of $k = 10^{0.771} \approx 5.9$. Based on these parameters, the Omori–Utsu model for the aftershock sequence of the 2009 Padang earthquake can be expressed as:

$$n(t) = \frac{5.9}{(t+1)^{0.7729}} \tag{6}$$

The value of the decay parameter p, which is less than one, indicates that the aftershock decay rate is relatively slower than that predicted by the classical Omori model, suggesting that aftershock activity persisted for several days following the mainshock. This p-value falls within the empirical range commonly reported for tectonically active regions, particularly subduction zones, and is consistent with the Omori–Utsu theory and previous studies reporting p-values in the range of 0.7–1.8 as typical for aftershock sequences in Sumatra and the Sunda subduction zone [23], [26]. Meanwhile, the moderate value of the constant K indicates that the initial aftershock activity level was not extreme but still reflects a significant seismic response immediately following the mainshock, particularly during the early post-earthquake phase [27].

The coefficient of determination obtained, $R^2 = 0.5162$, indicates that approximately 51.6% of the variation in aftershock data can be explained by the Omori–Utsu model. This value is considered reasonable given the relatively short data span of only 12 observation days and the substantial daily fluctuations in aftershock counts observed on several days. In short-term aftershock catalog analyses, R^2values in the range of 0.5–0.7 are generally regarded as adequate for representing the overall decay trend of seismic activity.

From a physical perspective, the p-value obtained from the Omori–Utsu analysis may be interpreted as reflecting the post-seismic stress adjustment process following the 2009 Padang earthquake. The relatively low p-value indicates that aftershock decay was not very rapid, suggesting that stress redistribution continued progressively after the mainshock. In a tectonically complex subduction environment such as West Sumatra, this behavior may be associated not only with continued readjustment on surrounding fault patches, but also with viscoelastic relaxation in the lithosphere and upper mantle. Furthermore, the segmented structure of the Mentawai subduction system may influence the temporal persistence of aftershocks, since stress transfer and release are unlikely to occur uniformly across all segments. As a result, the observed aftershock sequence may reflect a combination of fault heterogeneity, variable subduction coupling, and gradual post-seismic viscoelastic relaxation.

Overall, the aftershock decay curve and the estimated Omori–Utsu parameters demonstrate that the aftershock activity following the 2009 Padang earthquake follows a statistical behavior consistent with aftershock decay theory. From a disaster mitigation perspective, these results provide important insights into post-earthquake stress evolution and the critical time period following a major earthquake. The significant decrease in aftershock activity during the first few days indicates that the early post-earthquake phase represents a period of elevated secondary seismic risk, requiring heightened vigilance, emergency management, and stricter control of community activities. Although aftershock analysis cannot be used to directly predict the timing and location of future large earthquakes, decay patterns that follow the Omori–Utsu law can serve as a valuable basis for short-term risk assessment and more effective disaster response planning in the West Sumatra region.

Integrated Interpretation of Gutenberg–Richter and Omori–Utsu Parameters

Although the Gutenberg–Richter and Omori–Utsu analyses were carried out separately, both sets of parameters can be interpreted jointly to provide a more complete description of seismic behavior in West Sumatra. The b-value obtained from the Gutenberg–Richter law reflects the degree of stress heterogeneity and the relative proportion of small- to large-magnitude earthquakes, whereas the p-value derived from the Omori–Utsu law represents the rate of post-mainshock stress relaxation through aftershock decay. Therefore, the combined interpretation of these two parameters is important for understanding not only the magnitude distribution of earthquakes, but also the temporal evolution of seismic activity after a major event.

In this study, the relatively high b-value indicates that the seismicity of West Sumatra is dominated by small- to moderate-magnitude earthquakes. Such a pattern may reflect a tectonic environment with relatively heterogeneous stress distribution, where accumulated strain is released through numerous smaller fracture events rather than predominantly through larger ruptures. On the other hand, the p-value of 0.7729 indicates that the decay of aftershock activity following the 2009 Padang earthquake was relatively slow, implying that stress relaxation did not occur instantaneously but instead persisted for several days after the mainshock. Taken together, these results suggest that the tectonic system in West Sumatra accommodates deformation through distributed seismic release followed by gradual post-seismic adjustment.

A physically important question is whether a high b-value is associated with a low p-value. In principle, these two parameters do not have a simple or universal one-to-one correlation, because they describe different aspects of the earthquake process. However, from a seismotectonic perspective, a relatively high b-value may be consistent with a relatively low p-value when the crustal medium is heterogeneous and stress is redistributed across many small fault patches. Under such conditions, numerous small earthquakes may continue to occur after the mainshock, thereby prolonging aftershock activity and producing a slower decay pattern. Thus, although this study does not statistically test the correlation between b-value and p-value, the observed combination of high b-value and moderate-to-low p-value may indicate that stress heterogeneity in West Sumatra contributes to relatively sustained aftershock activity [14].

Another important aspect is whether the magnitude distribution influences the aftershock decay rate. The results of this study suggest that it may. A seismic sequence dominated by small-magnitude earthquakes tends to maintain a relatively persistent level of low-intensity seismic activity, because many small failures continue to occur as the crust adjusts after the mainshock. This condition can make the observed aftershock decay appear slower and lead to a lower p-value. In contrast, if the sequence were dominated by fewer but larger aftershocks, stress release might become more concentrated and the decay could proceed more rapidly. Therefore, the dominance of small- to moderate-magnitude earthquakes reflected by the high b-value in West Sumatra may partly explain the moderate-to-slow aftershock decay represented by the Omori–Utsu p-value.

From the perspective of seismic hazard, this combined interpretation shows that earthquake risk in West Sumatra is controlled not only by the high frequency of events, but also by the persistence of post-mainshock seismic activity. In other words, the regional hazard is shaped by both the frequency–magnitude structure of seismicity and the temporal decay characteristics of aftershocks. This finding highlights the importance of integrating Gutenberg–Richter and Omori–Utsu parameters in regional seismic studies, since such an approach provides a more physically meaningful basis for hazard assessment, emergency response planning, and post-earthquake risk mitigation.

CONCLUSION

This study demonstrates that the seismicity of West Sumatra is statistically well described by the Gutenberg–Richter and Omori–Utsu models. The estimated a-value of 13.481 indicates a high level of seismic activity in the region, while the b-value of 2.1349 suggests that the earthquake population is dominated by small- to moderate-magnitude events and may reflect relatively heterogeneous stress conditions. The Gutenberg–Richter relationship also shows an excellent fit, with R^2 close to 1, indicating that the frequency–magnitude distribution is highly consistent with the model. Although the estimated b-value is relatively high for a subduction-related setting, it should be interpreted with caution, and further investigation is required to evaluate catalog completeness, magnitude conversion effects, and the temporal stability of the estimated parameters.

For the 2009 Padang earthquake sequence, the estimated decay parameter $p = 0.7729$ suggests a relatively slow decrease in aftershock activity, indicating gradual post-seismic stress relaxation. The Omori–Utsu model produced a moderate fit with $R^2 = 0.516$, which is still sufficient to capture the general decay trend of the aftershock sequence despite daily fluctuations and the relatively short observation period.

Overall, these results confirm that West Sumatra is characterized by high seismicity, dominance of lower-magnitude earthquakes, and persistent post-mainshock activity. The combined interpretation of the a-, b-, p-values, and R^2 provides useful information for seismic hazard assessment, post-earthquake emergency response, and the development of more data-driven mitigation strategies in this tectonically active region.

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