Completeness magnitude (Mc) and b-value characteristics as important parameters for future seismic hazard assessment in The West Papua province Indonesia

by Richard Lewerissa

Completeness magnitude (Mc) and b-value characteristics as important parameters for future seismic hazard assessment in The West Papua province Indonesia

Richard Lewerissa[1*], Rizal Rumakey[1], Yasir Abdan Syakur[1], Laura Lapono[2]

[1] Department of Physics, Faculty of Mathematics and Natural Sciences, Papua University; Papua Barat, Manokwari 98314, Indonesia.

[2] Department of Physics, Faculty of Sciences and Engineering, Nusa Cendana University; Nusa Tenggara Timur, Kupang 85148, Indonesia.

[*]Corresponding Authors: r.lewerissa@unipa.ac.id

Abstract: West Papua Province in eastern Indonesia is located in a complex tectonic environment formed by the convergence of Australia, Pacific, and Eurasian plates. This interaction has many significant strike-slip faults, especially Koor, Sorong, Ransiki, and Yapen, all of which are susceptible to main and destructive earthquakes. The purpose of our research is to estimate and update seismotectonic parameters, such as the magnitude of completeness (Mc), a, and b values, which are important factors for seismic risk assessment using IRIS seismic catalog data of West Papua. The estimation first converts all types of magnitudes into moment magnitudes (M_w) to simplify the earthquakes declustering process. The de-clustering method divides this area into two main clusters. The frequency magnitude distribution (FMD) of the Gutenberg-Richter equation shows that the dominant earthquake occurs on the main fault line, and the average values of Mc, a, and b are 4.3, 7.02, and 0.92 ± 0.02, respectively. The b value in the study area is at a medium level, which is inferred to be related to the structural characteristics and the strike-slip focal mechanism (b~1). In particular, calculating the values of Mc, a, and b in the path around the Ransiki-Yapen fault shows that the value of b decreased by 0.84 ± 0.02, indicating that the crustal stress level has increased. The temporal variation of b values in the two major earthquakes of 2002, 7.5 M_w and 7.7 M_w in 2009, showed a pattern of decreasing b values several months before the event, then increasing after the major earthquakes. It may be connected to the building and the release of stress, the occurrence of ruptures, or many aftershocks. This work is expected to be useful in future research in determining parameters of input, seismic sources, and sites in West Papua utilizing probabilistic seismic hazard analysis (PSHA).

Key words: Magnitude of completeness; b-value; strike-slip faults; Seismic Hazard; West Papua.

1. Introduction

The convergence of the Australian, Eurasian, Pacific, and Philippine sea plates has resulted in a highly deformed area in eastern Indonesia. The Bird's Head region of West Papua province has a highly complicated geological structure. Oblique convergence at an angle of 60° between the Australian and Pacific plates occurs across Papua and West Papua in a complex zone of strain partitioning between shortening and left lateral shear. The majority of the westward shortening occurs in various structures in the New Guinea and Manokwari trenches, the Memberamo fold belt, and the central highlands to southern (Watkinson & Hall, 2017). In the northern part of West Papua province, the Manokwari trough is the boundary of tectonic plate convergence. The trench is generated by subduction of the Caroline-Pacific oceanic crust beneath the Australian continental crust at a rate of 114 mm/year. Manokwari trough is considered to be a source of earthquake activity in Papua's Bird's Head, which is associated to significant strike-slip faults including the Koor, Sorong, Ransiki, and Yapen faults (Daniarsyad & Suardi, 2017). According to the IRIS earthquakes explorer, between 1964 and 2021, there were 2807 earthquakes event with magnitudes ranging from 3.5 to 7.7, mainly shallow earthquakes (Figure 1).

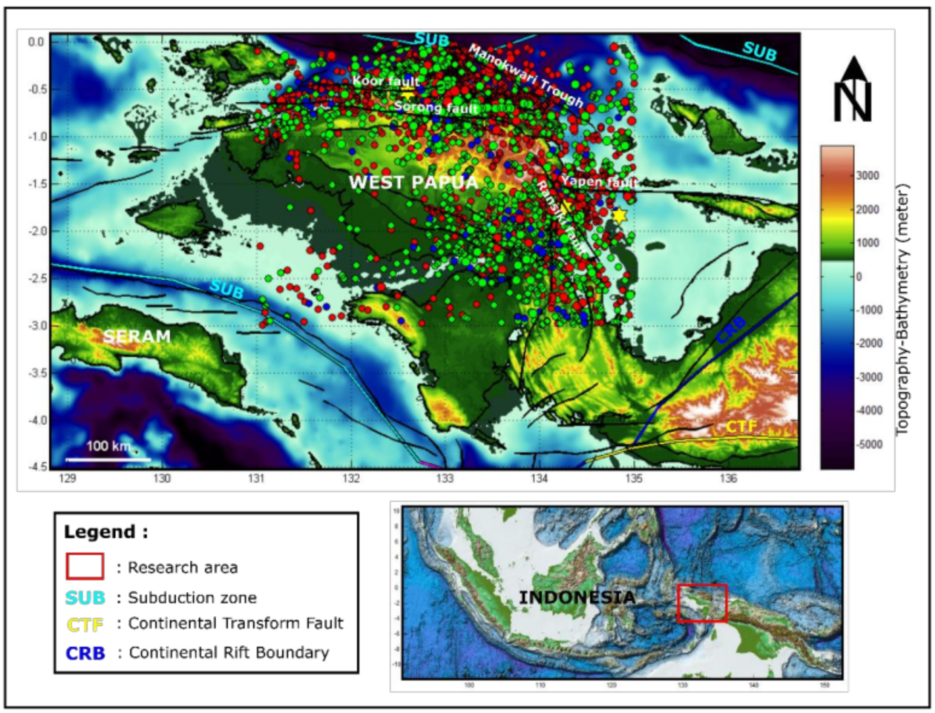


Figure 1. The distribution of earthquakes with magnitudes 3.5–8.0 in West Papua based on the USGS and ISC compilation catalogs from the IRIS Earthquakes Explorer (Modified from Bird, 2003; Luis, 2007).

On October 10, 2002, a large earthquake with a magnitude of 7.5 M_w struck the Ransiki fault line at a depth of 24.8 km. Furthermore, on January 3, 2009, a significant earthquake with a maximum magnitude of 7.7 M_w at a depth of 17 km near the Papua Bird Head on the Sorong and Koor fault lines caused some serious damage in the Sorong and Manokwari regions. This earthquake was caused by the active movement of the Sorong fault, which extends from West Papua to Maluku and the eastern part of Sulawesi (Rohadi, 2015). On 21 April 2012, the Ransiki area was hit by a major earthquake at a depth of 6.7M_w, inflicting moderate and significant structural damage and loss of life (Serhalawan & Sianipar, 2017). A comprehensive seismic study by growth and physical infrastructure in West Papua province will be necessary to evaluate the potential seismic risk of the earthquake to infrastructure in the region. Earthquakes have a very severe effect on people and are one of the most hazardous natural catastrophes. In general, seismic studies try to designate future earthquake-prone regions to minimize the negative human consequences (Kalaneh & Agh-Atabai, 2016). Seismic hazard analysis aims to predict earthquakes and subsequent shocks using a probabilistic framework to quantify uncertainties across complicated systems. There are two fundamental components: seismic sources and ground movements (M. C. Gerstenberger et al., 2020). Several researchers, especially West Papua, have previously performed earthquake and seismic hazard investigations in Papua Island.

Serhalawan and Sianipar, (2017) have researched the mechanism of earthquake sources to determine faults based on the occurrence of the Ransiki earthquake with a magnitude of 6.7 M_w in 2012. The results indicate that the Yapen Fault generated the earthquakes in the west-east a left shear mechanism, rather than the Ransiki Fault (Serhalawan & Sianipar, 2017). Other research has also been conducted on the fault system at the triple junction in East Indonesia with the Sorong, Koor, and Rasiki faults provide to evaluate quaternary activities and their impact on seismic hazards (Watkinson & Hall, 2017). The investigation was carried on spatial and temporal change in b value seismotectonic parameters to determine the seismic trend and future earthquakes in Papua and West Papuav(Rohadi, 2015). In two territories: Indonesia, and Papua New Guinea, Makrup et al. (2018) employed a PSHA method for the seismic hazards map for Papua Island. According to this research, the ground motion on Papua Island is 0.06 g–2.01 g at a probability of 10% over 50 years (Makrup et al., 2018).

Some relevant research shows that seismic investigations have been conducting in the regional territories of Papua and West Papua. In a smaller area, the focus of the infrastructure development of West Papua, more specialized research is required. Our research is a preliminary evaluation of the seismic hazard potential in West Papua Province as the main path of strike-slip faults of the Sorong, Koor, Ransiki, and Yapen in the Bird's Head region to prevent future earthquake damage using the PSHA approach. As the main parameters of the PSHA method, the magnitude of completeness (Mc), a, and b values are estimating from the earthquake catalog in the Province of West Papua. Accurate information from Mc is critical for determining various seismicity characteristics such as a and b values (Lamessa et al., 2019). Besides, the b value is an essential seismic parameter in assessing possible seismic hazards (Xie et al., 2019).

Small b values usually imply changes in rock characteristics, such as stress loads and strains, fractured media, rapid deformation, and major faults. A low b value is also the inverse of a high-stress level, which will be used to anticipate future large earthquakes (Hussain et al., 2020). The objective of our study is to estimate the variation of Mc and b values from the IRIS earthquake catalogs for the period 1964 – 2021 in West Papua, and specifically simulated in the regency of Manokwari and South Manokwari as provincial capitals and areas close to fault lines: Sorong, Ransiki and Yapen. The estimation stage begins with the conversion of various magnitudes to homogeneous magnitudes, notably M_w, earthquake catalog declustering, and analysis of temporal variations based on Mc, a, and b values before and after the 7.5 M_w Ransiki earthquake on October 10, 2002, and the 7.7 M_w Sorong earthquake on January 4, 2009. It is expected that this research will be able to provide an initial description of the updated seismotectonic parameters used to estimate the potential for earthquake hazards in the province of West Papua, which will be expanded for future PSHA analysis in several important development centers near and traversed by major Sorong and Ransiki faults.

2. Tectonic Setting

Eastern Indonesia includes complex tectonic features, especially small faults caused by the convergence of the Eurasian, Pacific, and Australian plates. In the Bird Head area of Papua Island, the active tectonic process is caused by the interaction between the larger plates and the deformation of several smaller microplates with significant strike-slip faults (Gold et al., 2017). The Ransiki fault in the eastern part of Birdhead is believed to be the result of the collision between the Australian plate and the continental arc, extending to the Cenderawasih Bay, east of the Wandamen and connected to the Weyland overthrust in the Central Mountains (Gold et al., 2017; Milsom, 1991; Milsom et al., 1992). At present, the arc rock is mainly formed in the basement of the northern edge of Papua Island, including the bird's head in the east, the Cenderawasih Bay and its islands. The Ransiki fault runs north-northwest (NNW) and is considered to be a right-lateral shear zone connecting the Sorong and Yapen faults, and is considered inactive (Charlton, 2010). The typical section of the Ransiki fault in West Papua is 20-50 km, with a maximum length of 100 kilometers. In addition, the Sorong Fault extends from the north of Salawati to the northeast, through the city of Sorong, and extends to the valley that cuts the northern continent to Manokwari. The width of the area between the mountains and valleys is 15 km (Watkinson & Hall, 2017). The east-west Koor fault is located in the northern part of the Sorong fault, 20-30 km away. The structure is located in the boundary zone between the southern Pacific plate and the continental crust (Dow & Sukamto, 1984).

3. Research Methods

3.1. Earthquake Catalog Data Compilation and Homogeneity in West Papua

This study used seismic data from the IRIS Data Management Center and extracted them at the coordinates 132°-135° E and 0°-3° S in West Papua Province using ZMAP 7 software (Reyes & Wiemer, 2019). The earthquake catalog provides information for identifying seismic sources and calculating seismic activity parameters, such as average seismic activity rate, Gutenberg-Richter b value, and maximum predicted earthquake magnitude (Rahman & Bai, 2018). The seismic event catalog data utilizes 2,574 earthquakes that occurred between 1964 and 2021. The earthquake magnitudes include moment magnitude (M_w), body magnitude (M_b), and local magnitude (M_L), and the depth ranges from 0 to 302.30 km. According to the catalog, three major earthquakes occurred in the study area: November 17, 1985, magnitude 7.1 M_w, October 10, 2002, magnitude 7.5 M_w, and January 4, 2009, magnitude 7.7 M_w (Figure 2).

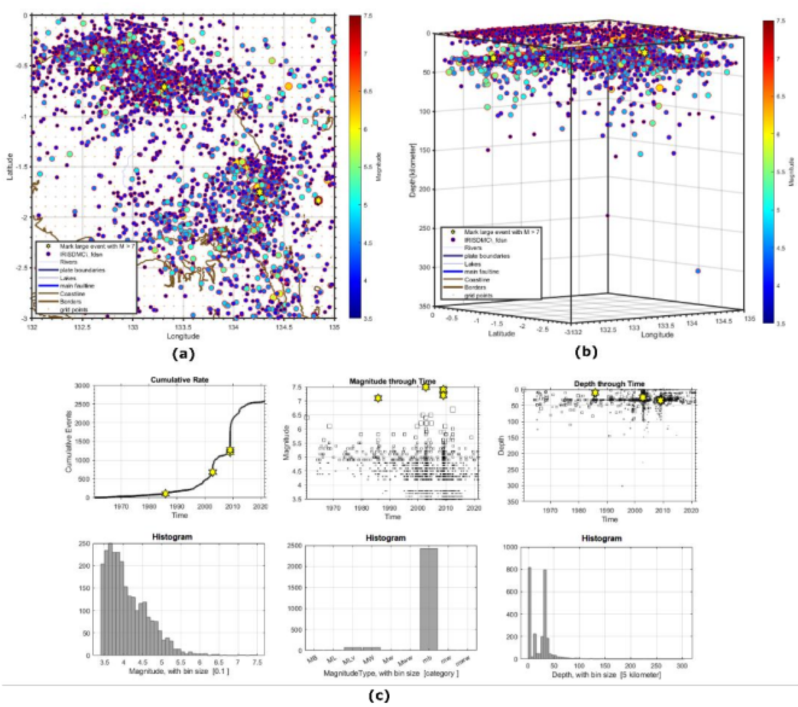


Figure 2. Earthquake catalog in West Papua province, 1964 – 2021; (a) Distribution of earthquake events with a magnitude of 3.5 – 8.0. (b) 3-D model of earthquake distribution in West Papua; (c) Earthquake attributes with respect to time: Cumulative Rate, Histogram of magnitude and depth.

Converting M_b and M_L to M_w into homogeneous magnitude is the first stage of the earthquake catalog processing in West Papua Province. The main goal of this conversion is to provide a standard catalog of all M_w scales to solve basic practical problems such as seismic risk assessment and crustal deformation modeling (Scordilis, 2006). Table 1 shows the statistical distribution of seismic frequency in western Papua divided by magnitude type.

Table 1. Distribution of earthquakes in the West Papua region by type of magnitude for the period 1964 – 2021.

Earthquake Frequency	Type of Magnitude	Minimum	Maximum
2419	M_b	3.5	6.2
85	M_w	4.9	7.7
70	M_L	3.5	4.3

We use a globally valid empirical relationship equation, allowing us to convert the magnitudes expressed on different scales to M_w (Di Giacomo et al., 2015; Scordilis, 2006):

$$M_w = 0.85\, M_b + 1.03;\, 3.5 \le M_b \le 6.2 \quad (1)$$

Convert M_L to M_w, using the relationship equation between M_L and M_w within a wide range acceptable globally (Malagnini & Munafò, 2018):

$$M_w = \frac{2}{3}\, M_L + 1.14;\; M_L \le 4.3 \quad (2)$$

De-clustering follows the algorithm developed by Reasenberg (1985) using a combination of ZMAP 6 and 7 software (Reasenberg, 1985; Reyes & Wiemer, 2019; Wiemer, 2001). The PSHA technique uses the Poisson process, in which the occurrence of future earthquakes has nothing to do with the occurrence of past earthquakes on the same source (Cornell, 1968; Taroni & Akinci, 2020). Poisson's hypothesis is applicable to catalog de-clustering. It records a main shock, but deletes or ignores subsequent earthquake events that cause ground shaking. Furthermore, regarding the spatial variability of future earthquake frequencies, the complete earthquake catalog (not de-clustering) may be biased (Taroni & Akinci, 2020).

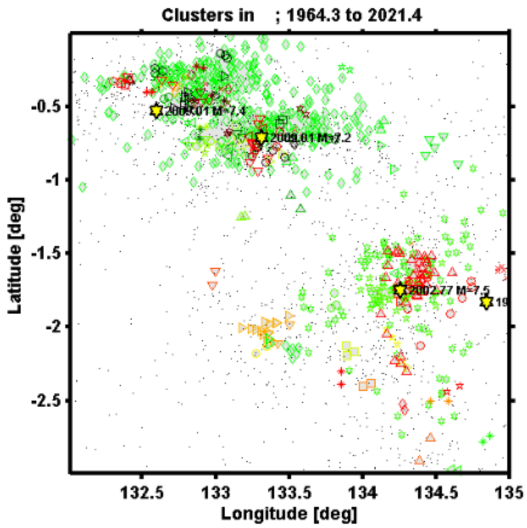


Figure 3. Earthquake declustering model in West Papua Province based on the Reasenberg algorithm (1985) using ZMAP 6 software (Wiemer, 2001).

The de-clustering process resulted in the two main clusters being concentrated on the strike-slip fault line. There were a total of 2,574 and 1,914 earthquakes, of which 742 earthquakes were lost (Figure 3).

3.2. Estimated Magnitude of Completeness (Mc) and b Value in West Papua

The first step in determining the seismic parameter values a and b is to calculate the Magnitude of Completeness (M_c) of the West Papua earthquake catalog. M_c denotes the minimum magnitude parameter of the whole record, which is critical for most seismicity investigations. As the number of seismographs and analysis methodologies rises, the M_c value in most earthquake catalogs tends to decrease with time (Wiemer & Wyss, 2000). The Maximum curvature technique is used to determine the M_c value in the study region. This method is simple and more efficient for computing Mc, and it is also effective for forecasting the spatial distribution of magnitude frequency correlations (FMD) (Hussain et al., 2020; Xie et al., 2019). We utilized a time window of 100 samples, a shift step of 10 events, and a bootstrapping technique to estimate the M_c confidence level from the West Papua earthquake catalog. The same approach is taken to determine the change in Mc with respect to time for a narrower area of Manokwari and South Manokwari as the Sorong, Ransiki, and Yapen fault lines, with a time window of 50 earthquake samples, a shift step of 5 events. Furthermore, after declassifying the catalog, the temporal variation as a function of magnitude is evaluated, and the cumulative number of occurrences is shown against time. The result of declustered earthquakes was used to determine the seismicity parameters a and b in the study region, which were utilized as input parameters in the PSHA in the next project. The Gutenberg-Richter magnitude frequency distribution can be shown through the equation (Foytong et al., 2020):

$$\log(N(M_w)) = a - bM_w \tag{3}$$

$N(M_w)$ is the magnitude of an earthquake larger than or equal to M_w, and a and b are the Gutenberg-Richter model parameter constants (Foytong et al., 2020). The value of an is a parameter indicating seismic activity in several locations at a given moment. It is known as the seismic index, whereas b is a tectonic parameter that specifies the slope of the distribution of the magnitude of the earthquake frequency. Variations in the b value have been applying to tectonic studies such as fault zones, magma chambers, and subduction zones (Montuori et al., 2010). In this study, the value of b was calculated using the Maximum Likelihood approach based on the maximum curvature value (Wiemer & Wyss, 2000). In particular, the value of a and b for the West Papua area will be utilized as the primary parameters for PSHA computation and analysis. The b-values were computed using Aki's (1965) Maximum Likelihood approach coupled with bootstrapping, which proved to be a valid and unbiased estimate for the majority of the b-value estimating using ZMAP 7 (Lamessa et al., 2019; Reyes & Wiemer, 2019):

$$b = \frac{\log_{10}(e)}{(M_{mean} - M_C)} \tag{4}$$

M_{mean} is the average value of the magnitude group with $M_{mean} \geq M_C$, and then the standard error value is also calculated for the b value of the frequency-magnitude relationship. The standard deviation of the b value calculated using the equation proposed by Shi and Bolt, 1982 (Rohadi, 2015; Shi & Bolt, 1982):

$$\partial(b) = 2.30b^2\sigma(M_{mean});\ \sigma(M_{mean}) = \sqrt{\sum_{i=1}^{n}(M_i - M_{mean})^2/n(n-1)} \tag{5}$$

n is the number of calculated sampling earthquakes.

4. Result and Discussion

4.1. Distribution of M_w Magnitude and Earthquake Declustering in West Papua Province

Various types of earthquake magnitudes have been converted to moment magnitude (M_w) to obtain a homogeneous magnitude type in West Papua. A large number of studies have been conducted in different seismic tectonic regions and environments to establish the relationship between different M_w magnitude categories to solve major difficulties in seismic risk assessment and crustal deformation estimation (Scordilis, 2006). In general, the occurrence of earthquakes in the study area consists of foreshocks-mainshocks-aftershocks.

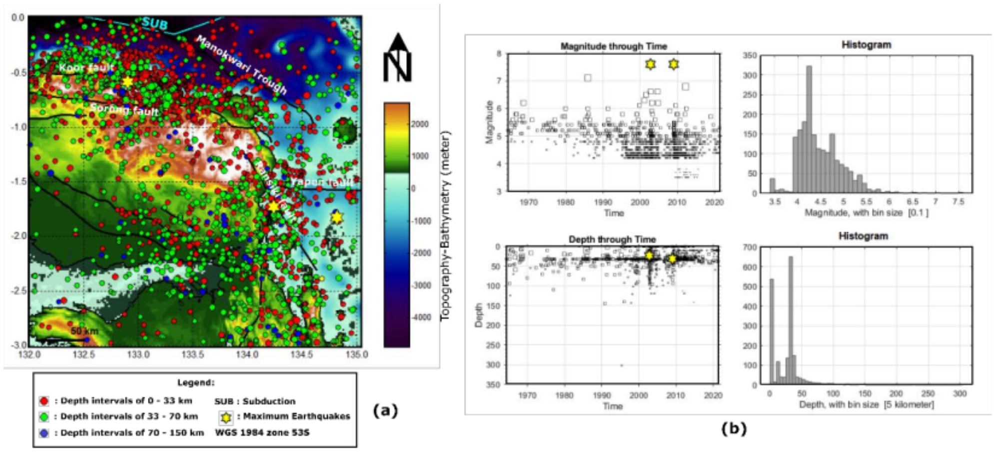


Figure 4. Earthquake declustering results in West Papua using the Reasenberg algorithm, 1985. (a) Distribution of earthquake occurrences from 1964 to 2021; (b) Variation and histogram of earthquake magnitude and depth as a function of time.

In many cases, it is necessary to distinguish the main shock from the foreshocks and aftershocks by de-clustering to avoid deviations related to the spatial variability of future earthquake frequencies (Marzocchi & Taroni, 2014; Taroni & Akinci, 2020). The earthquake de-clustering result based on the Haesenberg algorithm eliminates ± 25% of the West Papua earthquake catalog. The remaining 1914 earthquakes mostly indicate two main areas in the northern area associated with the Koor and Sorong faults, then the Ransiki and Yapen faults in the west southeast (Figure 4a). Figure 4b shows the distribution and histogram of the earthquake events in western Papua according to the magnitude and depth of the earthquake dominated at a relatively shallower depth of 70 km by earthquakes of magnitudes from 4 to 5.5 M_w. These findings are particularly relevant when seismic sources are detected in West Papua, in the context of the PSHA study.

4.2. Spatial and Temporal Distribution of Completeness Magnitude (M_c) and b Value in West Papua province.

The frequency magnitude distribution (FMD) in West Papua is estimated to be 4.3 on the basis of Maximum Likelihood method with bootstrapping based on IRIS earthquake catalogs from 1964 to 2021. The seismicity parameters a and b are 7.09 and 0.92, with a 2% deviation respectively (Figure 5). The square data shows cumulative earthquakes, while the red line is a linear fit to the Gutenberg-Richter equation distribution of earthquake frequency and size In a more specific area, these results tend to decrease when compared with a previous study on the whole territory of Papua for each parameter is 4.7, 7.97, and 0.982 (Rohadi, 2015).

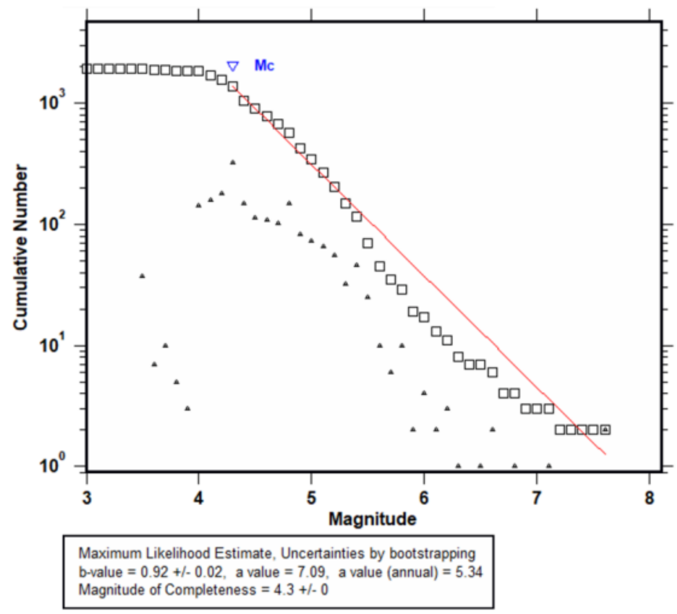
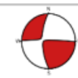
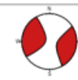
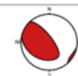
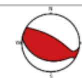


Figure 5. The cumulative magnitude frequency distribution (FMD) in the West Papua region based on the IRIS earthquake catalog from 1964 – 2021.

The decrease in the M_c is thought to be due to an increase in the number of recorded earthquake data in this area, as well as the smaller study area focused on the more tectonically active Koor, Sorong, Ransiki, and Yapen strike-slip faults. Changes in the Mc value will have an effect on the a and b values. The West Papua region has intense tectonic activity where earthquakes occur predominantly on four major strike-slip faults. The reduction of Mc is expected as a result of an increase in the quantity of recorded earthquake information in the area and the limited field of research concentrated on the more tectonically active faults of Koor, Sorong, Ransiki, and Yapen. Changes in the value of Mc will influence the values of a and b. West Papua has significant tectonic activity, mainly on four major strike-slip faults. The resultant parameter b value has an average value of $0{,}92 \pm 0{,}02$ at the intermediate level. Based on the Global CMT catalog in West Papua, we have delivered four major earthquakes (Table 2). This data shows the prevailing effect of strike-slip failures, with a minimum rake angle of 4^{o} on the Ransiki fault and a maximum rake angle of 174^{o} on the Yapen Fault, also two other occurrences happening on the Koor and Sorong faults.

Table 2. Focal mechanisms for major earthquakes in West Papua from Global CMT Catalog (http://ds.iris.edu/spud/momenttensor)

Event time (UTC)	Lon. (°)	Lat. (°)	Mag. (M_w)	Dep. (km)	Strike (°)	Dip (°)	Rake (°)	Focal Mechanism
1985-11-17; 09:40:36	134.710	-1.630	7.1	13.3	179	64	174	
2002-10-10; 10:50:41	134.300	-1.790	7.5	15.0	60	83	4	
2009-01-03; 19:44:09	132.830	-0.380	7.7	15.2	99	23	47	
2009-01-03; 22:33:44	133.480	-0.580	7.4	18.2	101	26	72	

Several investigations have discovered that the value of b is consistently dependent on the focal mechanism of earthquakes, with small values for thrusting faults, large values for normal faults, and medium values for strike-slip earthquakes (Gulia & Wiemer, 2010; Scholz, 2015). Schorlemmer et al., 2005, studied the relationship between fault models and b-values by categorizing earthquakes according to their focal mechanism. Regional and worldwide catalogs have been utilized to compute the value of b based on the rake angle of seismic occurrences. The findings reveal that the three faults have varying b values with normal fault related to high b value ($b_{NR} \approx 1.1$), strike-slip to intermediate level ($b_{SS} \approx 0.9$), and thrusting fault have low b value ($b_{TH} \approx 0.7$)(Gulia & Wiemer, 2010; Schorlemmer et al., 2005). The results of the strike-slip earthquake event show a minor deviation from the average regional b value of 0.9, only at an angle of 5° the b value is higher than the average value.

The value of b is the inverse of the stress level, with a low b value indicating high stress and a high b value indicating a low amount of stress (Hussain et al., 2020). According to these factors, the Bird's Head region of West Papua is typically located in the intermediate range of stress and b levels. A high value probably describes a high seismic activity in the study area. We also examined temporal variation Mc and b values from a catalog of earthquakes in the region of West Papua. It is necessary to determine the pattern of Mc and b values before and after the large earthquakes in Ransiki on October 10, 2002, and also in Sorong on January 4, 2009. The temporal variation of Mc and b values is performed using a window of 100 samples with 10 sample steps.

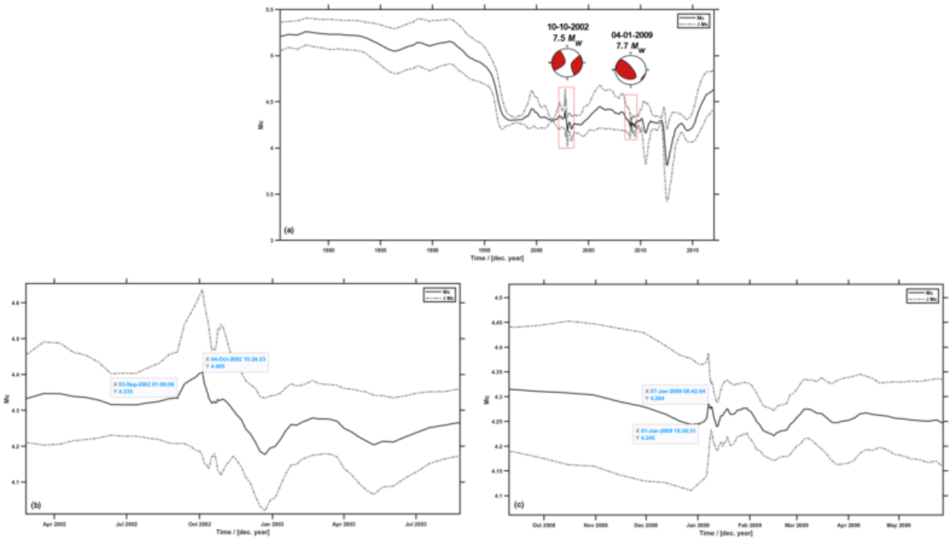


Figure 6. (a) Temporal variation of M_c for earthquake catalogs in West Papua from 1964 to 2021, calculated using the maximum curvature technique with bootstrapping. (b) Zoom in on the M_c of the October 10, 2002, a large earthquake on the Ransiki fault; (c) Zoom in on the M_c b of January 4, 2009, a main earthquake on the Sorong fault.

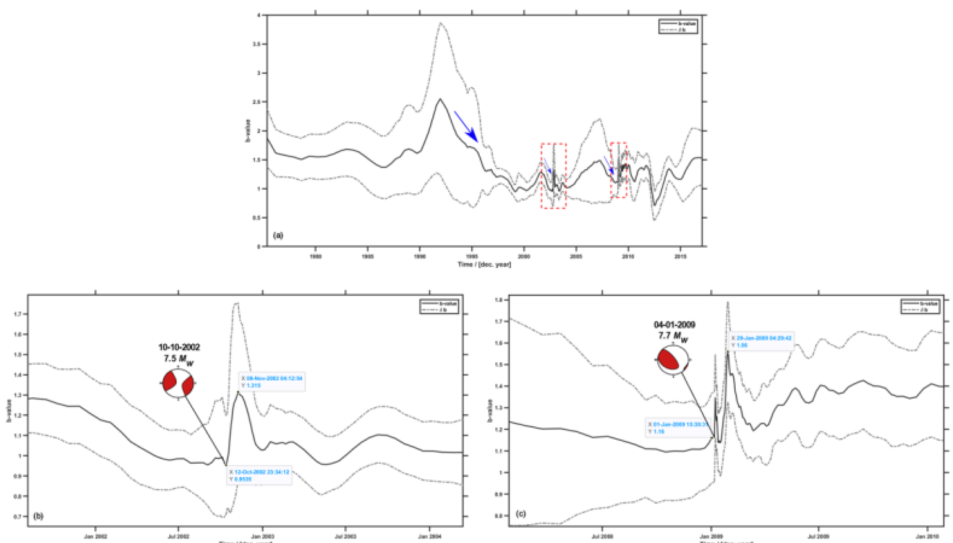


Figure 7. (a) Temporal variation of b value for earthquake catalogs in West Papua from 1964 to 2021, calculated using the maximum curvature technique with bootstrapping. (b) Zoom in on the b value of the October 10, 2002, a large earthquake on the Ransiki fault; (c) Zoom in on the b value b of January 4, 2009, a main earthquake on the Sorong fault.

These findings suggest that the M_c value in the research region was high and consistent before 1990 due to the limits or inadequacies of the seismograph network in detecting such events (Figure 6a). The M_c parameter interpretation is also supported by magnitude distributions that were uncommon in West Papua before 1990 (Figure 4b). The value of M_c has decreased and fluctuated from 1990 until today, particularly after the large earthquakes in 2002 and 2009. This is due to an increase in the number of network sensors that record earthquakes. According to Wiemer and Wyss (2000), the M_c value in most catalogs tends to decrease over time due to the addition of more seismographs and analysis capabilities (Wiemer & Wyss, 2000). We magnified or cut-off the 2002 earthquake (Figure 6b) and the 2009 earthquake (Figure 6c) to see fluctuations in the Mc value before and after the earthquake. It was discovered that Mc increased in the months preceding the main earthquake, then decreased after the main earthquake, and also the aftershocks. The magnitude of the b value in the study area is heavily influenced by the determination of the Mc value. The temporal variation of the b value in the study area also has a certain unique pattern (Figure 7a). After 1990, the b value decreased significantly until the early 2000s. There was a slight increase until mid-2001, and it also decreased until before the main Ransiki earthquake on 10 October 2002 (Figure 7b), then experienced a significant increase after the earthquakes, and was back down and relatively constant afterward.

A similar pattern happened in the Sorong 4 January 2009 earthquake, with a reduction in b-value before the major earthquake and a rise after that, but also two decreases soon after, indicating that a 7.4 M_w aftershock occurred after the initial 7.7 M_w earthquake (Figure 7c). The level of rock stress is expected to peak just before the major earthquake, followed by a release of energy that reduces tension and eventually returns to a stable state. El Isa and Eaton (2014) classified the temporal variation of b values based on studies conducted by several researchers around the world and discovered that there was a decrease in the value of b before the occurrence of a mainshock, for several years or more, followed by an increase in the value of b after the main earthquake. The decrease in the value of b may precede fluctuations at different periods in the earthquake cycle and represents an increase in stress, strain, coseismic rupture, and aftershocks (El-Isa & Eaton, 2014). These results are expected to be used to predict the pattern of the next major earthquake in West Papua.

This study also analyzes the variation of b value with depth in the region of the Koor, Sorong, Ransiki, and Yapen strike-slip faults, where high b values are recorded at shallow depths, then decrease gradually to depths of 25 km and then increase again to approximately 40 km. A high b value is considered to be generated by a more complex or heterogeneous layer of sediment and upper crust, whereas a low b value may be affected by layers below the lithosphere, which tend to be homogenous. This assumption is supported by a global earth's crust thickness model based on the CRUST 1.0 model in the West Papua area (Laske et al., 2013), which found differences in the thickness of the earth's crust of up to 40 km (Figure 8b).

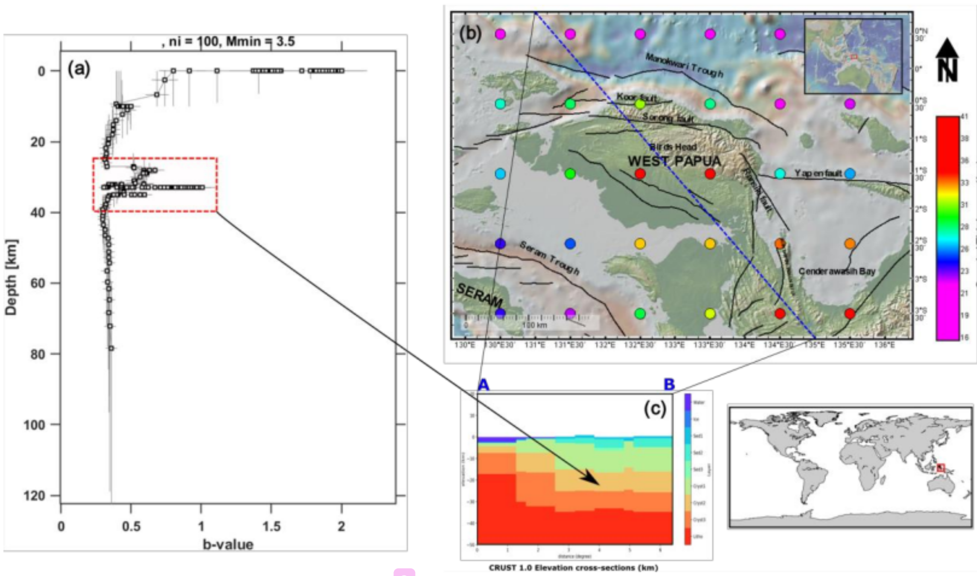


Figure 8. (a) Variation of b value with depth based on the West Papua earthquake catalog from 1964 to 2021. (b) The CRUST 1.0 model of the global earth crust in the research region. (c) CRUST 1.0 cross-section model in West Papua.

The diagonal cross-section from north to south (A-B) also shows the transition boundary between the lower crust and the mantle is estimated at a depth of between 25-30 km (Figure 8c). The increase in the value of b at a depth of 25 km (red box) is also estimated to be a turning point or transition from brittle to ductile conditions in the Earth's crust in West Papua. In general, the b values in the upper crust are substantially greater than in the lower crust in many areas. This is considered to be connected to increased heterogeneity at shallower depths, which reduces rupture development and creates more low-strength aftershocks. At deeper levels, heterogeneity is reduced, but lithostatic pressures increase, allowing for more fault development and fewer initial shocks (El-Isa & Eaton, 2014; M. Gerstenberger et al., 2001). According to Spada et al. (2013), the value of b exhibits a negative connection with differential stress and may use as a stress meter for the earth's crust. They also discovered turning points in depth gradients exceeding 15 km, which were interpreted as brittle-ductile transitions in different locations in the world, except for Switzerland, where they reached a depth of 25 km with a predominance of strike-slip faults (Spada et al., 2013).

4.3. Spatial and Temporal Distribution of Completeness Magnitude (Mc) and b Value on the Manokwari and South Manokwari Regencies.

Furthermore, for future seismic hazard assessment using the PSHA approach, this research is focused on the regency of Manokwari and South Manokwari as West Papua's provincial capitals, as well as areas near the main faults of Sorong, Ransiki, and Yapen (Figure 8a), and also frequently experience loss and infrastructure damage due to earthquakes in the area. However, because these two locations are in the lowlands and near the coastline area, they are vulnerable to tsunami tragedies if large and shallow earthquakes occur at sea.

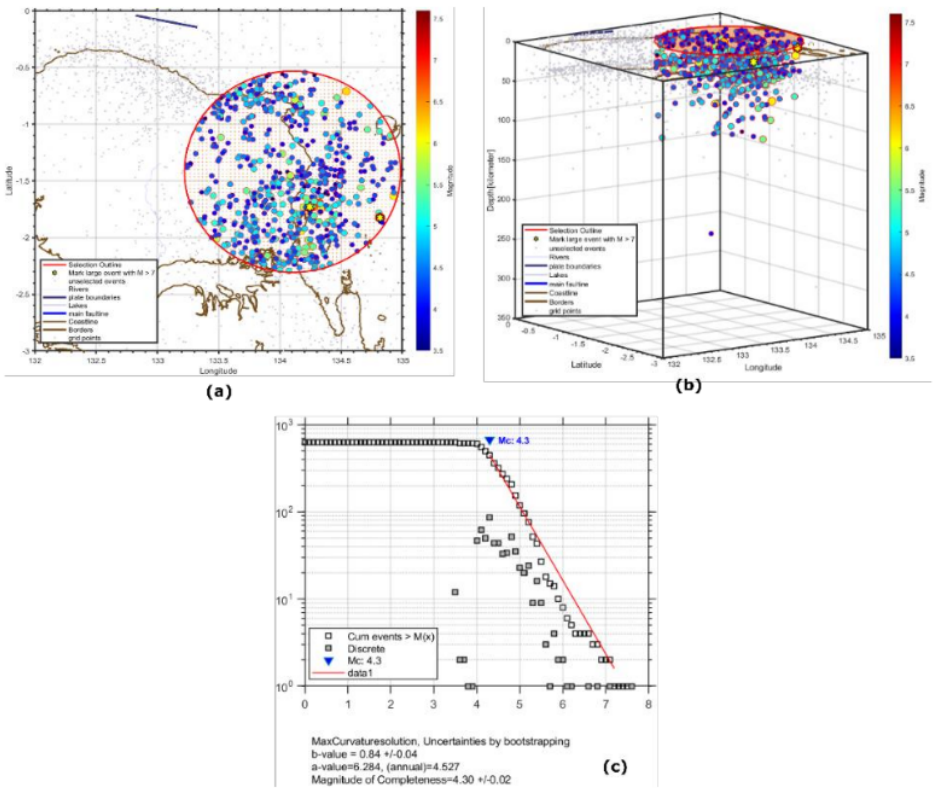


Figure 9. (a) Distribution of earthquakes in Manokwari and South Manokwari Regencies. (b) 3-D model of earthquake distribution is dominated by shallow earthquakes. (c) Distribution of the frequency magnitude of the Sorong-Ransiki-Yapen earthquake catalog for the period 1964 – 2021.

At the location, the two largest earthquakes occurred in 1985 with a magnitude of 7.1 M_w and 2002 of 7.5 M_w the sea (Figure 9a). We take the earthquakes in the form of a circle with a radius of < 100 km with a center in South Manokwari as a location close to the Ransiki Fault, belonging to the category of shallow earthquakes (Figure 9b).

The frequency distribution with magnitude (FMD) in this region produces a constant Mc value of 4.3 ± 0.02. Seismicity parameter values a and b decreased by 6.28 and 0.84 with an error of ± 4 % (Figure 9c).

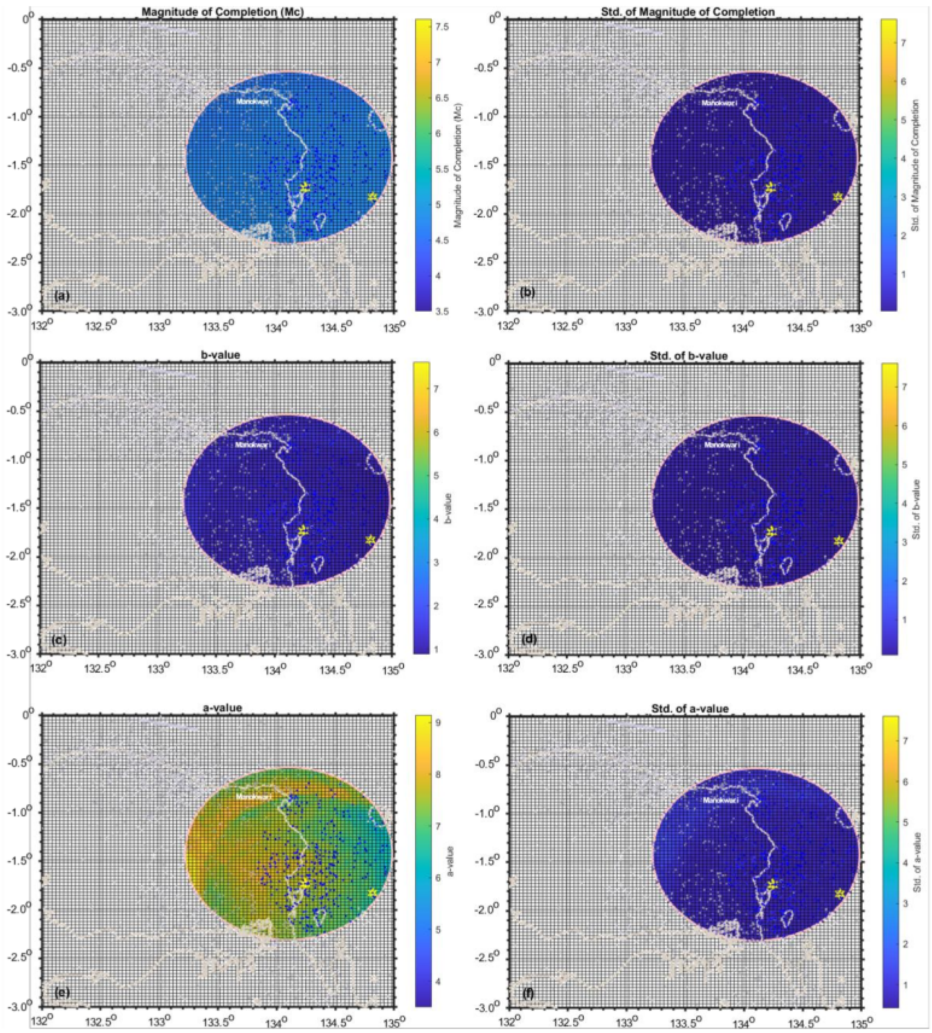


Figure 10. Spasial variation of Mc, b, and a values in Manokwari and South Manokwari Regencies. (a) Mc variation; (b) Standart deviation of Mc (c) b value variation; (d) Standart deviation of b value; (e) a value variation; (f) Standart deviation of a value.

The decreasing pattern of values of a and b is probably a contribution from the selection of earthquake catalog data in more tectonically active areas, resulting in many earthquake events. Due to a fault with a strike-slip focal mechanism, the resulting b value is still classified as an intermediate level. The decrease in b value indicates that the stress level on the rocks in this area is quite high. The change of b value depends on structural characteristics and focal mechanism. Normal faults b> 1, strike-slip b ~ 1, b <1 are related to thrust faults (El-Isa & Eaton, 2014; Schorlemmer et al., 2005). In this work, the spatial variation (x, y) of the seismic activity parameters (Mc, a and b) in Manokwari and South Manokwari was also studied (Figure 10). Figures 10a and 10b depict the spatial distribution of the minimum amplitude Mc and its standard deviation. Figures 10c and 10d show the spatial distribution of the b value and its standard deviation, while Figures 10e and 10f show the spatial distribution of the a value and its standard deviation. The spatial distribution of Mc and b shows homogeneous values throughout the area, while the variation in the values of a is generally high in the north of Manokwari to the south, and decreases towards the west in Cenderawasih Bay. The standard deviations for the three models tend to be small.

5. CONCLUSION

Estimates of the magnitude of completeness (Mc) and b value have been performing to determine important seismotectonic parameters for seismic hazard assessment in West Papua province in the future. The distribution of frequency and magnitude from the earthquake catalog shows that the dominant earthquake occurred on two main strike-slip fault lines, including the Koor-Sorong and Ransiki-Yapen faults, which resulted in the average values of Mc, a, b of 4.3, 7.02, and 0.92 ± 0.02. The value of b belongs to the intermediate level, estimated to be related to the tectonic characteristics and the dominance of the strike-slip focal mechanism in the study area. Temporal variations in the values of Mc and b show a decreasing trend in 1990 – 2021, presumably due to the increasing number of earthquake data recordings, also the increasing activity of tectonic conditions in the study area. Time series analysis of the value of b shows a decreasing pattern several years before the big earthquakes of Ransiki 7.5 M_w 10-10-2002 and Sorong 7.7 M_w 04-01-2009 and increased after the main earthquake occurred.

It considered that there is an increase in crust stress before the main earthquakes and a drop in stress level owing to energy release, followed by a constant towards stability, where b is the inverse of stress. Variations in the b value with depth indicate that high values are found on the surface up to several kilometers due to layers that tend to be heterogeneous, decreasing with increasing depth in more homogeneous layers. Furthermore, the value of b changed between depths of 25 and 30 km, regarded the limit of the bottom crust and mantle in the research region, or even the transition zone from ductile to brittle conditions. Estimation of parameter values of Mc, a, and b is using in the assessment of future seismic hazards through the application of PSHA analysis related to the determination of seismic source models and site observations under tectonic and geological conditions in West Papua.

Acknowledgments: We are grateful to IRIS for providing an earthquake catalog available for free use in this research. Thank you also to Mr. Weimer and Mr. Reyes for creating the free ZMAP 6 and 7 software for seismic data processing.

Author Contributions: R.L and L.L have formulated concepts and designs of the research. R.M and Y.A.S looking to the collection and processing of earthquakes catalog of West Papua province. RL writes and evaluates research results in the form of a published manuscript.

Data availability

The datasets used during the current study are available from the corresponding author for reasonable request.

Competing interests

The authors declare that they have no competing interests.

REFERENCES

Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems*, *4*(3). https://doi.org/10.1029/2001GC000252

Charlton, T. R. (2010). *The Pliocene-Recent Anticlockwise Rotation of the Bird's Head, the Opening of the Aru Trough – Cendrawasih Bay Sphenochasm, and the Closure of the Banda Double Arc*. http://archives.datapages.com/data/ipa_pdf/081/081001/pdfs/IPA10-G-008.htm

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, *58*(5), 1583–1606.

Daniarsyad, G., & Suardi, I. (2017). Stress triggering among MW≥6.0 significant earthquakes in Manokwari Trough. *AIP Conference Proceedings*, *1857*(1), 020014. https://doi.org/10.1063/1.4987056

Di Giacomo, D., Bondár, I., Storchak, D. A., Engdahl, E. R., Bormann, P., & Harris, J. (2015). ISC-GEM: Global Instrumental Earthquake Catalogue (1900–2009), III. Re-computed M and m, proxy M, final magnitude composition and completeness assessment. *Physics of the Earth and Planetary Interiors*, *239*, 33–47. https://doi.org/10.1016/j.pepi.2014.06.005

Dow, D. B., & Sukamto, R. (1984). Western Irian Jaya: The end-product of oblique plate convergence in the late tertiary. *Tectonophysics*, *106*(1), 109–139. https://doi.org/10.1016/0040-1951(84)90224-5

El-Isa, Z. H., & Eaton, D. W. (2014). Spatiotemporal variations in the b-value of earthquake magnitude–frequency distributions: Classification and causes. *Tectonophysics*, *615–616*, 1–11. https://doi.org/10.1016/j.tecto.2013.12.001

Foytong, P., Ornthammarath, T., Arjwech, R., Janpila, A., Areemit, N., Ruangrassamee, A., & Chindaprasirt, P. (2020). Probabilistic Seismic Hazard Assessment of North-Eastern Thailand. *KSCE Journal of Civil Engineering*, *24*(6), 1845–1857. https://doi.org/10.1007/s12205-020-1313-6

Gerstenberger, M. C., Marzocchi, W., Allen, T., Pagani, M., Adams, J., Danciu, L., Field, E. H., Fujiwara, H., Luco, N., Ma, K. -F., Meletti, C., & Petersen, M. D. (2020). Probabilistic Seismic Hazard Analysis at Regional and National Scales: State of the Art and Future Challenges. *Reviews of Geophysics*, *58*(2). https://doi.org/10.1029/2019RG000653

Gerstenberger, M., Wiemer, S., & Giardini, D. (2001). A systematic test of the hypothesis that the b value varies with depth in California. *Geophysical Research Letters - GEOPHYS RES LETT*, *28*. https://doi.org/10.1029/2000GL012026

Gold, D. P., Burgess, P. M., & BouDagher-Fadel, M. K. (2017). Carbonate drowning successions of the Bird's Head, Indonesia. *Facies*, *63*(4), 25. https://doi.org/10.1007/s10347-017-0506-z

Gulia, L., & Wiemer, S. (2010). The influence of tectonic regimes on the earthquake size distribution: A case study for Italy. *Geophysical Research Letters*, *37*(10). https://doi.org/10.1029/2010GL043066

Hussain, H., Shuangxi, Z., Usman, M., & Abid, M. (2020). Spatial Variation of b-Values and Their Relationship with the Fault Blocks in the Western Part of the Tibetan Plateau and Its Surrounding Areas. *Entropy*, *22*(9), 1016. https://doi.org/10.3390/e22091016

Kalaneh, S., & Agh-Atabai, M. (2016). Spatial variation of earthquake hazard parameters in the Zagros fold and thrust belt, SW Iran. *Natural Hazards*, *82*(2), 933–946. https://doi.org/10.1007/s11069-016-2227-y

Lamessa, G., Mammo, T., & K.Raghuvanshi, T. (2019). Homogenized earthquake catalog and b-value mapping for Ethiopia and its adjoining regions. *Geoenvironmental Disasters*, *6*(1), 16. https://doi.org/10.1186/s40677-019-0131-y

Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1.0—A 1-degree global model of Earth's crust. *Abstract EGU2013-2658 Presented at 2013 Geophys. Res. Abstracts 15*, *15*, 2658.

Luis, J. (2007). Mirone: A multi-purpose tool for exploring grid data. *Computers & Geosciences*, *33*, 31–41. https://doi.org/10.1016/j.cageo.2006.05.005

Makrup, L., Hariyanto, A., & Winarno, S. (2018). Seismic Hazard Map for Papua Island. *International Review of Civil Engineering (IRECE)*, *9*, 57. https://doi.org/10.15866/irece.v9i2.14090

Malagnini, L., & Munafò, I. (2018). On the Relationship between ML and Mw in a Broad Range: An Example from the Apennines, Italy. *Bulletin of the Seismological Society of America*, *108*. https://doi.org/10.1785/0120170303

Marzocchi, W., & Taroni, M. (2014). Some Thoughts on Declustering in Probabilistic Seismic-Hazard Analysis. *Bulletin of the Seismological Society of America*, *104*, 1838–1845. https://doi.org/10.1785/0120130300

Milsom, J. (1991). Gravity measurements and terrane tectonics in the New Guinea region. *Journal of Southeast Asian Earth Sciences*, *6*(3–4), 319–328. https://doi.org/10.1016/0743-9547(91)90077-B

Milsom, J., Masson, D., Nichols, G., Sikumbang, N., Dwiyanto, B., Parson, L., & Kallagher, H. (1992). The Manokwari Trough and the western end of the New Guinea Trench. *Tectonics*, *11*(1), 145–153. https://doi.org/10.1029/91TC01257

Montuori, C., Falcone, G., Murru, M., Thurber, C., Reyners, M., & Eberhart-Phillips, D. (2010). Crustal heterogeneity highlighted by spatial b-value map in the Wellington region of New Zealand: B-value map in the Wellington region. *Geophysical Journal International*, *183*(1), 451–460. https://doi.org/10.1111/j.1365-246X.2010.04750.x

Rahman, M. M., & Bai, L. (2018). Probabilistic seismic hazard assessment of Nepal using multiple seismic source models. *Earth and Planetary Physics*, *2*(4), 327–341. https://doi.org/10.26464/epp2018030

Reasenberg, P. (1985). Second-order moment of central California seismicity, 1969–1982. *Journal of Geophysical Research: Solid Earth*, *90*(B7), 5479–5495. https://doi.org/10.1029/JB090iB07p05479

Reyes, C., & Wiemer, S. (2019). *ZMAP7, a refreshed software package to analyze seismicity*. 13153.

Rohadi, S. (2015). DISTRIBUSI SPASIAL DAN TEMPORAL PARAMETER SEISMOTEKTONIK SEBAGAI INDIKASI TINGKAT AKTIVITAS KEGEMPAAN DI WILAYAH PAPUA. *Jurnal Meteorologi dan Geofisika*, *16*(3), Article 3. https://doi.org/10.31172/jmg.v16i3.289

Scholz, C. H. (2015). On the stress dependence of the earthquake b value. *Geophysical Research Letters*, *42*(5), 1399–1402. https://doi.org/10.1002/2014GL062863

Schorlemmer, D., Wiemer, S., & Wyss, M. (2005). Variations in earthquake-size distribution across different stress regimes. *Nature*, *437*(7058), 539–542. https://doi.org/10.1038/nature04094

Scordilis, E. M. (2006). Empirical Global Relations Converting MS and mb to Moment Magnitude. *Journal of Seismology*, *10*(2), 225–236. https://doi.org/10.1007/s10950-006-9012-4

Serhalawan, Y. R., & Sianipar, D. S. J. (2017). *PEMODELAN MEKANISME SUMBER GEMPA BUMI RANSIKI 2012 BERKEKUATAN MW 6,7*. *6*(1), 10.

Shi, Y., & Bolt, B. A. (1982). The standard error of the magnitude-frequency b value. *Bulletin of the Seismological Society of America*, *72*(5), 1677–1687.

Spada, M., Tormann, T., Wiemer, S., & Enescu, B. (2013). Generic dependence of the frequency-size distribution of earthquakes on depth and its relation to the strength profile of the crust. *Geophysical Research Letters*, *40*(4), 709–714. https://doi.org/10.1029/2012GL054198

Taroni, M., & Akinci, A. (2020). Good practices in PSHA: Declustering, b-value estimation, foreshocks and aftershocks inclusion; a case study in Italy. *Geophysical Journal International*, *224*(2), 1174–1187. https://doi.org/10.1093/gji/ggaa462

Watkinson, I. M., & Hall, R. (2017). Fault systems of the eastern Indonesian triple junction: Evaluation of Quaternary activity and implications for seismic hazards. *Geological Society, London, Special Publications*, *441*(1), 71–120. https://doi.org/10.1144/SP441.8

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

Wiemer, S., & Wyss, M. (2000). Minimum Magnitude of Completeness in Earthquake Catalogs: Examples from Alaska, the Western United States, and Japan. *Bulletin of the Seismological Society of America*, *90*(4), 859–869. https://doi.org/10.1785/0119990114

Xie, W., Hattori, K., & Han, P. (2019). Temporal Variation and Statistical Assessment of the b Value off the Pacific Coast of Tokachi, Hokkaido, Japan. *Entropy*, *21*(3), 249. https://doi.org/10.3390/e21030249

Completeness magnitude (Mc) and b-value characteristics as important parameters for future seismic hazard assessment in The West Papua province Indonesia

ORIGINALITY REPORT

4%	2%	3%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	pure.royalholloway.ac.uk Internet Source	1%
2	www.mdpi.com Internet Source	1%
3	A. Rigo, A. Souriau, M. Sylvander. "Spatial variations of b-value and crustal stress in the Pyrenees", Journal of Seismology, 2017 Publication	1%
4	Richard Lewerissa, Sismanto Sismanto, Ari Setiawan, Subagyo Pramumijoyo, Laura Lapono. "Integration of gravity and magnetic inversion for geothermal system evaluation in Suli and Tulehu, Ambon, eastern Indonesia", Arabian Journal of Geosciences, 2020 Publication	1%
5	S. Öztürk, H. Çinar, Y. Bayrak, H. Karsli, G. Daniel. "Properties of the Aftershock Sequences of the 2003 Bingöl, M D = 6.4,	1%

(Turkey) Earthquake", Pure and Applied Geophysics, 2008

Publication

Exclude quotes	On	Exclude matches	< 1%
Exclude bibliography	On		

Completeness magnitude (Mc) and b-value characteristics as important parameters for future seismic hazard assessment in The West Papua province Indonesia

GRADEMARK REPORT

FINAL GRADE

/0

GENERAL COMMENTS

Instructor

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15

PAGE 16

PAGE 17

PAGE 18

PAGE 19

PAGE 20

PAGE 21

CLAIM

Take an arguable position on the scientific topic and develop the essay around that stance.

ADVANCED	The essay introduces a precise, qualitative and/or quantitative claim based on the scientific topic or text(s), regarding the relationship between dependent and independent variables. The essay develops the claim and counterclaim fairly, distinguishing the claim from alternate or opposing claims.
PROFICIENT	The essay introduces a clear, qualitative and/or quantitative claim based on the scientific topic or text(s), regarding the relationship between dependent and independent variables. The essay effectively acknowledges and distinguishes the claim from alternate or opposing claims.
DEVELOPING	The essay attempts to introduce a qualitative and/or quantitative claim, based on the scientific topic or text(s), but it may be somewhat unclear or not maintained throughout the essay. The essay may not clearly acknowledge or distinguish the claim from alternate or opposing claims.
EMERGING	The essay does not clearly make a claim based on the scientific topic or text(s), or the claim is overly simplistic or vague. The essay does not acknowledge or distinguish counterclaims.

EVIDENCE

Include relevant facts, definitions, and examples to back up the claim.

ADVANCED	The essay supplies sufficient relevant, accurate qualitative and/or quantitative data and evidence related to the scientific topic or text(s) to support its claim and counterclaim.
PROFICIENT	The essay supplies relevant, accurate qualitative and/or quantitative data and evidence related to the scientific topic or text(s) to support its claim and counterclaim.
DEVELOPING	The essay supplies some qualitative and/or quantitative data and evidence, but it may not be closely related to the scientific topic or text(s), or the support that is offered relies mostly on summary of the source(s), thereby not effectively supporting the essay's claim and counterclaim.
EMERGING	The essay supplies very little or no data and evidence to support its claim and counterclaim, or the evidence that is provided is not clear or relevant.

REASONING

Explain how or why each piece of evidence supports the claim.

ADVANCED	The essay effectively applies scientific ideas and principles in order to explain how or why the cited evidence supports the claim. The essay demonstrates consistently logical reasoning and understanding of the scientific topic and/or text(s). The essay's explanations anticipate the audience's knowledge level and concerns about this scientific topic.

PROFICIENT	The essay applies scientific reasoning in order to explain how or why the cited evidence supports the claim. The essay demonstrates logical reasoning and understanding of the scientific topic and/or text(s). The essay's explanations attempt to anticipate the audience's knowledge level and concerns about this scientific topic.
DEVELOPING	The essay includes some reasoning and understanding of the scientific topic and/or text(s), but it does not effectively apply scientific ideas or principles to explain how or why the evidence supports the claim.
EMERGING	The essay does not demonstrate clear or relevant reasoning to support the claim or to demonstrate an understanding of the scientific topic and/or text(s).

FOCUS

Focus your writing on the prompt and task.

ADVANCED	The essay maintains strong focus on the purpose and task, using the whole essay to support and develop the claim and counterclaims evenly while thoroughly addressing the demands of the prompt.
PROFICIENT	The essay addresses the demands of the prompt and is mostly focused on the purpose and task. The essay may not acknowledge the claim and counterclaims evenly throughout.
DEVELOPING	The essay may not fully address the demands of the prompt or stay focused on the purpose and task. The writing may stray significantly off topic at times, and introduce the writer's bias occasionally, making it difficult to follow the central claim at times.
EMERGING	The essay does not maintain focus on purpose or task.

ORGANIZATION

Organize your writing in a logical sequence.

ADVANCED	The essay incorporates an organizational structure throughout that establishes clear relationships among the claim(s), counterclaims, reasons, and evidence. Effective transitional words and phrases are included to clarify the relationships between and among ideas (i.e. claim and reasons, reasons and evidence, claim and counterclaim) in a way that strengthens the argument. The essay includes an introduction and conclusion that effectively follows from and supports the argument presented.
PROFICIENT	The essay incorporates an organizational structure with clear transitional words and phrases that show the relationship between and among ideas. The essay includes a progression of ideas from beginning to end, including an introduction and concluding statement or section that follows from and supports the argument presented.
DEVELOPING	The essay uses a basic organizational structure and minimal transitional words and phrases, though relationships between and among ideas are not consistently

	clear. The essay moves from beginning to end; however, an introduction and/or conclusion may not be clearly evident.
EMERGING	The essay does not have an organizational structure and may simply offer a series of ideas without any clear transitions or connections. An introduction and conclusion are not evident.

LANGUAGE

Pay close attention to your tone, style, word choice, and sentence structure when writing.

ADVANCED	The essay effectively establishes and maintains a formal style and objective tone and incorporates language that anticipates the reader's knowledge level and concerns. The essay consistently demonstrates a clear command of conventions, while also employing discipline-specific word choices and varied sentence structure.
PROFICIENT	The essay generally establishes and maintains a formal style with few possible exceptions and incorporates language that anticipates the reader's knowledge level and concerns. The essay demonstrates a general command of conventions, while also employing discipline-specific word choices and some variety in sentence structure.
DEVELOPING	The essay does not maintain a formal style consistently and incorporates language that may not show an awareness of the reader's knowledge or concerns. The essay may contain errors in conventions that interfere with meaning. Some attempts at discipline-specific word choices are made, and sentence structure may not vary often.
EMERGING	The essay employs language that is inappropriate for the audience and is not formal in style. The essay may contain pervasive errors in conventions that interfere with meaning, word choice is not discipline-specific, and sentence structures are simplistic and unvaried.