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ORIGINAL PAPER

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

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Abstract

West Papua province in eastern Indonesia is located in a complex tectonic setting due to the convergence of the Australian, Pacific, and Eurasian plates. The interaction resulted in several major strike-slip faults, including Koor, Sorong, Ransiki, and Yapen, which are the main seismic routes in the study area. The development of infrastructure needs to address seismic hazards that can be triggered by earthquakes and reduce losses. The research purpose was to estimate and update the seismic parameters in the form of a magnitude of completeness (M_c) and *a* and *b* values, using the earthquake catalog from 1964 to 2021. Estimation is done by converting the overall magnitude to moment magnitude (M_w) to simplify the declustering process. West Papua is divided into two main clusters, which show that earthquakes predominantly occur on the fault line with average values of M_c, *a*, and *b* of 4.3 ± 0.02, 7.02, and 0.92, respectively. The resulting *b* value belongs to the intermediate level, presumably related to tectonic characteristics and a strike-slip focal mechanism. The *b* value around the Ransiki-Yapen fault gives a decreasing trend of 0.84 ± 0.02, indicating the possibility of an increase in stress on the earth's crust. Analysis of temporal variation of b value for two large earthquakes in 2002 and 2009 showed a decreasing of *b* value several times before the mainshock then increasing after the event. Fluctuations in the *b* value may relate to the accumulation and release of stress, rupture, and aftershocks. This work is likely to prove helpful for estimating seismic risk in West Papua using probabilistic seismic hazard analysis (PSHA).

Keywords Magnitude of completeness · *b*-value · Strike-slip faults · Seismic Hazard · West Papua

Introduction

The convergence of the Australian, Eurasian, Pacific, and Philippine sea plates has resulted in a highly deformed area in eastern Indonesia. The geological structure of the Birds Head area in West Papua Province is intensive and complex with oblique convergence of 60° between the Australian and Pacific plates that occurs across Papua and West Papua in a complex strain zone divided between shortening and left lateral shear. Most of the westward shortening occurs in various structures in New Guinea and the Manokwari troughs, Memberamo fold belt, and central highlands to southern (Watkinson and Hall 2017). In the northern part of West Papua, the Manokwari trough is the boundary of tectonic plate convergence, which is generated by the subduction of the Caroline-Pacific beneath an Australian crust at a rate of 114 mm/year. This trough is considered to be a source of seismic activity, associated with significant strike-slip faults like the Koor, Sorong, Ransiki, and Yapen (Daniarsyad and Suardi 2017). According to the IRIS earthquake explorer, between 1964 and 2021, there were 2807 earthquake events with magnitudes ranging from 3.5 to 8.0, mainly shallow earthquakes (Fig. 1).

On October 10, 2002, a large earthquake with a magnitude of 7.5 M_w struck the Ransiki fault at a depth of 24.8 km. Furthermore, on January 3, 2009, a large earthquake with a magnitude of 7.7 M_w at a depth of 17 km

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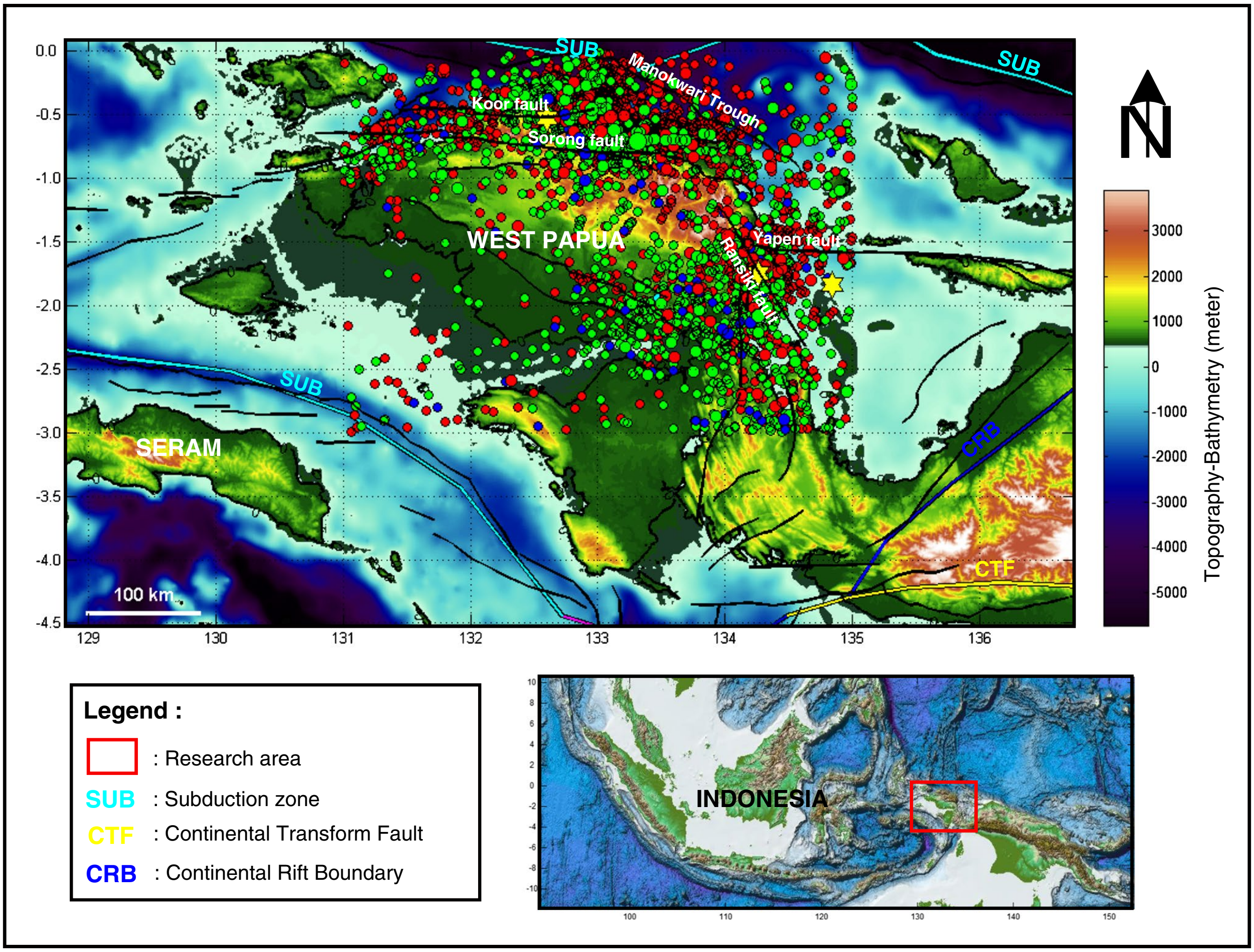


Fig. 1 The distribution of earthquakes with a magnitude range of 3.5–8.0 in West Papua based on the USGS and ISC compilation catalog from the IRIS Earthquake Explorer (Modified from Bird, 2003; Luis, 2007)

near the Papua Bird Head on the Sorong and Koor fault lines caused some damage in Sorong and Manokwari. 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). A strong 6.7 M_w earthquake struck Ransiki on April 21, 2012, causing moderate to massive structural damage and loss of life (Serhalawan and Sianipar 2017). The 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 and 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).

Research related to earthquakes and seismic hazards on Papua Island, especially West Papua, has been conducted by several previous researchers. Serhalawan and Sianipar (2017) studied the mechanism of the earthquake source to determine the fault based on the occurrence of the Ransiki earthquake with a scale of M_w 6.7 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 and Sianipar 2017). Additional research was also carried out on the fault system at the triple junction in Eastern Indonesia with the faults of Sorong, Koor, and Ransiki to assess the effects of quaternary activity on the seismic hazard (Watkinson and Hall 2017). The analysis was performed on spatial and temporal change of *b* value parameter to determine the seismic trend and future earthquakes in Papua and West Papua (Rohadi 2015). Makrup et al.

(2018) used a probabilistic seismic hazard analysis (PSHA) approach for the seismic hazard map for the island of Papua in two territories: Indonesia and Papua New Guinea. According to this research, the ground motion is 0.06–2.01 g, which is 10% over 50 years (Makrup et al. 2018).

Some related research shows that seismic investigations have been conducted in the regional areas of Papua and West Papua. In a smaller area, with a focus on the infrastructure development, more specialized research is required. Our study is a preliminary evaluation of the seismic hazard potential in West Papua Province to prevent future earthquake damage using the PSHA method. As the main parameters of the PSHA approach, magnitude completeness (M_c), a, and b values are calculated from the earthquake catalog in the region. Accurate information from M_c 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 probabilistic seismic hazard (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 is used to anticipate a large earthquake (Hussain et al. 2020). The objective of our study is to estimate the variation of M_c, a, and b values from the IRIS earthquake catalogs for the period 1964–2021 in West Papua, specifically simulated in the regencies of Manokwari and South Manokwari as provincial capitals and areas close to major fault lines. The estimation stage begins with the conversion of various magnitudes to homogeneous magnitudes, notably M_w, earthquake catalog declustering, and analysis of temporal variations of M_c, 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. The research is expected to provide an initial description of the updated seismotectonic parameters used to estimate the potential for earthquake hazards in the province of West Papua. Also, it will be expanded for future PSHA analysis in several important development centers near and traversed by major faults.

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's 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 Birds Head 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). 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 from north to 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 is 20–50 km, with a maximum length of 100 km. Moreover, the Sorong fault extends from the north of Salawati to the northeast, through Sorong City, and extends to the valley that cuts the northern continent at Manokwari. The width of the area between the mountains and valleys is 15 km (Watkinson and Hall 2017). The Koor fault, which runs from west to east, 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 and Sukamto 1984).

Research methods

Earthquake catalog data compilation and magnitude homogeneity

This study uses seismic data from the IRIS Data Management Center and utilizes ZMAP 7 software (Reyes and Wiemer 2019) to data extracting at the coordinates of 132–135° E and 0–3° S. 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 and Bai 2018). The seismic event catalog data utilizes 2574 earthquakes that occurred between 1964 and 2021. The earthquake magnitudes include moment magnitude (M_w), body magnitude (M_b), and local magnitude (M_L), with 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 (Fig. 2).

Converting M_b and M_L to M_w into homogeneous magnitude is the first stage of the earthquake catalog processing in the region. 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.

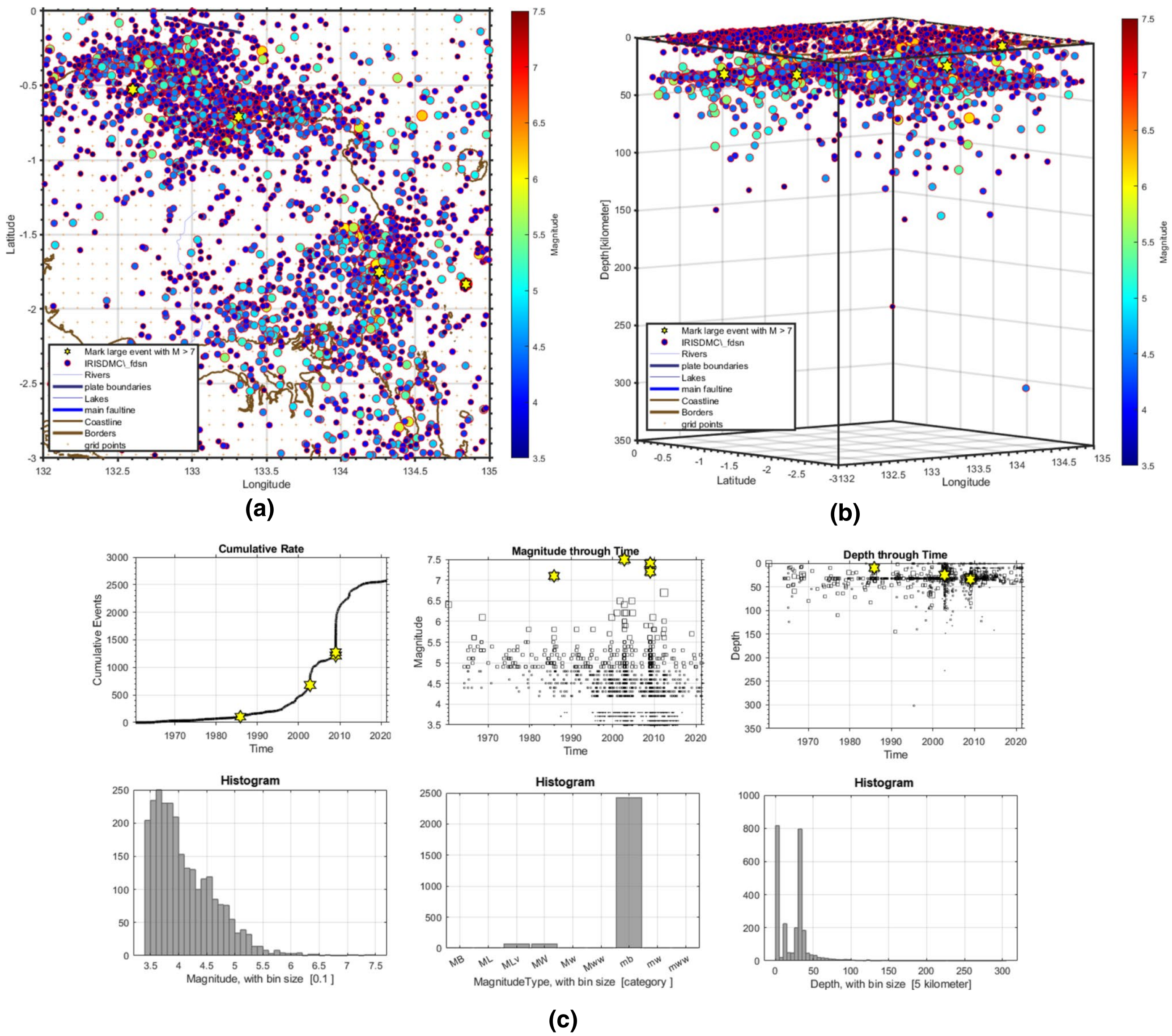


Fig. 2 Earthquake catalog in West Papua province period of 1964–2021. **a** Distribution of earthquake events with a magnitude of 3.5–8.0. **b** 3-D model of earthquake distribution. **c** Earthquake attributes with respect to time: cumulative rate, histogram of magnitude, and depth

Table 1 Distribution of earthquakes in the West Papua 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):

$$M_w = 0.85\ M_b + 1.03; 3.5\ \leq\ M_b\ \leq\ 6.2 \tag{1}$$

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

$$M_w = \frac{2}{3} M_L\ +\ 1.14; M_L\ \leq\ 4.3 \tag{2}$$

Furthermore, the earthquake catalog declustering process is carried out to separate the foreshocks and aftershocks from the main earthquake. Declustering follows the algorithm developed by Reasenberg (1985) using a combination of ZMAP 6 and 7 software (Reasenberg 1985; Reyes and 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 and Akinci 2020). Poisson's assumption applies to catalog declustering, where declustering stores the largest event and eliminates subsequent earthqu ake events that contribute to ground shaking. In addition, a complete earthquake catalog (not declustering) can be biased regarding the spatial variability of future seismic rates (Taroni and Akinci 2020).

The declustering process resulted in the two main clusters being concentrated on the strike-slip fault line. There were a total of 2574 and 1914 earthquakes, of which 742 earthquakes were lost (Fig. 3).

Estimated magnitude of completeness (M_c) 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 and 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 M_c, and it is also effective for forecasting the spatial distribution of

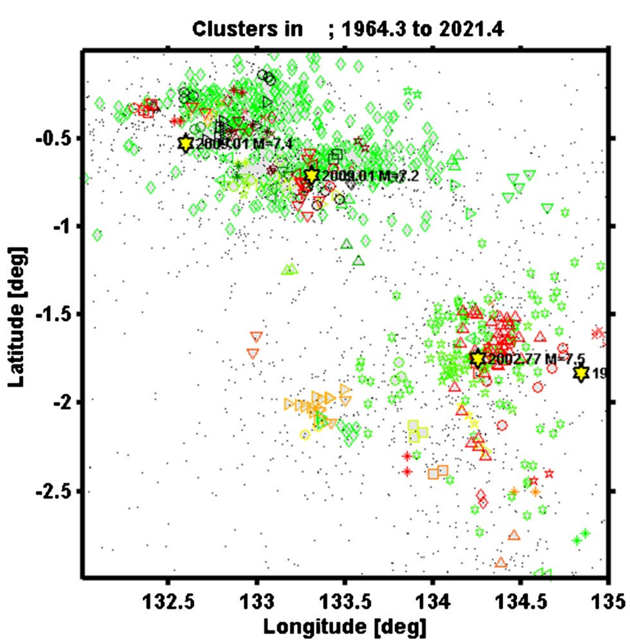


Fig. 3 Earthquake declustering model in West Papua Province based on the Reasenberg algorithm (1985) using ZMAP 6 software (Wiemer 2001)

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 M_c 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 a 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):

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

$N(M_w)$ 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 *a* 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 applied 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 and 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 and Wiemer 2019):

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

M_{mean} is the average value of the magnitude group with $M_{\text{mean}} \geq M_C$, 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 and Bolt 1982):

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

n is the number of calculated sampling earthquakes.

Result and discussion

Distribution of M_w magnitude and earthquake declustering in West Papua

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.

In many cases, it is necessary to distinguish the mainshock from the foreshocks and aftershocks by declustering to avoid deviations related to the spatial variability of future earthquake frequencies (Marzocchi and Taroni 2014; Taroni and Akinci 2020). The application of the PSHA method requires that the declustering seismicity level should eliminate dependent earthquake events from the calculation, leaving only independent earthquakes. The earthquake declustering 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 to southeast (Fig. 4a). The distribution of earthquake occurrences in the study area based on the parameters of magnitude and depth shows the dominance of magnitude ranging from 4 to 5.5 M_w at a relatively shallow depth of 70 km (Fig. 4b). The presence of plate subduction in the northern part of the Bird's Head of Papua associated with the Manokwari trough has resulted in many earthquakes occurring near the area, especially in the Koor, Sorong, Ransiki, and Yapen fault lines. Earthquake declustering results are very useful in determining seismic sources as part of the PSHA approach in the West Papua region in future studies. Based on the results in Fig. 4, we suggest seismic sources of this study for interest site location are point source of maximum earthquakes, line source based on fault lineaments, then an area source in form polygon in the Sorong area, and circle for Manokwari and South Manokwari. The dominance of shallow earthquakes with medium to large magnitudes needs to be a concern regarding the accumulation of earth crust stress in the study area. In addition, earthquakes that are centered in the sea and shallow have the potential to cause a tsunami if a large earthquake occurs.

Spatial and temporal variation of magnitude of completeness (M_c) and b value in West Papua

The results of the calculation or estimation of the M_c value based on the frequency magnitude distribution (FMD) in the West Papua region from the IRIS earthquake catalogs for the 1964–2021 period using the Maximum Likelihood method estimation with bootstrapping of 4.3 with an error of ± 2%. Another hand, seismicity parameter values *a* and *b* obtained are 7.09 and 0.92 (Fig. 5). The square data shows

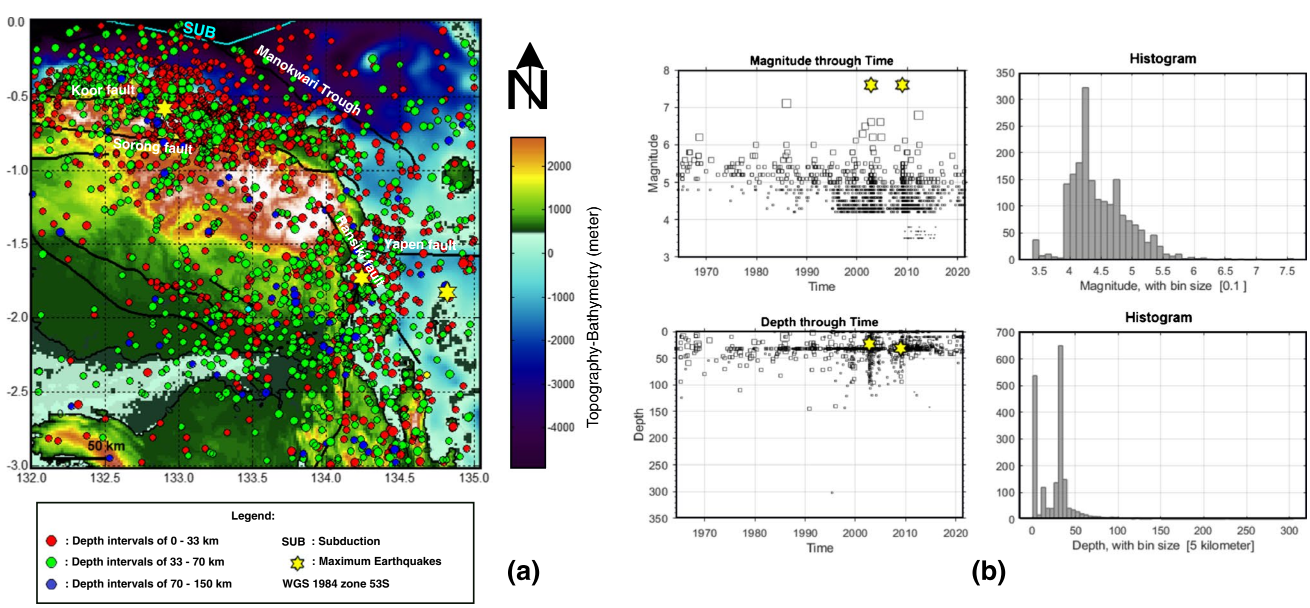


Fig. 4 Earthquake declustering results in West Papua using the Reasenberg algorithm, 1985. **a** Distribution of earthquake occurrences from 1964 to 2021. **b** Variation and histogram of earthquake magnitude and depth as a function of time

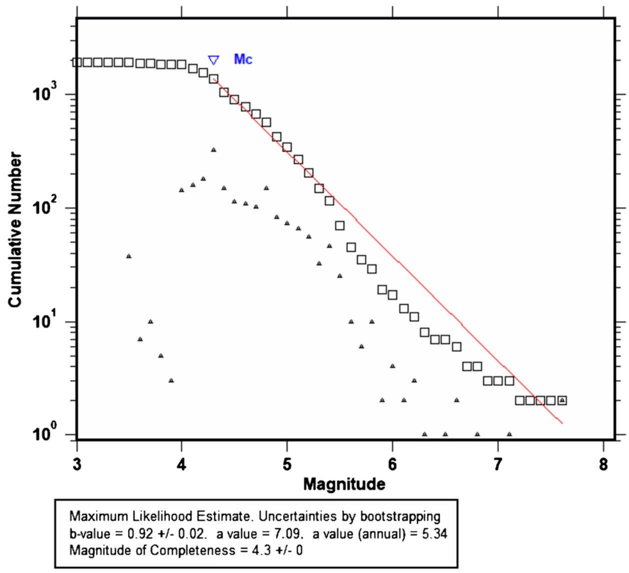


Fig. 5 The cumulative magnitude frequency distribution (FMD) in the West Papua region based on the IRIS earthquake catalog for period 1964–2021

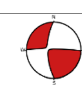
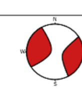
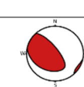
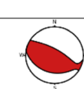
the cumulative earthquake occurrence, where the red line indicates the linear fit of the distribution of earthquake frequency and magnitude based on the Gutenberg-Richter equation. The estimates of M_c, *a*, and *b* values in West Papua are generally consistent with the results of previous studies on the entire island of Papua but tend to experience a slight decrease from the values of each parameter, including 4.7, 7.97, and 0.982 (Rohadi 2015).

The decrease in the value of M_c is thought to be due to the increase in the amount of data and recording time of earthquakes in this area, as well as the smaller study area focused on the main strike-slip fault line in the Bird's Head, Papua island, which is more tectonically active. Changes of M_c will affect in variation of *a* and *b* values. The average *b* value for the West Papua region is 0.92 with a deviation of 2% indicating that this region is at an intermediate level, where earthquake tectonic activity is intensely accumulating on the four main strike-slip faults. To confirm the results of the *b* value, we conducted a review of four major earthquakes that have occurred in the study area related to focal mechanism based on the global centroid moment tensor (CMT) catalog as shown in Table 2. This data shows the prevailing effect of strike-slip focal mechanism, with a minimum rake angle of 4° on the Ransiki fault and a maximum rake angle of 174° on the Yapen fault, also two other occurrences happening on the Koor and Sorong faults.

Several surveys have found that *b* value consistently depends on the focal mechanism of the earthquake. Thrust faults have smaller values, normal faults have larger values, and strike-slip faults have intermediate values (Gulia and Wiemer 2010; Scholz 2015). Schorlemmer et al. in 2005, studied the relationship between fault models and *b*-values by classifying earthquakes according to focal mechanisms. Regional and worldwide catalogs have been used to calculate the *b* value based on the rake angle of the earthquake. The result shows that the three faults have varying *b* values including normal fault related to a high value ($b_{NR} \approx 1.1$), strike-slip to intermediate ($b_{SS} \approx 0.9$), and thrusting fault correlated to low value $\left(b_{TH} \approx 0.7\right)$(Gulia and Wiemer 2010; Schorlemmer et al. 2005). The results of the strike-slip seismic 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 *b* value 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 level of *b* value and stress. In addition, a high of *a* value indicates a high and intense

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	

level of tectonic activity in the West Papua region. This study focused mainly on the main strike-slip fault in West Papua, which is linked with the strike-slip focal mechanism based on the occurrence of significant earthquakes in the past; therefore, we did not explore other earthquakes focal mechanisms for small areas and magnitude due to limitations of recording equipment and data.

Moreover, we also examined temporal variation M_c and b values from an earthquakes catalog in West Papua. It is necessary to determine the pattern of M_c 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 M_c and b values is performed using a window of 100 samples with 10 sample steps.

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 (Fig. 6a). The M_c parameter interpretation is also supported by magnitude distributions that were uncommon in West Papua before 1990 (Fig. 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 and Wyss 2000). We magnified or cutoff the 2002 earthquake (Fig. 6b) and the 2009 earthquake (Fig. 6c) to see fluctuations in the M_c value before and after the earthquake. It was discovered that M_c 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 M_c value. The temporal variation of the b value in the study area also has a certain unique pattern (Fig. 7a). After 1990, the b value decreased significantly until the early 2000. There was a slight increase until mid-2001, and it also decreased until before the main Ransiki earthquake on 10 October 2002 (Fig. 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 (Fig. 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

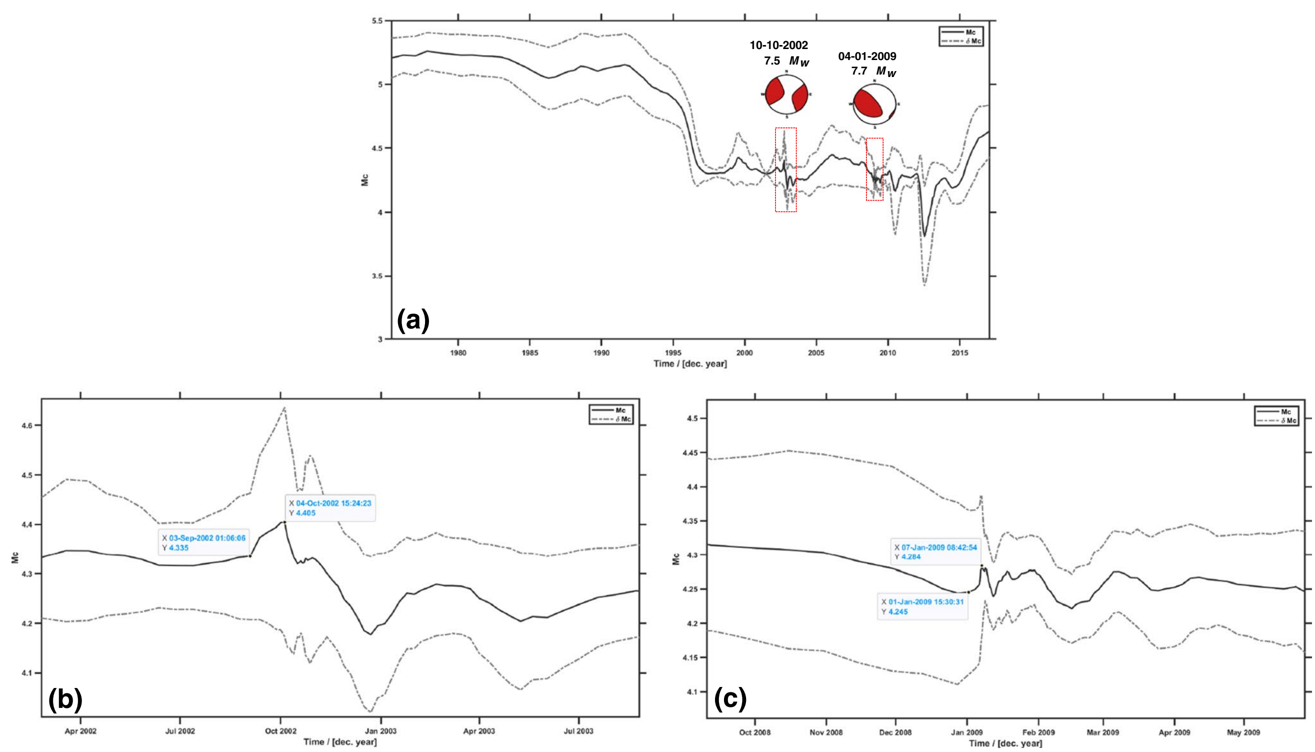


Fig. 6 **a** Temporal variation of M_c for earthquake catalogs in West Papua from 1964 to 2021, calculated using the maximum curvature technique with bootstrapping. **b** Zoom in on the M_c of October 10, 2002, a large earthquake on the Ransiki fault. **c** Zoom in on the M_c b of January 4, 2009, a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

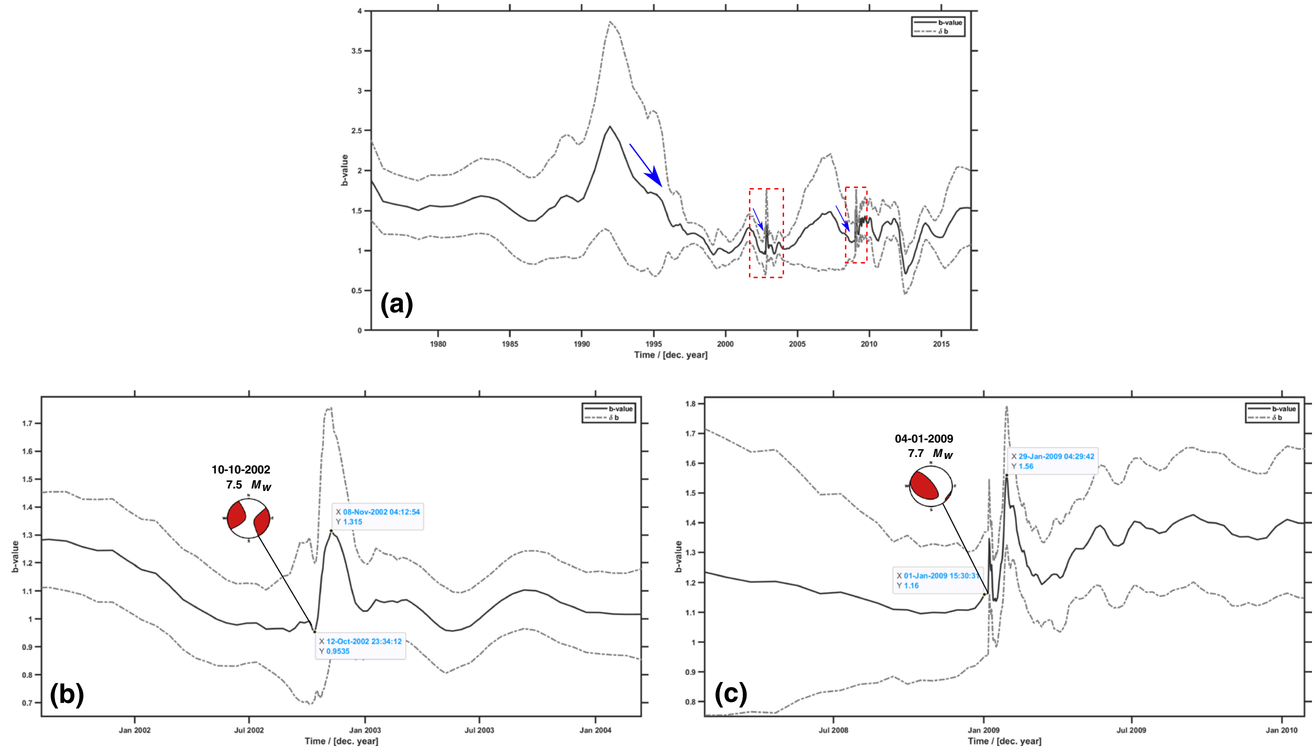


Fig. 7 **a** Temporal variation of *b* value for earthquake catalogs in West Papua from 1964 to 2021, calculated using the maximum curvature technique with bootstrapping. **b** Zoom in on the *b* value of October 10, 2002, a large earthquake on the Ransiki fault. **c** Zoom in on the *b* value of January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

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 and 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 (Fig. 8(b)).

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 and 30 km (Fig. 8(c)). 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 and 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).

Spatial and temporal distribution of completeness magnitude (M_c) and *b* value on the Manokwari and South *Manokwari regencies*

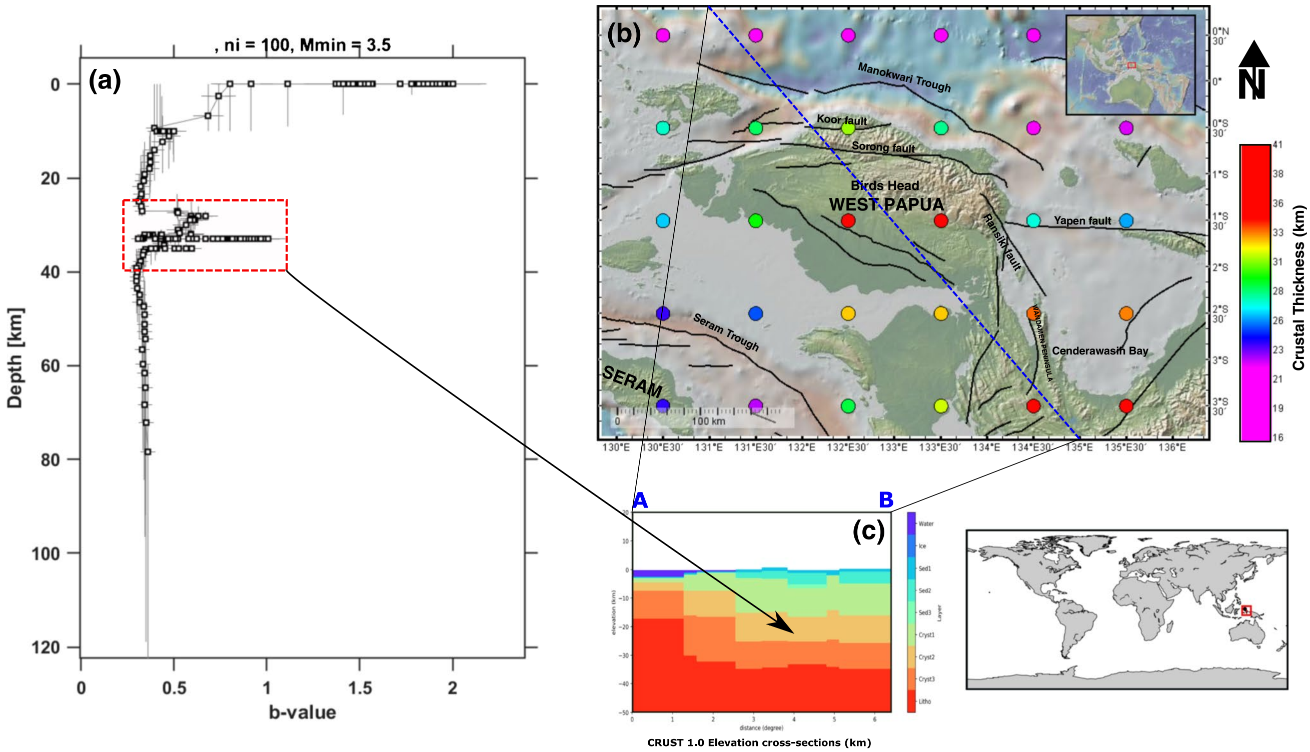


Fig. 8 **a** Variation of *b* value with depth based on earthquake catalog from 1964 to 2021 in West Papua. **b** The CRUST 1.0 model of the global earth crust in the research region. **c** CRUST 1.0 cross-section model in West Papua

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 (Fig. 9a), 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 a tsunami if large and shallow earthquakes occur at sea.

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

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 $b \sim 1$, and $b < 1$ are related to thrust faults (El-Isa and Eaton 2014; Schorlemmer et al. 2005). In this work, the spatial variation (*x*, *y*) of the seismic activity parameters (M_c, *a* and *b*) in Manokwari and South Manokwari was also studied (Fig. 10). Figure 10 a and b depict the spatial distribution of the minimum amplitude M_c and its standard deviation. Figure 10 c and d show the spatial distribution of the *b* value and its standard deviation, while Fig. 10 e and f show the spatial distribution of the *a* value and its standard deviation. The spatial distribution of M_c 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.

Conclusion

The estimation of the magnitude of completeness (M_c) and *b* value has been used to determine important seismotectonic parameters for the future seismic risk assessment of West Papua Province. The frequency and magnitude distributions in the earthquake catalog show that the dominant earthquake occurred on two major strike-slip fault lines, including the

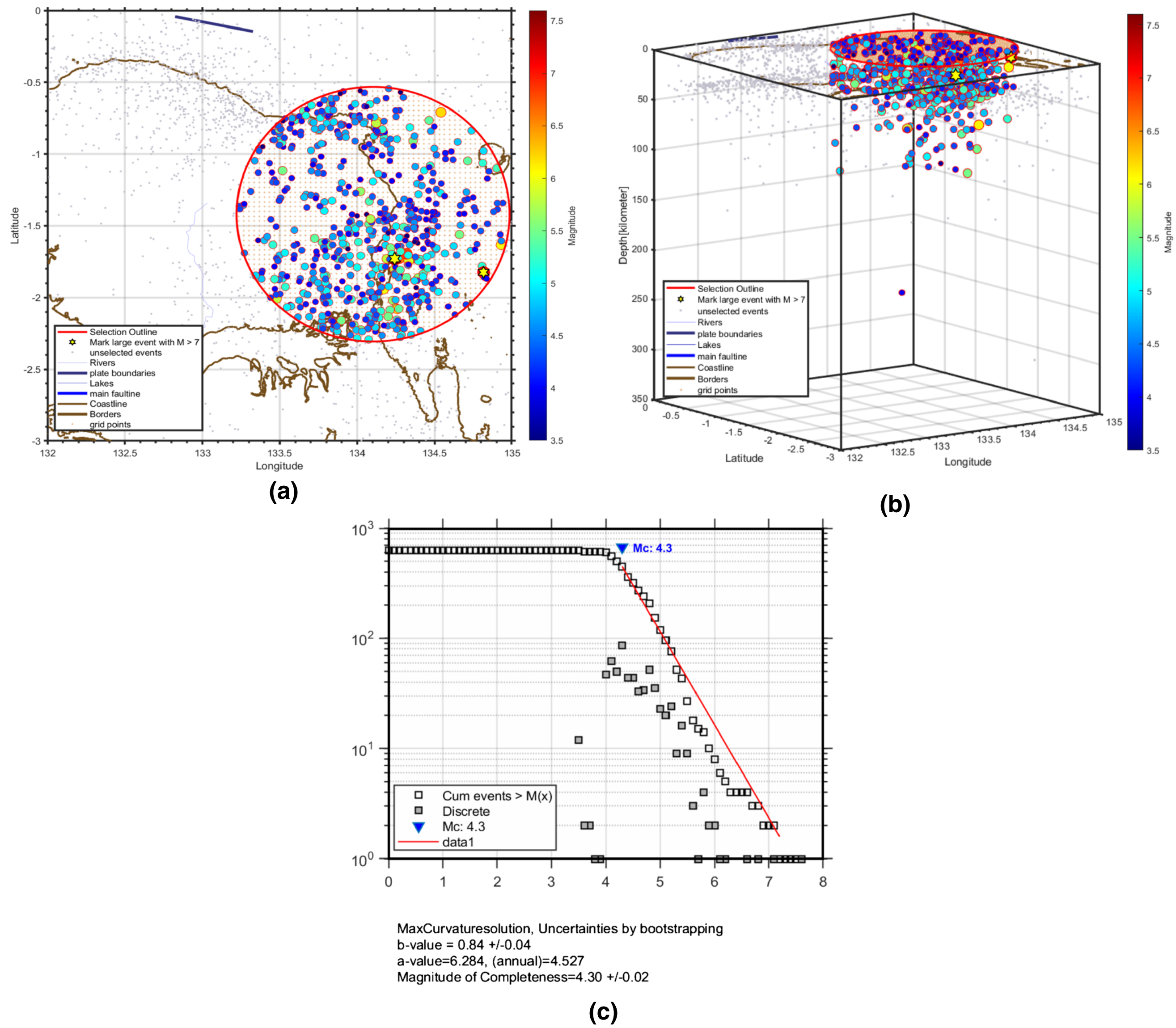


Fig. 9 **a** Distribution of earthquakes in Manokwari and South Manokwari regencies. **b** 3-D model of earthquake distribution is dominated by shallow earthquakes. **c** Distribution of the frequency magnitude of the Sorong-Ransiki-Yapen earthquake catalog for the period 1964–2021

Koor-Sorong and Ransiki-Yapen faults, resulting in an average value of 4.3 ± 0.02., 7.02, and *Mc*, *a*, and *b*. 0.92. The *b* value is at an intermediate level, which is estimated to be related to the structural characteristics of the study area and the dominance of the strike-slip focal mechanism. Temporal variation of *Mc* and *b* values showed a decreasing trend from 1990 to 2021, which may be due to the increase in the number of seismic data records and tectonic conditions in the region. Time series analysis shows a pattern of decreasing value of *b* several years before the large earthquake that occurred on October 10, 2002, with a magnitude of 7.5 M_w, and on January 4, 2009, with a magnitude of 7.7 M_w, then increased after the main earthquake occurred.

It is considered to be the increase in crustal stress before the main earthquake and the decrease in stress level due to energy release, and then a constant stabilizing, where *b* is the inverse of the stress level. 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 *b* value changed between depths of 25 and 30 km, regarded the boundary of the bottom crust and mantle in the research region, or even the transition zone from ductile to brittle conditions. The resulting seismic parameters will then be used for further seismic hazard assessment through the PSHA approach to determine the appropriate seismic source and site following the tectonic and geological conditions of the West Papua region.

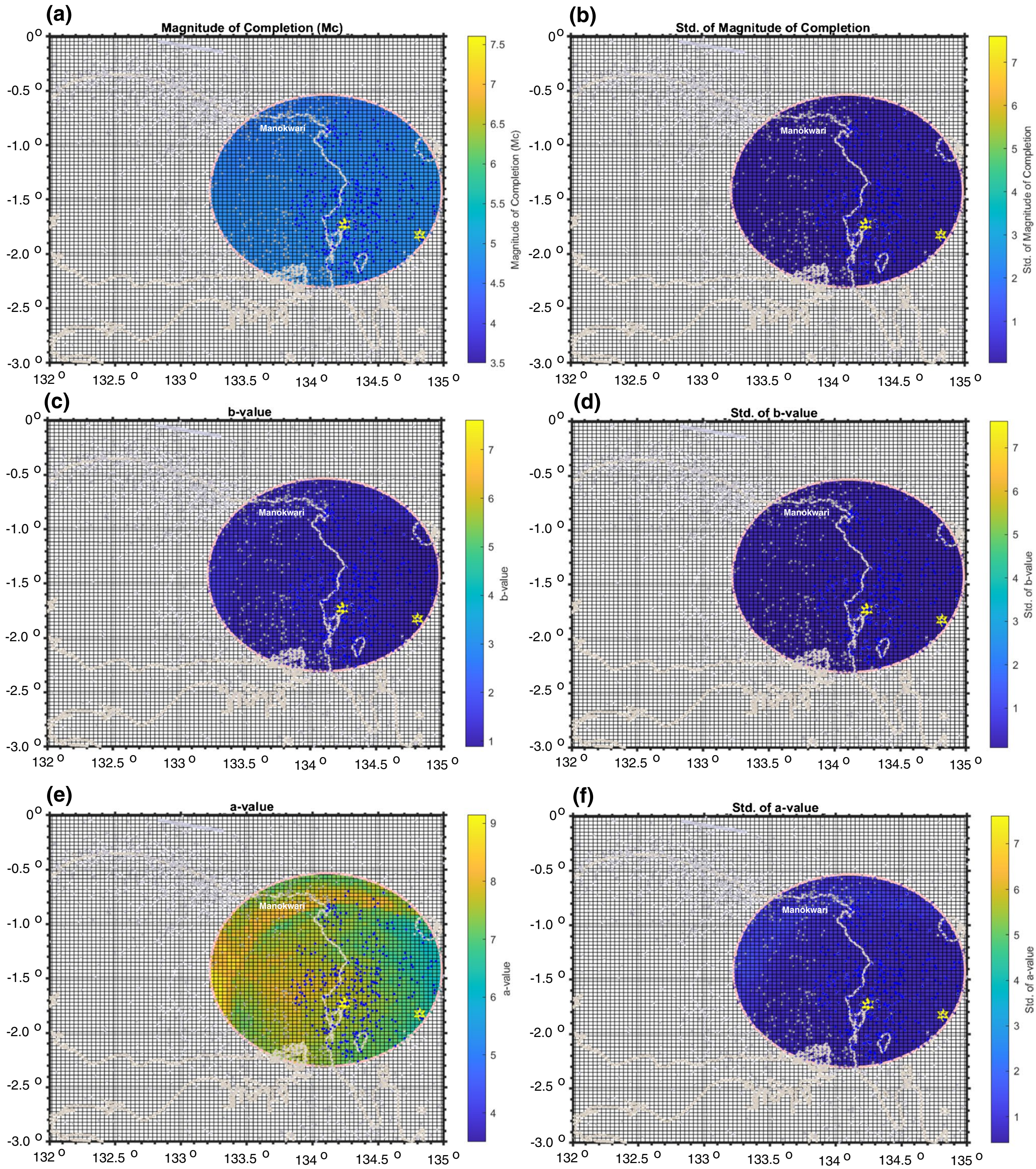


Fig. 10 Spatial variation of M_c, b, and a values in Manokwari and South Manokwari Regencies. **a** M_c variation. **b** Standard deviation of M_c. **c** b value variation. **d** Standard deviation of b value. **e** a value variation. **f** Standard deviation of a value

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Author contribution R.L and L.L have formulated concepts and designs of the research. R.R and Y.A.S look to the collection and processing of earthquakes catalog of West Papua province. R.L 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.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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