

Temporal and spatial distributions of precursory seismicity rate changes in the Thailand-Laos-Myanmar border region: implication for upcoming hazardous earthquakes

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Received: 17 September 2016 / Accepted: 26 September 2017 / Published online: 10 October 2017
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Abstract To study the prospective areas of upcoming strong-to-major earthquakes, i.e., $M_w \geq 6.0$, a catalog of seismicity in the vicinity of the Thailand-Laos-Myanmar border region was generated and then investigated statistically. Based on the successful investigations of previous works, the seismicity rate change (Z value) technique was applied in this study. According to the completeness earthquake dataset, eight available case studies of strong-to-major earthquakes were investigated retrospectively. After iterative tests of the characteristic parameters concerning the number of earthquakes (N) and time window (T_w), the values of 50 and 1.2 years, respectively, were found to reveal an anomalous high Z -value peak (seismic quiescence) prior to the occurrence of six out of the eight major earthquake events studied. In addition, the location of the Z -value anomalies conformed fairly well to the epicenters of those earthquakes. Based on the investigation of correlation coefficient and the stochastic test of the Z values, the parameters used here ($N = 50$ events and $T_w = 1.2$ years) were suitable to determine the precursory Z value and not random phenomena. The Z values of this study and the frequency-magnitude distribution b

values of a previous work both highlighted the same prospective areas that might generate an upcoming major earthquake: (i) some areas in the northern part of Laos and (ii) the eastern part of Myanmar.

Keywords Earthquake catalog · Seismicity rate change · Z value · Seismic quiescence · Precursor · Thailand-Laos-Myanmar border

1 Introduction

Within the intraplate seismotectonic setting in Mainland Southeast Asia (Fig. 1a), the Thailand-Laos-Myanmar border (TLMB) (Fig. 1b) encompass one of the more active seismogenic regions (Pailoplee and Choowong 2013, 2014). The M_w 6.8 earthquake generated on March 24, 2011, at Tarlay City (Wang et al. 2014) on the Thailand-Myanmar border destroyed a number of buildings and infrastructures while the tremors could be felt as far away as Hanoi (Vietnam) and in high-rise buildings in Bangkok (Thailand). The tremors generated by the M_w 6.1 earthquake on May 5, 2014, at the Prayao Fault Zone (no. 1 in Fig. 1b) (Ornthammarath and Warnitchai 2016) could be felt throughout northern Thailand as well as southwards as far as Bangkok. Therefore, the TLMB is currently classified as a seismic-prone area where the situation of seismic activities and hazards should be carefully studied.

Based on instrumental earthquake data, i.e., earthquake catalog, Pailoplee et al. (2013) investigated the spatial frequency-magnitude distribution (FMD)

First version (September 16, 2016). Second version (March 20, 2017). Third version (June 20, 2017). Fourth version (August 31, 2017)

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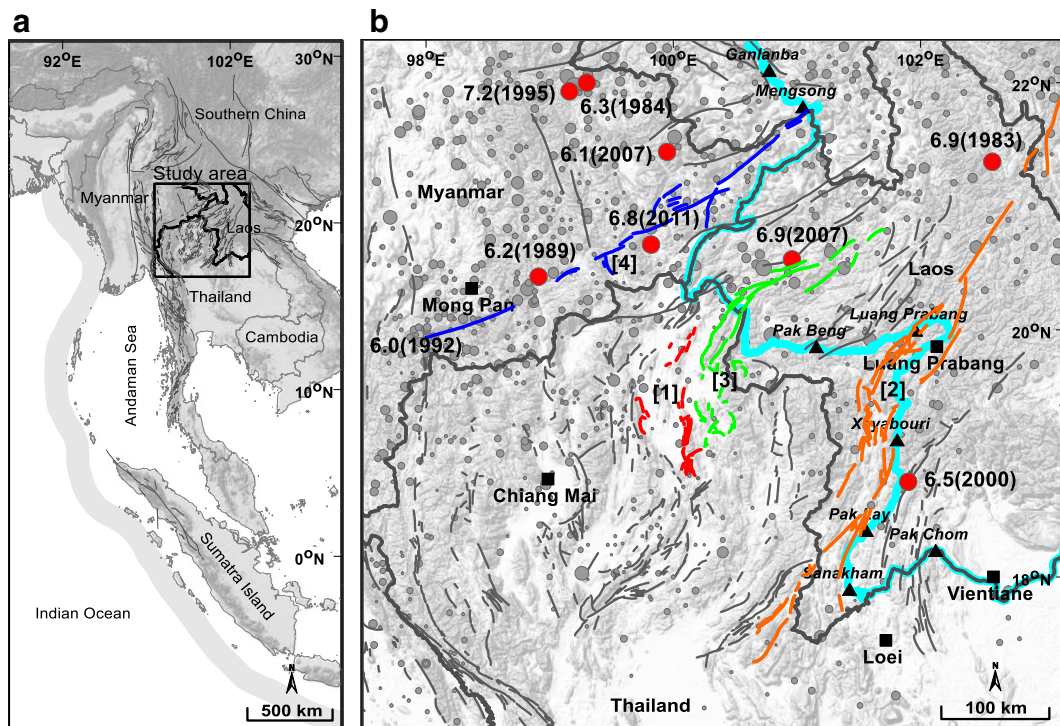


Fig. 1 **a** Map of Mainland Southeast Asia showing the Sumatra-Andaman Subduction Zone (thick gray line) and seismogenic faults proposed by Pailoplee et al. (2009) (thin black lines). The square denotes the study area of the Thailand-Laos-Myanmar border. **b** Shaded relief map of the TLMB area showing the completeness earthquake data recognized in this Z-value investigation (gray circles). Red circles are the strong-to-major

earthquakes ($M_w \geq 6.0$) used for the retrospective test of the Z value. Squares and triangles illustrate the location of major cities and dams, respectively, along the Mekong main stream (blue line). Gray lines denote the seismogenic faults proposed by Pailoplee et al. (2009). (1) Prayao, (2) Dein Bein Fu, (3) Mae Ing, and (4) Mengxing Fault Zones

(Gutenberg and Richter 1944) and mapped the distribution of the a - and b -coefficient values of the FMD. Following the approach of Yadav et al. (2011), both the a - and b -value maps were then estimated and proposed probabilistically the earthquake activities in the region of the TLMB in terms of the (i) possible maximum magnitude and (ii) return period of earthquake occurrence. As a result, Pailoplee et al. (2013) revealed that the TLMB is capable of generating an earthquake with a maximum magnitude of $4.0 \leq M_w \leq 6.0$ and $5.0 \leq M_w \leq 7.5$ in the next 10 and 50 years, respectively. In addition, based mainly on the assumption of Nuannin et al. (2005), Pailoplee et al. (2013) analyzed the earthquake catalog recorded during 1984–2010 and mapped the b values to represent the prospective areas of upcoming earthquakes. The b -value map illustrated that comparatively low b values, implying a high accumulated tectonic stress, were delineated in a NW–SE direction where the subsequent M_w 6.8 earthquake occurred, while the M_w 6.1 earthquake (Ornthammarath and

Warnitchai 2016) was generated at the external border of the mentioned anomalies (Pailoplee et al. 2013).

Based on Tiampo and Shcherbakov (2012), not only the anomalous b value but also a number of different statistical techniques were proposed to highlight the prospective area of forthcoming earthquakes, including the β value (Matthews and Reasenberg 1988), Z value (Wiemer and Wyss 1994), pattern informatics (Nanjo et al. 2006), and region-time-length algorithm (Huang 2004). Among these techniques, the seismicity rate change (Z value) is considered a powerful tool for mapping the precursory seismic quiescence of strong-to-major earthquakes (e.g., Rudolf-Navarro et al. 2010; Katsumata 2011a, b; Kawamura et al. 2014). To constrain the prospective areas of likely forthcoming earthquakes in the TLMB evaluated previously by the FMD b value (Pailoplee et al. 2013), the Z value was investigated in the same region in this study. The results indicate that not only the accumulated tectonic stress (i.e., b value) but also the seismic quiescence (i.e., Z

value) can be identified as an earthquake precursor in the TLMB.

2 Dataset and completeness

Instrumental earthquake data was compiled from the International Seismological Center (ISC; <http://www.isc.ac.uk/>) from within a 300-km radius extended from the study area. The obtained dataset consisted of 20,699 earthquake events in a magnitude range of 1.0–7.7, recorded from 1964 to 2015. The focal depths of most data were shallower than 40 km, implying the intraplate seismotectonic regime of the study area, as previously reported. To homogenize the magnitude scale, which was reported differently in the catalog, body-wave magnitude (m_b) and surface-wave magnitude (M_S) scales were converted directly to the moment-magnitude (M_w) using the empirically contributed relationships determined from the data available in the study area. For local magnitude scale (M_L), the relationship between m_b and M_L proposed by Palasri and Ruangrassamee (2010) was applied. Thereafter, the obtained m_b scale was reconverted to M_w using the M_w - m_b relationship used in the present study.

In statistical seismology, the temporal and spatial clustering of seismic events in foreshock, mainshock, and aftershock can be defined by using both fixed space and time windows relating to the earthquake magnitude. Conceptually, any earthquake that occurs within both predefined windows is deemed a cluster event. The largest event in each cluster is assumed as the mainshock, directly representing the seismotectonic activities. Different assumptions of fixed space and time windows have been previously proposed by Gardner and Knopoff (1974), Reasenbergs (1985), and Uhrhammer (1986). However, in case of earthquake declustering of events occurring in the Mainland Southeast Asia region, including the TLMB, Petersen et al. (2004) and Petersen et al. (2007) applied the Gardner and Knopoff (1974) assumption. Therefore, in this study, after homogenizing the earthquake magnitude to M_w , the earthquake data were declustered following Gardner and Knopoff (1974).

Empirically, the earthquake catalog can be subject to artifacts from changes in operational procedures that alter the reporting rate of earthquake data (Habermann 1983; Wyss 1991; Zuniga et al. 2005). To detect these artifacts, the Z values were analyzed continuously in

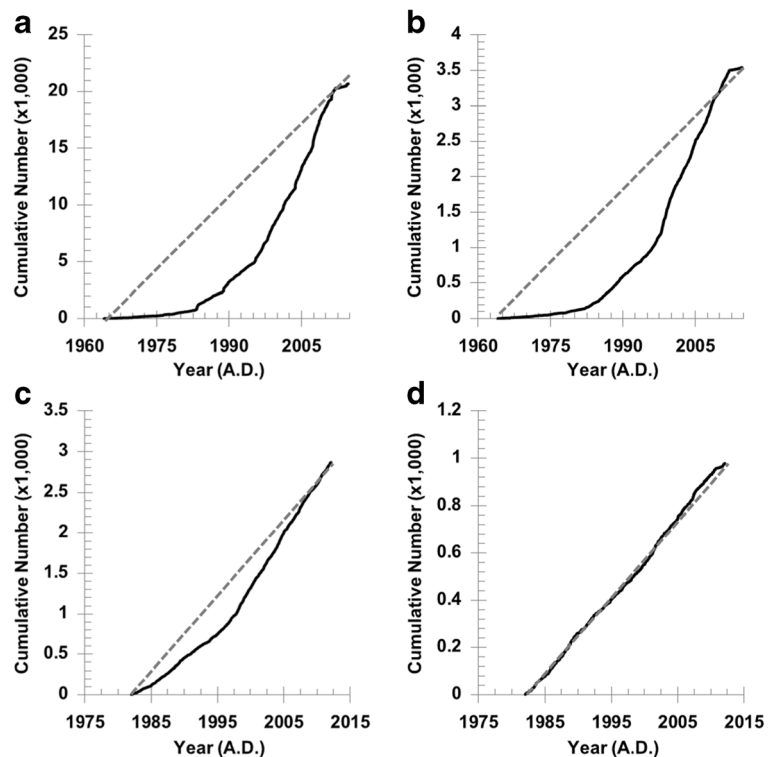
individual magnitude and time interval throughout the magnitude range (1.0–7.7 M_w) and the recording period of the dataset (1964–2015). To analyze the GENAS algorithm (Habermann 1983, 1987), ZMAP software (Wiemer 2001) was employed. As a result, the abovementioned man-made activities could be excluded from the earthquake catalog for $M_w > 2.5$ earthquakes during the 1983–2011 period. This obtained seismic recording network was then evaluated to determine the lowest earthquake magnitude detected using empirical FMD. According to the entire-magnitude range concept (Woessner and Wiemer 2005), earthquakes with $M_w > 3.6$ were always detected by the available seismological network.

To constrain seismicity data completeness, several works observed the relationship of the cumulative number of earthquakes as a function of time and reported that the temporal variation of the cumulative number smoothed out to form a straight line after the individual improvement process mentioned above (e.g., Bachmann 2001; Chouliaras 2009; Rudolf-Navarro et al. 2010; Katsumata 2011a; Katsumata and Sakai 2013). To constrain seismicity data completeness, this work also provided the cumulative number of earthquakes against time in each of the procedures (Fig. 2). At first, the cumulative curve of the total seismicity data showed a flat trend line generated between 1964 and 1982. Thereafter, the cumulative number of earthquakes rose gradually until 2015 (Fig. 2a). After declustering and removal of foreshocks and aftershocks, the shape of the cumulative curve (Fig. 2b) remained similar to that in the original seismicity data after magnitude conversion (Fig. 2a), even after the total number of the earthquakes in the dataset decreased after declustering from 20,699 to 3543 events. After removal of the artifacts from the seismicity data, the cumulative curve still did not show any flat trend compared with the previous ones, but rather the overall trend line was straighter for the dataset of 1983–2011 (Fig. 2c). Finally, the cumulative number of mainshocks with $M_w > 3.6$ gave an almost straight line for the entire period (Fig. 2d), thus defining the completeness of earthquake data that was suitable for statistical seismicity analysis, including the Z-value investigation.

3 Seismicity rate change (Z value)

To detect the spatiotemporal changes in the seismicity generated prior to the hazardous earthquakes, the Z

Fig. 2 Cumulative earthquake data in the TLMB plotted against time after **a** magnitude conversion, **b** declustering foreshocks and aftershocks, **c** analyses by the GENAS algorithm, and **d** the magnitude of completeness. Dashed lines indicate the linear trend line



value was examined (Wiemer and Wyss 1994), as defined by Eq. (1):

$$Z = \frac{R_{bg} - R_w}{\sqrt{\frac{S_{bg}^2}{N_{bg}} + \frac{S_w^2}{N_w}}}, \quad (1)$$

where Z denotes the changing levels of the seismicity rate represented by the difference between the average seismicity rate within a considered time window (R_w) and the background rate evaluated from the seismicity outside the recognized window (R_{bg}). The factors S_w and S_{bg} refer to the standard deviation, whereas N_w and N_{bg} are the number of earthquake data, respectively. Seismically, positive and negative values of Z imply that the seismicity rate is lower (i.e., seismic quiescence; Huang et al. 2001; Sobolev et al. 2002; Tiampo and Shcherbakov 2012) and higher (i.e., seismic activation; Huang et al. 2001; Rundle et al. 2011; Tiampo and Shcherbakov 2012) than the background rate, respectively. To derive the relationship between the change of seismicity and the occurrence of a subsequent hazardous earthquake, the eight strong-to-major earthquakes of $M_w \geq 6.0$ (Table 1) from the completeness earthquake data were recognized in the case study. In each individual

case, the Z values were evaluated retrospectively in both temporal and spatial aspects.

3.1 Retrospective temporal investigation

As regards temporal investigation, the free characteristic parameters were varied, including (i) the number of earthquakes (N ; 25–150 with 25 events intervals) and (ii) the time window (T_w ; 0.2–6 years with 0.2-year intervals). The iterative test of 174 (6×29) characteristic conditions revealed that the most suitable characteristic parameters were $N = 50$ events and $T_w = 1.2$ years. The retrospective temporal investigation found six seismicity precursors from the eight strong-to-major earthquake events. Due to the insufficiency of the seismicity data, the M_w 6.9 and M_w 6.3 earthquakes posed during 1983–1984 could not detect any anomalous Z value before the earthquake occurrences (Table 1). For each case study, the cumulative number of earthquakes was plotted versus time. Thereafter, the Z value was computed, using the long-term average function generated by Wiemer and Wyss (1994) as in Eq. (1).

For example, in Fig. 3a, the calculated Z value illustrates the peak ($Z = 1.9$) at 1984.56. Thereafter, around 5 years later, the M_w 6.2 earthquake was generated on

Table 1 List of strong-to-major earthquakes ($M_w \geq 6.0$) generated within the TLMB during 1983–2011 and some results of the Z-value investigation using $N = 50$ events and $T_w = 1.2$ years

No.	Longitude (° E)	Latitude (° N)	Date	Time (UTC)	Depth (km)	M_w	Z	Qs (years)	Q-time (years)
1.	102.58	21.36	June 24, 1983	09:07	33	6.9	–	–	–
2.	99.30	22.00	April 23, 1984	22:29	24	6.3	–	–	–
3.	98.91	20.43	September 28, 1989	21:52	10	6.2	1.9	1984.56	5.2
4.	99.16	21.93	July 11, 1995	21:46	13	7.2	4.5	1989.16	6.4
5.	101.90	18.77	June 7, 2000	21:48	33	6.5	3.5	1992.35	8.1
6.	100.96	20.57	May 16, 2007	08:56	15	6.9	2.6	2003.93	3.4
7.	99.95	21.44	June 23, 2007	08:17	17	6.1	6.8	1999.52	8.0
8.	99.82	20.69	March 24, 2011	13:55	8	6.8	6.8	1997.07	14.2

Z denotes the maximum Z value evaluated at each epicenter of the earthquake case study, while Qs and Q-time are the starting time of seismic quiescence and duration between the mentioned seismic quiescence and the main shock, respectively

September 28, 1989, at the eastern part of Mong Pan (no. 3 in Table 1). In Fig. 3b, the maximum Z value of 4.5 appears in 1989.16, and 6.4 years later, the M_w 7.2 earthquake was generated on July 11, 1995, at the western part of Mengsong. For Fig. 3c, the maximum Z value of 3.5 appears at 1992.35 and then, around 8 years later, the M_w 6.5 earthquake was generated on June 7, 2000, at the southern part of Xayabouri dam (Fig. 1b). However, in some case studies, several flat lines occurred along the cumulative number curve that led to more than one Z peak along the recognized time span. For example, in Fig. 3d, f, at least three peaks of maximum Z value are evident. To define the Z peak that was the earthquake precursor, the last peak of each graph was recognized in this study. As a result, the last Z peak at 2003.93 in Fig. 3d and Z peak at 1997.07 in Fig. 3f are defined as the precursory peak of both M_w 6.9 and M_w 6.8 earthquakes generated in the TLMB (nos. 6 and 8 in Table 1). In Fig. 3e, two Z peaks are evident in 1987.94 and 1999.52, but the last peak at 1999.52 is defined as the precursory seismic quiescence of the M_w 6.1 earthquake generated on June 23, 2007 (no. 7 in Table 1).

3.2 Retrospective spatial investigation

To constrain the potential Z value for detecting earthquake precursors in the TLMB region, the Z values were investigated spatially and mapped. The TLMB region was gridded by cells with a dimension of $0.25^\circ \times 0.25^\circ$, and in each individual grid node, the closest 50 events of the completeness earthquake data were identified and the Z value was determined temporally in the same manner as in the previous temporal investigation. According to the

quiescence time defined previously (Fig. 3 and column Qs in Table 1), the Z value of each grid node was selected, contoured, and mapped, and the resulting maps of six examples are shown in Fig. 4 and discussed below.

In the M_w 6.2 earthquake generated on September 28, 1989 (no. 3 in Table 1), the spatial distribution of the Z value mapped in 1984.56 (Fig. 4a) showed that although the positive Z value was similar throughout the study area, a comparatively high Z value could be defined fairly well in the eastern part of Mong Pan and the northwestern part of Pak Beng Dam, with a maximum Z value range of 2.0–3.0. The location of the subsequent M_w 6.2 earthquake was within the vicinity of the defined anomalous high Z (Fig. 4a). In addition, the spatial distribution of the Z value evaluated in 1989.16 (Fig. 4b) indicated a more prominent Z anomaly that was distributed widely over a 100×200 -km area in the northern part of Mong Pan. Then, 6.4 years later, the M_w 7.2 earthquake was generated on July 11, 1995 (no. 4 in Table 1), in the western part of Mengsong within the maximum Z anomaly area mentioned here (Fig. 4b).

For the Z map in 1992.35 (Fig. 4c), an anomalous Z value ($3.0 \leq Z \leq 7.0$) was distributed in a NW–SE direction over eastern Myanmar, northwestern Laos, and a large portion of northeastern Thailand. In addition, the Z anomalies decreased gradually southwards along the Thailand–Laos border. Thereafter, around 8.1 years since 1992.35, the epicenter of the M_w 6.5 earthquake generated on June 7, 2000 (no. 5 in Table 1), by the Dein Bein Fu Fault Zone (no. 2 in Fig. 1b; Zuchiewicz et al. 2004) was located along the Mekong Mainstream in the southernmost part of the Z anomalies with a positive Z value of 3.5 (Fig. 4c).

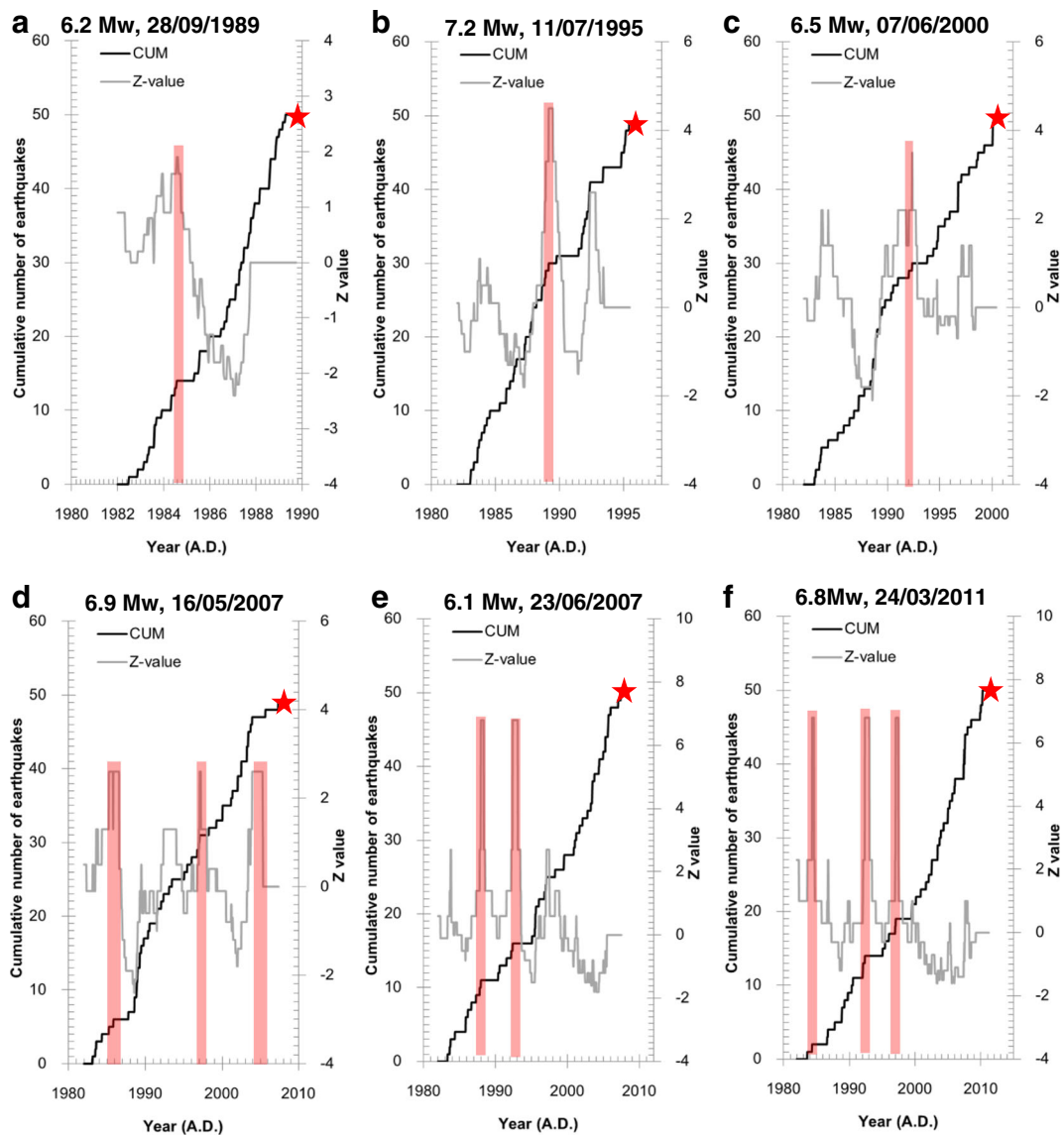


Fig. 3 Cumulative number of earthquakes (gray line) and Z value (black line) plot versus time for each of six strong-to-major earthquakes (nos. 3–8 in Table 1). The stars are the occurrence time of

each earthquake. The anomalous Z value recognized as the quiescence stage is illustrated by a transparent gray strip

When the Z values were spatially mapped on 2003.93 (Fig. 4d), a comparatively high Z value was located at northwestern Laos, and 3.4 years later, the earthquake with M_w 6.9 (no. 6 in Table 1) was generated in the Mae Ing Fault Zone (no. 3 in Fig. 1b; Fenton et al. 2003) on the rim of the Z-value anomalies. Finally, when the Z values were mapped in 1997.07 (Fig. 4f), a strip of anomalous high Z values were delineated in an E–W direction at the junction of the TLMB. Around 14.2 years later, the epicenter of the M_w 6.8 earthquake generated on March 24, 2011 (no. 8 in Table 1), was located within the high Z-

value zone occupied by the Mengxing Fault Zone (no. 4 in Fig. 1b; Lacassin et al. 1998). Therefore, anomalous high Z values in these spatial distributions evaluated using $N = 50$ events and $T_W = 1.2$ years seemed to act as reasonable earthquake precursors.

3.3 Correlation coefficient and stochastic test of the Z value

To test the sensitivity of the free characteristic parameters proposed for the TLMB (i.e., $N = 50$ events and

Fig. 4 Map of the TLMB area illustrating the spatial distribution of **a–f** the Z values for six of the eight major earthquakes (nos. 3–8 in Table 1) at the time slice of seismic quiescence evaluated from the temporal investigation (Fig. 3). Red and blue colors denote the decrease (+ Z) and increase ($-Z$) in the rate of seismicity, respectively. Blue stars represent the epicenter of the earthquake case study, including the M_w 6.1 earthquake on May 5, 2014. **g** Spatial distribution of the FMD b values, as analyzed from the completeness earthquake catalog, reported during 1984–2010 (Pailoplee et al. 2013)

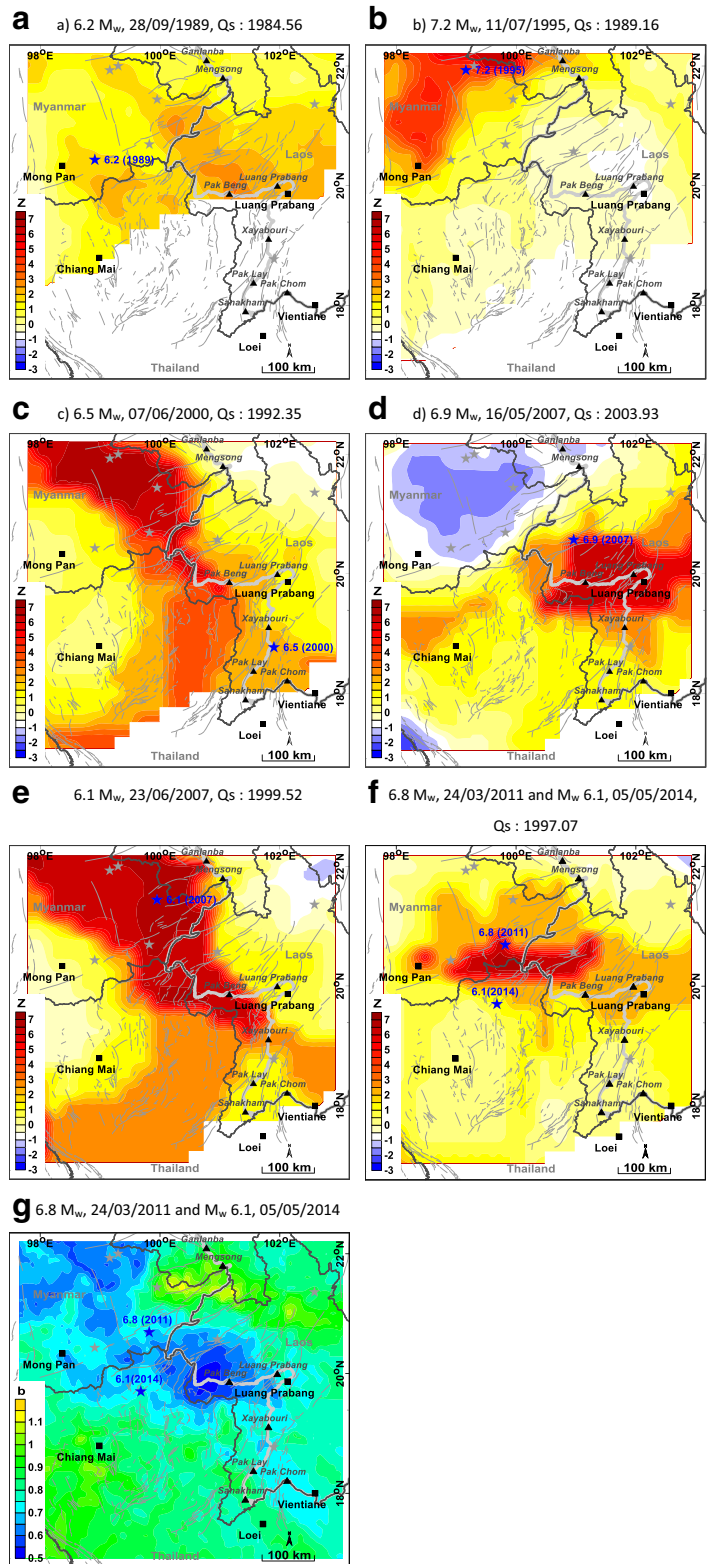


Table 2 Correlation coefficients of the Z values of the M_w 7.2 earthquake generated on July 11, 1995, compared between different N and T_w values

Case A	$N = 50$ events, $T_w = 1.2$ years			
Case B	$T_w = 1.0$ years	$T_w = 1.4$ years	$N = 30$ events	$N = 70$ events
Correlations A and B	0.81	0.84	0.91	0.91

$T_w = 1.2$ years), the correlation coefficient (Huang 2006) was investigated for the M_w 7.2 earthquake generated on July 11, 1995 (no. 4 in Table 1). When comparing the parameters $N = 50$ events and $T_w = 1.2$ years, both N and T_w were varied in different combinations (Table 2). In all varied conditions, variations of Z value were investigated temporally and correlated statistically with the Z value calculated by $N = 50$ events and $T_w = 1.2$ years (Fig. 5a). The correlation coefficients are in the range of 0.81–0.91 (Table 2), implying no significant effect of the free-parameter changes in this Z-value investigation.

To ascertain that the values of Z obtained in this study are not according to random phenomena, the stochastic

test (Huang 2006) was applied. At first, 10,000 earthquake catalogs were synthesized stochastically within the same study area and recording time of the completeness earthquake catalog used in this study (i.e., 1983–2011). In each synthesized catalog, Z values were computed at the epicenter of the M_w 7.2 earthquake (no. 4 in Table 1) using free characteristic parameters $N = 50$ events and $T_w = 1.2$ years. Thereafter, the probability of Z value accords to random phenomena was added (Fig. 5b). Based on the maximum Z value of 4.5 of the M_w 7.2 earthquake case study, the probability was estimated at 11% (Fig. 5b), implying that the Z values obtained in this study are significant and not due to random phenomena (Fig. 5b).

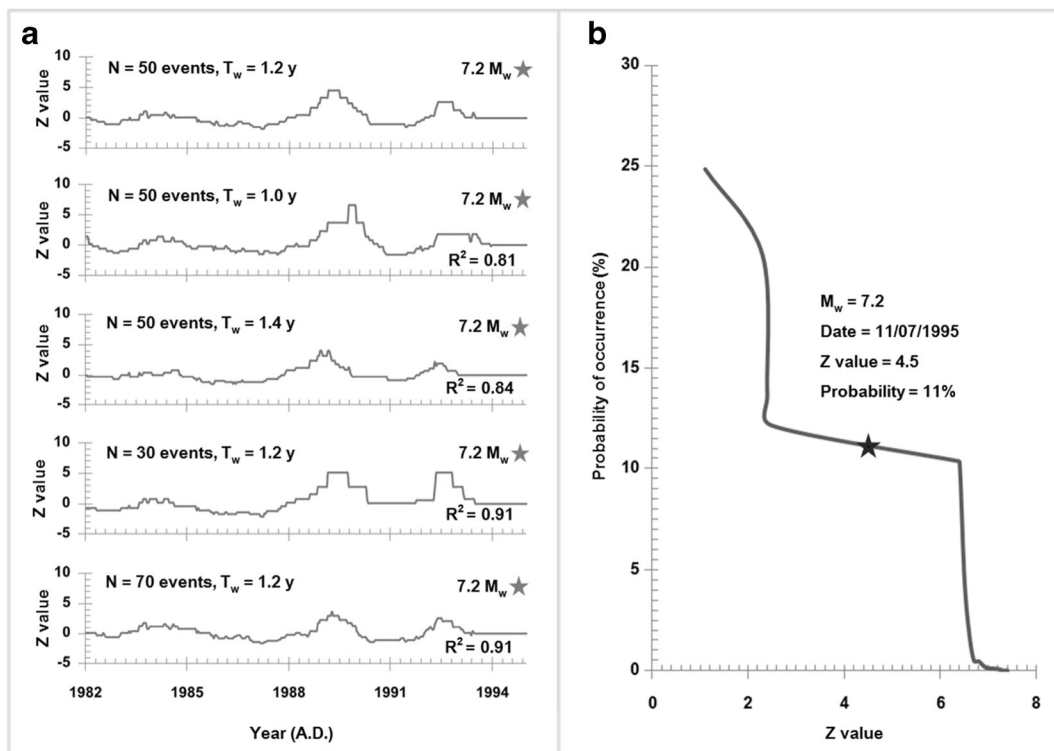


Fig. 5 Statistical investigation of Z value of the M_w 7.2 earthquake generated on July 11, 1995 (no. 4 in Table 1). **a** Temporal variation of Z value evaluated from different free characteristic parameters N and T_w . R^2 denotes the correlation coefficient of each

varied free characteristic parameter compared with the parameters $N = 50$ events and $T_w = 1.2$ years. **b** The probability (%) of various Z value accords to a random phenomena calculated at the epicenters of the M_w 7.2 earthquake

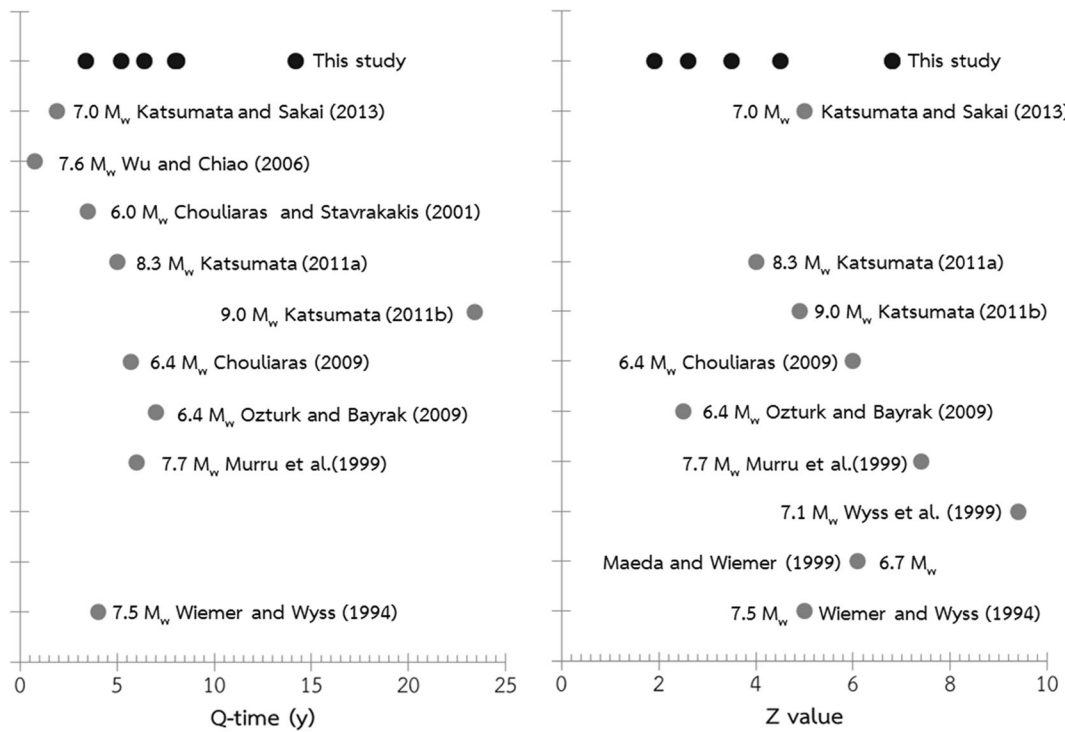


Fig. 6 a The time span between the recognized seismic quiescence and occurrence time of the mainshock evaluated by the Z value technique in this study compared with those in previous

studies. **b** Comparison of Z values at the mainshock location in this and previous studies

4 Discussion and conclusion

During the past decade, the TLMB region has experienced at least two strong earthquakes: the M_w 6.8 earthquake in 2011 and the M_w 6.1 earthquake in 2014. Therefore, the likeliness of upcoming earthquakes is needed to be determined through earthquake hazard studies and future mitigation plans. Thus, this work attempted to investigate the precursory seismicity rate changes (Z value) before the occurrence of strong-to-major earthquakes in the TLMB area. Using the characteristic parameters of Z of $N = 50$ events and $T_w = 1.2$ years, this study found meaningful precursory seismicity rate changes for six of the eight case studies of strong-to-major earthquakes. In addition, according to the comparison between previously reported works and this study, a number of interesting issues have been identified as follows.

This work compared the time span between the mentioned seismic quiescence and subsequent strong-to-major earthquake (Q-time in Table 1) from the Z-value investigation in this study and those in previous works.

According to the previous works, most Z-value investigations reported Q-time in the range of 0.8–7.0 years (Fig. 6a; Wu and Chiao 2006; Chouliaras 2009) prior to a hazardous earthquake (e.g., Murru et al. 1999; Öztürk and Bayrak 2009; Chouliaras 2009; Katsumata 2011a; Sorbi et al. 2012; Katsumata and Sakai 2013). Only one research study has indicated a quiescence detection of more than 20 years from the anomalous Z value, this being prior to the M_w 9.0 Tohoku earthquake (Katsumata 2011b). With respect to the Z-value investigation in the TLMB, the Q-time of six retrospective tests were in the range of 3.4–14.2 years (Fig. 6a), which could be fairly effective for intermediate-term forecasting (months–10 years).

In addition, previous reports on Z-value anomalies have indicated that the Z value at the location of the mainshock varied from 2.5 to 9.4, which is not markedly different from those in this study of 1.9–6.8 (Fig. 6b). Therefore, the Z-value investigation in the TLMB area using the Z parameters of $N = 50$ events and $T_w = 1.2$ years appears to clearly generate Z-value anomalies at the location of future strong-to-major

earthquakes, and all of the Z -value anomalies in this work are noticeable and obvious.

Regarding to the prospective areas of upcoming major earthquakes, the anomalous Z values obtained in this study were compared with the previously reported b -value study of the same area and time span (Pailoplee et al. 2013). Seismotectonically, a higher Z value implies a higher seismicity quiescence, while a lower b value is related empirically to a higher level of accumulated stress. The comparison revealed that an area of around 350 km² that mostly covers the triple junction of the TLMB had a high Z value since 1997.07 (Fig. 4f) and a low b value using the seismicity data reported during 1984–2010 (Fig. 4g). After this, two strong-to-major earthquakes generated in this area: the M_w 6.8 earthquake on March 24, 2011 (Wang et al. 2014), and the M_w 6.1 earthquake on May 5, 2014 (Ornthammarath and Warnitchai 2016). The correspondence between the overlapping areas of high Z values and low b values suggests that those areas without a subsequent strong-to-major earthquake are likely to be prospective areas for upcoming strong-to-major earthquakes, including (i) some areas in the northern part of Laos interpreted by both high Z and low b values (Fig. 4f, g) and (ii) the eastern part of Myanmar interpreted only by the low b value (Fig. 4g). Based on the earthquake activities analyzed by Pailoplee et al. (2013), it was revealed that both prospective areas mentioned above can generate an earthquake with a possible maximum magnitude of 5.5, 6.0, and 6.5 m_b in the next 5, 10, and 50 years, respectively. Therefore, the effective mitigation plan of seismic hazard in the TLMB should also be considered.

Acknowledgements This research was supported by the Ratchadapiseksomphot Endowment Fund 2017 of Chulalongkorn University to S Pailoplee. Thanks are also extended to T. Pailoplee for the preparation of the draft manuscript. The Office of Research Affairs, Chulalongkorn University, is also thanked for a critical review and improved English. The thoughtful comments and suggestions by T Braun, the associate editors, and M Choowong as well as anonymous reviewers that significantly enhanced the quality of this manuscript are acknowledged.

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