Bulletin of Earth Sciences of Thailand

Seismicity Change Prior to Major Earthquakesof the Sumatra-Andaman Subduction Zone; Implication for Tectonic Regime

Santawat Sukrungsri[1,2,*]and Santi Pailoplee[2]

[1]*Seismological Bureau, Thai Meteorological Department, Bangkok, 10260, Thailand*
[2]*Earthquake and Tectonic Geology Research Unit (EATGRU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand*
* Corresponding author E-mail: Sukrungsri.S@gmail.com

Abstract

In this study, the seismicity pattern changes prior to the 2004 Sumatra and 2012 Indian Ocean earthquakewere investigated statistically according to the Region-Time-Length (RTL) algorithm. The utilized earthquake catalogue was occupied by the International Seismological Centre (ISC). After details analysis, the earthquake dataset with $M_W \geq 4.4$ recorded during 1980-2015 were completeness in term of seismotectonic investigation.The temporal variation and the spatial distributions revealed consistent characteristics in seismicity pattern changes. The seismic quiescence anomalies generally started a few years before the occurrence of the interplate earthquakes, i.e., 2004 Sumatra earthquake while the earthquakes within an oceanic intraplate, i.e., 2012 Indian Ocean earthquake indicated seismic quiescence anomalies started a several years before the following earthquake posed. According to stochastic test, it is revealed that the RTL signal obtained here is not artifact. Therefore, we concluded preliminarily that the different time span of quiescence imply significantly the different tectonic regime.

Keywords: Earthquake Catalogue; Seismic Quiescence; *RTL* Algorithm; Interplate; Intraplate; Sumatra-Andaman Subduction Zone.

1. Introduction

After both ground shaking and tsunami devastations caused by the M_w-9.0 earthquake on December 26th, 2004 and the subsequent earthquake with 8.6 M_w posed on April 11th, 2012, coastal communities around the Indian Ocean realized that the Sumatra–Andaman Subduction Zone (SASZ) is the significant seismogenic source and so might pose a threat again in the future. Tectonically, this M_w-9.0 event was a typical interplate earthquake according to the Indo-Australian plate subducts underneath the Eurasian plate (Martin, 2005) while the M_w-8.6 event occurred differently in an oceanic intraplate setting within the Indo-Australian Plate (Vanessa and Kusala, 2014) (Figure 1).

Base on a number of previous works, some researches on precursors of the past earthquakes suggest that the particular space-time seismicity patterns including the phenomenon of precursory quiescence can be related to the seismo-tectonic processes that lead to earthquakes (Wyss and Habermann, 1988). However, they are still unclear about the difference between such precursory seismic quiescence of interplate and intraplate tectonic setting. Therefore, the purpose of this study is to identify and characterize a change in seismicity patterns, i.e., seismic quiescence, before the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake using Region-Time-Length algorithm (RTL). The results obtained here support the relation between tectonic setting and characteristic of seismic quiescence.

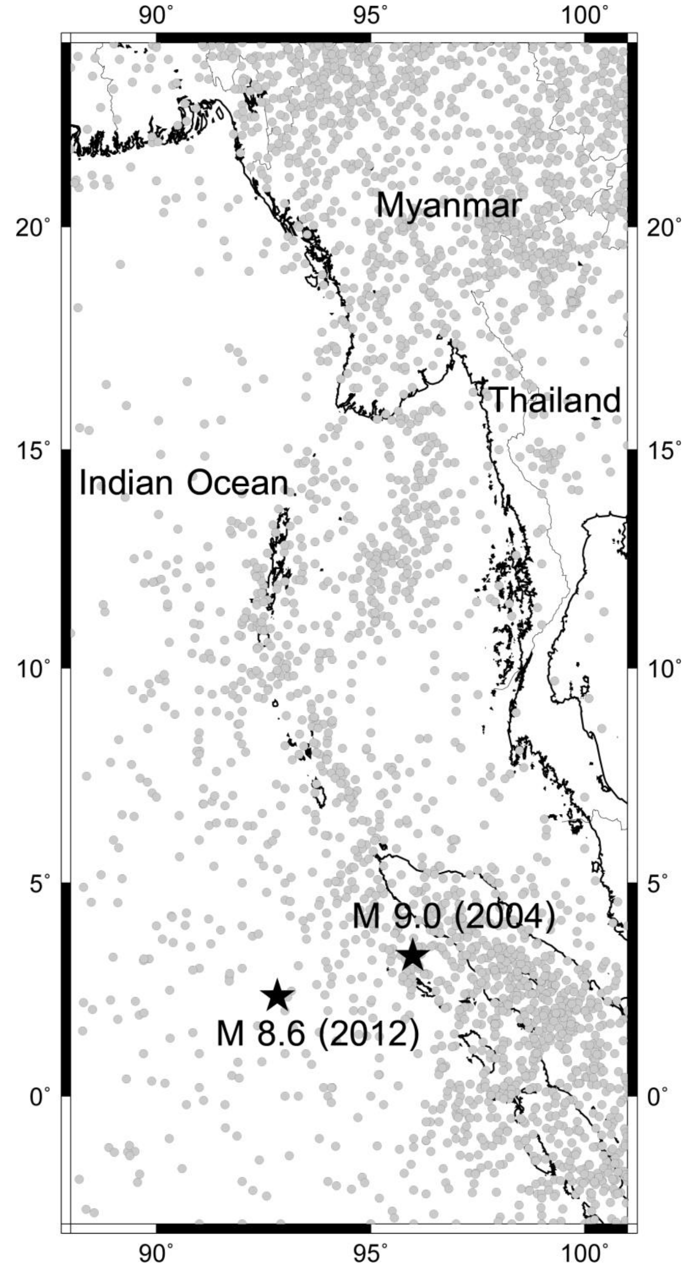

Figure 1 Map of the Sumatra-Andaman Subduction Zone showing epicenter distributions of the M_w-9.0 and M_w-8.6 earthquakes considered in this study (black stars). Grey circles mean the completeness earthquake main shocks with $M_w \geq 4.4$ recorded during 1980-2015 used in this study.

2. Analysis

The RTL algorithm (Sobolev and Tyupkin 1997; Huang et al. 2001), which is the main aim of this study, takes into account weighted quantities associated with all three parameters (time, place and magnitude) of earthquakes. The weight becomes larger when the earthquake is larger in magnitude or is closer to the investigated place or time. Therefore, the RTL parameter is defined as the product of the following three functions after normalized by their standard deviations: epicentral distance, R(x, y, z, t); time, T (x, y, z, t); and rupture length, L(x, y, z, t) (Equation1-3).

$$\mathrm{R(x,y,z,t)} = \left[\sum_{i=1}^{n} \exp\left(-\frac{r_i}{r_0}\right)\right] - R_{bk}(x,y,z,t), \qquad (1)$$

$$\mathrm{T(x,y,z,t)} = \left[\sum_{i=1}^{n} \exp\left(-\frac{t-t_i}{t_0}\right)\right] - T_{bk}(x,y,z,t), \qquad (2)$$

$$\mathrm{L(x,y,z,t)} = \left[\sum_{i=1}^{n} \left(\frac{l_i}{r_i}\right)\right] - L_{bk}(x,y,z,t), \qquad (3)$$

where l_i, t_i, and r_i are the rupture dimension (a function of magnitude M_i), the occurrence time, and the distance from the position (x, y, z) to the epicenter of the i^{th}earthquake, respectively; R_{bk}(x, y, z, t), T_{bk}(x, y, z, t) and L_{bk}(x, y, z, t) are the trends (background values) of R(x, y, z, t), T(x, y, z, t) and L(x, y, z, t); r_0 and t_0 are a characteristic distance and time-span, respectively; n is the number of events satisfying some criteria, e.g., $M_i \geq M_{min}$ (M_i is the magnitude of the i^{th} earthquake and M_{min} is the cut-off magnitude ensuring the completeness of the earthquake catalogue), $r_i \leq R_{max} = 2r_0$ and $(t - t_i) \leq T_{max} = 2t_0$ Thus, the RTL parameter describes the deviation from the background level of seismicity and is in units of the standard deviation and normalized (Equation 4).

$$\mathrm{RTL(x,y,z,t)} = \frac{R(x,y,z,t)}{R(x,y,z,t)_{\max}} \cdot \frac{T(x,y,z,t)}{T(x,y,z,t)_{\max}} \cdot \frac{L(x,y,z,t)}{L(x,y,z,t)_{\max}}, \qquad (4)$$

It makes the RTL function varied between -1 and 1. RTL>0 or RTL<0 imply respectively seismic activation or quiescence upon background values.

In addition in order to investigate spatially RTL algorithm, the parameter of Q(x, y, z, t_1, t_2) was develop by Huang et al. (2002). Mathermatically, Q parameter measure the average of the RTL values over some time window [t_1, t_2] as expressed in Equation (5).

$$\mathrm{Q(x,y,z,t_1,t_2)} = \frac{1}{m}\sum_{i=1}^{m} RTL(x,y,z,t_i), \qquad (5)$$

where m is the number of data points of RTL in the window [t_1, t_2] (RTL parameter is calculated by Equation(4) available in [t_1, t_2]).

3. Data and Completeness

The earthquake catalogue occupied by the International Seismological Center network were provide in the vicinity of latitudes -3–24 ºN and longitudes 88–101 ºE. The earthquake data consists of 86,442 events reported during January 1th, 1964 and April 30th, 2012 (Figure 1). Thereafter, the different magnitude scales were converted to the M_w (Figure 2a and 2b). In order to investigate only the interplate earthquake, the events with focal depth < 45 km along the Sumatra-Andaman Subduction Zone were selected.

The cumulative number of earthquakes versus magnitude for the catalogue was checked to estimate the degree of magnitude completeness, Mc, by using a method of Woessner and Wiemer (2005). As a result, Mc is approximately 4.4 from 1980 to 2012 (Figure 2c). Clustered events such as foreshocks and aftershocks are removed from the catalogue by using a Gardner and Knopoff 's algorithm.

Eventually, the earthquake data about 1,413 events were selected from the earthquake catalogue between 1980 and 2012 with depth shallower than 45 km, with the moment magnitude of $M_w \geq$ 4.4. The cumulative number of earthquakes did not show any sudden increases, imply that the seismicity data improve here represent directly the seismo tectonic activities were defined (Figure 2d).

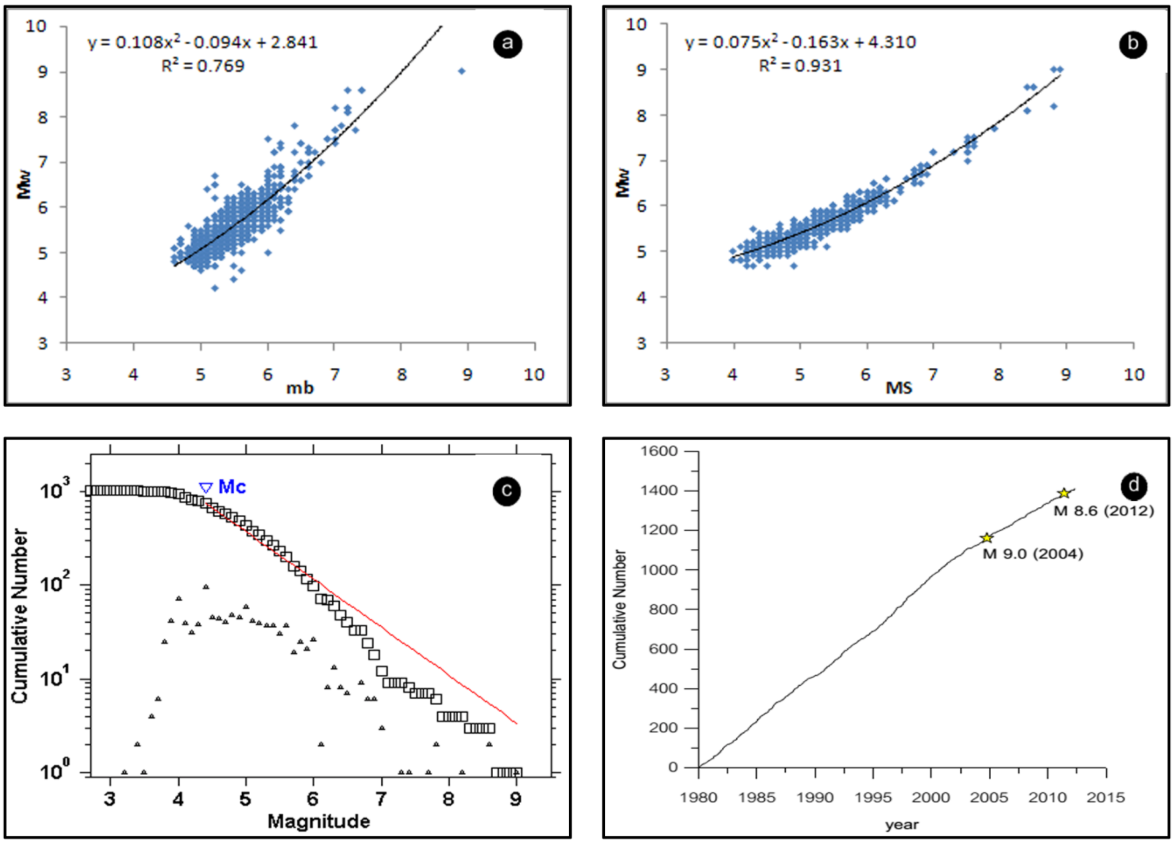

Figure 2. Frequency magnitude distribution plot of the seismicity data recorded during 1980-2014. Triangles indicate the number of earthquakes of each magnitude; squares represent the cumulative number of earthquakes equal to or larger than each magnitude. The solid line is the line of best fit according to Woessner and Wiemer (2005). Mc is defined as the magnitude of completeness.

4. Result

4.1. Estimation of Characteristic Parameters

In this study, the tested time t_0 has been varied from 0.25 to 7.5 years with steps of 0.25 year; the tested r_0 from 25 to 125 km with steps of 25 km, r_0 is as small as possible, in order to reduce the dimension of the quiescence area and the number of earthquakes used to calculate RTL is not too small to supply reliable results. I have considered the RTL to be reliable if at least 50 earthquakes are used for calculation.

RTL present a well defined seismic quiescence some years before the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake with r_0=100 km and t_0 = 2 years, is able to detect seismic quiescence in 2.1 and 15.9 years from the time of the two main shock respectively (Figure 3).

4.2. Temporal Variation

Figure 3 shows the temporal variation of the RTL parameter, which was calculated using the above model parameters, at the epicenter of the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake (Figure 3a and 3b), showed that a seismic quiescence started in 2002 and 1997, respectively. A recovery stage from the quiescence pattern to the background seismicity followed.

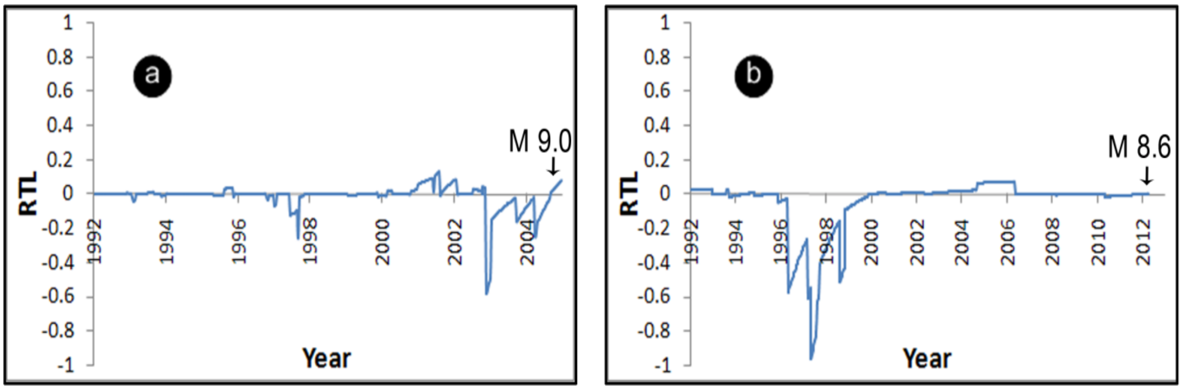

Figure 3. Temporal variation of the RTL parameter, (a) at the epicenter of the 2004 Sumatra earthquake. (b) at the epicenter of the 2012 Indian Ocean earthquake.

4.3. Spatial Distribution

In addition regarding spatial investigation, the quiescence region has been mapped in this study by the Q parameter (Huang et al. 2002). Figure 4 shows the spatial distribution of seismicity quantified by the Q-parameter from November, 2002 to August, 2004 (Figure 4a), from May to August, 1997 (Figure 4b). The seismic quiescence appeared in a broad area around the epicenter of the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake, respectively.

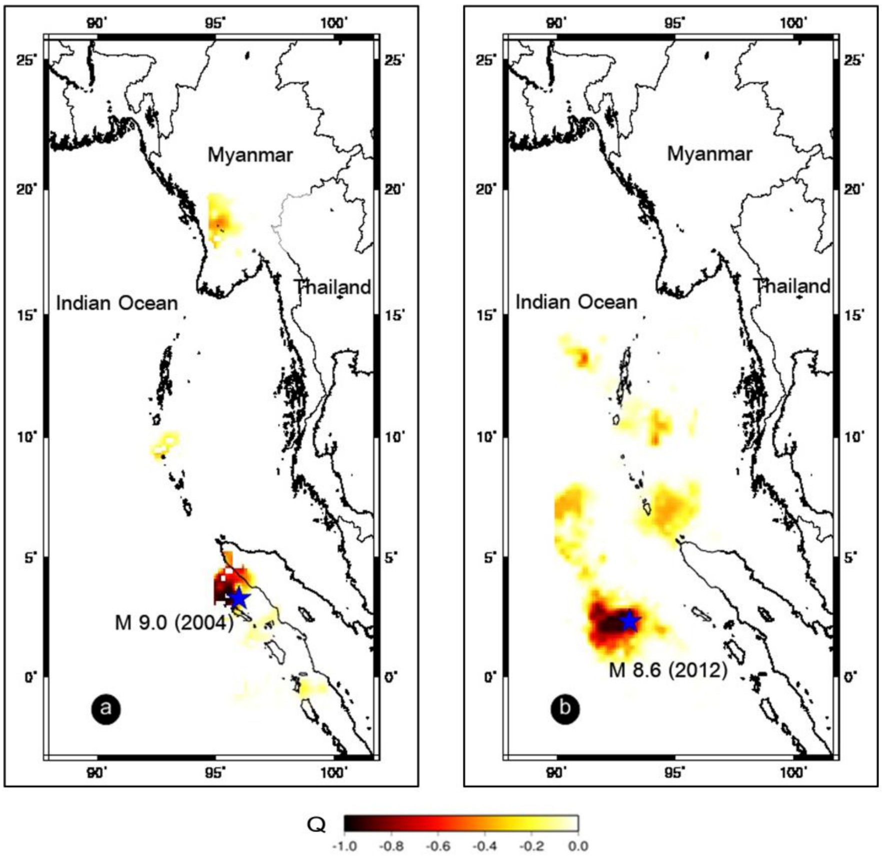

Figure 4. Spatial distribution of seismic quiescence anomalies in the investigated region (a) from November, 2002 to August, 2004. (b) from April, 1996 to October, 1998. The star indicates the epicenter of the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake, respectively.

4.4. Evaluation of the Reliability of a Precursor

Generally, different model parameters lead to different results. However, if the model results are sensitive to the model parameters, e.g., a reasonable change of model parameters may lead to significant difference of model results or even lead to a contrary conclusion, the reliability of the above model results cannot be ensured. Therefore, the influence due to the selections of model parameters should be evaluated. For the model in this study, the above influence can be evaluated by comparing the correlation of the cases of different model parameters. In this study, I repeated the model calculations after changing the model parameters such as the characteristic distance, the characteristic time-span, and so on. Quite similar temporal changes of the RTL parameter to Figure 5 were obtained. Thus, the conclusion that a seismicity anomaly was detected before the 2004 Sumatra earthquake and 2012 Indian Ocean earthquake held for various model parameters. Table 1 shows the correlation coefficients of different model parameters. The statistical analysis indicated that all the cases listed in Table 1 correlated at a significance of 0.05. Therefore, one can conclude that the seismic quiescence anomalies, which were detected before the 2004 Sumatra and the 2012 Indian Ocean earthquakes, were not an artificial anomalies due to the selections of model parameters.

Table 1. Correlation of RTL values between different model parameters of characteristic distance r_0 and characteristic time-span t_0 at the epicenter of the 2004 Sumatra earthquake.

Case	A	(a) r_0 = 100 km, t_0 = 2 year			
	B	(b) r_0 = 75 km	(c) r_0 = 125 km	(d) t_0 = 1.75 year	(e) t_0 = 2.25 year
correlation between A and B		0.82	0.91	0.81	0.81

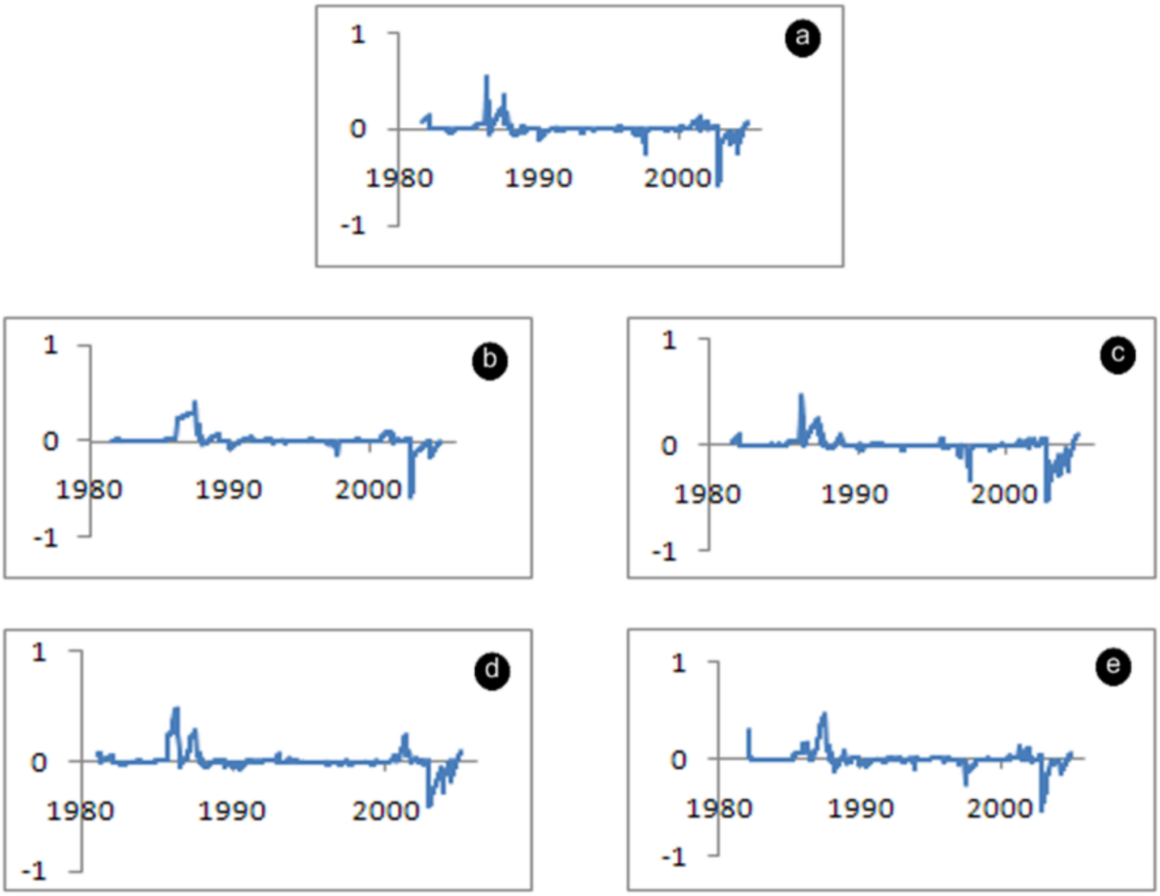

Figure 5. Estimation of characteristic parameters for the 2004 Sumatra earthquake and Temporal variation of the RTL, close to the epicenter and occurrence time.

Besides the analyses of artificial effects, the significance of the anomaly should be also investigated using the stochastic test to enhance the reliability of the anomaly. The details of the stochastic test include: First, random earthquake catalogues (e.g., N =10,000) were generated by randomizing the time and space (longitude and latitude) of the seismological catalogue. Then, for each random catalogue, the RTL parameter was calculated at the epicenter of the investigated earthquake. The same criteria used in the calculations for the real catalogue were chosen in the calculations. After quantifying the negative anomaly of the RTL parameter, one can estimate whether an RTL anomaly appears or not. Finally, one can calculate the RTL parameters at the epicenter for all random catalogues and estimate the probability of occurrence of an RTL anomaly. As an example of the 2004 Sumatra earthquake, the chance probability of the observed RTL anomalies before the main shock is 0.01 (Figure 6). Thus, one can conclude that the RTL anomaly, which was obtained before the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake, is unlikely to be chance anomaly, so is significant.

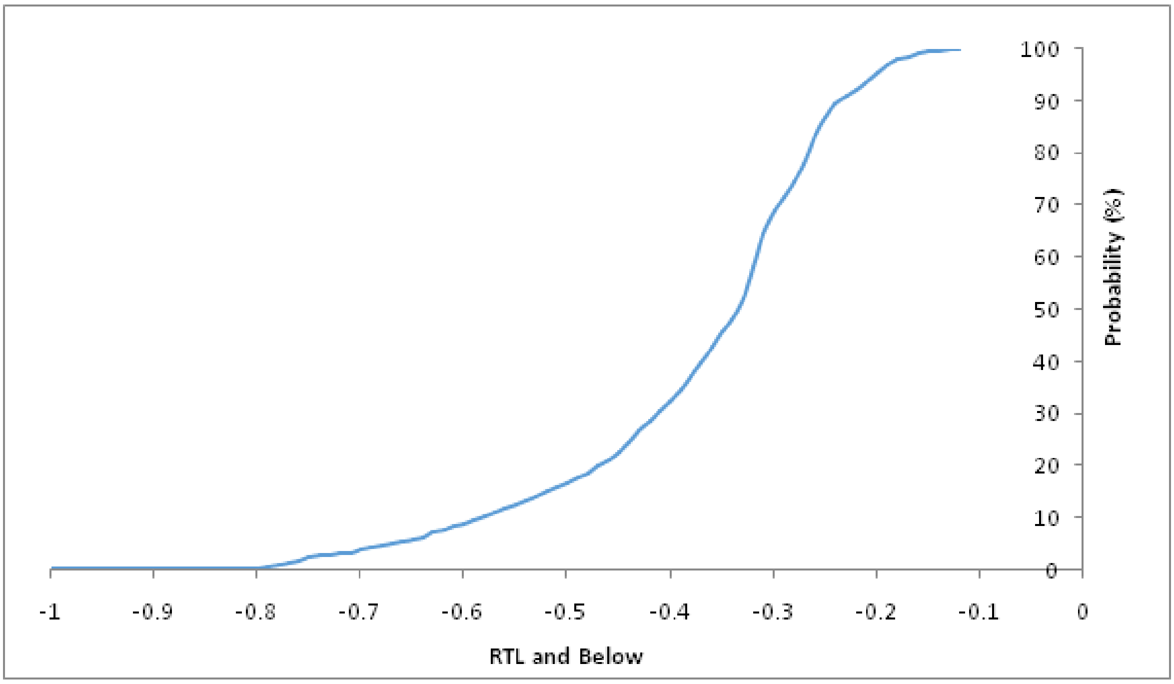

Figure 6.Probability of detection of quiescence for the 2004 Sumatra earthquake**.**

5. Conclusions and Remarks

In this study, the statistical method called RTL algorithm were investigated with the major earthquakes generated from different tectonic regime of the Sumatra-Andaman Subduction Zone. According to the completeness earthquake data, both temporaland spatial RTL anomalies revealed consistent characteristics in seismicity pattern changes and the following major earthquake recognized. However regarding to tectonic setting, the quiescence generally started a few years before the occurrence of the interplate earthquake (M_w-9.0) meanwhile the intraplate earthquake (M_w-8.6) illustrates dramatically long oftime span between the quiescence and occurrence time of the mentioned M_w-8.6 earthquake.

The evaluation of the reliability of a precursor indicated that the seismic quiescence anomaly detected before the 2004 Sumatra earthquake and the 2012 Indian Ocean earthquake were not due to the artificial disturbances of the earthquake data or the selections of model parameters. Therefore, the different of quiescence time span between the interplate and intraplate earthquake were significant which imply the seismotectonic regime.

6. Acknowledgments

This research was supported by the Ratchadapiseksomphot Endowment Fund 2016 of Chulalongkorn University under the Climate Change and Disaster Management Cluster (CCDM 59-CU). Thanks are also extended to T. Pailoplee for the preparation of the draft manuscript. I acknowledge thoughtful comments and suggestions by the editors and anonymous reviewers that enhanced the quality of this manuscript significantly.

7. References

Gardner, J.K., Knopoff, L., 1974. Is the sequence of earthquakes in SouthernCalifornia, with aftershocks removed, Poissonian?, *Bulletin of the Seismological Society of America*; 64(1), 363–367.

Martin, S., 2005.Intensity distribution from the 2004 M 9.0 Sumatra-Andaman earthquake, *Seismological Research Letters*; 76, 321–330.

Huang, Q., Nagao, T., 2002.Seismic quiescence before the 2000 M=7.3 Tottori earthquake, *Geophys.Res. Lett.*; 29(12), 1578.

Huang,Q.,Oncel,A.O., Sobolev,G.A., 2002.Precursory seismicity changes associated with the Mw=7.4 1999 August 17 Izmit (Turkey) earthquake, *Geophys. J. Int.*; 151(1), 235-242.

Huang, Q., Sobolev, G.A., 2002.Precursory seismicity changes associated with the Nemuro Peninsula earthquake, January 28, 2000, *J. Asian. Earth. Sci.*; 21(2), 135–146.

Huang, Q.,Sobolev, G.A., Nagao, T.,2001. Characteristics of the seismic quiescence and activation patterns before the M=7.2 Kobe earthquake, January 17, 1995, *Tectonophysics*; 337(1-2), 99-116.

Sobolev, G.A., Tyupkin, Y.S., 1997. Low seismicity precursors of large earthquakes in Kamchatka, *Volc. Seismol.*; 18, 433-446.

Vanessa, A., Kusala, R., 2014. The April 2012 Indian Ocean earthquakes: Seismotectonic context and implications for their mechanisms, *Tectonophysics*; 617, 126-139.

Woessner, J., Wiemer, S., 2005. Assessing the Quality of Earthquake Catalogueues: Estimating the Magnitude of Completeness and Its Uncertainty,*Bulletin of the Seismological Society of America* 95(2), 684–698.

Wyss, M., Habermann, R.E., 1988. Precursory seismic quiescence, *Pure Appl.Geophys.*; 126, 319-332.