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Seismicity variations prior to the 2016 M_L 6.6 Meinong, Taiwan earthquake

Yi-Ying Wen[1] and Chien-Chih Chen[2,*]

[1] Department of Earth and Environmental Sciences, National Chung Cheng University, Chiayi County, Taiwan
[2] Department of Earth Sciences, National Central University, Taoyuan City, Taiwan

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ABSTRACT

The 2016 M_L 6.6 Meinong earthquake struck southern Taiwan and caused serious damage due to the strong ground shaking. Anomalous seismicity spatiotemporal signature changes were identified prior to the 2016 Meinong event. We investigate the seismicity rate changes associated with the 2016 Meinong mainshock by applying the region-time-length (RTL) algorithm. The temporal result reveals a long obvious seismic quiescence stage soon after the 2012 Wutai event lasting until the 2016 Meinong mainshock. The spatial pattern of different background period lengths all exhibit that the 2016 Meinong event occurred near the abnormal seismic quiescence patch. Our study shows that the spatiotemporal information of the seismicity change could be a useful indication for potential seismic-hazard assessment.

1. INTRODUCTION

The 2016 M_L 6.6 Meinong earthquake occurred in southern Taiwan on 5 February 2016. According to the Central Weather Bureau (CWB) report, the epicenter was about 20 km west of the 2010 M_L 6.4 Jiashian event and 35 km northwest of the 2012 M_L 6.4 Wutai event (Fig. 1). The focal mechanism determined by the Broadband Array in Taiwan for Seismology (BATS; Fig. 1) indicated that the mainshock ruptured on a northeast dipping fault plane with WNW-ESE strike, which differs from the nearby north-south trending faults. The strong ground shaking with peak ground acceleration (PGA) > 400 gal were recorded at several seismic stations in Tainan City. Serious damage was caused, including 117 deaths and 551 casualties.

Although the 2016 Meinong earthquake struck a region surrounded by some active faults, except for the 2010 Jiashian event, there were no large earthquakes recorded since 1901. Wen et al. (2016) revealed the spatiotemporal signatures of abnormal seismicity changes related to the seismic activation and quiescence prior to the 2010 Jiashian event. Several approaches were developed to explore the anomalous seismicity changes prior to a notable earthquake (e.g., Sobolev and Tyupkin 1997; Holliday et al. 2005; Chen and Wu 2006; Huang and Ding 2012). Here, we used the region-time-length (RTL) algorithm (Sobolev and Tyupkin 1997, 1999; Huang et al. 2001, 2002; Chen and Wu 2006), which was successfully applied to analyze the seismicity variation before the 1999 Chi-Chi earthquake, the 2003 Chengkung earthquake, and the 2010 Jiashian earthquake (Chen and Wu 2006; Wu et al. 2008; Wen et al. 2016), to investigate the seismicity variation before the 2016 Meinong mainshock. Although the increased seismicity following the 2010 Jiashian event continued up to two years (Chan and Wu 2012), our result shows that an abnormal seismic quiescence stage started soon after the 2012 Wutai event, lasting until the 2016 Meinong mainshock.

2. RTL ALGORITHM AND DATA

The RTL algorithm is proposed by Sobolev and Tyupkin (1997, 1999) to detect the occurrence of seismic quiescence. The basic concept is that each prior event has some influence on the target event. This approach was widely and successfully applied to inspect seismic activation and

* *Corresponding author*
E-mail: chencc@earth.ncu.edu.tw

quiescence phenomena before some notable earthquakes (e.g., Huang 2004; Chen and Wu 2006; Nagao et al. 2011; Huang and Ding 2012). The weighted RTL value, which takes account of the location, occurrence time, and magnitude of n prior events occurred in a defined space-time window with the characteristic distance r_0 and the characteristic time span t_0, exhibits a decreasing (negative) or an increasing (positive) seismicity compared with the background level at the position (x, y, z) and time t of the main event under investigation. The three dimensionless factors, R, T, and L, are defined as (Huang et al. 2001):

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

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

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

where r_i is the distance between the investigated point and the ith prior event (with the occurrence time t_i and rupture length l_i). Following Chen and Wu (2006), the rupture dimension (in km) is obtained from the relation with earthquake magnitude, $\log l_i = 0.5M_i - 1.8$ (Kasahara 1981). R_{bk}, T_{bk}, and L_{bk} are background trends for the three factors, respectively. The RTL function can then be calculated as the product of R, T, and L after being normalized by their standard deviations, respectively.

To reduce the ambiguity in determining the model parameters (r_0 and t_0), Chen and Wu (2006) proposed a systematical generalization of r_0 and t_0 by adopting the correlation analysis over pairs of the RTL results. Huang and Ding (2012) then improved the correlation analysis procedure for searching the optimal model parameters. When the correlation coefficient criterion C_0 is set, we can then calculate the weight W of combination with correlation coefficients equal to or larger than C_0 for each model parameters of r_{0i} ($i = 1 \sim m$) and t_{0j} ($j = 1 \sim n$). Following Huang and Ding (2012), the weight W can be represented as

$$W_{ij} = \frac{\sum_{k=1}^{m} I(C_{ik} \ge C_0) + \sum_{l=1}^{n} I(C_{jl} \ge C_0)}{m + n} \tag{4}$$

where $I(\Phi)$ is the logical function, defined as

$$I(\Phi) = \begin{cases} 1, & \Phi \textit{ is true} \\ 0, & \textit{otherwise} \end{cases} \tag{5}$$

As the criterion weight ratio W_0 is set, the optimal model parameters of r_0 and t_0 can be then calculated using the following formulas (Huang and Ding 2012).

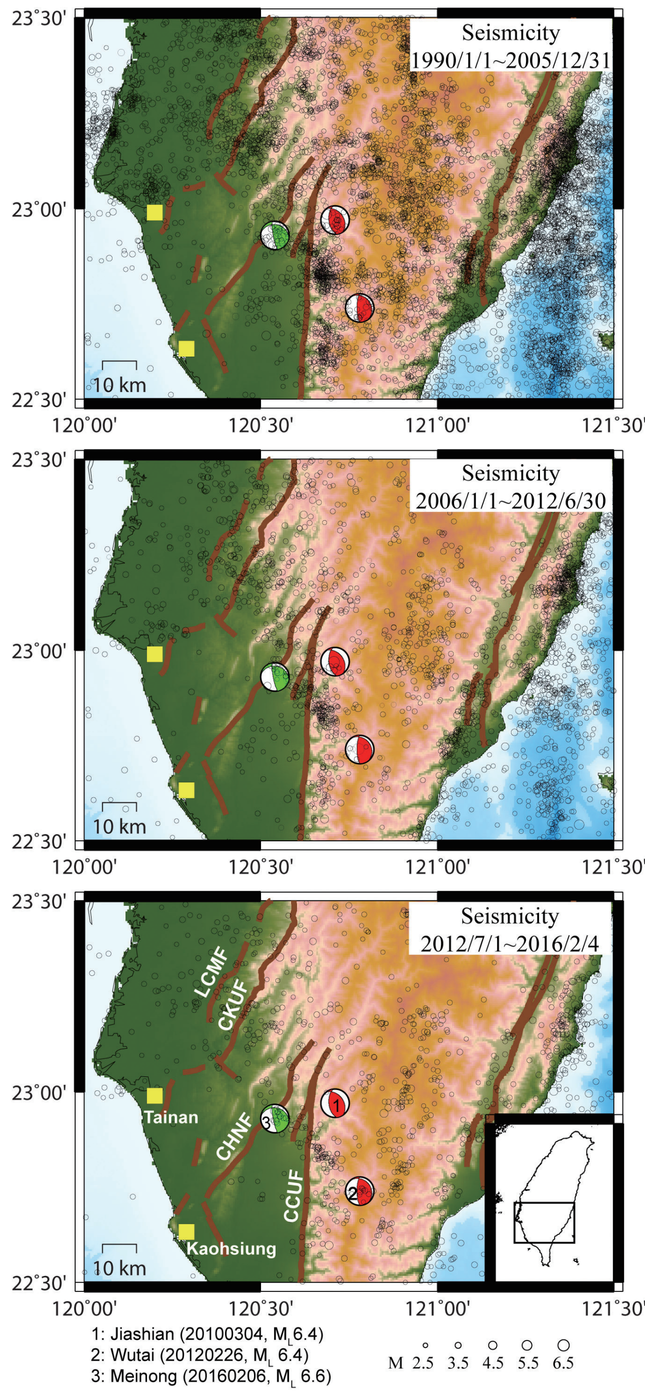

Fig. 1. Focal mechanisms of 2010 Jiashian, 2012 Wutai, and 2016 Meinong earthquakes. Circles represent the background seismicity after declustering process for different time periods, with M ≥ 2.5 and depth ≤ 35 km. The squares show the locations of some major cities. The active faults (thick lines) identified by the Central Geological Survey of Taiwan are also shown. LCMF: Liuchia-Muchiliao fault; CKUF: Chukou fault; CHNF: Chishan fault; CCUF: Chaochou fault. (Color online only)

$$\tilde{r}_0 = \frac{\sum_{j=1}^{n}\sum_{i=1}^{m} W_{ij} I(W_{ij} \geq W_0) r_{0i}}{\sum_{j=1}^{n}\sum_{i=1}^{m} W_{ij} I(W_{ij} \geq W_0)} \tag{6}$$

$$\tilde{t}_0 = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} W_{ij} I(W_{ij} \geq W_0) t_{0j}}{\sum_{i=1}^{m}\sum_{j=1}^{n} W_{ij} I(W_{ij} \geq W_0)} \tag{7}$$

Wen et al. (2016) obtained $\tilde{r}_0$ = 47.5 km and $\tilde{t}_0$ = 1.15 yr for 2010 Jiashian event with criterion of $C_0 = 0.6$ and $W_0 = 0.7$, which means at least 70% of the total combination pairs with correlation coefficient $C \geq C_0 = 0.6$. These model parameters are similar to those used in Chen and Wu (2006) for the 1999 Chi-Chi earthquake. Since the occurrence time and location of the 2016 Meinong mainshock are close to that for the 2010 Jiashian event, we adopt the $\tilde{r}_0$ = 47.5 km and $\tilde{t}_0$ = 1.15 yr model parameters. The earthquake catalogue maintained by the Central Weather Bureau is used in this study. We selected events in the CWB catalog for the entire Taiwan area with M ≥ 2.5 and depth ≤ 35 km between 1 January 1990 to 30 April 2016 and applied a declustering procedure proposed by Gardner and Knopoff (1974) to avoid disturbing the RTL characteristics in seismicity for the large events using the aftershocks.

3. RESULTS

A change in the RTL function value (positive/negative) indicates that the seismicity rate changes into a different state (activation/quiescence) with respect to the background level. We should emphasize that the goal of this study is not to isolate the seismic precursor but to investigate the seismicity change prior to the target event, which might be considered a useful indication for potential seismic-hazard assessment. The thick black line in Fig. 2 shows the temporal variation in the RTL function at the nearest grid (120.5°E, 22.9°N) to the 2016 Meinong event epicenter.

An obvious seismic quiescence stage can be found soon after the 2012 Wutai event. This abnormal seismicity decrease persisted until the 2016 Meinong mainshock. Huang et al. (2002) proposed the Q-map, which is the averaged RTL map over a certain time window to quantify the seismic quiescence spatial pattern. Figure 3 shows the seismic quiescence distribution (with grid size of 0.1° × 0.1°), which is the summation for the period with temporal negative RTL value from June 2012 to January 2016 (as marked by the rectangle in Fig. 2). Similar to the phenomenon found by previous studies, the 2016 Meinong event occurred on the edge of the seismic quiescence area (e.g., Huang et al. 2001; Nagao et al. 2011; Huang and Ding 2012). However, there is a notable patch with very low RTL value in the southwest area. Rare events occurred there during the investigation period, as shown in Fig. 1. Since the influence weight of the RTL function is contributed from the location, occurrence time and magnitude of the prior events, the sufficient number of background seismicity should be considered as a criterion. Here, for each grid, we set up two conditions: (1) the total number of events within the area of 0.1° × 0.1°, with M ≥ 2.5 during 1990 - 2015 after declustering procedure, must be more than 26 (e.g., at least 1 event occurred every year); (2) the total events within a circle of $2\tilde{r}_0$ in radius, with M

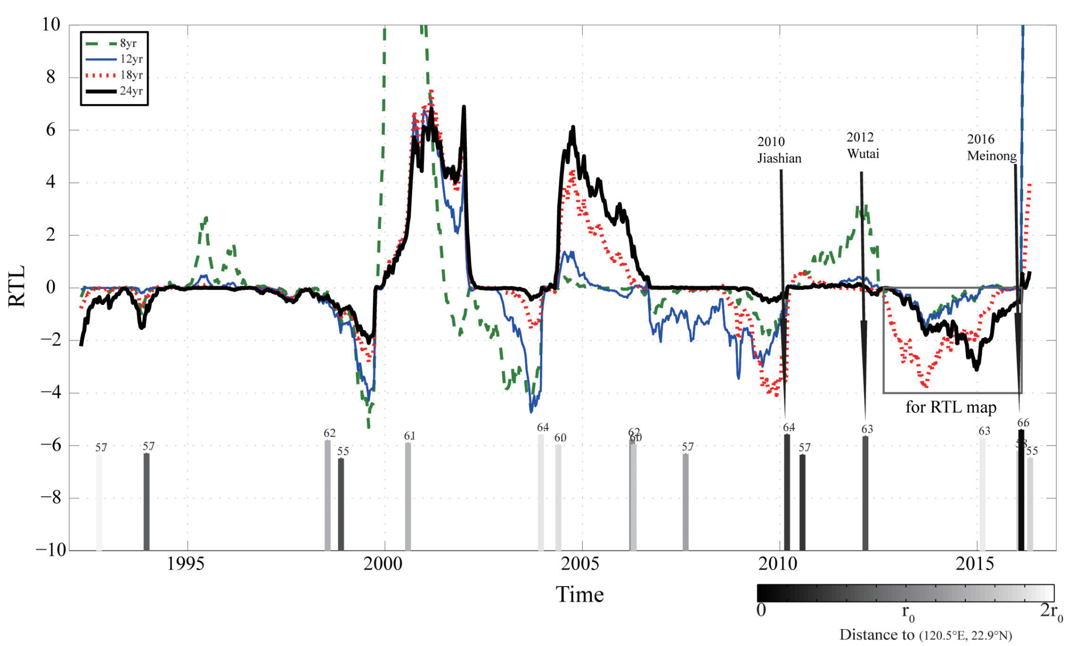

Fig. 2. Temporal variation of the RTL function for different background seismicity lengths at (120.5°E, 22.9°N) for the optimal model parameters. The bar chart represents the occurrence time of M ≥ 5.5 events within the distance of $2\tilde{r}_0$ from (120.5°E, 22.9°N); each number above the bar is the magnitude. (Color online only)

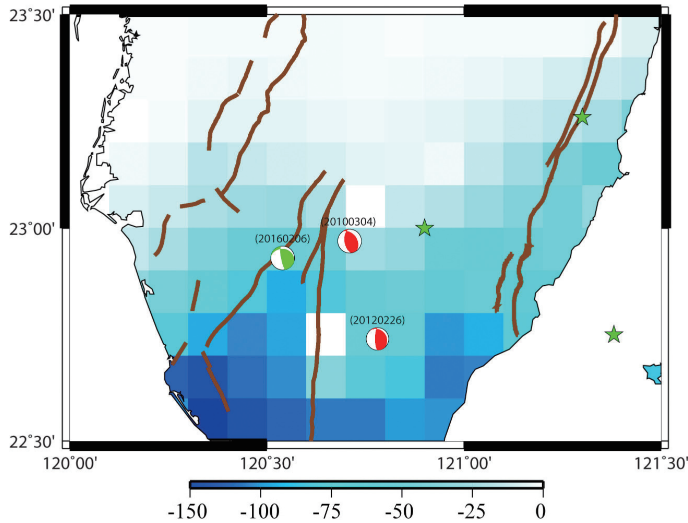

Fig. 3. The summed seismic quiescence map for the period with temporal negative RTL value from June 2012 to January 2016 (as marked by rectangle in Fig. 2). (Color online only)

≥ 2.5 during 1990 - 2015 after declustering procedure, must be more than 9360 (e.g., at least 30 events occurred every month). These conditions would strengthen the reliability of the RTL function. As shown in Fig. 4, the west coast area (grids colored in grey) does not fit the criterion.

We applied the stochastic test (Huang 2004) to examine and strengthen the reliability of this significant seismic quiescence prior to the 2016 Meinong event. Here, we generated 1000 random earthquake catalogs by randomizing the occurrence time and location (both longitude and latitude) of the real catalog. We then calculated the temporal RTL function for each random catalog. Using the observed anomaly prior to the 2016 Meinong event as the criteria (the duration of RTL negative anomaly longer than 3 yrs after the 2012 Wutai event), the chance probability of the anomaly for the 1000 random catalogs is 0.038. This suggests that the observed seismic quiescence is not an outcome of a chance anomaly.

4. DISCUSSION AND CONCLUSION

The temporal RTL function (thick black line in Fig. 2) can be roughly divided into three periods, which are consistent with the seismicity shown in Fig. 1; (1) before 2006, there are two obvious seismic activation stages; (2) during 2006 to 2012 Wutai event, it seems maintain as the background seismicity level; and (3) after the 2012 Wutai event, a long period of anomalous seismic quiescence until the 2016 Meinong mainshock. Compared with the RTL analysis for the 1999 Chi-Chi earthquake, the 2003 Chengkung earthquake and the 2010 Jiashian earthquake (Chen and Wu 2006; Wu et al. 2008; Wen et al. 2016), different seismic quiescence and activation processes of about 2 - 4 yrs were found prior to all of these significant events. The RTL analysis traditionally accounts for the long-period background seismicity. For example, in this study, we used 24-yrs background seismicity for calculation (thick black line in Fig. 2). However, for some areas, the earthquake catalog might be limited due to the late construction of seismic stations. We wanted to further understand the influence of the background seismicity, which might reflect the stress state, as shown in Fig. 2. The weighted RTL value is contributed from the location, occurrence time and magnitude of earthquakes, nevertheless, the temporal RTL functions of four different background lengths show similar main patterns as mentioned above, especially for the long anomalous seismic quiescence period prior to the 2016 Meinong mainshock. For the shorter background seismicity (e.g., 8- or 12-yrs), a large proportion is the abnormal seismic quiescence period prior to the occurrence of the 2010 Jiashian event. Therefore, the seismic quiescence stage prior to the 2016 Meinong mainshock became relatively unobvious. However, regardless which background length was considered, an abnormal seismic quiescence stage started soon after the 2012 Wutai event until the 2016 Meinong mainshock was revealed. This suggests that this observed seismic quiescence cannot be produced by chance. Figure 4 shows the spatial pattern of this seismic quiescence stage for four different background lengths, and all reveal that the 2016 Meinong event occurred near the seismic quiescence area. Figure 4a, which reflects the recent seismicity variation, in particular reveals the anomalous seismic quiescence area which is consistent with the aftershock distribution around the 2016 Meinong mainshock. On the other hand, as the background period length decreases, the anomalous seismic quiescence patch in southeast area disappears. When looking into seismicity in Fig. 1, it indeed shows that the southeast area roughly maintains a slight low seismicity after 2006. Here, we also

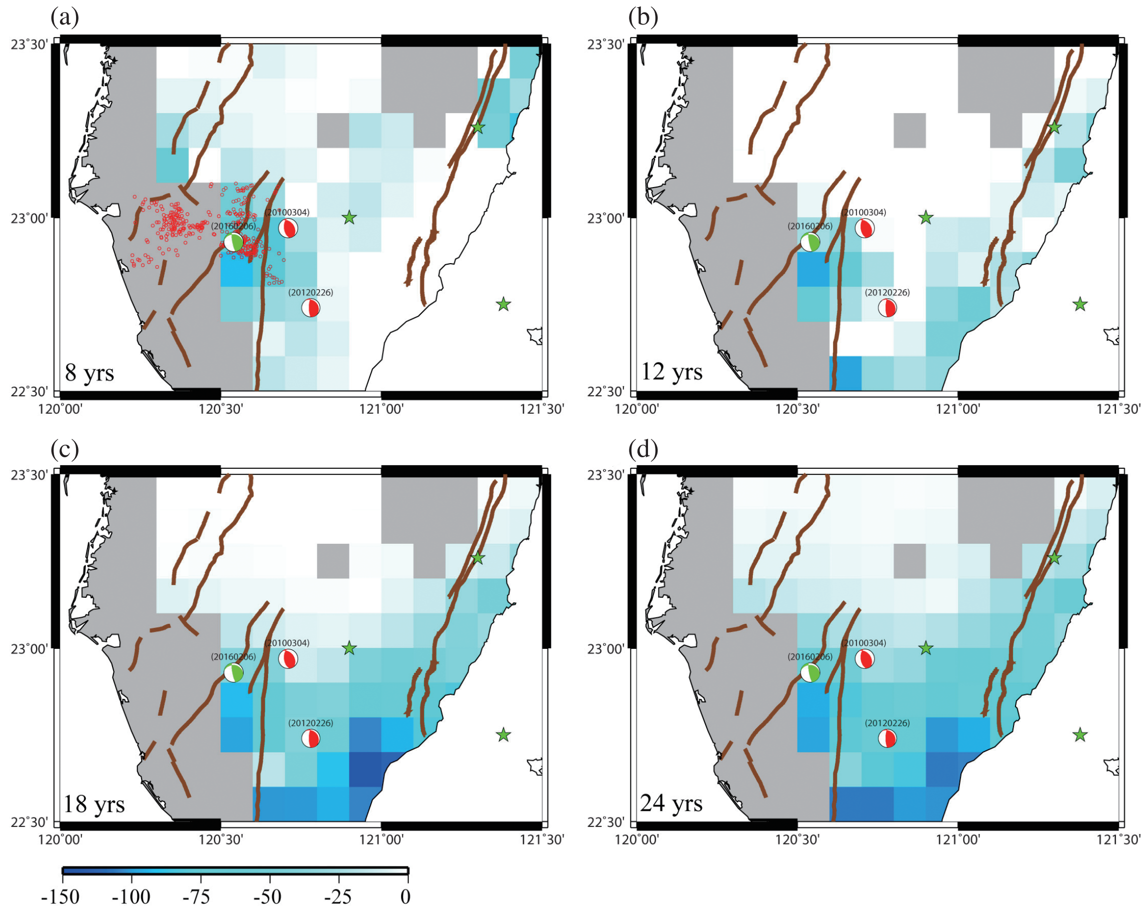

Fig. 4. The summed seismic quiescence map for the period with temporal negative RTL value from June 2012 to January 2016 (as marked by rectangle in Fig. 2) for different background period lengths: (a) 8 yrs; (b) 12 yrs; (c) 18 yrs; and (d) 24 yrs, respectively. The starts represent the M > 5 events occurred during 1 January 2016 to 30 July 2016. The circles indicate the M ≥ 2 aftershocks of the 2016 Meinong mainshock. The grids which do not pass the criterion of background seismicity are colored in grey. (Color online only)

mark all M > 5 event (starts in Fig. 4) within the study area during 1 January 2016 to 30 July 2016. We found that the M > 5 inland events occurred near the anomalous seismic quiescence patch of four different background lengths.

The three moderate-sized events, the 2010 Jiashian, the 2012 Wutai and the 2016 Meinong earthquakes, occurred in a small region within 10 yrs and all caused some damage. Moderate-sized events occur frequently in Taiwan, with some originating from buried faults. We should therefore pay more attention to seismic hazard mitigation. Our results show that RTL analysis with different background seismicity lengths can help to examine the abnormal seismicity stage as well as the anomalous seismic quiescence area. This spatiotemporal information of the seismicity change could be useful hint for potential seismic-hazard assessment.

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