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Key Points:

- Abnormal seismicity change before 2010 Jiashian earthquake are revealed by PI and RTL algorithms
- The epicenter area experienced negative to positive Coulomb stress changes before the main shock
- Large earthquake could occur on the region with anomalous seismicity and stress state change

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Spatiotemporal investigation of seismicity and Coulomb stress variations prior to the 2010 M_L 6.4 Jiashian, Taiwan earthquake

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Abstract The 2010 M_L 6.4 Jiashian earthquake struck southern Taiwan and caused some damage due to the strong ground shaking. Since the epicenter is located in a relatively low background seismicity area, we want to investigate seismicity rate changes associated with the Jiashian main shock by applying the region-time-length and pattern informatics algorithms. Both temporal and spatial results exhibit signatures of abnormal seismicity change related to the seismic activation and quiescence prior to the 2010 Jiashian main shock. In addition, patch of abnormal seismicity changes coincides with the region with Coulomb stress change during the same period. Our study demonstrates that the epicenter area of the 2010 Jiashian earthquake experienced a long period of seismicity rate changes and stress accumulation and thus suggests that both the variations in Coulomb stress and seismicity rate play fundamental roles in the nucleation process of impending earthquakes.

1. Introduction

The 2010 Jiashian earthquake, a moderate size event with magnitude M_L 6.4, occurred in southern Taiwan on 4 March 2010. The epicenter is close to Kaohsiung city (Figure 1), which is largest metropolitan area in southern Taiwan. Due to the strong ground shaking for more than 30 s, as a result, some damage was caused, and two high-speed trains were also disrupted at the time of quake. The focal mechanism determined by the Broadband Array in Taiwan for Seismology (BATS; Figure 1) and previous studies indicated that the main shock ruptured on a northeast dipping fault plane with NW-SE strike, which differs from the nearby north-south trending Chaochou fault, and could be related to the Chishan transfer fault zone [*Hsu et al.*, 2011; *Huang et al.*, 2011; *Rau et al.*, 2012] which may also be related to the very recent 2016 M_L 6.6 Meinong earthquake.

The 2010 Jiashian event struck a region of low seismicity surrounded by high seismicity [*Hsu et al.*, 2011; *Huang et al.*, 2011], where no large earthquakes were recorded since 1901. Following the main shock, about 70 aftershocks occurred during the same day. Furthermore, within the following 2 years, the 25 July 2010 M_L 5.5 Taoyuan earthquake and the 26 February 2012 M_L 6.4 Wutai earthquake occurred south to the 2010 Jiashian event (Figure 1). *Chan and Wu* [2012] suggested that the increased seismicity due to the 2010 Jiashian event continued up to 2 years.

There are many reports discover the anomalous seismicity change prior to a notable earthquake [e.g., *Sobolev and Tyupkin*, 1997; *Chen et al.*, 2005; *Holliday et al.*, 2005; *Chen and Wu*, 2006; *Huang and Ding*, 2012]. In this study, first, we used the region-time-length (RTL) algorithm to investigate the seismicity variation before the 2010 Jiashian main shock. Then, the method of pattern informatics (PI) was applied to validate the anomalous seismic activity related to the 2010 Jiashian event. The integrated analyses show that an abnormal seismic quiescence stage started from late 2006 to the occurrence of the 2010 Jiashian main shock, and high PI anomaly between the Chishan fault and the 2010 Jiashian epicenter corresponded to the region with Coulomb stress changes. This result suggests that the region with anomalous seismicity change and increased Coulomb stress change indicates high probability for the future large earthquake.

2. RTL Analysis and Results

The RTL algorithm, which takes account of location, occurrence time, and magnitude of earthquakes, is widely used to inspect seismic activation and quiescence phenomena before some notable earthquakes [e.g., *Chen and Wu*, 2006; *Huang*, 2004, 2008; *Huang and Ding*, 2012]. The weighted RTL value, which is

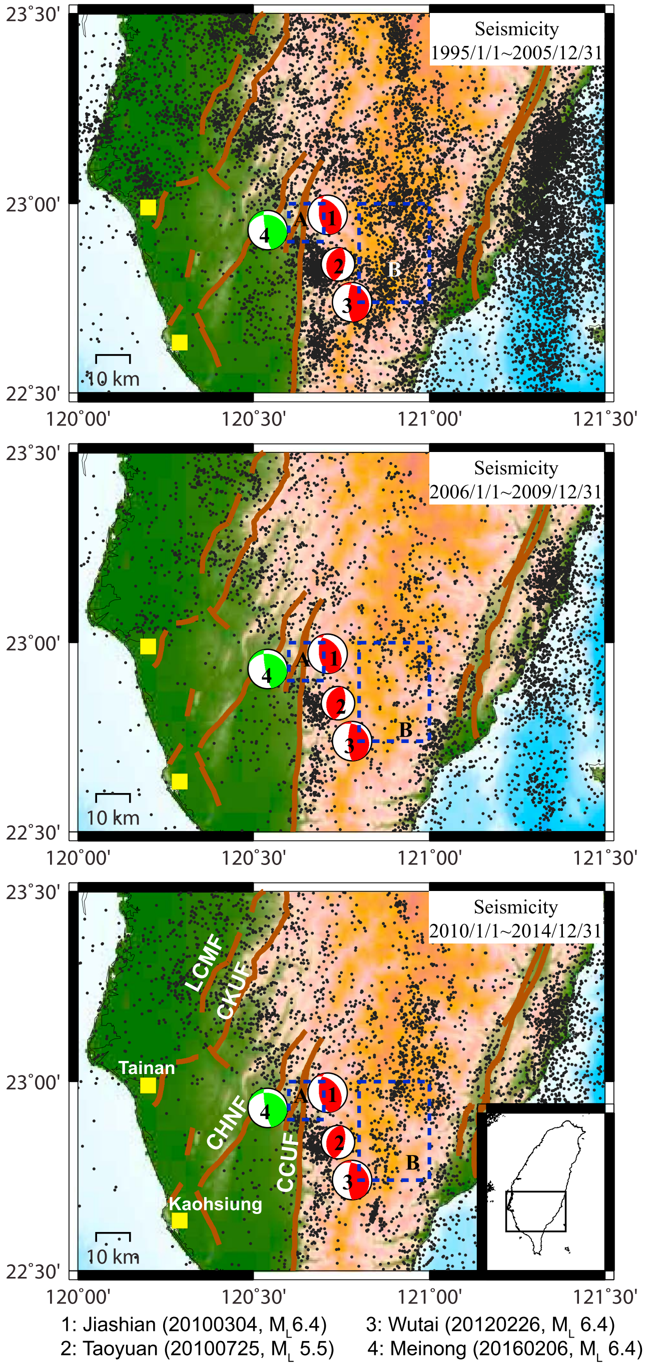

Figure 1. Focal mechanisms of 2010 Jiashian, 2010 Taoyuan, 2012 Wutai, and 2016 Meinong earthquakes. Dots represent the background seismicity for different time periods. The squares show the locations of some major cities. The active faults (thick lines) identified by the Central Geological Survey of Taiwan are also shown. LCMF: Liuchia–Muchiliao fault, CKUF: Chukou fault, CHNF: Chishan fault, and CCUF: Chaochou fault.

contributed from each prior event occurred in a defined space-time window with the characteristic distance r_0 and the characteristic time span t_0, presents 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 weighted coefficient statistical approach has been clearly described in previous studies [e.g., *Huang et al.*, 2001; *Chen and Wu*, 2006]. 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] improved further the technique of correlation analysis for searching the optimal model parameters.

In this study, the earthquake catalogue maintained by Central Weather Bureau (CWB) is used. We selected events in the CWB catalog for whole Taiwan area with $M \geq 2.5$ and depth ≤ 35 km between 1995 and 2015 and applied a declustering procedure proposed by *Gardner and Knopoff* [1974]. Following the procedure of *Huang and Ding* [2012], we calculated various combination of r_0 (ranging between 25 and 100 km with a step of 2.5 km) and t_0 (ranging between 0.25 and 2.0 year with a step of 0.05 year). As the correlation coefficient criterion C_0 is set, we can calculate the ratio W (or weight) of combination with correlation coefficients equal to or larger than C_0 for each model parameters of r_{0i} ($i = 1 \sim m$; $m = 31$) and t_{0j} ($j = 1 \sim n$; $n = 36$) and then generate the contour map for the ratio W, as shown in Figure 2a.

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

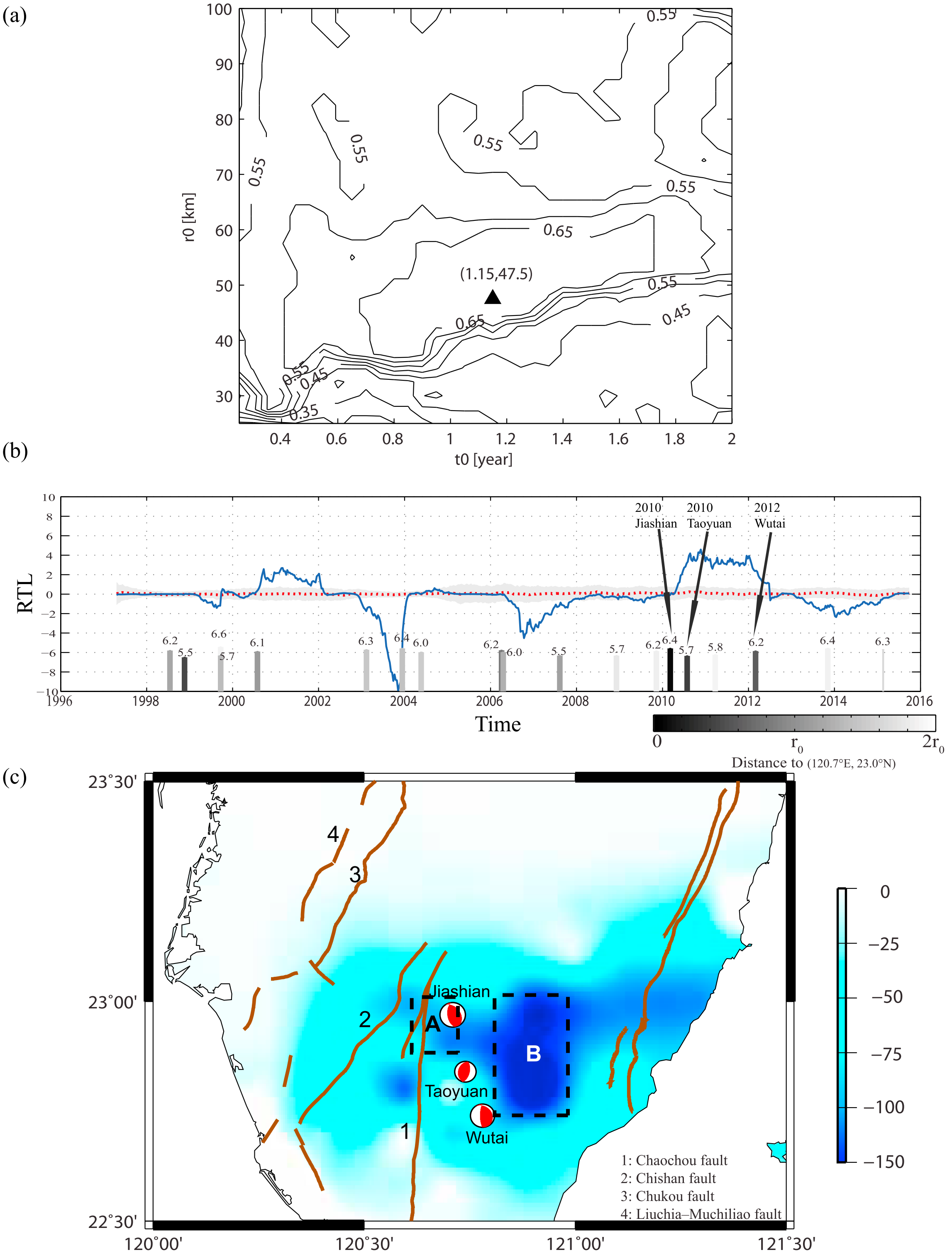

Figure 2. (a) Contour map of ratio W for various combinations of model parameters of r_0 and t_0, with $C_0 = 0.6$. The triangle shows the optimal model parameters. (b) Temporal variation of the RTL function (blue line) at (120.7°E, 23.0°N) for the optimal model parameters, and the mean (red dotted line) and the interquartile range (gray shadow) of the 1000 random catalogs. The bar chart represents the occurrence time of $M \geq 5.5$ events within the distance of $2r_0$ from (120.7°E, 23.0°N); each number above the bar is the magnitude. (c) The summed seismic quiescence map for the period with temporal RTL value less than -2.0 during 2006–2007.

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

$$I(\Phi) = \begin{cases} 1, & \Phi \text{ is true} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

When the criterion ratio W_0 is set, the optimal model parameters of r_0 and t_0 can be calculated by following formulas:

$$\widetilde{r_0} = \frac{\sum_{j=1}^{n}\sum_{i=1}^{m} W_{ij} I\left(W_{ij} \geq W_0\right) r_{0i}}{\sum_{j=1}^{n}\sum_{i=1}^{m} W_{ij} I\left(W_{ij} \geq W_0\right)} \tag{3}$$

$$\widetilde{t_0} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} W_{ij} I\left(W_{ij} \geq W_0\right) t_{0j}}{\sum_{i=1}^{m}\sum_{j=1}^{n} W_{ij} I\left(W_{ij} \geq W_0\right)} \tag{4}$$

After testing many sets of criterion coefficient C_0 and criterion ratio W_0, we considered $C_0 = 0.6$ and $W_0 = 0.7$, which means at least 70% of the total combination pairs with correlation coefficient $C \geq C_0 = 0.6$. Then, we obtained $\widetilde{r_0} = 47.5$ km and $\widetilde{t_0} = 1.15$ year (triangle in Figure 2a) by averaging the parameter values passed the criterion. Our test also reveals that the RTL result is more affected by t_0 than r_0, which is consistent with the finding in *Chen and Wu* [2006].

A change in RTL value (positive/negative) represents that the seismicity rate changes to different state (activation/quiescence) with respect to the background level. Here we do not attempt to catch the seismic precursor but focus on the seismicity change prior to the target event, which might become useful hint for potential seismic-hazard assessment. Figure 2b shows the temporal variation in the RTL function at the nearest grid (120.7°E, 23.0°N) of epicenter of the 2010 Jiashian event. An obvious seismic quiescence stage can be found during 2006–2007, and this abnormal seismicity decrease persisted till the occurrence of the 2010 Jiashian main shock. The seismicity increase (activation stage), started from the 2010 Jiashian main shock, took about 2 years, which is consistent with the result using the rate-and-state friction model by *Chan and Wu* [2012]. Previous studies derived the averaged RTL map, called Q-map, over certain time window to quantify the spatial pattern of seismic quiescence [*Huang et al.*, 2002; *Huang*, 2004, 2008; *Huang and Ding*, 2012]. To view the seismic quiescence distribution (with grid size of $0.1° \times 0.1°$), the summation for the period with temporal RTL value less than -2.0 during 2006–2007 is shown as Figure 2c. Similar with previous studies that the 2010 Jiashian event occurred on the edge of the seismic quiescence area [e.g., *Huang et al.*, 2001; *Huang and Ding*, 2012]. It is notable that the seismic quiescence area (area A and B in Figure 2c) is consistent with the relative low seismicity during 2006–2009 (Figure 1, middle).

Here we applied the stochastic test [*Huang*, 2004] to examine and strengthen the reliability of this significant seismic quiescence prior to the 2010 Jiashian event. We generated 1000 random earthquake catalogs by randomizing the time and location (both longitude and latitude) of the real catalog, and then we calculated the RTL parameters for each random catalog. Figure 2b also shows the mean (red dotted line) and the interquartile range (gray shadow) of the temporal variation in the RTL function at the grid (120.7°E, 23.0°N) from the 1000 random catalogs. For comparison, we used the observed anomaly prior to the 2010 Jiashian event as criteria, and the chance probability of the anomaly for the 1000 random catalogs is 0.044. It suggests that the observed seismic quiescence is unlikely to be a chance anomaly.

3. PI Analysis and Results

The recently proposed PI algorithm is also successfully adopted to investigate precursory seismic pattern [*Rundle et al.*, 2003; *Chen et al.*, 2005; *Holliday et al.*, 2005]. Here following the detailed procedure described in *Chen et al.* [2005], we also use PI algorithm with CWB catalog to check whether any anomalous change of seismicity corresponds with the 2010 Jiashian event. In a PI map, hot spots highlight the change in probability of occurrence relative to the background, i.e., $\Delta P(x_i, T0, T1, T2) = P(x_i, T0, T1, T2) - \mu_P$. Here $P(x_i, T0, T1, T2)$ is computed by mean squared seismic-strength (the average number of earthquake in the searching dimension) change in grid x_i with grid size of $0.1° \times 0.1°$, indicates the probability of a future earthquake, and μ_P represents the average background probability for the entire computed area. The time parameters are set up as follows: (i) beginning time of data used $T0 = 1$ January 1994; (ii) start time of change interval $T1 = 1$

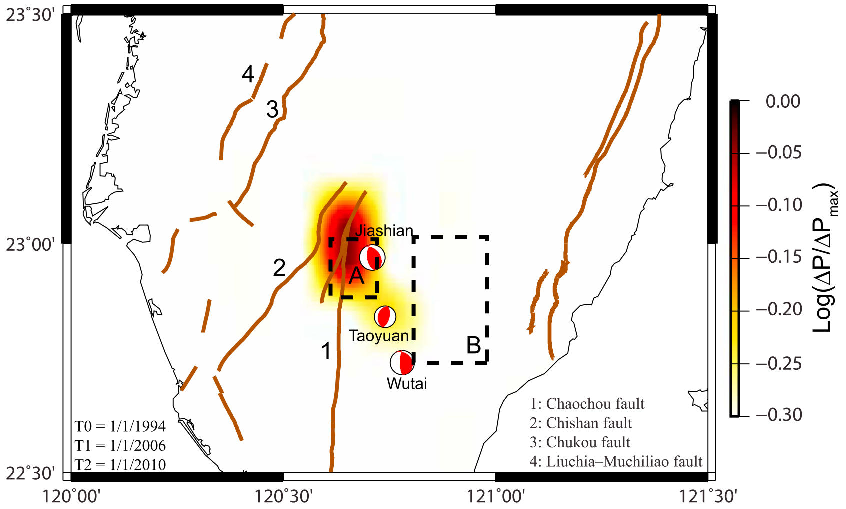

Figure 3. PI map for the 2010 Jiashian earthquake. Colored hot spots highlight areas with abnormal seismicity changes caused by both the seismic activation and quiescence, indicating high probability for future large events.

January 2006; (iii) end time of change interval $T2 = 1$ January 2010. The so-called change interval from $T1$ through $T2$ in this PI analysis is right corresponding to the quiescent span as revealed in the RTL analysis for the Jiashian event.

Here for comparing with the RTL analysis with a characteristic distance of 47.5 km, we slightly modified the searching dimension of Moore neighbors to radius R0 of 50 km. Figure 3 shows the hot spot map for the 2010 Jiashian main shock. It is very interesting that the hot spot is close to the epicenter of the 2010 Jiashian earthquake as well as corresponds to the seismic quiescence area A in Figure 2c. Furthermore, *Hsu et al.* [2011] and *Lee et al.* [2013] both derived a main asperity between the Chishan fault and the epicenter of the 2010 Jiashian earthquake, and this is consistent with the hot spot in Figure 3.

4. Discussion and Conclusion

Both RTL and PI analyses reveal that the epicenter of the 2010 Jiashian earthquake exhibited temporal and spatial anomalous seismicity related to the seismic activation and quiescence. The seismicity rate change is a proxy for the stress state change [*Dieterich*, 1994; *Dieterich et al.*, 2000]. Since PI result can be physically interpreted in terms of stress accumulation and release [*Chen et al.*, 2005], the PI hot spot indicates the area with significant temporal stress rate change over the change interval. We modeled the Coulomb stress change (ΔCFS) using the software Coulomb 3.3 [*Toda and Stein*, 2002] for further investigation. Following the procedure proposed by *Chan and Wu* [2012], we determined spatially variable receiver faults for each $0.02° \times 0.02°$ grid and calculated the maximum Coulomb stress change, imparted by 12 $M \geq 5$ events occurred during 2006 to 2009, among seismogenic depth. Figures 4a–4d show the Coulomb stress change for different period, and we can have the following observations. (a) The region around the 2010 Jiashian epicenter mainly exhibited decrease in ΔCFS during 2006 to 2007, and this is consistent with the significant seismic quiescence area A in Figure 2c; (b) ΔCFS of 2010 Jiashian epicenter represented decreased during 2006–2007 (−0.017 bars) and became increased during 2008–2009 (+0.05 bar), which is also corresponding with the temporal variation of the RTL function (Figure 2b); and (c) The area between the Chishan fault and the 2010 Jiashian epicenter changed from slight decrease to obvious increase in ΔCFS during 2006 to 2009, and this coincides with the stress state variation indicated by PI result (Figure 3) as well as the derived main asperity by *Hsu et al.* [2011] and *Lee et al.* [2013]. On the other hand, while the seismic quiescence area B in Figure 2c indeed reflects the decrease in seismicity during 2006 to 2009 (Figure 1), the ΔCFS in area B almost keeps the same value over this span (Figure 4). Interestingly, in the meanwhile no PI hot spot appears in this area (Figure 3), which could be the consequence of the unchanged stress level. Since the PI hot spot is sensitive to the temporal change in seismicity, observation in area B thus suggests that both stress state change and significant seismicity rate change do matter to the occurrence of a large earthquake like the 2010 Jiashian event.

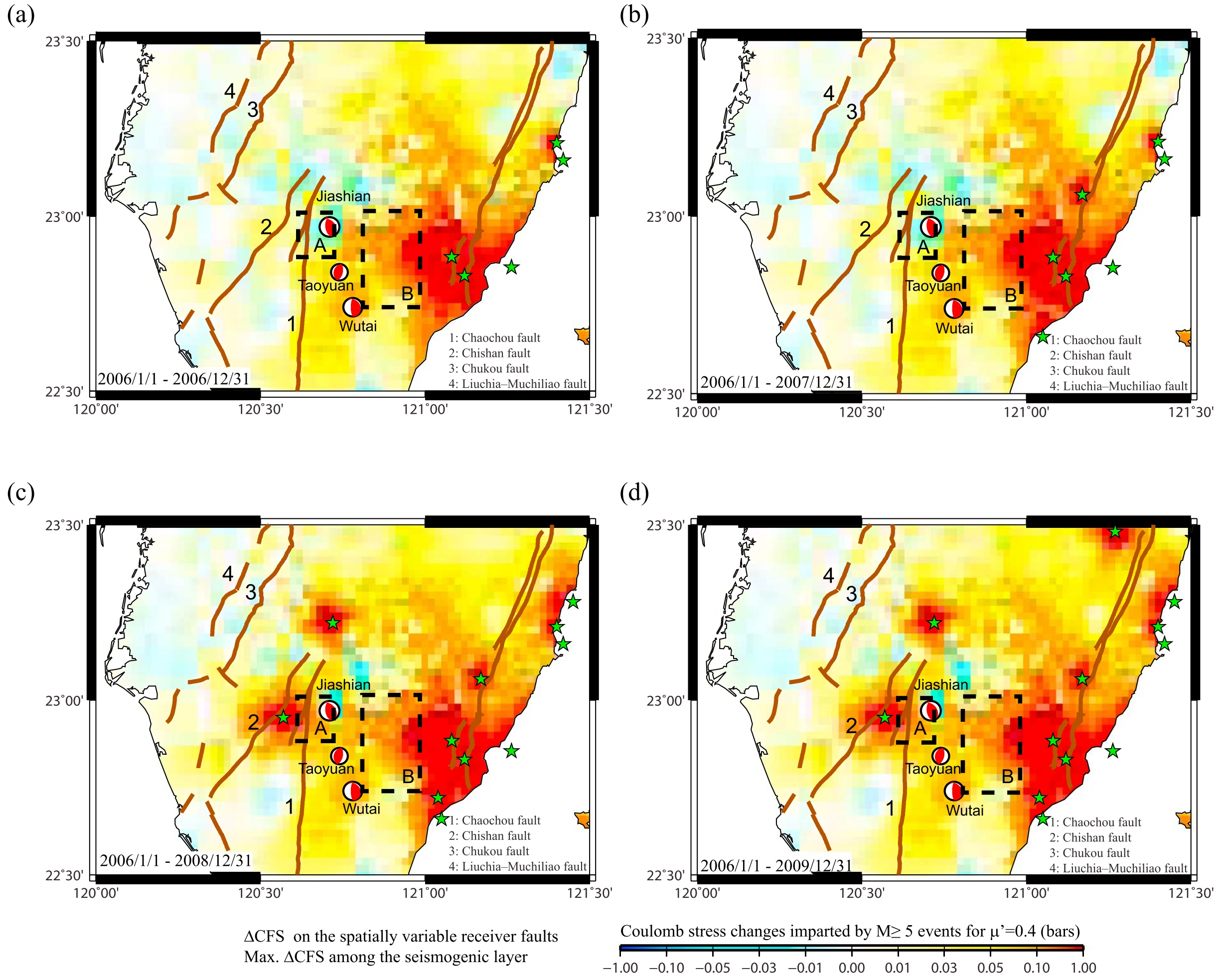

Figure 4. The Coulomb stress change imparted by $M \geq 5$ events occurred during the period of (a) 2006; (b) 2006–2007; (c) 2006–2008, and (d) 2006–2009. Stars indicate the locations of $M \geq 5$ events occurred during each period.

Avoiding the singularity issue addressed by *Huang* [2008], we can evaluate the seismicity change after the target event through the nearest grid. The 2 year seismicity increase (activation stage) following the 2010 Jiashian main shock (Figure 2b) is consistent with the result of *Chan and Wu* [2012]. The increase in Δ*CFS* can lead to either high small-magnitude seismicity or occurrence of relatively large earthquakes, prior to which the seismicity might be low. The 2010 Taoyuan and the 2012 Wutai events mainly located on the continuously increased Δ*CFS* area during 2006 to 2009, which agreed well with the slightly high seismicity in Figure 1. In addition, both RTL (Figure 2c) and PI (Figure 3) results do not reveal anomalous phenomenon adjacent to the 2010 Taoyuan and the 2012 Wutai epicenters; therefore, their occurrence might be related to the 2010 Jiashian earthquake, and they could be regarded as aftershocks [*Chan and Wu*, 2012].

The seismicity rate change corresponds to the stress change, and the occurrence of main shock can be interpreted as a perturbation of background seismicity by the stress state change [*Dieterich*, 1994; *Dieterich et al.*, 2000]. Figure 4d shows the Coulomb stress change imparted by $M \geq 5$ events occurred during the period of 2006–2009, and the regions of increased and decreased stress correspond to regions of high and low seismicity (Figure 1), respectively. The 2010 Jiashian main shock was occurred on a region with stress state changing from decrease to increase. This result may indicate that the large earthquake could occur on the region with anomalous seismicity and stress state change.

Through our comprehensive study, we propose the following procedure for retrieving the information of the seismicity change for potential seismic-hazard assessment. (i) since RTL analysis is more sensitive to the time parameter, the temporal RTL variation can point out the abnormal seismicity stage, which can be used as reference for determining the change interval of PI analysis and the period of Coulomb stress change calculation; (ii) next step is to generate the hot spot map by PI analysis, with different searching dimension; and (iii) the final step is to compare Coulomb stress change calculation with the RTL and PI analyses for obtaining the integrated result.

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