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Seismic reversal pattern for the 1999 Chi-Chi, Taiwan, M_W 7.6 earthquake

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Abstract

We in this study have calculated the standard normal deviate *Z*-value to investigate the variations in seismicity patterns in the Taiwan region before and after the Chi-Chi earthquake. We have found that the areas with relatively high seismicity in the eastern Taiwan became abnormally quiet before the Chi-Chi earthquake while the area in the central Taiwan with relatively low seismicity showed unusually active. Such a spatially changing pattern in seismicity strikingly demonstrates the phenomenon of “seismic reversal,” and we here thus present a complete, representative cycle of “seismic reversal” embedding in the changes of seismicity patterns before and after the Chi-Chi earthquake.

Keywords: Seismic reversal; Seismic quiescence; Seismic activation; Chi-Chi earthquake

1. Introduction

Taiwan is located on the western Circum-Pacific seismic belt. In the vicinity of Taiwan, the Philippine Sea plate subducts northward under the Eurasian plate along the Ryukyu trench to the northeast of Taiwan, whereas the Eurasian plate subducts eastward under the Philippine Sea plate off the southern tip of Taiwan (Tsai et al., 1977; Wu, 1978). Tectonically, most of the Taiwan region is under NW–SE compression with a measured convergence rate of about 8 cm/year (Yu et al., 1997). The collision of those two plates causes the Taiwan area many complex geological features and high seismicity (Wang, 1998). Many disastrous earthquakes had occurred in this area in the past.

The 1999, M_W 7.6, Chi-Chi earthquake is the largest event on the Taiwan Island in the last century (Shin et al., 2000; Chang et al., 2000; Wu et al., 2000; Teng et al., 2001). It heavy struck the central Taiwan and resulted in serious damage (Tsai et al., 2001; Wu et al., 2002, 2003a, 2004). Solid star shown in Fig. 1 denotes the epicenter of the Chi-Chi main shock and nearby lines show its surface ruptures.

There was no any precursory phenomenon reported *before* the occurrence of the Chi-Chi earthquake, although many *retrospective* studies related to various precursory phenomena of this event can be found (e.g. Chen et al., 2000; Liu et al., 2000, 2001; Akinaga et al., 2001; Ohta et al., 2001; Chuo et al., 2002; Song et al., 2003; Lee and Tsai, 2004; Liu et al., 2004; Yen et al., 2004). Very recently, there also appear some *retrospective* analyses of seismicity in the Taiwan region, focusing on searching the signature of seismicity changes before the Chi-Chi earthquake. By using the

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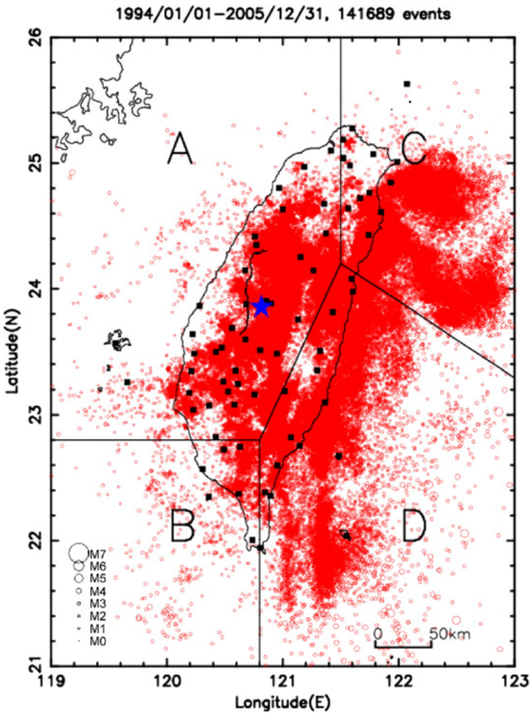

Fig. 1. Epicenters of selected 141,689 events used in this study (open circles). The locations of the telemetered stations of the Central Weather Bureau Seismic Network are marked by solid squares. The epicenter of the Chi-Chi earthquake is indicated by solid star, whereas the solid line marks the surface rupture induced by the main shock. We divide the study area into four seismic zones: Zones A, B, C and D, based on seismic characteristics and tectonics.

CWB catalogue released in Shin and Teng (2001), Chen (2003) has found activation of moderate-sized earthquakes before the Chi-Chi event and discussed the important implication to the self-organizing spinodal model of earthquakes (Rundle et al., 2000). Examination of the frequency-magnitude statistics of seismicity in the years prior to the Chi-Chi earthquake shows that precursory activation of earthquakes with magnitude larger than 5 started at the end of 1993, lasting about 6 years up to the main shock. On the other hand, Wu and Chiao (2006) found that the Chi-Chi earthquake was preceded by a notable decrease in regional seismicity rate of smaller events with magnitude larger than 2. The anomalous reduced seismicity started from January 1999 and lasted about 9 months up to the occurrence of the main shock. It should be noted that seismic activation mainly emphasizes the increasing activity of moderate-sized earthquakes (e.g. Sykes and Jaume, 1990) while earthquake magnitude participates in quiescence could be even small (e.g. Wiemer and Wyss, 1994; Zoller et al., 2000; Huang et al., 2001). With the pattern informatics (PI) method, systematic scan (Sheu et al., 2002; Chen et al., 2005) over the whole Taiwan region for the anomalous area of seismic activity indicates that the location of the epicenter of the Chi-Chi main shock had exhibited strongly anomalous activity before the occurrence of the Chi-Chi earthquake. While a weak signature of the Chi-Chi event appears on the so-called PI map in Sheu et al. (2002), a more striking and correlated PI hotspot patchwork was obtained by the modified PI method in Chen et al. (2005).

The seismicity patterns reflect a space-time correlation with the crustal stress and strain fields. By means of the seismicity variation within a time interval, we could investigate the anomalous seismicity patterns related to a forthcoming large earthquake. Abovementioned four papers regarding the Chi-Chi earthquake (Sheu et al., 2002; Chen, 2003; Chen et al., 2005; Wu and Chiao, 2006) focused their issues on the seismicity variation before the main shock. Here, in the present study, we further analyze seismicity data from 1994 to 2005. Thus we compare seismic activities before and after the Chi-Chi earthquake. We find that seismicity patterns in the Taiwan region greatly changed before and after the Chi-Chi earthquake. We thus conclude the phenomenon of “seismic reversal” (Shebalin and Keilis-Borok, 1999) may take place to the Chi-Chi sequence.

2. Data

Catalog data from the Taiwan Central Weather Bureau (CWB) were used in this study. The Taiwan Telemetered Seismographic Network (TTSN) (Wang, 1989) merged to the CWB seismic network and updated to modern seismometers since 1991. It is characterized by an integrated earthquake observation system, the Central Weather Bureau Seismic Network (CWBSN). The CWBSN consists of a central recording system with 73 telemetered stations that are equipped with 3-component S13 seismometers. Solid squares shown in Fig. 1 are the CWBSN stations. Seismic signals digitized at 12 bits and 100 Hz for each station are transmitted through a dedicated telephone line to the central station located at the Bureau in Taipei. The signals are then used to manually pick the P and S arrivals for determining the earthquake location and the local magnitude M_L (Shin, 1993). The location error for the CWB catalogue has not been systematically estimated. But, based on previous analyses (Wu et al., 2003b; Kuochen et al., 2004), the error of hypocenter location is about within 5 km and 10 km in the western and eastern Taiwan, respectively.

The CWBSN system was operated in a trigger-recording mode before the end of 1993. Since 1994, the operation has been changed to a continuously recording mode and the manual identification of earthquake events, thus greatly enhancing the detective sensitivity of events with the magnitude completeness of about 2.0. Shown in Fig. 2 is the frequency-magnitude plot of the Gutenberg-Richter relation of the CWBSN data from 1994 to 2005. We have used the catalog data of $M_L \geq 2.0$ and focal depth less than 35 km for our analysis. A focal depth cutoff of 35 km is comparable to the thickness of the seismogenic zone for the Taiwan region. Most of shallow earthquakes occurring in the Taiwan region have focal depths less than 35 km (Wang et al., 1994).

3. Seismic provinces

The spatial distribution of earthquakes is the first indicator characterizing the seismicity. Hsu (1971) divided the whole Taiwan region into three seismic zones, i.e. West seismic zone, East seismic zone, and Ryutai seismic zone. Such division does not fit well to the geological settings and the seismicity patterns. Tsai et al. (1981) then, based on the TTSN data, divided the Taiwan area into three different seismic zones. However, seismic zoning is a difficult problem affected by numerous factors. Currently, an acceptable seismic zoning map in Taiwan region has not been constructed yet (Wang, 1998). For the convenience of describing the seismicity changes in the following sections, we based

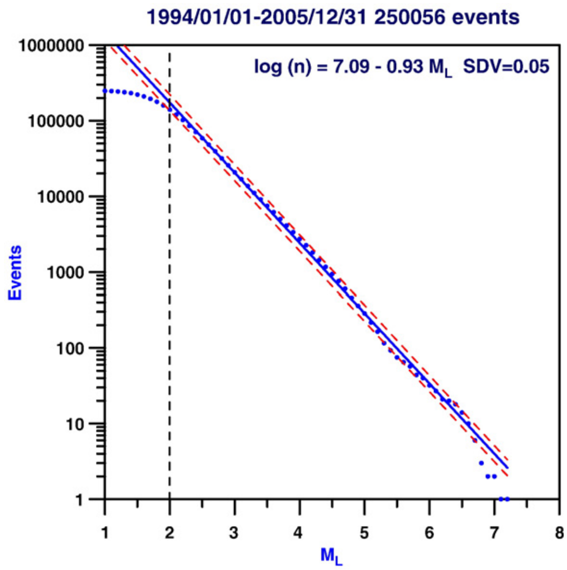

Fig. 2. Frequency-magnitude distribution of selected events. The solid line is regressed from the least squares fitting, and two dash lines mark bounds of two standard deviations. Magnitude completeness is 2.0 for CWBSN data.

on the seismic characteristics and tectonics divide the Taiwan region into four seismic zones (Fig. 1):

(a) Western Seismic Zone (briefly, Zone A) located in the Eurasian plate: Most of the earthquakes occurred in this zone are associated with active faults on the Taiwan Island. There were many large damaging earthquakes, the Chi-Chi earthquake for example, occurred in this zone (Wang, 1998; Hsu, 2003).
(b) Southwestern Seismic Zone (briefly, Zone B): Most part of this zone is located in the South China Sea plate. In seismic activity, this zone is the less active zone among four zones. So far, no any damaging earthquake occurred in this zone was reported in documentation.
(c) Northeastern Seismic Zone (briefly, Zone C) includes the Ryukyu trench subduction system, the Okinawa trough system, and some volcanic activities as well. Many large subduction earthquakes accompanied with high seismic activity occurred in this zone, and some of them caused damage (Wang, 1998).
(d) Southeastern Seismic Zone (briefly, Zone D) is a seismic zone mainly caused by the collision of the Eurasian plate and the Luzon island arc on the Philippine Sea plate. Due to the active collision between the island arc and the continent most of the seismic activity in the Taiwan region, and many large earthquakes as well, occurred in this zone (Wang, 1998).

4. Method

Many techniques have been used to identify and describe seismic activity and most of them focus on the phenomenon of seismic quiescence. Visual inspection of the epicenter distribution, the time-distance plots and some statistic methods as well are widely used by researchers (e.g. Ishida and Kanamori, 1977, 1978; Kanamori, 1981). The standard normal deviate Z test (Meyer, 1975) is one of the statistic methods frequently used for analyzing the seismic quiescence (Wyss, 1986; Habermann, 1988; Wiemer and Wyss, 1994; Wu and Chiao, 2006). In this study we use the method of standard normal deviate Z test to calculate the map showing the seismic activity, which is similar to the popular ZMAP analysis (Wiemer and Wyss, 1994).

First of all, the spacing of the spatial grid is set in 0.2° for considering the locating error of hypocenters, which may be as large as to 10 km. We thus yield a map with the resolution of 0.2° × 0.2°. For each grid point we binned the earthquake population into many binning spans of 60 days. The local Z-value at each grid point is then computed by the following equation

$$Z(x,y,t) = (R_{tar} - R_{bg}) \Bigg/ \sqrt{\frac{\sigma_{bg}^2}{n_{bg}} + \frac{\sigma_{tar}^2}{n_{tar}}} \quad (1)$$

where R_{bg} and R_{tar} are the means of the seismicity intensity, i.e. the earthquake number, function at a given pixel calculated over the whole (background) span through January 1994 to December 2005 and over some target span, respectively. Similarly, σ_{bg} and σ_{tar} are the standard deviations of the seismicity intensity function over the background and target spans, respectively. n_{bg} and n_{tar} are the numbers of binning spans for the corresponding periods. A positive Z-value thus indicates a raise in seismicity and a negative for a decrease.

Events with focal depth ≤35 km and $M_L \geq 2.0$ were used for our analysis, which fulfill the requirement of catalogue completeness (Fig. 2). Totally, 141,689 events were used in this study. Open circles shown in Fig. 1 are the distribution of selected epicenters. Importantly, the calculation of the background seismicity intensity function was from the declustered catalogue while we used the original catalogue to calculate the seismicity intensity function for each target span. This operation is different from the usual ZMAP analysis.

For the declustering algorithm, we had applied the method of spatiotemporal double-link cluster analysis to eliminate aftershocks in the catalogue. This method is similar to the single-link cluster analysis proposed by Davis and Frohlich (1991). Given a magnitude threshold of main shocks, the declustering algorithm specifies two linking parameters in the time and space scales, 3 days and 5 km for example. An event would be identified as an aftershock when its epicenter and occurrence time lay within the prescribed spatiotemporal window of some main shock. Then, the procedure iteratively searches for *secondary* aftershocks, i.e. the aftershock of an earlier aftershock. The whole catalogue turns out to be separated by many sequences of main shock and aftershocks. By using the temporal and spatial linking parameters of 3 days and 5 km, we had removed the aftershock events generated from main shocks with $M_L > 4.5$. Those linking parameters were usually used for declustering the CWBSN catalogue (Wu and Chiao, 2006).

5. Results

Fig. 3 shows the changes in number of events with $M_L \geq 2.0$ through 1994 to 2005. The time spans have

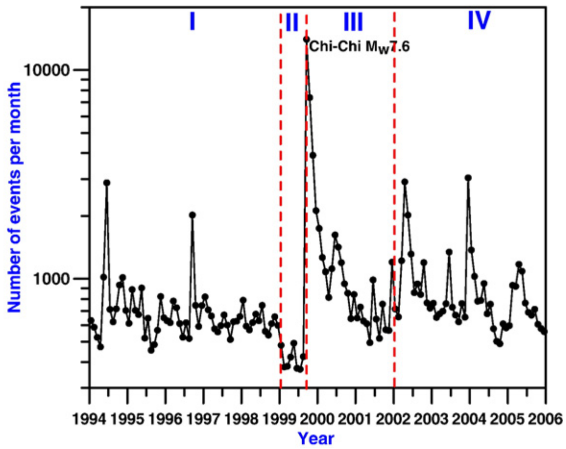

Fig. 3. Monthly event numbers of Taiwan earthquakes for $M_L \geq 2.0$ from 1994 to 2005. We grouped the studied span before and after the Chi-Chi earthquake into four stages for data analysis.

been normalized to 30 days for comparison. According to the variation in the number of earthquakes, we have grouped the whole catalogue into four time spans for our analysis: Periods I, II, III and IV. Shown in Fig. 4 are the obtained maps of Z-value for those four spans before and after the 1999 Chi-Chi earthquake. We describe major characteristics for each span as below:

(a) Period I through 1994 to 1998 (Fig. 4a): Most of the earthquakes occurred in this period were widely distributed in the eastern Taiwan region, including both Zones C and D. For most areas in Zones C and D, their Z-values thus had positive values. On the other hand, most areas in Zone A were in the low-seismicity mode (i.e. negative Z-values), except for the Tainan area. Moderate seismic activity happened in Zone B. Since eastern Taiwan most of the time has highly active seismicity, we suggest the seismicity pattern in this period may represent the "normal" type of seismic activity in the Taiwan region.
(b) Period II through January 1999 to 19 September 1999, before the Chi-Chi earthquake (Fig. 4b): The low-seismicity patterns could be obviously found around the whole Taiwan region during this period. Areas with abnormally negative Z-values appeared not only in Zone A, but also in both Zones C and D. On the other hand, some unusually active seismicity nearby the epicenter of the Chi-Chi earthquake could be also found from the seismicity pattern in this period. We notice that the activation phase nearby the epicenter of the Chi-Chi main shock can be strikingly exposed in

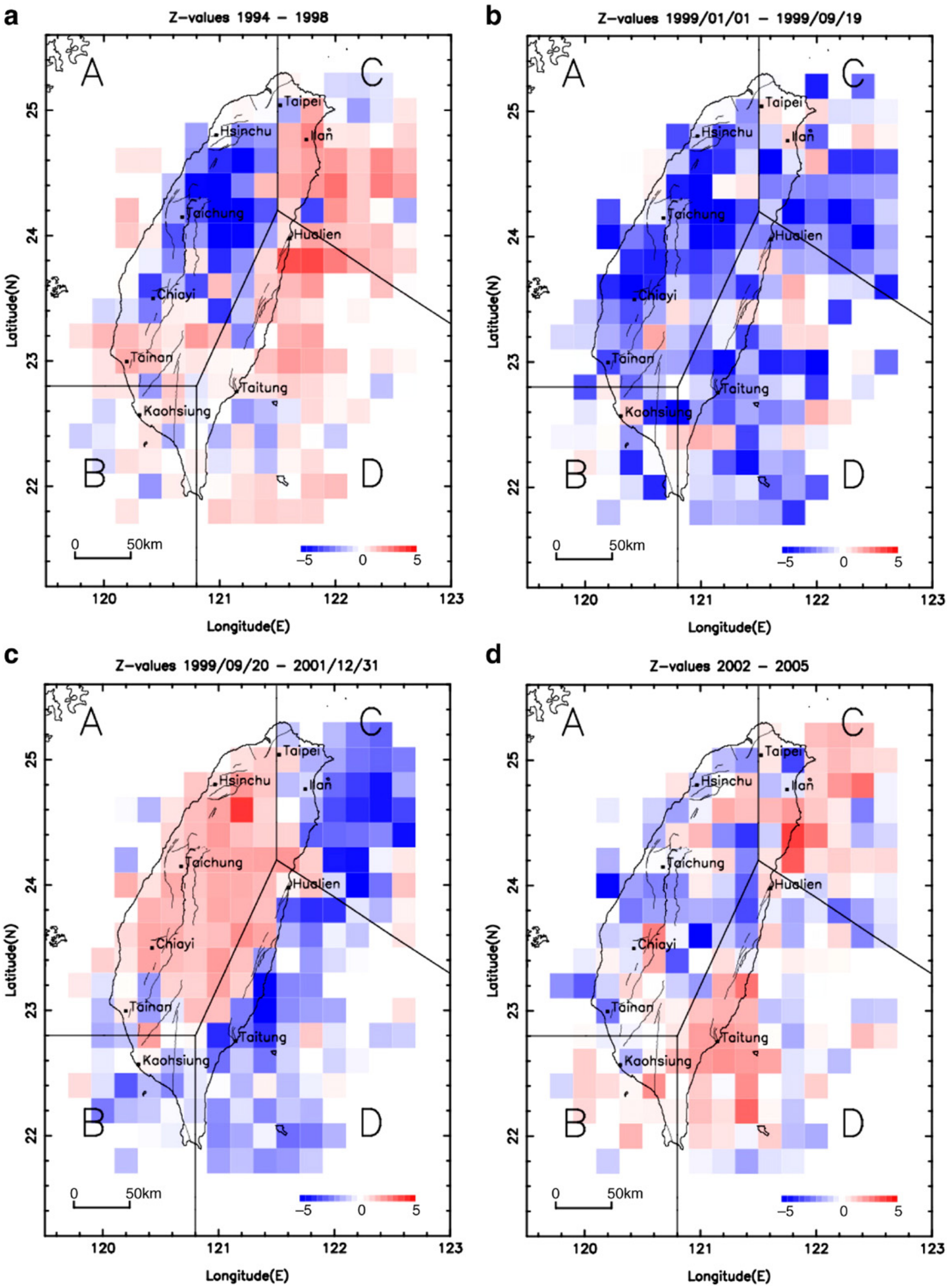

Fig. 4. Plots from (a) to (d) show seismicity patterns with Z-value distributions corresponding to four time spans before and after the Chi-Chi earthquake. For details please see the text.

the ZMAP analysis by Wu and Chiao (2006) and in the PI analysis by Chen et al. (2005) as well.

(c) Period III from 20 September 1999 to 2001 (Fig. 4c): Much of the seismic activity occurred in this period was induced by the aftermath of the Chi-Chi main shock. Bursting seismicity appeared around the epicenter of the Chi-Chi earthquake in Zone A, while all the other Zones (B, C and D) were relatively in the low-seismicity mode.

(d) Period IV from 2002 to 2005 (Fig. 4d): During this period, seismicity in the surrounding area of the Chi-Chi main shock (Zone A) was still active but, compared with the previous Period III, became less active. Contrary to Zone A, seismic activities in other regions were becoming more active than what they were in the previous period. The seismicity pattern in this period was much similar to, and had returned to, the "normal" type of seismic activity (Fig. 4a) in the Taiwan region.

6. Discussion

Drawing the scenarios of seismicity evolution from abovementioned results, we suggest that the seismicity pattern in Period I represents the "normal" type of seismicity in the Taiwan region, which means relatively high seismicity in the eastern Taiwan and low in the western. In Period II the seismicity is in a phase of "seismic reversal," which may indicate a critical condition before the forthcoming Chi-Chi earthquake. Important signature to the reversal phase is the abnormally low seismicity in Zones C and D and the slightly increased seismicity in the areas surrounding the epicenter of the Chi-Chi event. The low seismicity could be mainly related to the reduction of small events with $M_L \leq 4.0$ (Wu and Chiao, 2006). We thus propose a physical picture that the tectonic stress loading had resulted in the closure of existing micro-fractures in the eastern Taiwan, which then gradually induced the migration and accumulation of strains in the western Taiwan and eventually activated the Chi-Chi earthquake. We have noted that such kind of seismicity migration could be found in the numerical modeling of block structure dynamics (e.g. Rundquist and Soloviev, 1999). In Period III, due to the catastrophic Chi-Chi event, the crustal strength in Zone A was widely weak and most of the cumulated strain energy was released. Finally, in Period IV, the crustal strength in Zone A might be raised again, although the aftershocks of the Chi-Chi main shock occasionally occurred in Zone A. Relative to Period III, seismicity in Zones C and D for this period became much more active. The seismicity pattern in Period IV thus implies the return to the "normal" type of seismic activity in the Taiwan region.

The concept of "seismic reversal" was originally proposed by Shebalin and Keilis-Borok (1999) and depicts premonitory reversal of territorial distribution of seismicity (Shebalin and Keilis-Borok, 1999; Shebalin et al., 2000). The phenomenon of "seismic reversal" could be found several months before a forthcoming strong earthquake, within a distance of about 100 km from the epicenter of the strong earthquake. Abnormally quiescent and active zones are manifestations of such phenomenon; zones with relatively high seismicity, such as Zones C and D in Fig. 4, become unusually quiet while some other zones with relatively low activity, like Zone A (Fig. 4), show unusually active. The specific feature of "seismic reversal" is basically a combination of seismic quiescence (a decline in seismic activity) and seismic activation (an increase of seismicity).

The mechanism underlying the phenomenon of "seismic reversal" has not been solved yet. Shebalin and Keilis-Borok (1999) described two possible qualitative explanations. The first explanation could be drawn from the popular hypothesis that a strong earthquake is a breakup of an asperity (Kanamori, 1981). The rise in seismicity around the epicenter of the strong earthquake indicates that the asperity starts to fracture while the seismicity drop elsewhere indicates that local stress concentration has been released by fracturing earlier. The second explanation invokes the reorganization of the spatio-temporal structure of a chaotic dynamical system, such as the earthquake fault system. Reorganization of the spatio-temporal structure is one of the symptoms of the critical transition in many chaotic systems, and the lattice model of earthquakes (e.g. Rundquist and Soloviev, 1999) might reproduce the specific reorganization pattern, depicted as the "seismic reversal" phenomenon, before a strong earthquake.

7. Conclusion

Based on the *Z* test analysis, we conclude that the changes in seismicity patterns before and after the Chi-Chi earthquake demonstrate a complete and representative cycle of "seismic reversal." Seismicity patterns before and after the Chi-Chi earthquake mimic a seismic cycle, ebbing and flowing around the epicenter of the main shock. "Normal" seismicity pattern occurred in Period I. Most of the epicenters were distributed in the eastern Taiwan. The pattern in Period II indicates an abnormal stage associated with the phenomenon of "seismic reversal" for the critical condition of the catastrophic Chi-Chi earthquake. Then, the earthquake activity in Period III marks a re-adjustment phase of crustal stress by a large amount of aftershock events of the Chi-Chi main shock. Most areas in Zone A accumulated strains before the Chi-Chi event and released the cumulated deformation in Period III. During Period IV, seismic activity started to diffuse from the central Taiwan to the other regions and, eventually, returned to the eastern Taiwan.

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