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Induced transtensional earthquakes after the 1999 Chi-Chi earthquake in the compressional collision belt of western Taiwan

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SUMMARY

Static stress changes after major earthquakes are generally believed to influence the spatial and/or temporal distribution of aftershocks and subsequent earthquake events. Aftershock sequences, for example, tend to occur in areas with an increase in Coulomb stress with similar mechanisms to the main shock. However, in regions with pre-existing crustal structures with different mechanisms, the corresponding Coulomb stress change may result in different seismic characteristics. In this study, we demonstrate that a transtensional aftershock sequence was induced by the 1999 Chi-Chi earthquake on a pre-existing normal fault, in the compression-dominated western Taiwan fold-and-thrust belt. We used relocated seismicity and earthquake focal mechanisms to show that this sequence is likely occurred along a subsurface fault that strikes N10°W and dips 80° to the east, at depths greater than 5 km. A Coulomb stress change analysis also shows that this aftershock sequence were located in the area of stress increase due to the Chi-Chi earthquake. Such pre-existing normal faults are found throughout the western coastal plains of Taiwan, thus may pose important earthquake hazards for the populous cities located in the area.

Key words: Earthquake source observations; Earthquake interaction, forecasting, and prediction; Seismicity and tectonics; Dynamics: seismotectonics; Crustal structure.

1 INTRODUCTION

It has been generally accepted that the static stress changes after major earthquakes influence the spatial and/or temporal distribution of aftershocks and subsequent large events (e.g. King *et al.* 1994; Harris 1998; Stein 1999; Freed 2005; Steacy *et al.* 2005, and references therein). Generally speaking, the subsequent events occur in regions with an increase in Coulomb stress caused by the major event, and earthquakes become fewer in regions subject to a negative Coulomb stress change. Whereas the subsequent earthquake events are commonly similar in mechanism as the major event since the fundamental tectonic and stress regime does not change by the Coulomb stress change, in places where pre-existing structures are present, the stress change may result in the occurrence of events with different mechanisms.

In areas with rich information of seismic catalogue and abundant structures such as the island of Taiwan, the patterns of earthquakes before and after a major event are good for observing the effect of Coulomb stress changes on pre-existing structures. The 1999 M_w 7.6 Chi-Chi earthquake was the largest onland event ever recorded in Taiwan's instrumental history. The earthquake was produced by rupture along a ∼90-km-long segment of the Chelungpu fault (e.g. Chen *et al.* 2001, 2002; Shyu *et al.* 2005a; Fig. 1), and resulted in significant damages and losses in western central Taiwan. Based on the observation that the overall earthquake patterns of the area changed after the Chi-Chi event, it has been shown that the stress field has changed (e.g. Ma *et al.* 2005). However, the influences of pre-existing structures on the stress field have not been analysed in detail. In this paper, we present an analysis of an earthquake sequence occurred after the Chi-Chi earthquake in the footwall block of the Chelungpu fault, where subsurface pre-existing faults are present, and have influenced the mechanisms of the subsequent earthquake sequence.

2 GEOLOGICAL SETTINGS

Taiwan is located at the convergent plate boundary of the Philippine Sea Plate and the Eurasian Plate (Fig. 1). The mountainous island is the product of the ongoing collision between the Eurasian continental margin and the Luzon volcanic island arc, part of the Philippine Sea Plate (e.g. Teng 1987, 1990; Shyu *et al.* 2005b, and references therein). This ongoing collision produced a fold-and-thrust belt in western Taiwan, where Neogene continental margin

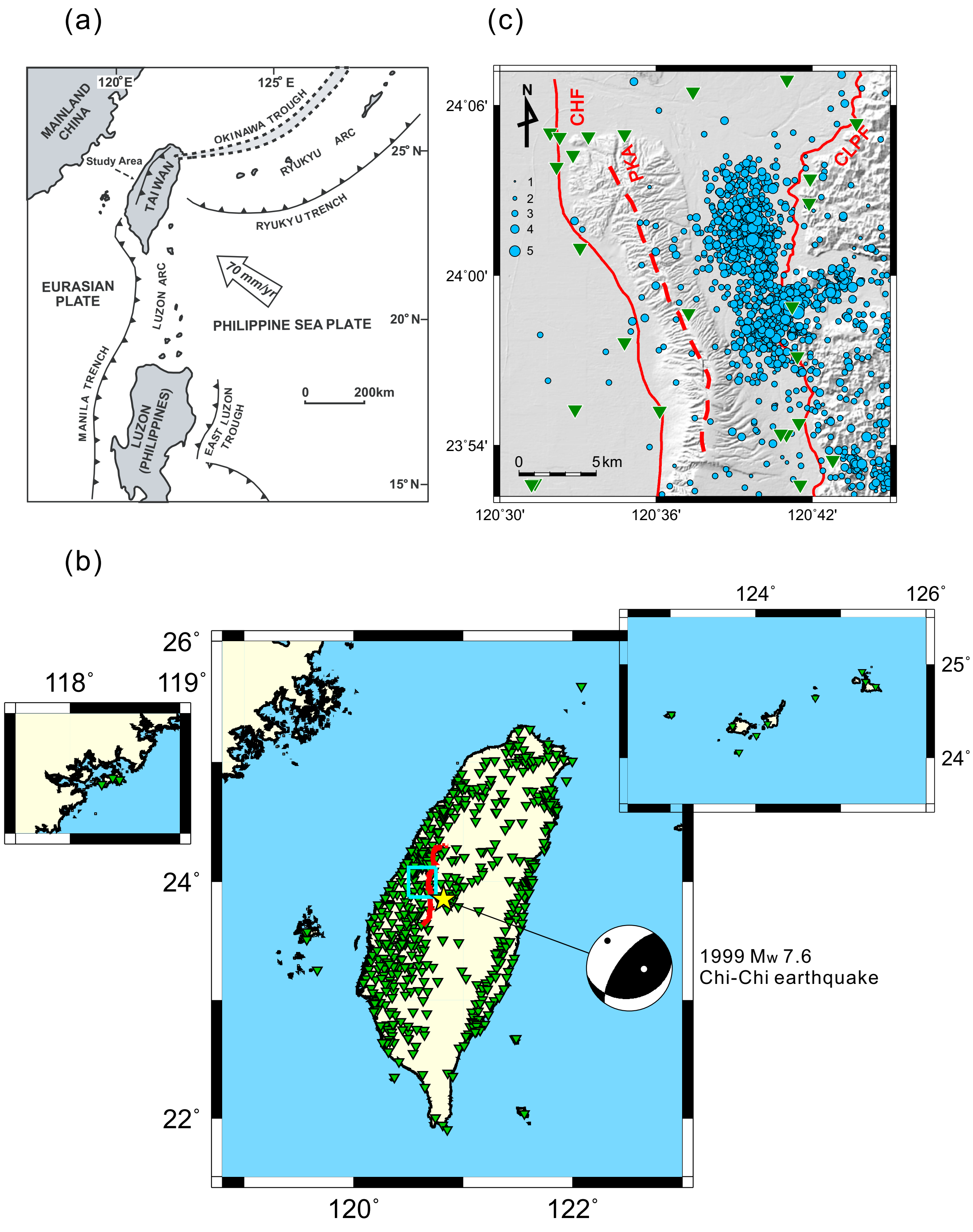

Figure 1. (a) Taiwan is located on the collision boundary between the Eurasian and Philippine Sea plates. The fold-and-thrust belt in western Taiwan is the product of this ongoing collision. (b) The 1999 Chi-Chi earthquake was produced by rupture on the Chelungpu fault (shown in red) in the western Taiwan fold-and-thrust belt. The seismic stations used in this study, including CWBSN, TSMIP, and JMA stations, are shown as green triangles. (c) West of the Chelungpu fault (CLPF), the Changhua fault (CHF) is another major thrust fault in western central Taiwan. The Pakua anticline (PKA) exists in the hanging-wall block of CHF, deforming young Quaternary sediments to produce a clear N–S trending hill. Many earthquakes occurred east of PKA just after the Chi-Chi earthquake (shown by blue dots). Seismic stations located in the study area are also shown. The study area of (c) is shown as the light blue box in (b).

sediments are deformed by a series of imbricated thrust faults (e.g. Suppe 1976, 1980). Among the major faults, the Chelungpu fault in western central Taiwan is the seismogenic structure of the 1999 Chi-Chi earthquake. Numerous seismologic and structural studies have focused on this fault since this event.

West of the Chelungpu fault, another major thrust fault, the Changhua fault, is present (e.g. Shyu *et al.* 2005a; Central Geological Survey 2010). In the hanging-wall block of the Changhua fault, the Pakua anticline deformed young Quaternary sediments and produced a clear N–S trending hill (Fig. 1). It has been noted that the earthquake sequence was remarkably activated beneath the east side of the Pakua anticline just after the Chi-Chi event (Fig. 1). Not only these events are peculiar since they are located in the footwall block of the Chelungpu fault, but the area does not have any identified active structure at the surface (e.g. Shyu *et al.* 2005a; Central Geological Survey 2010). Since none of the aftershock had accompanying surface ruptures, we decided to investigate the seismogenic characteristics of the area by analysing the seismicity distribution and focal mechanisms of those events.

3 DATA AND METHODS

For relocating the earthquakes occurred in central western Taiwan, we used the earthquake catalogue collected by the Central Weather Bureau Seismic Network (CWBSN) of Taiwan from 1991 January to 2010 December. CWBSN consists of a central recording system and 71 telemetered stations that are equipped with three-component Teledyne/Geotech S13 seismometers, and is responsible for the regional earthquake monitoring in Taiwan (Shin 1992, 1993). Two criteria were used for the selection of earthquake records: (1) the earthquakes have arrivals recorded by more than eight stations and (2) the event occurred in the study region during 1999–2010. In total, 1483 events were selected.

We adapted the 3-D location with station correction (3DCOR; Wu *et al.* 2003) as the method to relocate the earthquakes. This method is modified from the 3-D location method of Thurber & Eberhart-Phillips (1999), and uses the 3-D velocity model of Taiwan (Wu *et al.* 2007, 2009). It has been shown that using this 3-D velocity model in the relocation processes we are able to get better and more reliable earthquake locations, especially in a tectonically complex region such as Taiwan (e.g. Wu *et al.* 2008a). Other than CWBSN, data from 680 Taiwan Strong-Motion Instrumentation Program (TSMIP) stations and 18 Japan Meteorological Agency (JMA) stations are also utilized in the earthquake relocation processes in order to improve the station coverage (Fig. 1). According to Wu *et al.* (2008a), the catalogue completeness of the relocated earthquakes in Taiwan is M_L about 2.0. Our relocation follows the same process of Wu *et al.* (2008a). Thus we suggest that the relocated catalogue includes most, if not all, of events larger than M_L 2.0 in the study area.

In order to characterize the earthquake sequences after the Chi-Chi earthquake, it is necessary to identify the main shock–aftershock sequence connection by observing the pattern of earthquake occurrence after the main event. In this study, we picked up aftershock sequences of the 1999 Chi-Chi main shock using time and spatial double-link cluster analysis (Wu & Chiao 2006), with 3 d and 5 km as the linking parameters. This method is similar to the single-link cluster analysis method (Davis & Frohlich 1991). The double-link cluster analysis with 3 d and 5 km as parameters recognizes an earthquake *Y* as an aftershock of a given main shock event *X* if the earthquake occurred within a radius of 5 km of the main shock *X* in 3 d. Aftershocks of event *Y* were then recognized using the same criteria. Repeating these procedures, we will be able to identify all aftershocks of the main shock *X*. Using this method with these parameters, it has been successfully demonstrated that there was a seismic quiescence before the 1999 Chi-Chi earthquake in Taiwan (Wu & Chiao 2006). Since we also focused on earthquakes related to the Chi-Chi event in central Taiwan, we decided to utilize this method with the same parameters as used in Wu & Chiao (2006).

In addition, we have utilized a genetic algorithm to determine the focal mechanisms of events that are greater than magnitude 4. As first shown by Kobayashi & Nakanishi (1994), using a genetic algorithm to determine focal mechanism by polarities of P-first motion requires less amount of calculations compared to using grid search methods. Thus it is a powerful tool in solving such nonlinear problems. For the Taiwan region, Wu *et al.* (2008b) adopted and modified this method to determine the focal mechanisms of 1635 earthquakes in Taiwan from 1991 to 2005. They also included 1000 synthetic tests in order to find the optimal parameters for providing reliable solutions, and estimated uncertainties and solution quality. The uncertainty is defined by determining the mean of each cluster on the primary planes and auxiliary planes and then calculating the 2σ standard deviation. A quality index is defined by considering several parameters such as gap angle, fitness, readings, and polarity (Wu *et al.* 2008b). In general, a quality index higher than 1 is considered a good solution. In this study, we adopted the method of Wu *et al.* (2008b) when determining focal mechanisms. Except for one small event, the quality indexes of all events are higher than 1.

Finally, in order to understand the relationship between the Chi-Chi main shock and the aftershock sequences, we calculated the Coulomb failure stress on specified fault planes obtained from the aftershock focal mechanisms using the program COULOMB 3.3 (Toda & Stein 2002; Chan & Stein 2009). Since faults with rough surfaces or small cumulative slip would have relatively higher effective friction coefficient (μ'; e.g. Parsons *et al.* 1999; Lin & Stein 2004), we assumed a relatively higher μ' of 0.8, based on the fact that these aftershocks did not occur on mapped major faults of this area.

4 RESULTS

4.1 Earthquake distribution and focal mechanisms

From the number of earthquakes occurred in the study area, it is clear that earthquake occurrence increased considerably on the date of the Chi-Chi main shock (Figs 2a and b). The connection between the main shock and the earthquake sequence east of Pakua anticline is even more prominent by their spatial and temporal relationships (Figs 2c and d). Most of the aftershock events in this area occurred after September 1999. We can further separate the earthquake events into two groups: one trends NNW–SSE and the other trends NE–SW. Earthquakes belonging to the NE–SW trending group occurred steadily after the Chi-Chi main shock, and even extended after 2003–2010. On the other hand, earthquakes of the NNW–SSE trending group occurred almost exclusively between the Chi-Chi main shock and 2001. Thus we believe the NNW–SSE trending group is more related with the Chi-Chi event, and is likely a main shock–aftershock sequence.

The results of our 3DCOR earthquake relocation are shown in Fig. 3. In the map view, the seismicity after relocation became closer to each other compared with that before relocation (Figs 3a and b).

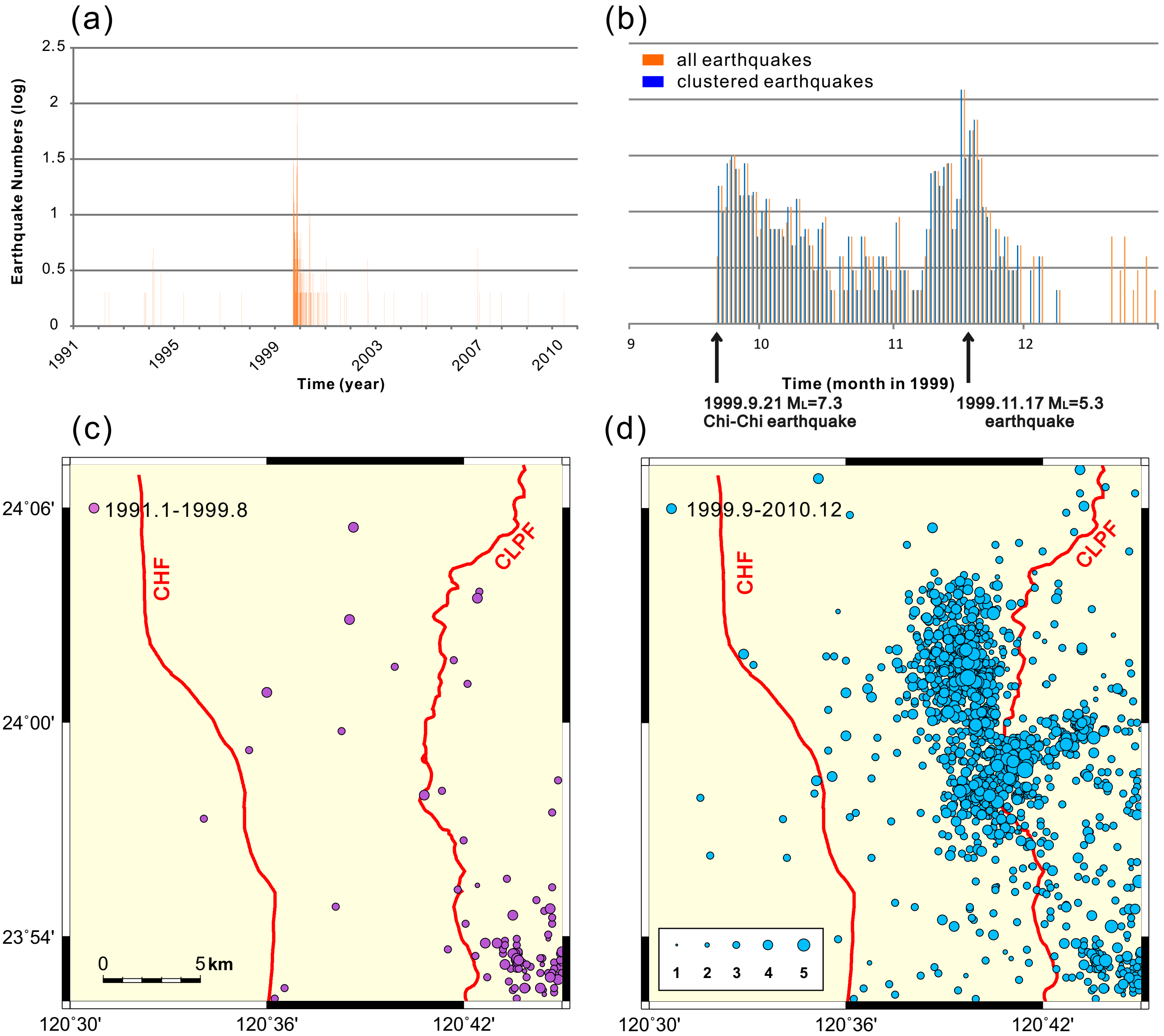

Figure 2. (a) Earthquake numbers versus time from 1991 to 2010. It is clear that earthquake number increased significantly after the 1999 Chi-Chi earthquake. (b) Earthquake numbers versus time from 1999 September to December. Two peaks of seismic activities are present. The first peak occurred right after the Chi-Chi main shock on 21 September, and a second peak occurred after a *M*5.3 event on 1999 November 17. (c) Earthquake occurred in the study area between 1991 and 1999 August. (d) Earthquake occurred in the study area between 1999 September and 2010 December. CLPF, the Chelungpu fault; CHF, the Changhua fault.

The depth changes of the earthquakes, however, are not very significant (Figs 3c–f). After the application of 3DCOR earthquake relocation, the rms of traveltime residuals decreased from 0.134 to 0.129 s. The location errors at horizontal (ERH) and depth (ERZ) directions also decreased from 0.116 to 0.110 km, and from 0.171 to 0.163 km, respectively. Unlike several previous reports (e.g. Huang *et al.* 2012), the reduction of error after relocation in this study is not very large. This indicates the quality of hypocentre locations in the catalogue is already high in this area, since the seismic station coverage in central Taiwan is quite good (e.g. Chan *et al.* 2012a). Still, the location quality improved after our relocation, and the seismicity after relocation shows a more linear pattern, which suggests these earthquakes may have occurred on a subsurface fault.

After our double-link cluster analysis, 879 clustered events were extracted from 1483 events as an aftershock sequence of the Chi-Chi main shock (Figs 3g and h), which we named Sequence A hereinafter. These 879 events occurred between the main shock and 2000 January, and mostly belong to the NNW–SSE trending group. Declustered earthquakes, on the other hand, mainly belong to the other group that trends NE–SW. This is consistent with our hypothesis that the NE–SW trending group may not have tight connection with the Chi-Chi main shock. Thus we focused our analysis to the NNW–SSE trending group only.

In order to identify the geometry of the possible subsurface fault that produced these aftershocks, we made several seismicity cross-sections in the study area. We found that the seismicity distribution shows a good linear pattern along a cross-section that trends N80°E (section A–A′, Fig. 4). Focal mechanisms of earthquakes greater than magnitude 4 are also shown in the figure. Most of the focal mechanisms show nodal planes perpendicular to the cross-section

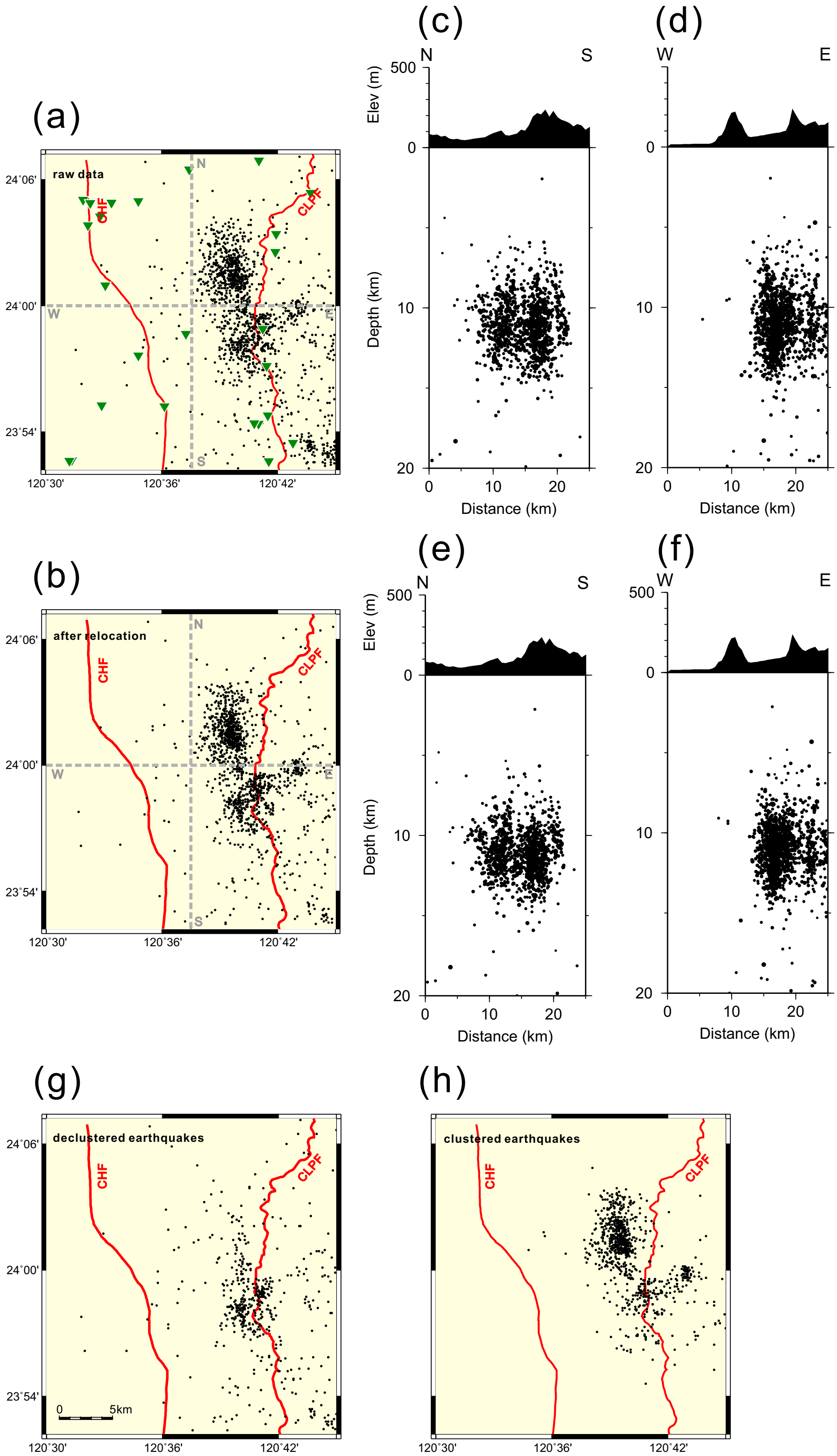

Figure 3. Distribution of seismicity after the Chi-Chi event in the study area. The seismicity after relocation (b) became closer to each other compared with that before relocation (a). The distributions of earthquake before (c, d) and after (e, f) relocation are also shown in E–W and N–S profiles. The depth changes of the earthquakes before and after relocation are not very significant. Declustered earthquakes after our double-link cluster analysis (g) mainly belong to a group that trends NE–SW, and clustered seismicity (h) mostly belong to a group that trends NNW–SSE. CLPF, the Chelungpu fault; CHF, the Changhua fault.

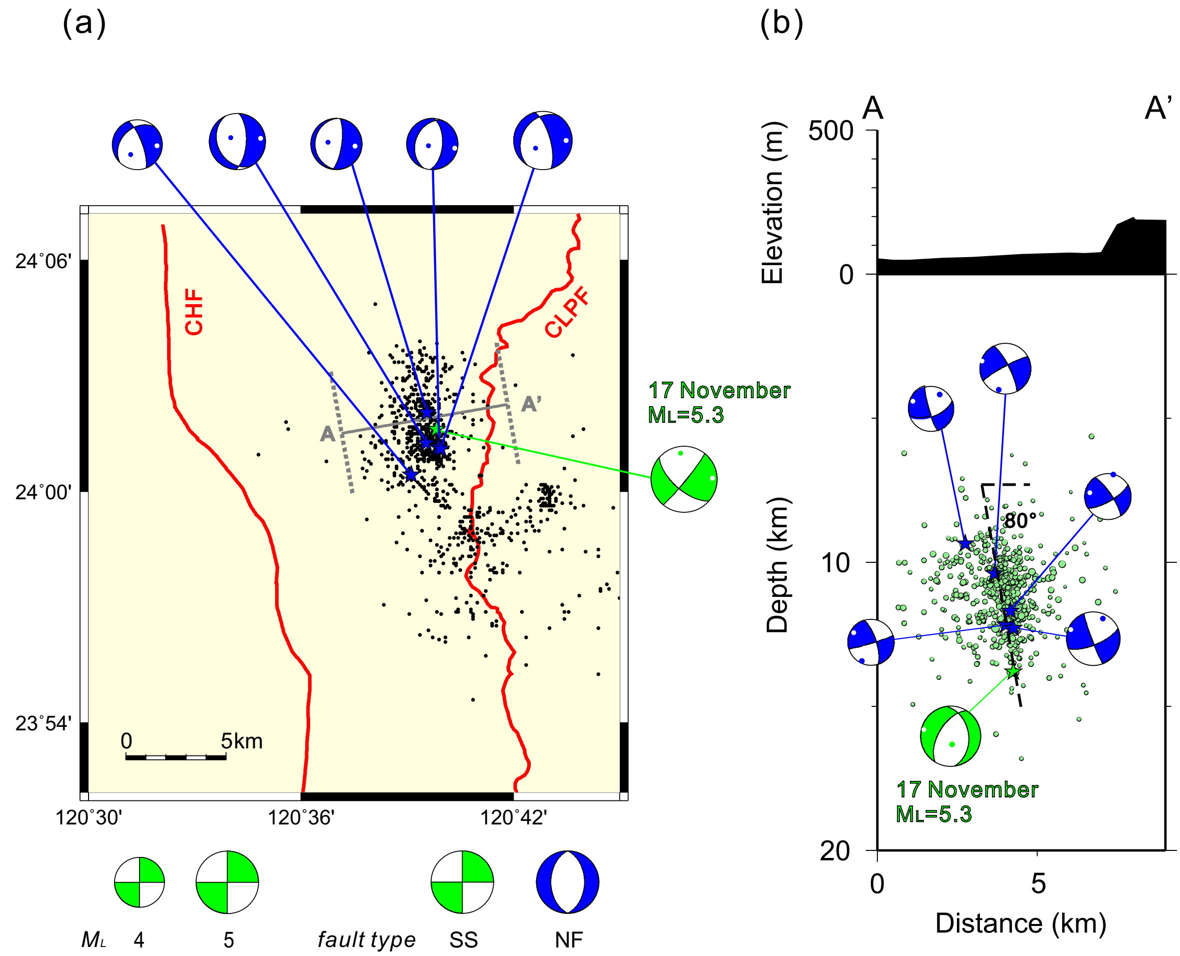

Figure 4. (a) Map view of the earthquake distribution of Sequence A, with focal mechanisms of events greater than *M*4. (b) A seismicity cross-section along A–A′, and the geometry of the proposed subsurface normal fault. Blue colour indicates normal faulting mechanism and green colour indicates strike-slip mechanism. CLPF, the Chelungpu fault; CHF, the Changhua fault.

plane. Thus the fault plane may strike N10°W. Moreover, most of the focal mechanisms indicate normal faulting with dipping angle averages at 80° to the east, consistent with the linear pattern of the seismicity distribution.

When we observe the temporal distribution of earthquakes in Sequence A, we found that there are in fact two peaks of seismic activities (Fig. 2b). The first peak occurred right after the Chi-Chi main shock, and a second peak occurred after an earthquake of *M*5.3 on 1999 November 17, which is the largest event of Sequence A. Thus we further divided this earthquake sequence into two parts, before and after the November 17 event. Although there was no obvious difference in focal mechanism types of events before and after the November 17 earthquake, the aftershocks before November 17 are quite scattered, whereas events after November 17 show a much better linear distribution both in map view and along profile A–A′ (Fig. 5). This indicates that seismic activity of the proposed normal fault was further triggered by the *M*5.3 earthquake on November 17.

4.2 Potential seismogenic structure of the aftershock sequence

From the seismicity distribution patterns and focal mechanisms of Sequence A after the Chi-Chi main shock, we suggest that the earthquakes occurred on a normal fault that strikes N10°W and dips 80° to the east. Such a fault has never been observed at the surface, since the area is characterized by two major thrust faults in Taiwan's western fold-and-thrust belt (e.g. Shyu *et al.* 2005a; Central Geological Survey 2010). Therefore, it is necessary to justify the hypothesis of such a fault.

According to several previous subsurface seismic reflection investigations, the structures in the western coastal plains of Taiwan were predominantly normal faults before the collision began (e.g. Suppe 1986). These faults can be attributed to a rifting episode occurred along southeastern Chinese continental margin in early Neogene (e.g. Suppe 1986). A seismic reflection profile (Yang *et al.* 2007, line 6; Fig. 6) that is nearest but slightly north of our profile reveals the existence of such a fault. This profile runs east–west along the southern bank of the Tatu River. Along the profile, a high-angle fault is present in the footwall block of the Chelungpu fault, about midway between the fault and the Changhua fault, and appears to have normal motion. The fault, however, does not have any evidence at the surface. If we project the seismic profile together with our profile A–A′, our proposed normal fault can connect approximately with the high-angle fault mapped along the seismic profile (Fig. 7; profile B–B′). Therefore, we believe that Sequence A occurred as reactivation of a pre-existing normal fault in the footwall block of the Chelungpu fault after the Chi-Chi main shock. Although the proposed normal fault illuminated by Sequence A

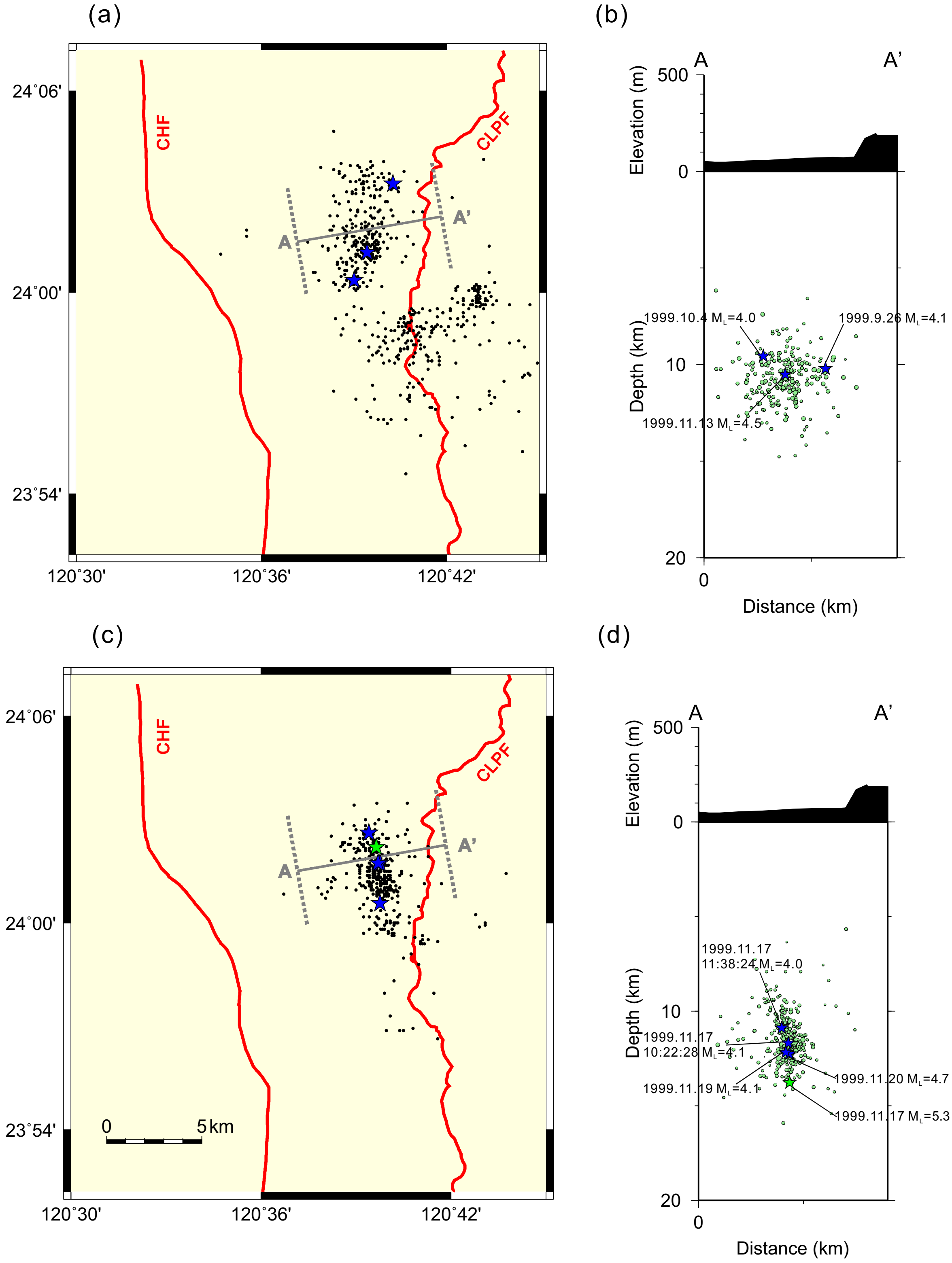

Figure 5. (a) Map view and (b) cross-section of the seismicity distribution before the *M*5.3 earthquake on 1999 November 17, and (c) map view and (d) cross-section of the seismicity distribution after the earthquake. Blue colour indicates normal faulting mechanism, and green colour indicates strike-slip mechanism. CLPF, the Chelungpu fault; CHF, the Changhua fault.

does not connect perfectly with the high-angle fault identified in the seismic profile, this may be due to the fact that the two profiles are located at different latitudes and some geometrical variations of the faults are present. This would be consistent with the bending of the CHF in map view. Alternatively, Sequence A may have occurred on some yet unidentified subsurface fault in the footwall block of the Chelungpu fault, with similar characteristics as the high-angle fault shown in Fig. 7.

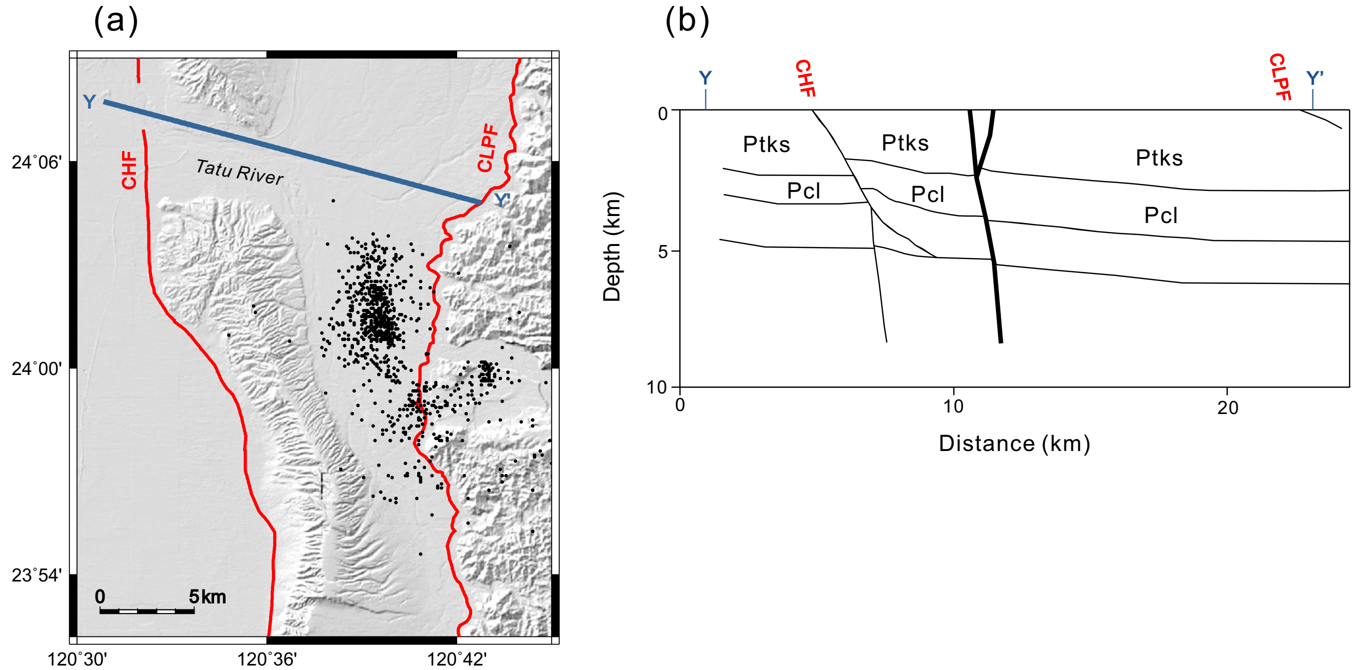

Figure 6. A pre-existing subsurface normal fault (shown as bold black line) is found in the footwall block of the Chelungpu fault, about midway between the fault and the Changhua fault, along an E–W seismic reflection profile (Y–Y′). Modified from line 6 of Yang *et al.* (2007). CLPF, the Chelungpu fault; CHF, the Changhua fault; Ptks, Pleistocene Toukoshan Formation; Pcl, Plio-Pleistocene Cholan Formation.

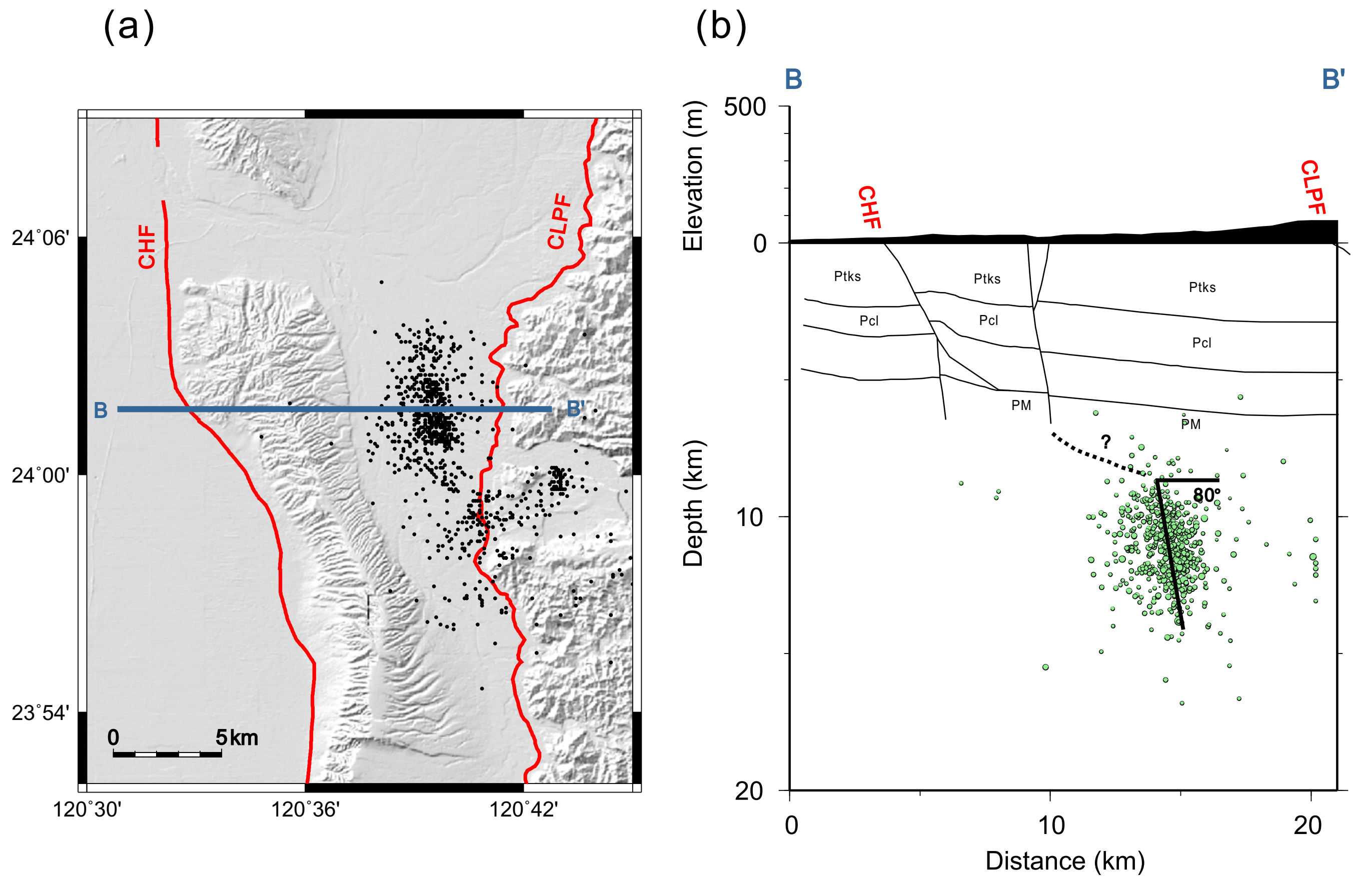

Figure 7. A combined projection of the seismicity profile with the seismic reflection profile along B–B′ suggests that the proposed subsurface normal fault that may produce the aftershocks of Sequence A can connect approximately with the high-angle fault mapped along the seismic reflection profile. CLPF, the Chelungpu fault; CHF, the Changhua fault; Ptks, Pleistocene Toukoshan Formation; Pcl, Plio-Pleistocene Cholan Formation; PM, Pre-Miocene basement.

The fact that there is no Sequence A seismicity above the depth of 6 km indicates that the proposed normal fault is not active at shallow depths. Along the seismic profile, it is clear that the Changhua fault turns into nearly horizontal at a depth of 5–6 km, and connects with the main décollement of western Taiwan (e.g. Carena *et al.* 2002; Yang *et al.* 2007). As a result, the upper part of the normal fault is indeed located in the hanging-wall block of the Changhua fault, and should have experienced compressional stress field once the Changhua fault began to be active. Such compressional stress may have healed the fault plane above the depth of 6 km, thus Sequence A only occurred below that depth.

4.3 Coulomb stress changes in the area

In order to further understand the connection between the Chi-Chi earthquake and the subsequent Sequence A, we performed Coulomb stress change calculations of the study area. For the analysis, we first adapted the fault geometry obtained from the coseismic fault slip model (Ji *et al.* 2003) of the Chi-Chi earthquake as the input source fault. For the geometry of the receiver fault, we chose the focal mechanism of the November 20 earthquake, which was one of the largest events in Sequence A and the obtained focal mechanism has better quality than other events.

The results of the analysis are shown in Fig. 8. It is clear that at our target depth of 11 km, basically the entire area west of the Chelungpu fault shows an increase of the Coulomb stress (Fig. 8a). A cross-section along A–A′ shows that most events of Sequence A occurred in areas with Coulomb stress increase. This is consistent with our hypothesis that this earthquake sequence was induced by the Chi-Chi event. We also obtained a Coulomb stress increase of +0.18 bar on the focal plane of the $M5.3$ earthquake on November 17. This suggests that the $M5.3$ event was also triggered by the coseismic stress change of the Chi-Chi earthquake.

We further analysed the influence of the $M5.3$ earthquake on November 17 by using the focal mechanism of that event as the geometry of the source fault to calculate again the Coulomb stress change. The results show that almost all of the seismicity after the November 17 event was located in areas with Coulomb stress increase (Fig. 8b). This again supports our idea that the proposed subsurface normal fault was further loaded by the $M5.3$ event.

5 DISCUSSION

5.1 Comparison of different data sets

It is noteworthy that the $M5.3$ earthquake occurred on November 17, the largest event of Sequence A, appears to have strike-slip focal mechanism. This is not consistent with the proposed subsurface normal fault that may be the seismogenic structure of Sequence A. We suspect that this is because the focal mechanisms in this study are determined by polarities of P-first motion, which is representative of the initial rupture of a fault.

Interestingly, the focal mechanism of this event is listed as a normal faulting event in the centroid moment tensor (CMT) catalogue of Broad-band Array in Taiwan for Seismology (BATS; http://bats.earth.sinica.edu.tw/). Instead of P-first motion, the BATS catalogue determines focal mechanisms by waveform inversion, which is representative of the averaged rupture process (e.g. Kao & Angelier 2001; Kao & Jian 2001). According to the BATS catalogue, this event had a normal faulting nodal plane that strikes N34°W, and this fault plane solution is similar to all other focal mechanisms of Sequence A (Fig. 9). Therefore, the focal mechanisms of the BATS data, which represents the averaged rupture process, may reflect more completely the geometry of the seismogenic structure.

5.2 Evidence from geodetic measurements

It may seem peculiar that an active normal fault would exist between two major active thrust faults in the fold-and-thrust belt of western Taiwan, even though the normal fault may only be active at depth. However, geodetic observations before and right after the Chi-Chi earthquake may assist to solve this apparent contradiction. According to several GPS analyses, the horizontal component of the coseismic displacements related to the Chi-Chi earthquake appear differently in the hanging-wall block and the footwall block of the Chelungpu fault (Yang *et al.* 2000; Chuang *et al.* 2008). East of the fault in its hanging-wall block, the coseismic displacements are predominantly to the northwest, with values as high as 8.5 m. West of the fault, on the other hand, the crust appears to move slightly toward the southeast for about 0.6–0.8 m. Another GPS observation also indicates that the footwall block of the Chelungpu fault moved 0.5–1.5 m southeastward following the Chi-Chi earthquake, and the amount of displacement increased toward the fault (Hou *et al.* 2000). This indicates that as the Chelungpu fault ruptured, the footwall block of the fault extended due to the relaxation of the crust. As a result, reactivation of and movement along the subsurface normal fault was induced.

It is noteworthy that the southeastward movement of the Chelungpu footwall block appears to extend farther north than the Tatu River, where the subsurface normal fault is illuminated in the seismic profile, at least in some reports (e.g. Yang *et al.* 2000). The normal faulting aftershocks of Sequence A, however, did not occur north of the river. Therefore, we suspect that this subsurface fault terminates near the Tatu River. Alternatively, the pre-Chi-Chi compressional stress field north of the river may be so large that the magnitude of co-seismic stress change was not high enough to induce normal faulting aftershocks there.

In central Taiwan, since pre-Chi-Chi datasets are insufficient for us to determine the pre-shock stress field of this area, we instead utilized the optimally oriented plane (OOP) approach proposed by King *et al.* (1994) in order to estimate possible focal mechanisms after Chi-Chi. The OOP after an earthquake corresponds to the plane with the maximum Coulomb stress. The corresponding procedure has been described in several previous studies (e.g. Chan *et al.* 2012b; Wu *et al.* 2013). We calculated the spatial distribution of OOP in the study area after the Chi-Chi earthquake (Fig. 10). In most part of the study area, the maximum principal stress axis is close to vertical, and suggests a favourable mechanism of normal faulting. Such result is consistent with our observations. In addition, similar favourable mechanisms are also present further to the north, where no Sequence A event occurred. This phenomenon implies the northern termination of Sequence A aftershocks may be attributed to stress heterogeneity and/or structural discontinuity of this area before the Chi-Chi earthquake.

5.3 Implications for seismotectonics and future earthquake hazards of western Taiwan

Large earthquake events sometimes trigger seismicity with various focal mechanisms, including faulting mechanisms that are different from the regional tectonic background. Such phenomenon was particularly evident after the giant 2011 $M_w = 9.0$ Tohoku-Oki

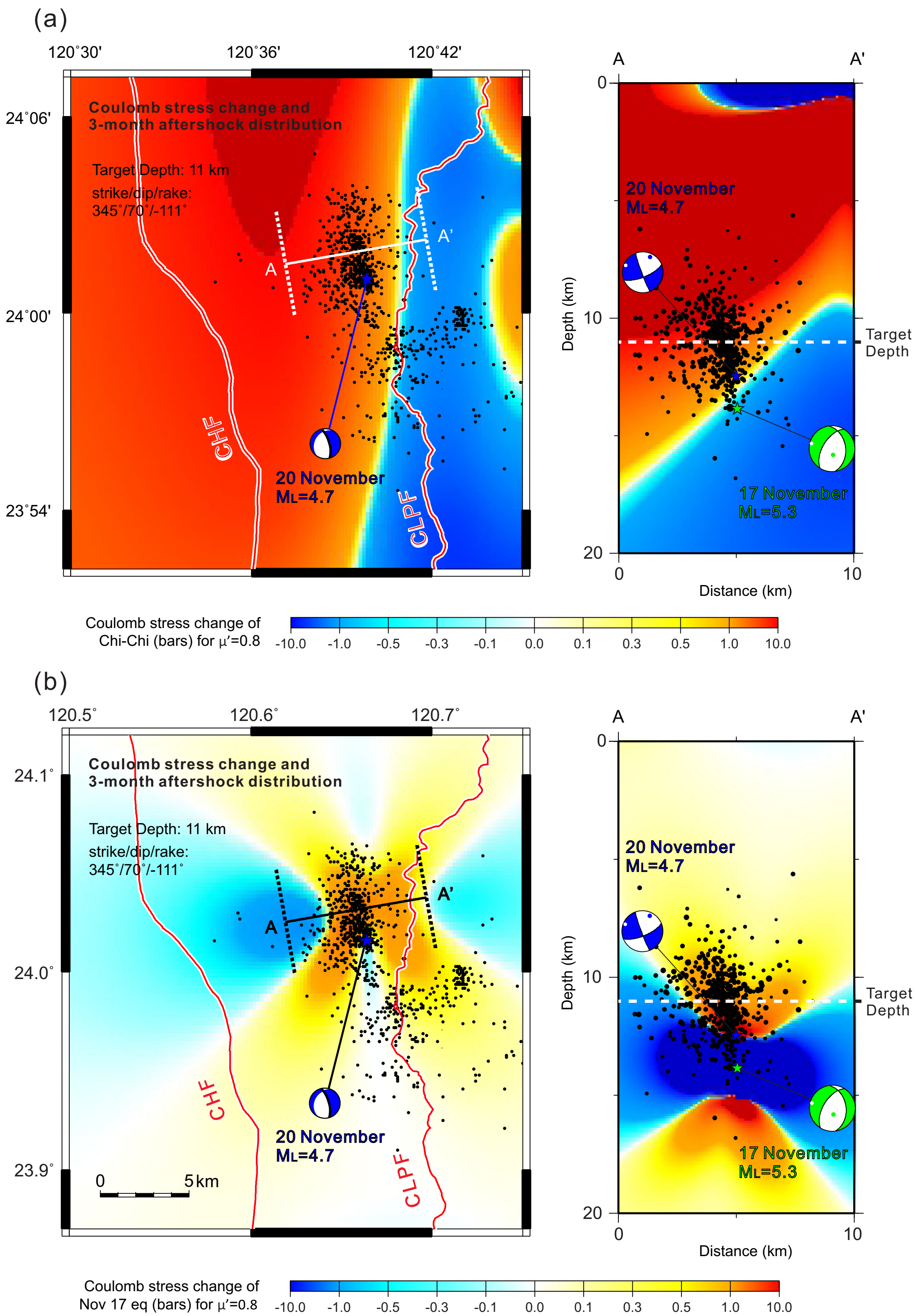

Figure 8. Results of our Coulomb stress change analysis. (a) Results using the coseismic fault slip model of Chi-Chi earthquake as the input source fault and the focal mechanism of the November 20 aftershock as the receiver fault. At the target depth of 11 km, basically the entire area west of the Chelungpu fault shows an increase of the Coulomb stress. A cross-section along A–A′ shows that most events of Sequence A occurred in areas with Coulomb stress increase. (b) Results using the focal mechanism of the November 17 aftershock as the input source fault and the focal mechanism of the November 20 aftershock as the receiver fault. Almost all of the seismicity after the November 17 event was located in areas with Coulomb stress increase.

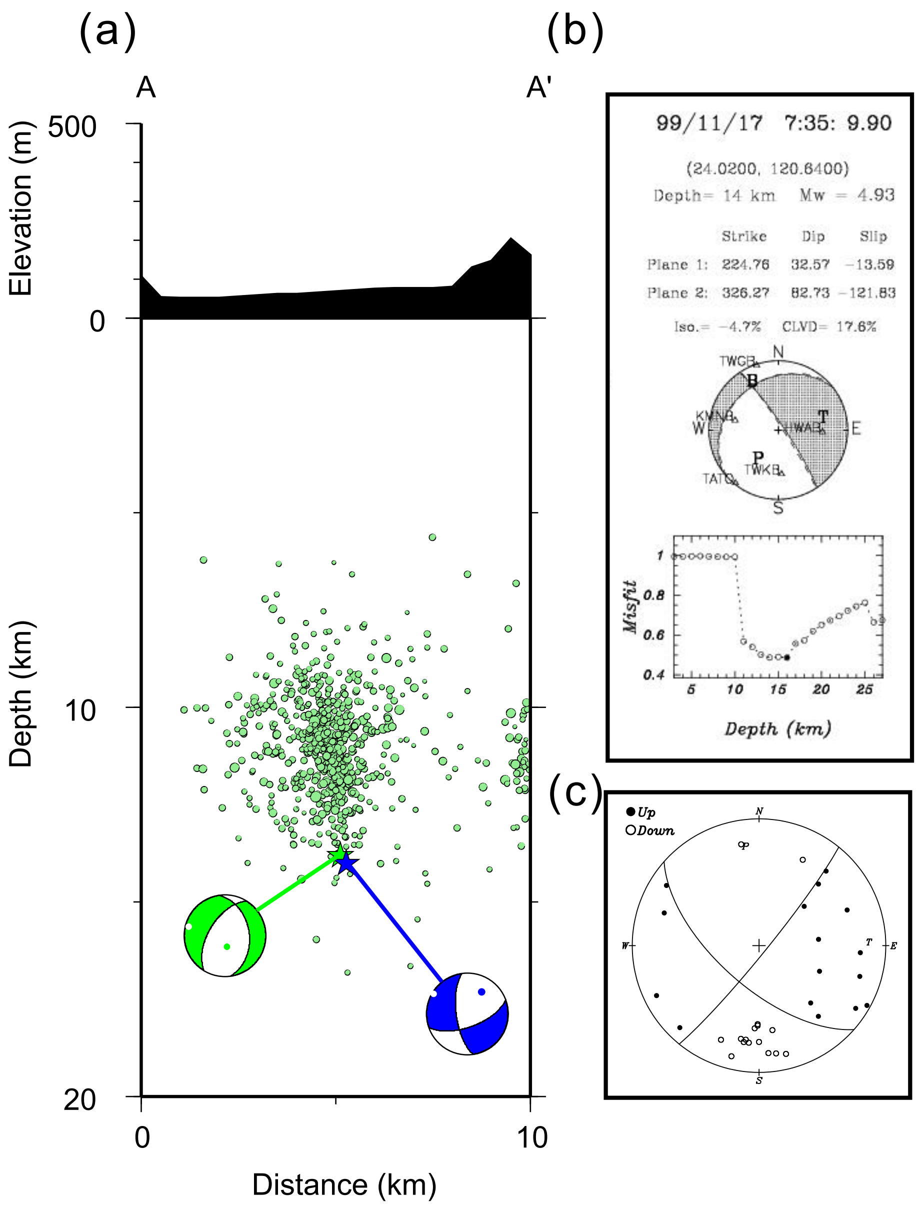

Figure 9. Different focal mechanism results of the M5.3 earthquake on 1999 November 17, obtained from different methods. (a) View along profile A–A′ of Fig. 8(a). The blue coloured focal mechanism indicates the normal faulting mechanism listed in the BATS catalogue obtained by waveform inversion (b), and the green coloured focal mechanism indicates strike-slip mechanism obtained in this study by polarities of P-first motion (c).

earthquake of Japan (e.g. Toda *et al.* 2011; Imanishi *et al.* 2012; Yoshida *et al.* 2012). As shown in the seismic sequences after the 2011 Tohoku-Oki earthquake, the occurrence of such events may represent a combination of the Coulomb stress change by the main shock and a local pre-shock stress field (e.g. Imanishi *et al.* 2012).

Based on a systematic analysis of 115 aftershocks of the Chi-Chi earthquake, Kao & Angelier (2001) noticed a small group of normal faulting aftershocks in the footwall of the Chelungpu fault, and estimated the normal fault stress regime by performing stress inversions. Although the group of normal faulting aftershocks reported by Kao & Angelier (2001) is approximately our Sequence A, the focus of Kao & Angelier (2001) was more on the regional stress field, and they did not interpret in detail the implications of such an extensional stress field. In this study, we provide a reasonable interpretation for the normal faulting aftershocks on the basis of Coulomb stress change and pre-existing geologic structures, and point out the potential importance of such structures in the aftershock occurrences.

The 1999 Chi-Chi earthquake was the most disastrous seismic event in Taiwan's recorded history. Following the event, much effort has been made in understanding the future earthquake hazards of Taiwan, on the basis of detailed active structure investigation and seismic hazard assessment. However, almost all of these results are focused on structures that are visible at the surface.

In recent years, several moderate earthquakes occurred along structures that are not visible at the surface, or blind faults, in Taiwan. These events include the 2010 M_w 6.3 Jiasian earthquake (e.g. Huang *et al.* 2011), the 2012 M_L 6.4 Wutai earthquake (e.g. Chen *et al.* 2013), and the 2013 M_L 6.2 and 6.5 Nantou earthquake series (e.g. Chuang *et al.* 2013). None of the seismogenic structures of these events crop out at the surface. These phenomenon, combined with our analysis of the Sequence A after the Chi-Chi

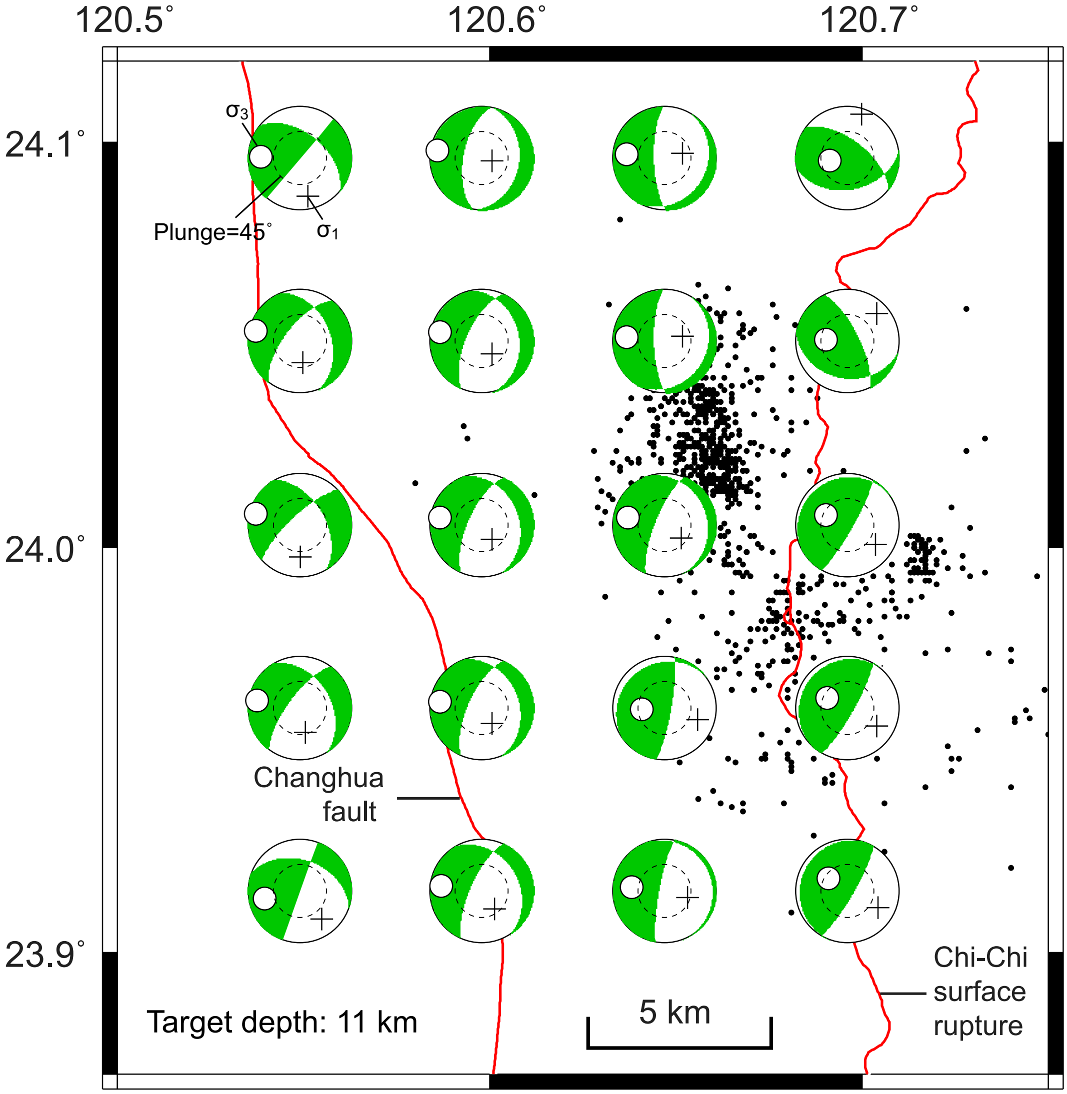

Figure 10. Modelled OOP after the Chi-Chi earthquake. Cross and circle in the focal mechanism represent orientations of the maximum (σ_1) and minimum (σ_3) stress axes, respectively. The dashed circle represents the plunge of 45°. The target depth for OOP calculation is 11 km.

event in central Taiwan, suggest that such structures at depth also pose important earthquake threats for Taiwan. In western Taiwan, many pre-existing normal faults have been reported at depth by seismic reflection investigations. As a result, it is necessary to consider these structures as potential seismic sources in future earthquake hazard assessments in western Taiwan.

6 CONCLUSIONS

We analysed an earthquake sequence occurred after the 1999 Chi-Chi earthquake in central Taiwan. The earthquake distribution pattern of this sequence and the focal mechanisms suggest that this sequence may have occurred as the reactivation of a subsurface normal fault that strikes N10°W and dips 80° to the east. According to our Coulomb stress change analysis, seismic activities along this subsurface fault were induced first by the Chi-Chi main shock, and then further triggered by a *M*5.3 on 1999 November 17.

The subsurface normal fault that may be responsible for the earthquake sequence appears to be a pre-existing structure at depth in western Taiwan. Such structures are found throughout the western coastal plains of Taiwan, and are related to a rifting episode occurred along southeastern Chinese continental margin in early Neogene. The existence of, and the possible movements along, this subsurface fault can also be observed by coseismic geodetic observations of the Chi-Chi earthquake. Many subsurface structures are found in western Taiwan, and have produced several moderate earthquakes in recent years. Therefore, it is necessary to consider these structures as potential seismic sources in future earthquake hazard assessments in Taiwan.

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REFERENCES

Carena, S., Suppe, J. & Kao, H., 2002. Active detachment of Taiwan illuminated by small earthquakes and its control of first-order topography, *Geology,* **30,** 935–938.

Central Geological Survey, 2010. Active fault map of Taiwan, Central Geological Survey, MOEA, Taipei.

Chan, C.-H. & Stein, R.S., 2009. Stress evolution following the 1999 Chi-Chi, Taiwan, earthquake: consequences for afterslip, relaxation, aftershocks and departures from Omori decay, *Geophys. J. Int.,* **177,** 179–192.

Chan, C.-H., Wu, Y.-M., Tseng, T.-L., Lin, T.-L. & Chen, C.-C., 2012a. Spatial and temporal evolution of *b*-values before large earthquakes in Taiwan, *Tectonophysics,* **532–535,** 215–222.

Chan, C.-H., Hsu, Y.-J. & Wu, Y.-M., 2012b. Possible stress states adjacent to the rupture zone of the 1999 Chi-Chi, Taiwan, earthquake, *Tectonophysics,* **541–543,** 81–88.

Chen, C.-H., Huang, H.-H., Chao, W.-A., Wu, Y.-M. & Chang, C.-H., 2013. Re-examining source parameters of the 2012 Wutai, Taiwan earthquake, *Terr. Atmos. Ocean. Sci.,* **24,** 827–835.

Chen, Y.-G., Chen, W.-S., Lee, J.-C., Lee, Y.-H., Lee, C.-T., Chang, H.-C. & Lo, C.-H., 2001. Surface rupture of 1999 Chi-Chi earthquake yields insights on active tectonics of central Taiwan, *Bull. seism. Soc. Am.,* **91,** 977–985.

Chen, Y.-G., Chen, W.-S., Wang, Y., Lo, P.-W., Liu, T.-K. & Lee, J.-C., 2002. Geomorphic evidence for prior earthquakes: Lessons from the 1999 Chichi earthquake in central Taiwan, *Geology,* **30,** 171–174.

Chuang, R.Y., Johnson, K.M., Wu, Y.-M., Ching, K.-E. & Kuo, L.-C., 2013. A midcrustal ramp-fault structure beneath the Taiwan tectonic wedge illuminated by the 2013 Nantou earthquake series, *Geophys. Res. Lett.,* **40,** 5080–5084.

Chuang, S.-Y., Chen, H.-C., Ching, K.-E., Rau, R.-J. & Hou, C.-S., 2008. Crustal deformation in central Taiwan before and after the 1999 Chi-Chi earthquake from GPS observations, 1996–2006, *Cent. Geol. Surv. Spec. Pub.,* **20,** 63–80 (in Chinese with English abstract).

Davis, S.D. & Frohlich, C., 1991. Single-link cluster analysis, synthetic earthquake catalogues, and aftershock identification, *Geophys. J. Int.,* **104,** 289–306.

Freed, A.M., 2005. Earthquake triggering by static, dynamic, and postseismic stress transfer, *Ann. Rev. Earth planet. Sci.,* **33,** 335–367.

Harris, R.A., 1998. Introduction to special section: stress triggers, stress shadows, and implication for seismic hazard, *J. geophys. Res.,* **103,** 24 347–24 358.

Hou, C.-S., Lai, T.-C., Fei, L.-Y., Wang, J.-S. & Chen, W.-H., 2000. Highly accurate surveying in the study of the Chelungpu active fault—comparison of the data before and after the Chi-Chi earthquake, *Cent. Geol. Surv. Spec. Pub.,* **12,** 191–210 (in Chinese with English abstract).

Huang, H.-H., Wu, Y.-M., Lin, T.-L., Chao, W.-A., Shyu, J.B.H., Chan, C.-H. & Chang, C.-H., 2011. The preliminary study of the 4 March 2010 Mw 6.3 Jiasian, Taiwan earthquake sequence, *Terr. Atmos. Ocean. Sci.,* **22,** 283–290.

Huang, H.-H., Shyu, J.B.H., Wu, Y.-M., Chang, C.-H. & Chen, Y.-G., 2012. Seismotectonics of northeastern Taiwan: kinematics of the transition from waning collision to subduction and post-collisional extension. *J. geophys. Res.,* **117,** B01313, doi:10.1029/2011JB008852.

Imanishi, K., Ando, R. & Kuwahara, Y., 2012. Unusual shallow normal-faulting earthquake sequence in compressional northeast Japan activated after the 2011 off the Pacific coast of Tohoku earthquake, *Geophys. Res. Lett.,* **39,** L09306, doi:10.1029/2012GL051491.

Ji, C., Helmberger, D.V., Wald, D.J. & Ma, K.-F., 2003. Slip history and dynamic implications of the 1999 Chi-Chi, Taiwan, earthquake, *J. geophys. Res.,* **108**(B9), 2412, doi:10.1029/2002JB001764.

Kao, H. & Angelier, J., 2001. Stress tensor inversion for the Chi-Chi earthquake sequence and its implications on regional collision, *Bull. seism. Soc. Am.,* **91,** 1028–1040.

Kao, H. & Jian, P.-R., 2001. Seismogenic patterns in the Taiwan region: insights from source parameter inversion of BATS data, *Tectonophysics,* **333,** 179–198.

King, G.C.P., Stein, R.S. & Lin, J., 1994. Static stress changes and the triggering of earthquakes, *Bull. seism. Soc. Am.,* **84,** 935–953.

Kobayashi, R. & Nakanishi, I., 1994. Application of genetic algorithms to focal mechanism determination, *Geophys. Res. Lett.,* **21,** 729–732.

Lin, J. & Stein, R.S., 2004. Stress triggering in thrust and subduction earthquakes, and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, *J. geophys. Res.,* **109,** B02303, doi:10.1029/2003JB002607.

Ma, K.-F., Chan, C.-H. & Stein, R.S., 2005. Response of seismicity to Coulomb stress triggers and shadows of the 1999 Mw = 7.6 Chi-Chi, Taiwan, earthquake, *J. geophys. Res.,* **110,** B05S19, doi:10.1029/2004JB003389.

Parsons, T., Stein, R.S., Simpson, R.W. & Reasenberg, P.A., 1999. Stress sensitivity of fault seismicity: a comparison between limited-offset oblique and major strike-slip faults, *J. geophys. Res.,* **104,** 20 183–20 202.

Shin, T.-C., 1992. Some implications of Taiwan tectonic features from the data collected by the Central Weather Bureau Seismic Network, *Meteorol. Bull.,* **38,** 23–48 (in Chinese).

Shin, T.-C., 1993. Progress summary of the Taiwan strong motion instrumentation program, in *Proceeding of Symposium on Taiwan Strong Motion Instrumentation Program,* Central Weather Bureau, Taipei, Taiwan, pp. 1–10 (in Chinese).

Shyu, J.B.H., Sieh, K., Chen, Y.-G. & Liu, C.-S., 2005a. Neotectonic architecture of Taiwan and its implications for future large earthquakes, *J. geophys. Res.,* **110,** B08402, doi:10.1029/2004JB003251.

Shyu, J.B.H., Sieh, K. & Chen, Y.-G., 2005b. Tandem suturing and disarticulation of the Taiwan orogen revealed by its neotectonic elements, *Earth planet. Sci. Lett.,* **233,** 167–177.

Steacy, S., Gomberg, J. & Cocco, M., 2005. Introduction to special section: stress transfer, earthquake triggering, and time-dependent seismic hazard, *J. geophys. Res.,* **110,** B05S01, doi:10.1029/2005JB003692.

Stein, R.S., 1999. The role of stress transfer in earthquake occurrence, *Nature,* **402,** 605–609.

Suppe, J., 1976. Décollement folding in southwestern Taiwan, *Petrol. Geol. Taiwan,* **13,** 25–35.

Suppe, J., 1980. Imbricated structure of western foothills belt, southcentral Taiwan, *Petrol. Geol. Taiwan,* **17,** 1–16.

Suppe, J., 1986. Reactivated normal faults in the western Taiwan fold-and-thrust belt, *Mem. Geol. Soc. China,* **7,** 187–200.

Teng, L.S., 1987. Stratigraphic records of the late Cenozoic Penglai orogeny of Taiwan, *Acta Geol. Taiwanica,* **25,** 205–224.

Teng, L.S., 1990. Late Cenozoic arc-continent collision in Taiwan, *Tectonophysics,* **183,** 57–76.

Thurber, C.H. & Eberhart-Phillips, D., 1999. Local earthquake tomography with flexible gridding, *Comput. Geosci.,* **25,** 809–818.

Toda, S. & Stein, R.S., 2002. Response of the San Andreas fault to the 1983 Coalinga-Nuñez earthquakes: an application of interaction-based probabilities for Parkfield, *J. geophys. Res.,* **107**(B6), doi:10.1029/2001JB000172.

Toda, S., Stein, R.S. & Lin, J., 2011. Widespread seismicity excitation throughout central Japan following the 2011 M = 9.0 Tohoku earthquake and its interpretation by Coulomb stress transfer, *Geophys. Res. Lett.,* **38,** L00G03, doi:10.1029/2011GL047834.

Wu, Y.-M. & Chiao, L.-Y., 2006. Seismic Quiescence before the 1999 Chi-Chi, Taiwan, Mw 7.6 Earthquake, *Bull. seism. Soc. Am.,* **96,** 321–327.

Wu, H.-Y., Chan, C.-H., Kinoshita, M. & Saito, S., 2013. Stress field observation and modeling from the NanTroSEIZE scientific drillings in the Nankai Trough system, SW Japan, *Tectonophysics,* **600,** 99–107.

Wu, Y.-M., Chang, C.-H., Hsiao, N.-C. & Wu, F.T., 2003. Relocation of the 1998 Rueyli, Taiwan, earthquake sequence using three-dimensions velocity structure with stations corrections, *Terr. Atmos. Ocean. Sci.,* **14,** 421–430.

Wu, Y.-M., Chang, C.-H., Zhao, L., Shyu, J.B.H., Chen, Y.-G., Sieh, K. & Avouac, J.-P., 2007. Seismic tomography of Taiwan: improved constraints from a dense network of strong-motion stations, *J. geophys. Res.,* **112,** B08312, doi:10.1029/2007JB004983.

Wu, Y.-M., Chang, C.-H., Zhao, L., Teng, T.-L. & Nakamura, M., 2008a. A comprehensive relocation of earthquakes in Taiwan from 1991 to 2005, *Bull. seism. Soc. Am.,* **98,** 1471–1481.

Wu, Y.-M., Zhao, L., Chang, C.-H. & Hsu, Y.-J., 2008b. Focal mechanism determination in Taiwan by genetic algorithm, *Bull. seism. Soc. Am.,* **98,** 651–661.

Wu, Y.-M., Shyu, J.B.H., Chang, C.-H., Zhao, L., Nakamura, M. & Hsu, S.-K., 2009. Improved seismic tomography offshore northeastern Taiwan: implications for subduction and collision processes between Taiwan and the southernmost Ryukyu, *Geophys. J. Int.,* **178,** 1042–1054.

Yang, K.-M., Huang, S.-T., Wu, J.-C., Ting, H.-H., Mei, W.-W., Lee, M., Hsu, H.-H. & Lee, C.-J., 2007. 3D geometry of the Chelungpu thrust system in central Taiwan: its implications for active tectonics, *Terr. Atmos. Ocean. Sci.,* **18,** 143–181.

Yang, M., Rau, R.-J., Yu, J.-Y. & Yu, T.-T., 2000. Geodetically observed surface displacements of the 1999 Chi-Chi, Taiwan, earthquake, *Earth Planets Space,* **52,** 403–413.

Yoshida, K., Hasegawa, A., Okada, T., Iinuma, T., Ito, Y. & Asano, Y., 2012. Stress before and after the 2011 great Tohoku-oki earthquake and induced earthquakes in inland areas of eastern Japan, *Geophys. Res. Lett.,* **39,** L03302, doi:10.1029/2011GL049729.