Terr. Atmos. Ocean. Sci., Vol. 25, No. 1, 27-38, February 2014 doi: 10.3319/TAO.2013.09.23.01(T)

Seismogenic Structure Beneath Décollement Inferred from 2009/11/5 M_L 6.2 Mingjian Earthquake in Central Taiwan

Che-Min Lin[1,*], Tao-Ming Chang[1], Kuo-Liang Wen[1,2], Chun-Hsiang Kuo[1], and Hung-Hao Hsieh[1]

[1] *National Center for Research on Earthquake Engineering, Taiwan, R.O.C.*
[2] *Department of Earth Science and Graduate Institute of Geophysics, National Central University, Taiwan, R.O.C.*

Received 6 April 2013, accepted 23 September 2013

ABSTRACT

One decade after the 1999 Chi-Chi earthquake, central Taiwan experienced more strong ground shaking [Central Weather Bureau (CWB), intensity VII] induced by a M_L 6.2 earthquake on 5th November 2009. This earthquake occurred in the Mingjian Township of Nantou County, only 12 km southwest of the Chi-Chi earthquake epicenter. The broadband micro-earthquake monitoring network operated by the National Center for Research on Earthquake Engineering (NCREE) observed numerous aftershocks in the five days following the mainshock. The relocated aftershocks and the mainshock focal mechanism indicated a NE-SW striking fault dipping 60° toward the northwest. This fault plane is inside the pre-Miocene basement and the rupture extends from the lower crust to 10 km depth just beneath the basal décollement of the thin-skinned model that is generally used to explain the regional tectonics in Taiwan. The fault plane is vertically symmetrical with the Chelungpu fault by the basal décollement. The NW-SE compressive stress of plate collision in Taiwan, as well as the deep tectonic background, resulted in the seismogenic structure of the Mingjian earthquake at this location.

Key words: Mingjian earthquake, Thin-skinned model, Chi-Chi earthquake, Décollement

Citation: Lin, C. M., T. M. Chang, K. L. Wen, C. H. Kuo, and H. H. Hsieh, 2014: Seismogenic structure beneath décollement inferred from 2009/11/5 M_L 6.2 Mingjian earthquake in central Taiwan. Terr. Atmos. Ocean. Sci., 25, 27-38, doi: 10.3319/TAO.2013.09.23.01(T)

1. INTRODUCTION

On 5th November 2009, a M_L 6.2 earthquake struck central Taiwan one decade after the 1999 Chi-Chi earthquake, the largest earthquake on the island for one hundred years. According to the Central Weather Bureau (CWB), the epicenter was located in the Mingjian Township of Nantou County, a distance of 12 km southwest of the 1999 Chi-Chi earthquake (Fig. 1). The strong ground shaking, seismic intensity VII on the CWB Intensity Scale, induced by the Mingjian earthquake reawakened the public's fear about events such as the Chi-Chi earthquake. Fortunately, the Mingjian earthquake did not cause a serious disaster because it had a deeper hypocenter, at 24.1 km depth, than the Chi-Chi earthquake. However, any correlations between the seismogenic structures of the Mingjian and the 1999 Chi-Chi earthquakes may provide more insights toward understanding the regional tectonics.

Taiwan is the result of ongoing orogeny induced by complex arc-continent collisions between the Philippine Sea plate and the Eurasian plate (Barrier and Angelier 1986; Suppe 1984; Tsai 1986; Teng 1990). The Philippine Sea plate moves north-westerly toward the Eurasian plate at a speed of about 7 - 8 cm yr^{-1} (Seno 1977; Yu et al. 1997). On the northeastern offshore of Taiwan, the Philippine Sea plate subducts northward beneath the Eurasian plate along the Ryukyu trench that is connected to the subduction system of Japan in the northeast. Oppositely, the Eurasian plate subducts eastward beneath the Philippine Sea plate along the Manila trench that is connected to the subduction system of the Philippines in the south. The active collisions frequently caused earthquakes and resulted in major tectonic features in and around Taiwan. To explain the orogeny of Taiwan, the thin-skinned model is generally seen as the most suitable hypothesis when matching geologic, seismologic, and geophysical observations (Suppe 1980, 1981; Teng 1990; Wang et al. 2000; Yue et al. 2005). In this model, the compression of mountain building dominates the wedge-shaped structure thrust over the décollement, which is a low frictional

* *Corresponding author*
E-mail: cheminlin@gmail.com

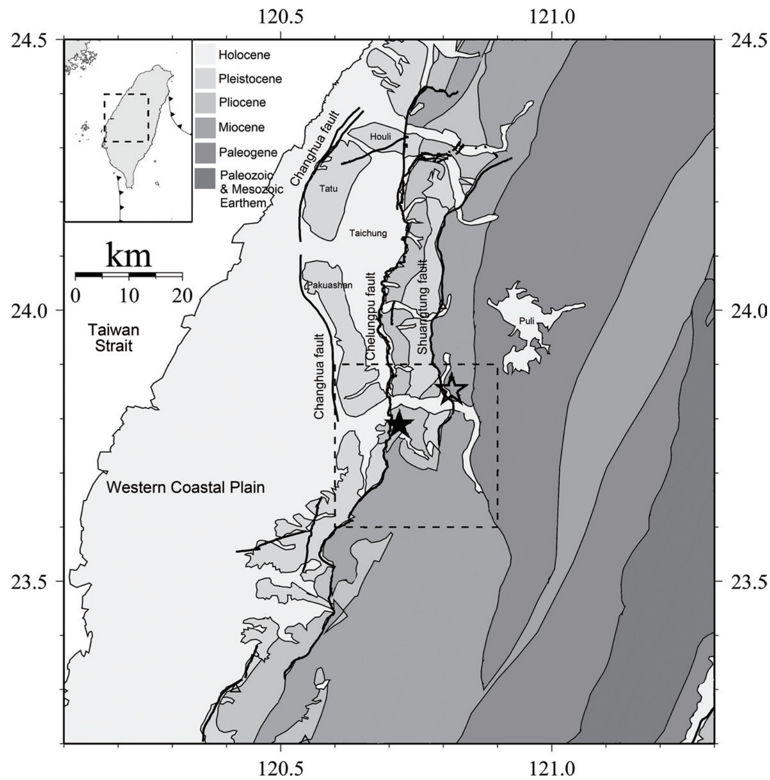

Fig. 1. Geological map of central Taiwan with the active faults and the epicenters of the 1999 Chi-Chi (open star) and 2009 Mingjian (solid star) earthquakes. The discussion is about the rectangular dashed region.

resistance interface. The overlying mountain wedge was approximated as a wedge of Coulomb material at compressive failure, analogous to a wedge of soil that develops in front of a bulldozer (Suppe 1981). The fold-and-thrust structure exposed in the Western Foothills and Central Range of Taiwan shows a typical example of an accretionary wedge conforming to the thin-skinned model. Although another hypothesis, the lithosphere collision model, was also proposed to explain the orogeny of Taiwan based on the existence of thick root under the Central Range (Wu et al. 1997; Wu and Rau 1998), the 1999 Chi-Chi earthquake and its subsequent studies showed vigorous evidence that the structures under Taiwan, or at least the Western Foothills belt, conform to the thin-skinned model (Wang et al. 2000, 2002, and 2004; Yue et al. 2005).

The Chi-Chi earthquake occurred in central Taiwan on September 21th 1999 with a magnitude of M_W 7.6 (M_L 7.3) and focal depth of 8.0 km. The earthquake ruptured the Chelungpu fault, a north-south-trending thrust fault, with over 90 km of fault trace on the surface. The NS-oriented fault trace turned eastwards causing abnormally large displacements both on the surface (up to 9.8 m horizontally and 5.6 m vertically) and underground (up to 12 m) at its northern end (Chung and Shin 1999; Ma et al. 2000; Lee et al. 2002). The strong ground-shaking and displacement characteristics of the earthquake caused huge damage, including more than 2400 fatalities, 11000 injuries, and 50000 collapsed buildings. However, the outcrop and shallow dip of the fault plane (30°), and the plentiful seismic data collected by the CWB provide a valuable opportunity to understand the complex local tectonics. The Chelungpu fault was generally seen as a major thrust fault in the frontal portion of the fold-and-thrust belt based on the thin-skinned model. The hanging wall was thrust along the underlying Chinshui Shale, the décollement, to induce this massive earthquake. These kinds of rupture processes repeatedly occurred on the Chelungpu and surrounding faults to develop the imbricate structures that can now be seen in the Western Foothills (Chen et al. 2004; Hung et al. 2009).

In the thin-skinned model, the seismicity is focused on a fold-and-thrust wedge above the décollement, in this case about 8 - 10 km deep under the Chelungpu fault in the Western Foothills (Wang et al. 2002). However, the M_L 6.2 Mingjian earthquake occurred just beneath the 1999 Chi-Chi earthquake inside the underlying basement at a depth of 24.1 km, much deeper than the décollement. Can the assumed model still expound the seismogenic structure of the Mingjian earthquake due to its unique source position? This paper examines the numerous aftershocks of the Mingjian earthquake observed by the NCREE broadband micro-earthquake monitoring network to delineate the fault plane of the mainshock. Then, the connection between the Mingjian and

Chi-Chi earthquakes is investigated, and the reasons for the Mingjian earthquake occurring at this location are explained based on the existing regional tectonic model. Inferences about the seismogenic structure of the Mingjian earthquake will supplement the deficiencies of the assumed model, particularly at depths below the décollement, for the Western Foothills in Taiwan.

2. REGIONAL GEOLOGY AND SEISMICITY

The Mingjian earthquake occurred adjacent to the east side of the Chelungpu fault that separates the Western Foothills, underlain by Mio-Pliocene sediments on the east, from the late Quaternary plain and basin areas on the west, and acts as a geological boundary in central Taiwan (Fig. 1). In this area, tectonic compression from the east resulted in a sequence of linear fold-and-thrust structures with a north-south trend. The sequence of strata involved in the overthrusting of the Chelungpu fault is in the following order: the Toukoshan Formation (Pleistocene), the Cholan Formation (late Pliocene), the Chinshui Formation (Chinshui Shale, early Pliocene), and the Kueichulin Formation (Miocene) (Chang 1971; Chou 1971). The Chelungpu fault is the bedding thrust fault that slips along the Chinshui Shale. The Pliocene sediments of the Chinshui Shale and the overlying Cholan Formation are exposed as hills in the eastern hanging wall of the thrust and dip gently 20 - 40° to the southeast. The slip occurred along the 150 - 300 m thick Chinshui Shale and generally developed parallel to the bedding. The Chinshui Shale, composed of greyish fine-grained shale or mudstone, is weak and has a high pore-fluid pressure. It therefore has the appropriate properties for sliding as a shallow décollement for the development of this thin-skinned thrust fault, called the Chelungpu fault (Suppe and Wittke 1977; Wang et al. 2000).

There are two N-S trending active thrust faults on both flanks of the Chelungpu fault that run approximately parallel to this fault. The eastern thrust fault, the Shuangtung fault, is the boundary between Miocene formations on the east and Toukoshan Formations on the west. Some slight fractures were observed along the Shuangtung fault, which is on the hanging wall side of the Chelungpu fault, during the Chi-Chi earthquake. The western fault, the Changhua fault, thrusts Toukoshan Formations out to form a series of gravel terraces (Houli, Tatu, and Pakuashan) and an elongated Holocene basin, the Taichung basin, between itself and the Chelungpu fault. On the western side of the Changhua fault, the Western Coastal Plain was filled with thick Quaternary sediments covering all the older geologic features and creating a low and flat terrain. Under the Western Coastal Plain, a pre-Miocene basement high, the Peikang Basement High, acts as a prominent tectonic barrier in the middle of western Taiwan (Meng 1968, 1971; Sun 1982). This basement high also dominated the distributions of the overlying sediments (Pan 1967; Shaw 1996; Lin et al. 2009). The Peikang Basement High is regarded as an extension of the continental shelf of the Eurasian plate. The Philippine Sea plate that moves northwest and mounts the Eurasian plate along the shallow-dipping basement surface was blocked by this Peikang Basement High, causing the imbricated structure that we see in central Taiwan. Generally, the regional structures can be explained by the thin-skinned model.

The top of the Peikang Basement High is near Penghu Island in the Taiwan Strait and dips gradually into Taiwan Island. The basement surface becomes deeply buried about 6 km below the surface near the Changhua fault and continues dipping eastward, contributing to the development of the overlying thin-skinned thrust structures. Wang et al. (2000) proposed a structural model for the Chi-Chi earthquake based on the thin-skinned model. This model, which matches the uplift of the Peikang Basement High, has an overall décollement surface just above the basement with a slope of about 8 degrees at a depth between 10 and 20 km. However, the décollement of the Chelungpu fault, the Chinshui Shale, was thought to be at a shallower depth (less than 10 km) (Wang et al. 2000; Yue et al. 2005).

The uplifted pre-Miocene basement, the Peikang Basement High, beneath the Western Coastal Plain, produced a semi-circular region, opening westward, with low background seismicity (Fig. 2a). Although there are several active faults around the Chelungpu fault and the epicenter of Chi-Chi earthquake, there were just scattered earthquakes and a small group occurred within this region. The aseismic background near the Chi-Chi earthquake resulted in an accumulation of crustal strain energy, which was then released to trigger this large earthquake. Two linear high seismicity zones are located in the northeast and southeast of this semi-circular low-seismicity region. The NE zone, the Sanyi-Puli seismic zone, is a shear zone trending in a NW-SE direction. The earthquakes of the Sanyi-Puli seismic zone are mostly small, and can be divided into two groups dipping to the southeast with different angles as a double seismic zone (Chen and Chen 2002). The SE zone is the northern part of the Chia-Yi seismic zone where both small and large earthquakes occur, and is seen as one of the highest potential areas for the next disastrous earthquake in Taiwan.

The numerous aftershocks of the Chi-Chi earthquake mostly surrounded this semi-circular region (Fig. 2b). Most aftershocks were located 25 km east of the Chelungpu fault and filled the seismic gap between the Sanyi-Puli and Chia-Yi seismic zones. The region between the Chelungpu and Shuangtung faults exhibited relatively few aftershocks. In the western part of the Chelungpu fault, aftershocks were almost non-existent except for a NW-SE trending swarm near the Pakuashan terrace.

One year after the Chi-Chi earthquake, the aftershock sequence could be viewed as over. However, the seismicity did not return to the same pattern as before the Chi-Chi earthquake, but emerged as a combination of the original and Chi-Chi aftershock patterns (Fig. 2c). This new pattern includes a northeast extension of the Sanyi-Puli seismic zone and a NW-SE trending swarm near the Pakuashan terrace. The low seismicity semi-circular region is still obvious. However, the 2009 Mingjian earthquake and its aftershock sequence occurred unexpectedly in this region with the largest magnitude, M_L 6.2, recorded to the east of the Chi-Chi earthquake location. Before the Mingjian earthquake, its epicenter region was almost devoid of seismicity, even during the Chi-Chi earthquake.

3. DATA AND ANALYSIS

The high-technology industry has become the most vigorous economic resource of Taiwan due to its major development over the past two decades. However, all highly technological Science Parks in Taiwan inevitably face a seismic threat due to the active tectonics of the entire island. Since 2005, NCREE has carried out a series of studies on active faults to evaluate the seismic risks to Science Parks in Taiwan, including numerical simulations of ground motions, site effects and earthquake precursors. One such study

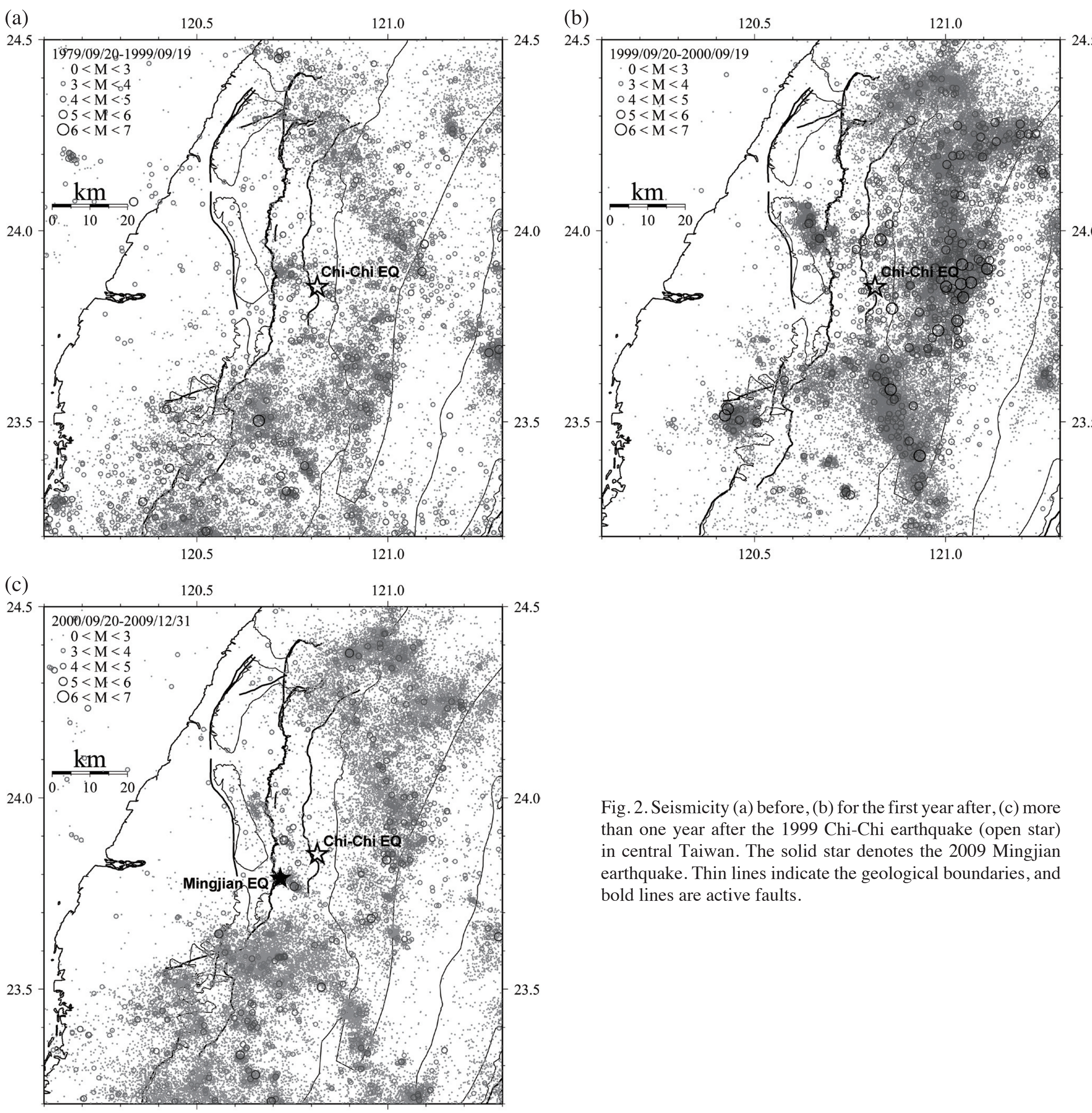

Fig. 2. Seismicity (a) before, (b) for the first year after, (c) more than one year after the 1999 Chi-Chi earthquake (open star) in central Taiwan. The solid star denotes the 2009 Mingjian earthquake. Thin lines indicate the geological boundaries, and bold lines are active faults.

was to observe the seismicity and source parameters of the active faults around the Science Parks using broadband micro-earthquake monitoring networks. Three monitoring networks were established for the Hsinchu Science Park (HSP), the Southern Taiwan Science Park (STSP) and the Central Taiwan Science Park (CTSP), and were finally combined into one integrated network. This integrated network was composed of forty-seven stations covering most of the active faults between Hsinchu and Tainan in western Taiwan (Fig. 3). A high-sensitivity broadband seismometer, Guralp CMG-6TD, was installed at each station. Every station was equipped with solar energy equipment and a GPS antenna to supply the electricity and correct the internal clock of the seismometer. Recording is continuous at 100 samples per second. Because the Central Weather Bureau Seismographic network (CWBSN) and Taiwan Strong Motion Instrumentation Program (TSMIP) network operated by CWB provide superior seismic monitoring and CWB is responsible for the announcement of strong motion events in Taiwan (Liu et al. 1999; Shin et al. 2013), the micro-earthquake monitoring network of NCREE was built to focus on small earthquakes with a magnitude lower than 3 (duration magnitude, M_d) to study the significance of small tremors related to the faults.

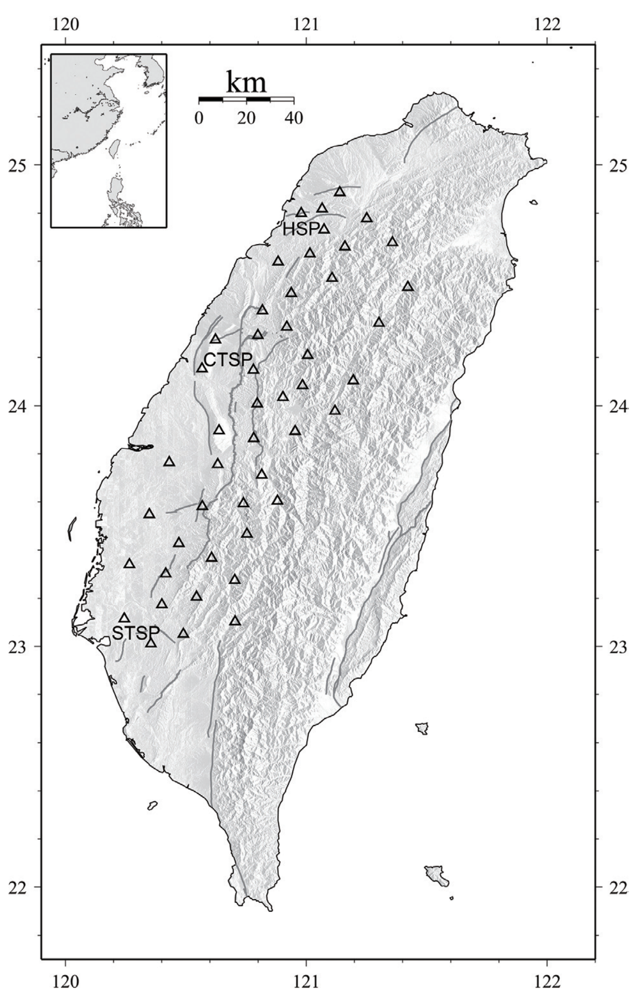

Fig. 3. Broadband micro-earthquake monitoring network of NCREE for the Science Parks, including Hsinchu Science Park (HSP), Southern Taiwan Science Park (STSP) and Central Taiwan Science Park (CTSP).

The Mingjian earthquake occurred at 17:32 (Taiwan local time) on November 21st, 2009. Figure 4 is a map of peak ground accelerations (PGA) observed by the TSMIP network for the mainshock. The whole island of Taiwan felt the seismic motion caused by this earthquake. The largest PGA was recorded by station TCU129 and reached about 400 gal near the epicenter. Although this high PGA was considered to be the effect of a faulty concrete recording pier at TCU129 (Wen et al. 2001) rather than the short epicentral distance or local seismic site condition (Kuo et al. 2012), some nearby stations also observed PGA greater than 200 gal.

In the five days after the mainshock of the Mingjian earthquake, 203 aftershocks were located by the NCREE network. These events were relocated using the double-difference hypocenter location (hypoDD) algorithm (Waldhauser and Ellsworth 2000) to determine high-resolution aftershock locations. The epicentral distribution of 155 relocated aftershocks is shown in Fig. 5. The observed distribution is identical to that of the large aftershocks ($M_L > 3$) located by CWB. The aftershocks were concentrated to the southeast of the mainshock and were bounded by the end of the Shuangtung fault on the east: the aftershocks roughly form two groups. The first group was closer to the mainshock but dispersed, and the second group was more concentrated to the southeast. Figure 6 shows a NW-SE cross-section of the relocated hypocenters. When plotted as a function of depth, the aftershocks also show the division into two groups by depth. However, the origin times and focal mechanisms of the aftershocks do not provide further information about the two groups, which may result from bending or branching of the fault plane.

All aftershocks fell into a 10 - 20 km depth range with the plotted foci dipping steeply from southeast to northwest (Fig. 6). The downward extension line of the aftershock sequence intersects the mainshock hypocenter at a depth of 24.1 km. The aftershock distribution clearly suggests that the mainshock and aftershocks are mostly on the same plane. According to the CWB moment-tensor solution, the focal mechanisms of both the mainshock and the largest aftershock (M_L 5.7) were thrusting with two nodal planes that trend northeast and northwest (Fig. 5). The NW dipping rupture plane indicated by the aftershocks agrees with the mainshock's NE trending nodal plane. Again the aftershock rupture plane is about a 60° angle as the mainshock's nodal plane. The results therefore prove that the Mingjian earthquake thrust along a NE-SW striking fault plane dipping to the northwest. This fault plane was ruptured by the mainshock, and extended from the lower crust to the upper crust at 10 km depth.

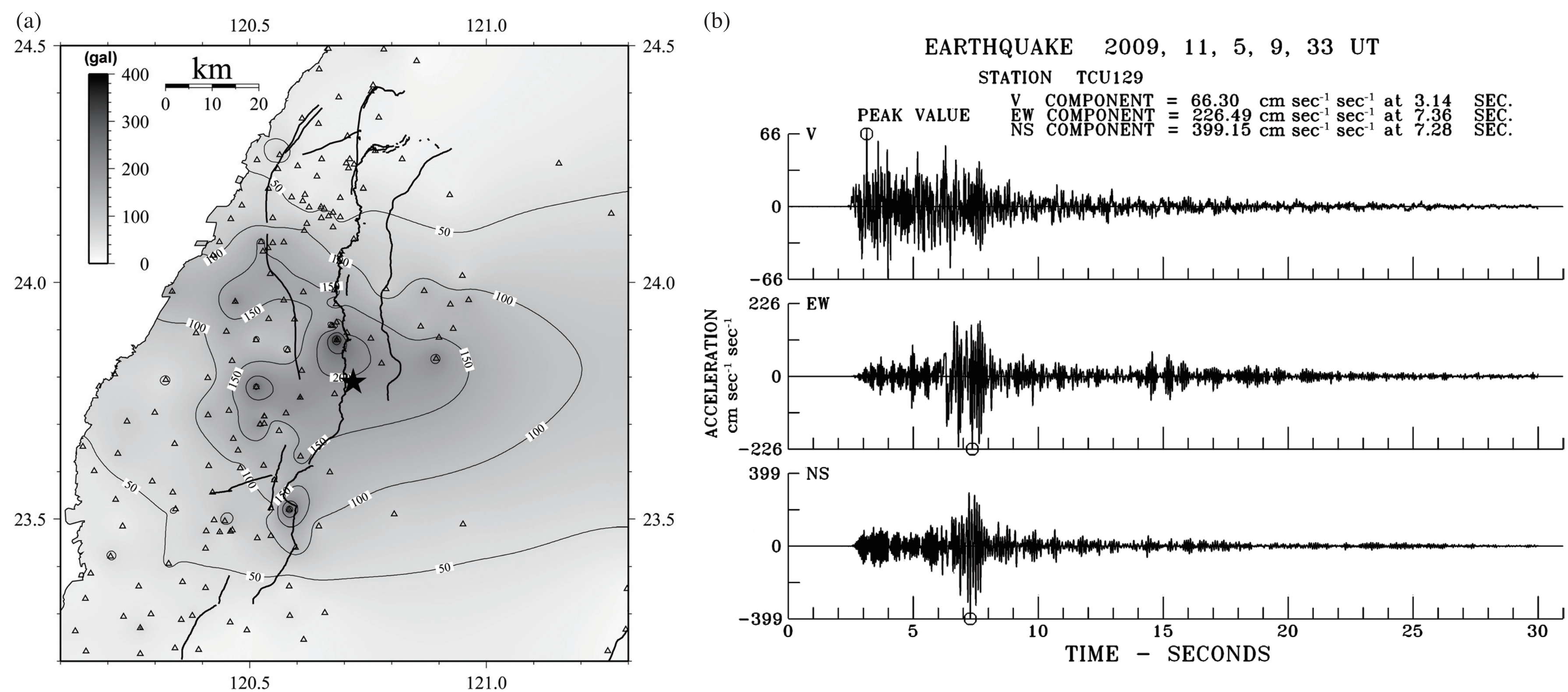

Fig. 4. (a) The PGA map of the Mingjian earthquake observed by the TSMIP network in central Taiwan, and (b) the three-component accelerograms recorded at TCU129.

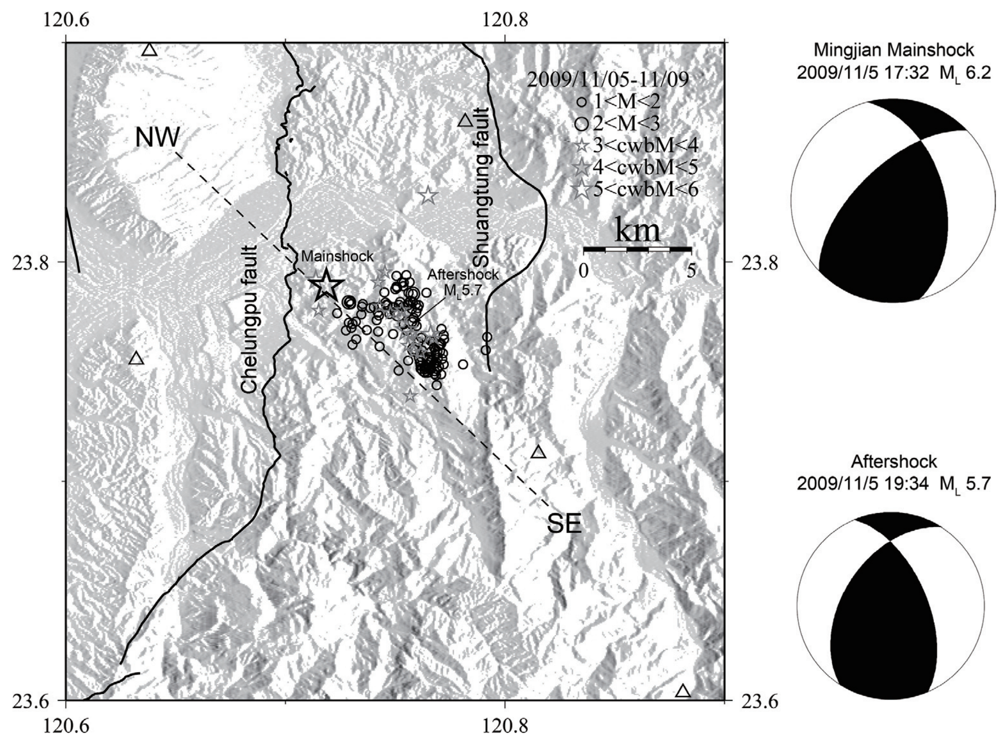

Fig. 5. The aftershocks located by the NCREE network (open circles) and by TSMIP of CWB (light stars) in the first five days after the mainshock (open star). The focal mechanisms of the mainshock and the largest aftershock (M_L 5.7) derived by CWB are shown on the right hand side.

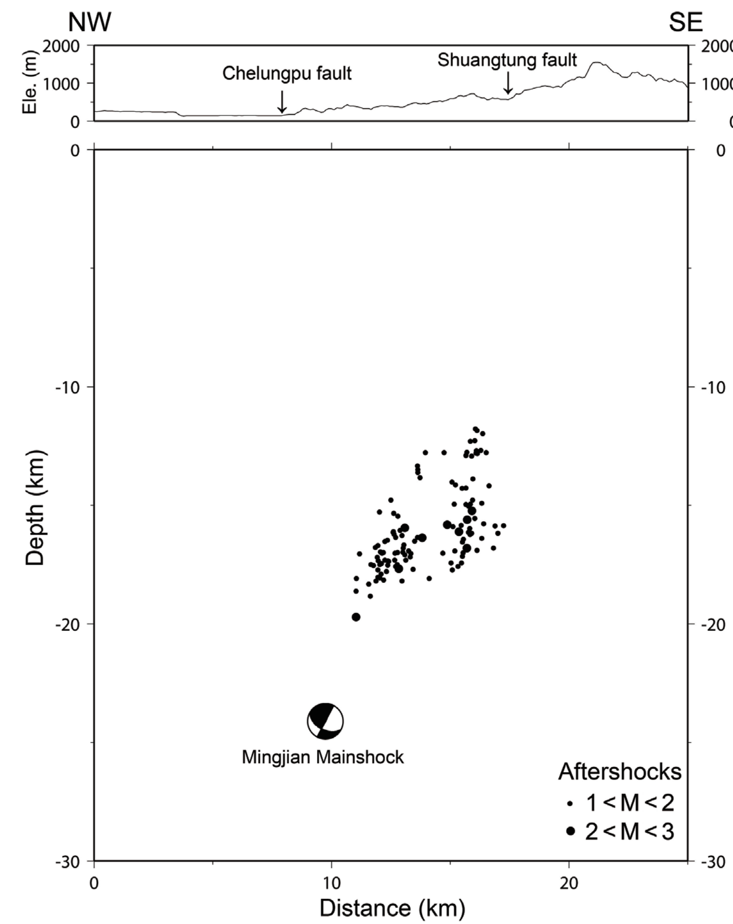

Fig. 6. NW-SE cross-section of the Mingjian aftershock relocated hypocenters. The beach ball denotes the hypocenter and focal mechanism of the mainshock.

4. SEISMOGENIC STRUCTURE

The major active faults in the Western Foothills are all N-S trending and east dipping thrust faults that are dominated by the direction of the plate collision based on the thin-skinned model. The northwest-dipping thrust fault plane of the Mingjian earthquake, which is deeper than 10 km, is beneath the décollement and exhibits entirely different features from the shallow structures (Fig. 7). This blind fault fractured within the ancient and stiff basement, which is regarded as an extension of the Eurasian plate. However, the thin-skinned model concentrated on explaining tectonic evolution only above a décollement; the model disregards all underlying structures. It is therefore important to seek a tectonic model that can provide a reasonable seismogenic structure for the Mingjian earthquake.

Wang et al. (2000) proposed a fold-and-thrust structure model (Fig. 7) responsible for the Chi-Chi earthquake, based on the thin-skinned thrust idea (Suppe 1980), seismic profiles and borehole data. In this model, the Chelungpu fault acted as a weak, lubricated double décollement plane to release the strain energy accumulated in the mountain-building process. The triggering fault ruptures caused huge volumes of material to slide on the décollement, the Chinshui Shale, from deep down where the detachment originated. The basal décollement is situated at the base of imbricated structures at depths from 10 to 20 km, with a gentle slope of 8 degrees. This model proposes that the detachment boundary should be a weak layer caused by strong lithologic contrast. When the deeper detachment was blocked by a steep ramp of basement, stresses accumulated locally and steered the thrusting movement along another shallow, weak boundary to extend to the surface. This shallow, weak layer, in the case of the Chi-Chi earthquake, is the Chinshui Shale that creates the Chelungpu fault along its bedding plane (Wang et al. 2000). The Mingjian earthquake sequence was projected onto the thin-skinned model as shown in Fig. 7. The Mingjian mainshock's NW dipping rupture controls the eastward trend of the aftershock thrusts, and stops at the depth of the basal décollement under the Chi-Chi earthquake. In this model, the terminal point is close to the junction point of the basal décollement where a branch develops upward to join the Chelungpu fault.

The major compressional tectonic stress from southeast to northwest is the foundation of the regional tectonic model in Taiwan. Although the thin-skinned model considers that most tectonic stress acts on the overlying accretionary wedge, causing it to slide on the décollement and form imbricated structures at the front, it is undeniable that compressional stress also acts on the underlying basement. Additionally, the maximum slippage of the rupture plane was 15 m during the Chi-Chi earthquake (Ma et al. 2001). The Chelungpu thrust has detached with an overall displacement of 14 km on the décollement (Yue et al. 2005). This large amount of sliding on the basal décollement would produce westward friction on the underlying basement. If the junction point

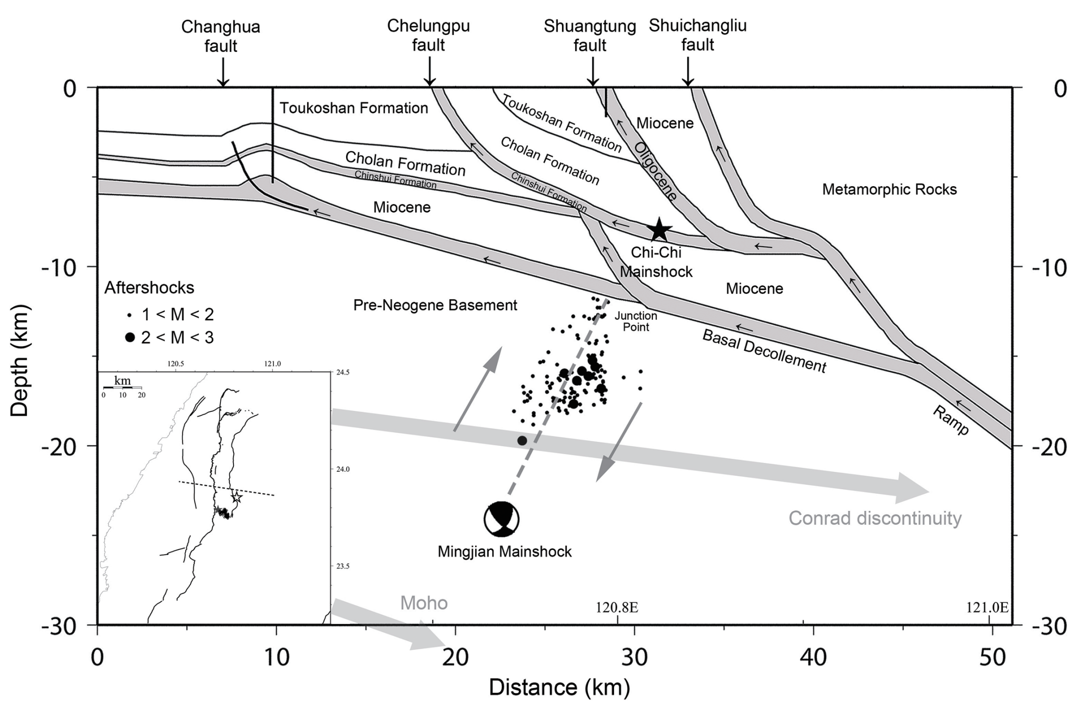

Fig. 7. The 1999 Chi-Chi earthquake can be explained by fold-and-thrust structures based on the thin-skinned thrust idea (Suppe 1980), seismic profiles and borehole data (Wang et al. 2000). The Mingjian mainshock's NW dipping rupture was upward thrusting that stopped at the depth of the basal décollement, and defines the aftershock locations (solid circles).

of the basal décollement in Fig. 7 actually exists, the enormous amount of material sliding along the basal décollement would turn upward and extend to outcrop on the Chelungpu fault. The massive sliding between the two sides of the junction point makes frictional strain energy accumulate at this point. Therefore, the horizontal principal stress acting on the basement of the Chelungpu fault is composed of mountain-building tectonic stress and décollement frictional stress. The resultant stress of the seismogenic region of the Mingjian earthquake also indicates a NW-SE compression. However, the thick, stiff massif to the west (Peikang Basement High) will prohibit the propagation of the compressional strain energy westward and confine it to the very eastern part just beneath the hypocenter of the Chi-Chi earthquake. When the overlying accretionary wedge kept uplifting as occurred during the Chi-Chi earthquake, it caused additional weight to exert a downward stress on the basement. After long-term accumulation of tectonic stress with the NW-SE and downward components, the basement beneath Chi-Chi earthquake ruptured to result in the high-angle NW dipping thrust fault of the Mingjian earthquake.

5. DISCUSSION

The NW dipping thrust fault plane of the Mingjian earthquake has been established based on the mainshock focal mechanism and the aftershock hypocenters. According to a hypothetical thin-skinned tectonic model, the seismogenic region of this earthquake is just beneath the 1999 Chi-Chi earthquake. The junction point of the basal décollement is believed to play an important role. The steep ramp at this junction point hinders deeper detachment on the décollement, and forces the hanging wall to turn upwards and to merge into the Chelungpu fault system in the overlying accretionary wedge. Similar tectonic influence also acted on the underlying basement. Furthermore, friction was generated on this junction point while large amounts of the hanging wall were sliding westward over it. Then long-term friction generates deformations and this accumulated strain energy is stored inside the basement. When the 1999 Chi-Chi earthquake occurred, the basement beneath the basal décollement sank downward, causing the Mingjian earthquake a decade later. Because this junction point of basal décollement dominated the seismogenic process, the Mingjian earthquake fault plane is vertically symmetric with the Chelungpu fault by the basal décollement.

Chen et al. (2002) attributed a group of deeper aftershocks, including two moderate events (M_L = 6.3 and 6.0) located southeast of the 1999 Chi-Chi mainshock, to a steep west-dipping fault system which is seen as a conjugate fault of the Chelungpu fault. The west-dipping fault extending from 10 to 30 km (Fig. 8) can be explained reasonably by the regional stress field around the near-surface east-dipping Chelungpu fault. Although there are obvious dissimilarities between the models of Wang et al. (2000) and Chen et al. (2002), their tectonic models were both based on the thin-skinned model. The Mingjian earthquake fault plane is similar to the west-dipping Chi-Chi aftershock fault plane proposed by Chen et al. (2002). They are both steep west-dipping thrusts beneath the basal décollement of imbricated

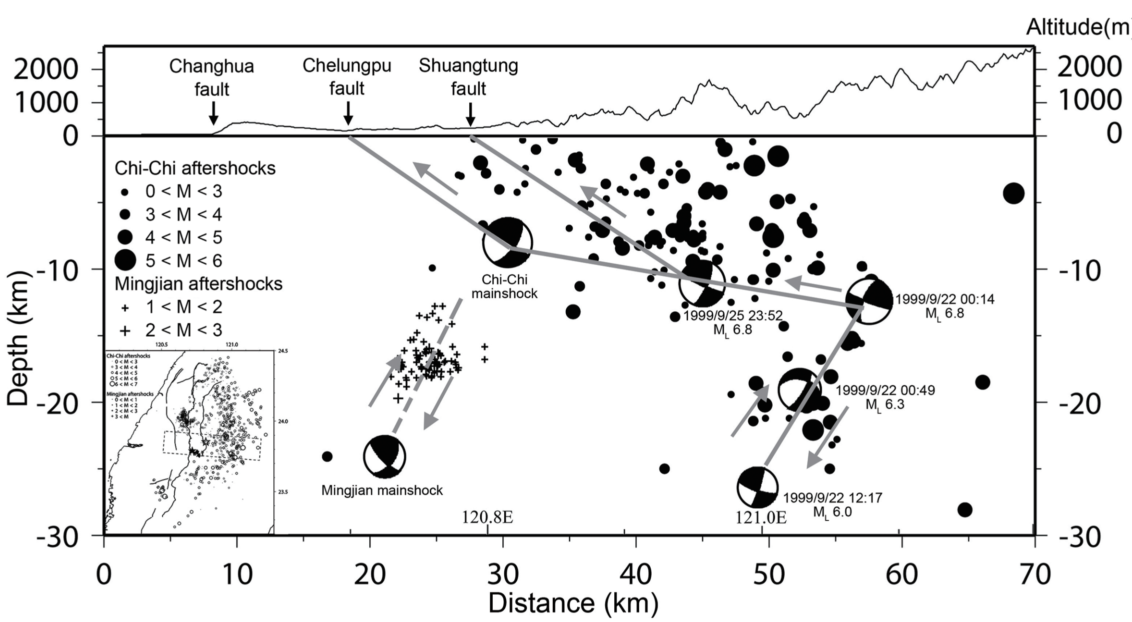

Fig. 8. A cross-section of the 1999 Chi-Chi (solid circles) and 2009 Mingjian (crosses) earthquake sequences with the focal mechanisms of the Chi-Chi and Mingjian mainshocks, and four big Chi-Chi aftershocks. The gray lines display the fault geometry inferred by Chen et al. (2002) for the Chi-Chi sequence. A steep west-dipping fault system extending from 10 to 30 km was located to the southeast of Chi-Chi mainshock. The fault plane of the Mingjian earthquake (dashed gray line) shows a similar west-dipping thrust just beneath the Chi-Chi mainshock.

structures in central Taiwan, growing inside the ancient basement, which is regarded as an extension of the Eurasian plate. If the top of these two deep fault planes reaches the décollement of the thin-skinned model under the Chelungpu fault, the décollement is almost flat at 10 km depth. It is different from the dip angle of the décollement in both models (Figs. 7 and 8). However, the top of the Mingjian fault plane just reaches the basal décollement in the model of Wang et al. (2000) (Fig. 7). The basal décollement and its junction point in this model explain well the seismogenic structure of the Mingjian fault and why it stops at the décollement depth.

Nevertheless, these two deeper earthquake sequences shown in Fig. 8 similarly reflect westward tectonic movements in front of the Eurasian plate, and match the SE-NW direction of plate-collision stress. The colliding stress not only acts on the overlying fold-and-thrust structure, seen as a major deformation zone in the thin-skinned model, but also partially on the underlying basement. The stronger material and the higher lithostatic pressure make it less likely to produce small earthquakes in this zone. However, long-term accumulated stress inside the basement will eventually cause rupture and produce a moderate earthquake like the 2009 Mingjian earthquake. The tectonic background results in sparse seismicity inside the basement beneath the basal décollement compared with seismicity within the overlying, easily-sliding imbricated structures (Fig. 9). The seismicity inside the basement is mostly composed of moderate earthquakes and their aftershocks, except the Sanyi-Puli double seismic zone observed after the 1999 Chi-Chi earthquake (Fig. 9b).

In the Western Foothills and Coastal Plain, the Moho depth is about 28 - 35 km and deepens eastward (Fig. 7), reaching a maximum depth of about 55 km beneath the eastern Central Range (Kim et al. 2004, 2005). The Conrad discontinuity averages 18 km in depth beneath the Western Foothills and also deepens eastward (Chen and Chen 2000). The distribution of Mingjian aftershocks and the mainshock focal mechanism support a rupture plane extending from 24.1 km, the mainshock hypocenter, to 10 km in depth. This fault plane inside the front of the Eurasian plate ruptured from the lower to middle crust. So far there is no observational evidence to indicate that the fault penetrated downward through the Moho, since no deeper aftershocks were observed.

The dimensions of the fault zone of the 2009 Mingjian earthquake are about 15 × 7 × 5 km, which is significantly smaller than the Chelungpu fault, and its magnitude (M_L 6.2) is predictably lower than that of the 1999 Chi-Chi earthquake. There are no earthquakes under any part of the Chelungpu fault with seismogenic mechanisms similar to the Mingjian earthquake. The area affected by the Mingjian earthquake is small compared to the length (over 90 km) of the Chelungpu fault. This kind of structure may contribute to local tectonic characteristics, e.g., fragile zones, existing faults in the basement, and the appearance of décollement. The magnitude of the earthquake is limited by these local tectonic characteristics. However, as the Philippine Sea plate keeps moving north-westward, thereby thickening the accretionary wedges, other inside-basement thrusts

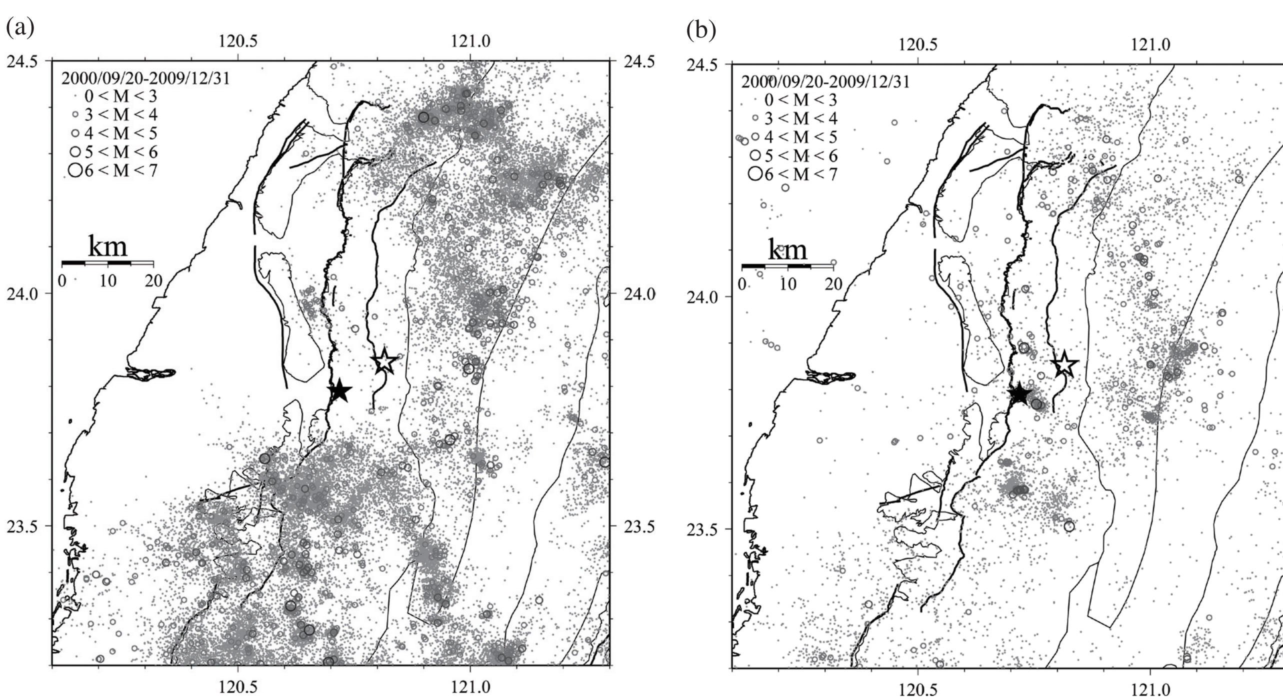

Fig. 9. Seismicity (a) above and (b) below 15 km depth one year after the 1999 Chi-Chi earthquake (open star). The solid star denotes the 2009 Mingjian earthquake. Thin lines indicate the geological boundaries, and bold lines are active faults.

may rupture with similar mechanisms to the Mingjian earthquake sequence.

6. CONCLUSIONS

A NW, 60°-dipping thrust fault plane of the 2009 Mingjian earthquake was established, based on aftershock locations from the NCREE micro-earthquake monitoring network in western Taiwan, and on the mainshock focal mechanism. The fault plane extended from 24.1 km, the hypocenter of the mainshock, to 10 km in depth. This blind fault ruptured in the ancient and stiff basement, and exhibited different features compared with the shallow east-dipping faults in this region. The top end of the fault plane stops beneath the basal décollement for existing tectonic models (Wang et al. 2000; Chen et al. 2002).

The thin-skinned model for the orogenic structure of Taiwan considers that most north-westward tectonic stress of the plate collision acts on the overlying accretionary wedges to cause slip along the décollement and form imbricated structures at the front, but the possible driving forces for the Mingjian earthquake also included a component of deeper tectonic stress. Because of the large amounts of upper sliding, the friction generated on the décollement also acts on the underlying stiff basement. Furthermore, the overlying accretionary wedge imposed additional downward stresses causing thrusting within the basement. After long-term tectonic stress with both NW-SE and downward components, the ancient basement ruptured and was locally depressed at a high angle toward the northwest; this caused the northwest dipping thrust fault of the M_L 6.2 Mingjian earthquake just beneath the Chelungpu fault ten years after 1999 Chi-Chi earthquake.

Acknowledgements The authors are grateful to the Central Weather Bureau for providing the high quality earthquake data we used in this paper. We also sincerely thank the Institute of Earth Sciences, Academia Sinica, Taiwan, for the catalogue of 1999 Chi-Chi aftershocks located by a temporary network.

REFERENCES

Barrier, E. and J. Angelier, 1986: Active collision in eastern Taiwan: The Coastal Range. *Tectonophysics*, **125**, 39-72, doi: 10.1016/0040-1951(86)90006-5. [Link]

Chang, S. L., 1971: Subsurface geologic study of the Taichung Basin, Taiwan. *Petrol. Geol. Taiwan*, **8**, 21-45.

Chen, C. C. and C. S. Chen, 2000: Preliminary report on the Sanyi-Puli seismic zone conductivity anomaly and its correlation with velocity structure and seismicity in the Northwestern Taiwan. *Earth Planets Space*, **52**, 377-381, doi: 10.5636/eps.52.377. [Link]

Chen, C. C. and C. S. Chen, 2002: Sanyi-Puli conductivity anomaly in NW Taiwan and its implication for the tectonics of the 1999 Chi-Chi earthquake. *Geophys. Res. Lett.*, **29**, 7-1-7-3, doi: 10.1029/2001GL013890. [Link]

Chen, K. C., B. S. Huang, J. H. Wang, and H. Y. Yen, 2002: Conjugate thrust faulting associated with the 1999 Chi-Chi, Taiwan, earthquake sequence. *Geophys. Res. Lett.*, **29**, 118-1-118-4, doi: 10.1029/2001GL014250. [Link]

Chen, W. S., K. J. Lee, L. S. Lee, D. J. Ponti, C. Prentice, Y. G. Chen, H. C. Chang, and Y. H. Lee, 2004: Paleoseismology of the Chelungpu Fault during the past 1900 years. *Quat. Int.*, **115-116**, 167-176, doi: 10.1016/S1040-6182(03)00105-8. [Link]

Chou, J. T., 1971: A sedimentologic and paleogeographic study of the Neogene formations in the Taichung region, Western Taiwan. *Petrol. Geol. Taiwan*, **9**, 43-66.

Chung, J. K. and T. C. Shin, 1999: Implications of the rupture process from the displacement distribution of strong ground motions recorded during the 21 September 1999 Chi-Chi, Taiwan earthquake. *Terr. Atmos. Ocean. Sci.*, **10**, 777-786.

Hung, J. H., K. F. Ma, C. Y. Wang, H. Ito, W. Lin, and E. C. Yeh, 2009: Subsurface structure, physical properties, fault-zone characteristics and stress state in scientific drill holes of Taiwan Chelungpu Fault Drilling Project. *Tectonophysics*, **466**, 307-321, doi: 10.1016/j.tecto.2007.11.014. [Link]

Kim, K. H., J. M. Chiu, H. Kao, Q. Liu, and Y. H. Yeh, 2004: A preliminary study of crustal structure in Taiwan region using receiver function analysis. *Geophys. J. Int.*, **159**, 146-164, doi: 10.1111/j.1365-246X.2004.02344.x. [Link]

Kim, K. H., J. M. Chiu, J. Pujol, K. C. Chen, B. S. Huang, Y. H. Yeh, and P. Shen, 2005: Three-dimensional V_P and V_S structural models associated with the active subduction and collision tectonics in the Taiwan region. *Geophys. J. Int.*, **162**, 204-220, doi: 10.1111/j.1365-246X.2005.02657.x. [Link]

Kuo, C. H., K. L. Wen, H. H. Hsieh, C. M. Lin, T. M. Chang, and K. W. Kuo, 2012: Site classification and Vs30 estimation of free-field TSMIP stations using the logging data of EGDT. *Eng. Geol.*, **129-130**, 68-75, doi: 10.1016/j.enggeo.2012.01.013. [Link]

Lee, J. C., H. T. Chu, J. Angelier, Y. C. Chan, J. C. Hu, C. Y. Lu, and R. J. Rau, 2002: Geometry and structure of northern surface ruptures of the 1999 Mw = 7.6 Chi-Chi Taiwan earthquake: Influence from inherited fold belt structures. *J. Struct. Geol.*, **24**, 173-192, doi: 10.1016/S0191-8141(01)00056-6. [Link]

Lin, C. M., T. M. Chang, Y. C. Huang, H. J. Chiang, C. H. Kuo, and K. L. Wen, 2009: Shallow S-wave velocity structures in the western coastal plain of Taiwan. *Terr. Atmos. Ocean. Sci.*, **20**, 299-308, doi: 10.3319/TAO.2007.12.10.01(T). [Link]

Liu, K. S., T. C. Shin, and Y. B. Tsai, 1999: A free-field strong motion network in Taiwan: TSMIP. *Terr. Atmos. Ocean. Sci.*, **10**, 377-396.

Ma, K. F., T. R. A. Song, S. J. Lee, and H. I. Wu, 2000: Spatial slip distribution of the September 20, 1999, Chi-Chi, Taiwan, earthquake (M_w7.6) -inverted from teleseismic data. *Geophys. Res, Lett.*, **27**, 3417- 3420, doi: 10.1029/2000GL011393. [Link]

Ma, K. F., J. Mori, S. J. Lee, and S. B. Yu, 2001: Spatial and temporal distribution of slip for the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seismol. Soc. Am.*, **91**, 1069-1087, doi: 10.1785/0120000728. [Link]

Meng, C. Y., 1968: Geologic concepts relating to the petroleum prospects of Taiwan Strait. *Petrol. Geol. Taiwan*, **6**, 11-13.

Meng, C. Y., 1971: A conception of the evolution of the island of Taiwan and its bearing on the development of the western Neogene sedimentary basins. *Petrol. Geol. Taiwan*, **9**, 241-258.

Pan, Y. S., 1967: Interpretation and seismic coordination of the Bouguer gravity anomalies over west-central Taiwan. *Petrol. Geol. Taiwan*, **5**, 99-115.

Seno, T., 1977: The instantaneous rotation vector of the Philippine Sea plate relative to the Eurasian plate. *Tectonophysics*, **42**, 209-226, doi: 10.1016/0040-1951(77)90168-8. [Link]

Shaw, C. L., 1996: Stratigraphic correlation and isopach maps of the western Taiwan basin. *Terr. Atmos. Ocean. Sci.*, **7**, 333-360.

Shin, T. C., C. H. Chang, H. C. Pu, H. W. Lin, and P. L. Leu, 2013: The Geophysical Database Management System in Taiwan. *Terr. Atmos. Ocean. Sci.*, **24**, 11-18, doi: 10.3319/TAO.2012.09.20.01(T). [Link]

Sun, S. C., 1982: The Tertiary basins of offshore Taiwan. Proceedings 2nd ASCOPE Conference and Exhibition, Manila, Philippines, 126-135.

Suppe, J., 1980: Imbricated structure of western Foothills belt, southcentral Taiwan. *Petrol. Geol. Taiwan*, **17**, 1-16.

Suppe, J., 1981: Mechanics of mountain building and metamorphism in Taiwan. *Mem. Geol. Soc. China*, **4**, 67-89.

Suppe, J., 1984: Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan. *Mem. Geol. Soc. China*, **6**, 21-33.

Suppe, J. and J. H. Wittke, 1977: Abnormal pore-fluid pressures in relation to stratigraphy and structure in the active fold-and-thrust belt of northwestern Taiwan. *Petrol. Geol. Taiwan*, **14**, 11-24.

Teng, L. S., 1990: Geotectonic evolution of late Cenozoic arc-continent collision in Taiwan. *Tectonophysics*, **183**, 57-76, doi: 10.1016/0040-1951(90)90188-E. [Link]

Tsai, Y. B., 1986: Seismotectonics of Taiwan. *Tectonophysics*, **125**, 17-37, doi: 10.1016/0040-1951(86)90005-3. [Link]

Waldhauser, F. and W. L. Ellsworth, 2000: A double-difference earthquake location Algorithm: Method and application to the northern Hayward fault, California. *Bull. Seismol. Soc. Am.*, **90**, 1353-1368, doi: 10.1785/0120000006. [Link]

Wang, C. Y., C. H. Chang, and H. Y. Yen, 2000: An interpretation of the 1999 Chi-Chi earthquake in Taiwan based on the thin-skinned thrust model. *Terr. Atmos. Ocean. Sci.*, **11**, 609-630.

Wang, C. Y., C. L. Li, and H. Y. Yen, 2002: Mapping the northern portion of the Chelungpu fault, Taiwan by shallow reflection seismics. *Geophys. Res. Lett.*, **29**, 37-1-37-3, doi: 10.1029/2001GL014496. [Link]

Wang, C. Y., C. L. Li, and H. C. Lee, 2004: Constructing subsurface structures of the Chelungpu fault to investigate mechanisms leading to abnormally large ruptures during the 1999 Chi-Chi earthquake, Taiwan. *Geophys. Res. Lett.*, **31**, L02608, doi: 10.1029/2003GL018323. [Link]

Wen, K. L., H. Y. Peng, Y. B. Tsai, and K. C. Chen, 2001: Why 1G was recorded at TCU129 site during the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seismol. Soc. Am.*, **91**, 1255-1266, doi: 10.1785/0120000707. [Link]

Wu, F. T. and R. J. Rau, 1998: Seismotectonics and identification of potential seismic source zones in Taiwan. *Terr. Atmos. Ocean. Sci.*, **9**, 739-754.

Wu, F. T., R. J. Rau, and D. Salzberg, 1997: Taiwan orogeny: Thin-skinned or lithospheric collision? *Tectonophysics*, **274**, 191-220, doi: 10.1016/S0040-1951(96)00304-6. [Link]

Yu, S. B., H. Y. Chen, and L. C. Kuo, 1997: Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, **274**, 41-59, doi: 10.1016/S0040-1951(96)00297-1. [Link]

Yue, L. F., J. Suppe, and J. H. Hung, 2005: Structural geology of a classic thrust belt earthquake: The 1999 Chi-Chi earthquake Taiwan (M_w=7.6). *J. Struct. Geol.*, **27**, 2058-2083, doi: 10.1016/j.jsg.2005.05.020. [Link]