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3D Geometry of the Chelungpu Thrust System in Central Taiwan: Its Implications for Active Tectonics

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ABSTRACT

This study is aimed at constructing a 3D subsurface geometry of the Chelungpu thrust and its associated structures, as well as examining the implications of the studies results for active tectonics in the area. Nine balanced cross-sections were constructed across the foothills belt in the study area to delineate the subsurface geometry of the major thrusts in the foreland of the fold-and-thrust belt.

The Chelungpu thrust cuts down to the subsurface invariably along the base of the Chinshui Shale and is merged with the Changhua thrust into a common décollement at a depth of 5 to 7 kilometers below the sea level. There is a pre-existing normal fault underneath the common décollement of the Changhua and Chelungpu thrusts which accommodates the thickened strata in the hanging wall of the Chelungpu thrust.

The restored cross-sections indicate that during its propagation toward the foreland the Chelungpu thrust originally was a low-angle thrust before it met a pre-existing high-angle normal fault, which was then reactivated and became the frontal ramp of the thrust. In the latest stage, displacement along the Changhua thrust left the normal fault behind and kept it underneath the common décollement.

The subsurface geometry of the Chelungpu thrust is a uniform curved plane striking N-S, with some local wavy features and a ramp striking E-W

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in the northern part of the thrust. To the north of the ramp, the fault plane transforms into a spoon-shaped geometry. In the southern part of the study area, the southern end of the Chelungpu thrust is cut off, and its displacement is transferred into a splay thrust that strikes NE-SW and connects the Chelungpu and Shuangtung-Hsiaomao thrusts.

At the hypocenter of the Chi-Chi earthquake, not only is the dip angle of the décollement of the Chelungpu thrust gentler, but the depth much shallower than that of the mainshock. As the hypocenter of the mainshock is very close to the pre-existing normal fault underneath the décollement, a connection between them is highly implied. We also suggest that the ramp in the northern part of the Chelungpu thrust provides a stronger strain guide during the subsurface rupture propagation thereby creating the bended surface rupture.

(Key words: Structural geology, Chelungpu thrust, 3D geometry)

1. INTRODUCTION

The active Chelungpu thrust is regarded as a typical earthquake fault in terms of thrust tectonics in a mountain-building belt. Many studies have provided some detailed geological and geophysical descriptions of the surface and subsurface characteristics of the active thrust fault (Lee et al. 2000, 2003; Lee and Ma 2000; Lin et al. 2000; Ma et al. 2001; Wang et al. 2000, 2002a, b; Yu et al. 2001). Huang et al. (2002) and Tanaka et al. (2002) analyzed cores from shallow drilled wells at the northern and southern ends of the thrust fault. They provided some clues as to the characteristics of the slip surface penetrated by the drilled wells. Nonetheless, the relationships between the active thrust fault and its extended parts to the north and south still needs clarification. Several seismotectonic models have been proposed to interpret the characteristics of the surface ruptures of the Chi-Chi earthquake (Chen et al. 2001a; Chen et al. 2001b; Lee et al. 2002). The proposed models are based on the speculated and simplified subsurface geometry of the thrust and its associated structures. Results of various models of slip distribution and the history of subsurface rupture (Lee and Ma 2000; Chi et al. 2001; Ma et al. 2001; Wang et al. 2001; Wu et al. 2001; Yoshida 2001; Zeng and Chen 2001), rupture processes (Ji and Helmberger 2003; Lee and Ma 2000; Ma et al. 2001; Wu et al. 2001; Zeng and Chen 2001) and static stress transfer (Wang 2000; Wang and Chen 2001) are highly related to the oversimplified 3D geometry of the active Chelungpu thrust presumed in the models. The importance of a detailed 3D geometry of the thrust for future research has been noted (Ma et al. 2001). On the other hand, a finer 3D subsurface shape for the Chelungpu thrust has been inferred based on best-fit between the measured and modeled coseismic surface slip distribution (Johnson and Segall 2004). Or, as in one case, it was independently reconstructed in order to compare the characters of measured surface and modeled subsurface slip distributions (Yue et al. 2005). Still, there are some discrepancies between the inferred and constructed subsurface shape of the thrust.

This study is aimed at constructing the 3D subsurface geometry of the Chelungpu thrust and its associated structures. Chang (1971) first proposed, based on seismic results from conventional shooting (Huang 1969), a subsurface structural map of top of the Chinshui Shale. He did not recognize the structural form as the subsurface geometry of the Chelungpu thrust. After the Chi-Chi earthquake in 1999, a similar subsurface structural map of the Chinshui Shale was built by Lee et al. (2000), without any explanation of the method for mimicking the subsurface geometry of the Chelungpu thrust. Recently, Yue et al. (2005) constructed 47 lines of balanced cross-sections to build a finer 3D subsurface geometry of the Chelungpu thrust. Except for several long lines, most of their lines only cover the frontal part of the subsurface of the Chelungpu thrust. Their study area extends from the Ta-An River in the north to the Choshui River in the south. We constructed balanced cross sections in this study to build the 3D subsurface geometry of the Chelungpu thrust exclusively based on surface geology, well bore and seismic data, without reference to any measurements or models of coseismic slip distribution; this means that the balanced cross-sections illustrate long-term deformation as a result of the most recent orogeny. Yet our study area extends from the San-I in the north to the Chia-I in the south (Fig. 1) and covers the segment of the fold-and-thrust belt where the Chelungpu thrust system laterally transforms into adjacent belts to the north and south. In this study, transitional characteristics at the ends of the adjacent belts are investigated.

Below, Section 2 introduces regional geology and previous studies; Section 3 gives a detailed account of our constructed balanced cross-sections; Section 4 discusses and comments on previous interpretations of the geological sections, making comparisons between these sections. Some characteristics of the Chelungpu thrust system, such as evolutionary kinematics and along-strike variation, and the 3D geometry of the Chelungpu thrust itself are then described and analyzed. Finally, the implications of the constructed 3D subsurface geometry of the Chelungpu thrust for the active tectonics are discussed.

2. REGIONAL GEOLOGY AND PREVIOUS STUDIES

The foothills belt of central Taiwan is characterized by a typical imbricate thrust system associated with nonmetamorphic deformation of open folding. The fold-and-thrust belt strikes mainly NNE-SSW and appears as an S-shaped orocline; this appears to be the result of structural feature of the pre-orogenic basement (Chiu 1971; Biq 1992; Lacombe and Mouthereau 2002; Mouthereau et al. 2002; Lacombe et al. 2003). The salient aspect of the northern part of the fold-and-thrust belt faces the Taihsi Basin, while the recess of its central part is buttressed by the Peikang Basement High. Multiple sets of thrusts and associated folds in northwestern Taiwan (Meng 1965; Chiu 1971; Namson 1981, 1983, 1984; Lee et al. 1993; Chinese Petroleum Corporation (CPC) 1994; Yang et al. 1994, 1996a, 1997) transform into the typical imbricate thrust belt of central Taiwan and the transitional zone is in the San-I area. To the south, the San-I thrust is apparently connected with the Chelungpu thrust at the surface (CPC 1994). However, slip surfaces indicated by the exposed hanging wall (HW) of the thrusts are in different formations; the former is along the base of the Tungkeng Formation of the Upper Miocene whereas the latter, appearing during the Chi-Chi earthquake, is in the base of the Chinshui Shale of the Pliocene.

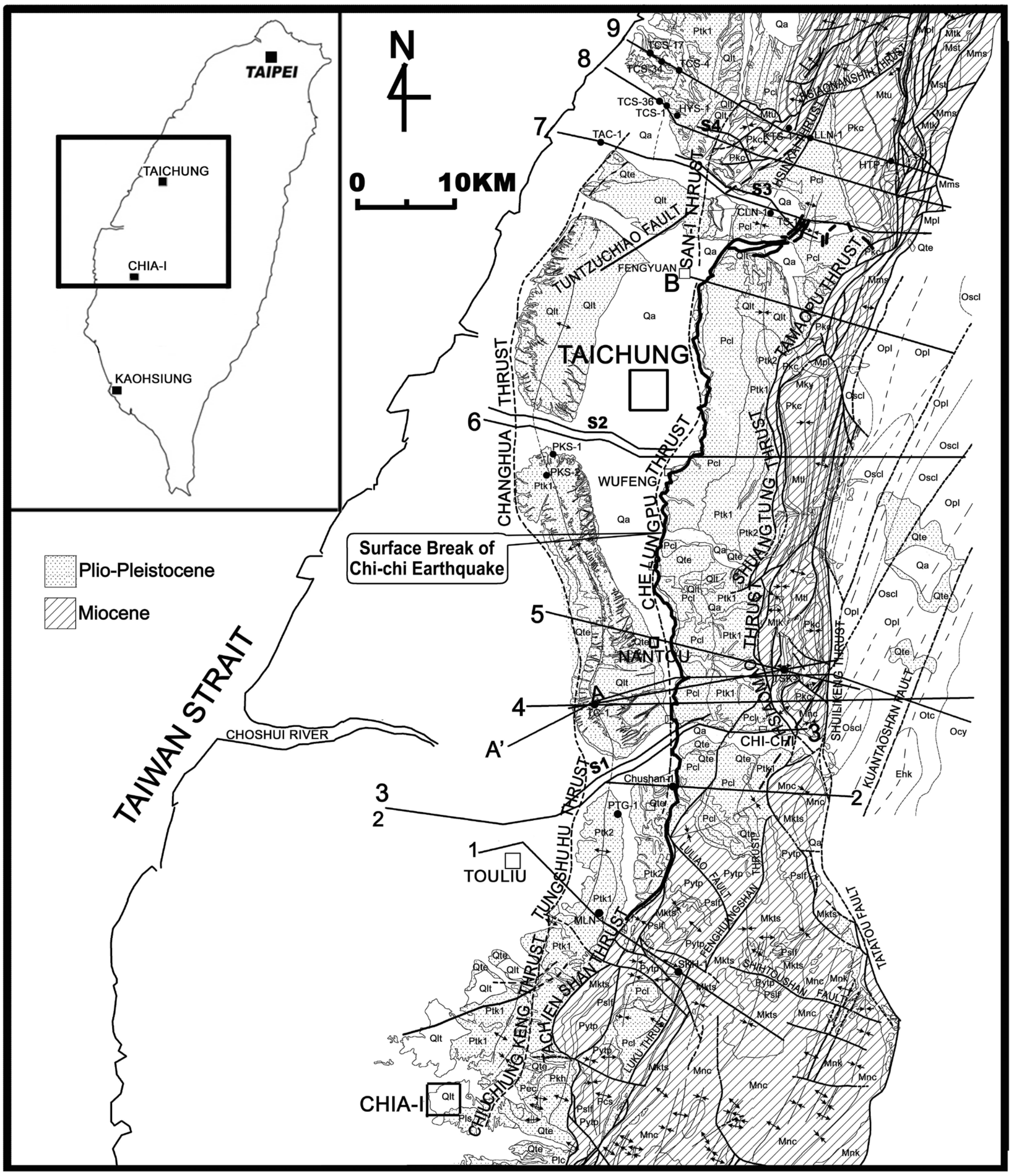

Fig. 1. Regional geological map of central Taiwan, showing major structural settings (compiled from Chinese Petroleum Corporation, 1982, 1986, 1994, Central Geological Survey, 1999) and locations of balanced cross-sections shown in this study. Formations indicated by abbreviations are shown in Fig. 5.

In general, along the surface of the Chelungpu thrust, both sides feature piggy-back type monoclines, which to the west of the thrust result from westward slip along the Changhua thrust in the frontal part of the foothills belt and form the present configuration of Taichung-Nantou Basin. The other side developed as a result of slip along the thrust in itself. Farther east, tighter synclines are formed by slip along a couple of narrowly spaced thrusts. Tectonically, from west to east four major thrusts including the Changhua, Chelungpu, Tamaopu-Shuangtung-Hsiaomao and Shuichangliu thrusts exist in the foothills belt of central Taiwan. The second one is regarded as an active fault of the first category as they cut upsection through the Quaternary strata (Chang et al. 1998; Lin et al. 2000a). On the other hand, the Changhua thrust remains to be identified as a suspicious active fault due to its poor outcrop. The Changhua-2 well of the CGS (Central Geological Survey) penetrated the thrust at a depth of 370 m below sea level and showed a fault plane with a dip angle of 13°. Finally, the Chelungpu thrust which is a coseismic fault of the 1999 Chi-Chi earthquake ($M_w = 7.6$) with its consequent surface ruptures and deformations stretches for 80km from its northern end at Cholan to southern end at Tungtou (CGS 1999).

In the southern part of the study area, the Chelungpu thrust merges with a splay fault extending from the Shuangtung-Hsiaomao thrust, steps across a tear fault, the Luliao fault, and turns into the Tachienshan-Chukou thrust to the south (Fig. 1). This zone can be viewed as the transitional zone between the imbricate thrust system comprised of the Changhua, Chelungpu and Tamaopu-Shuangtung-Hsiaomao thrusts to the north and that comprised of Tungshuhu-Chiuchiungkeng, Tachienshan-Chukou and Luku-Fenghuangshan thrusts to the south. The differences between the imbricate thrust systems are: 1) an open fold of the gentle Pakuashan anticline in the HW of the Changhua thrust, changes into a tight fold of the Neilin anticline in the HW of the Tungshuhu thrust; and 2) the slip surface of the Chelungpu thrust along the base of the Chinshui Shale transforms into that of the Tachienshan thrust along the base of the Kuechulin Formation to the Nanchuan Formation, and such a change seems related to the splay fault that connects the Shuangtung-Hsiaomao thrust to the Tachienshan thrust and cuts downsection from the Cholan Formation down to the Kuechulin Formation on the surface (Fig. 1). In addition, lateral change in the structural style of the HWs along the Hsiaomao-Luku thrust can be observed.

Suppe (1985) interpreted that, in the central part of the study area, the Chelungpu thrust develops along the base of the Chinshui Shale as its slip surface and runs all the way down to the subsurface to a depth of 5.5 km below sea level, where the thrust turns into a décollement and is merged with the décollement of the Changhua thrust (Fig. 2a). Recently, Yue et al. (2005) proposed a new interpretation for the thrust system (Figs. 2b, c). The balanced cross-sections of Yue et al. (2005) and Suppe (1985) are similar in the subsurface structure of the Changhua and Chelungpu thrusts. The major difference is the interpretation of the Shuangtung-Hsiaomao thrust; the former shows that the thrust cuts down at a high angle to merge with the décollement of the Chelungpu thrust, while in the latter it is a shallow low-angle thrust and parallel with the Chelungpu thrust in the subsurface (Figs. 2a, b). In order to accommodate the discrepancy between the depth of décollement and the mainshock, Yue et al. (2005) proposed an alternative interpretation and depicted a high angle thrust underneath the décollement to connect with the hypocenter (Fig. 2c).

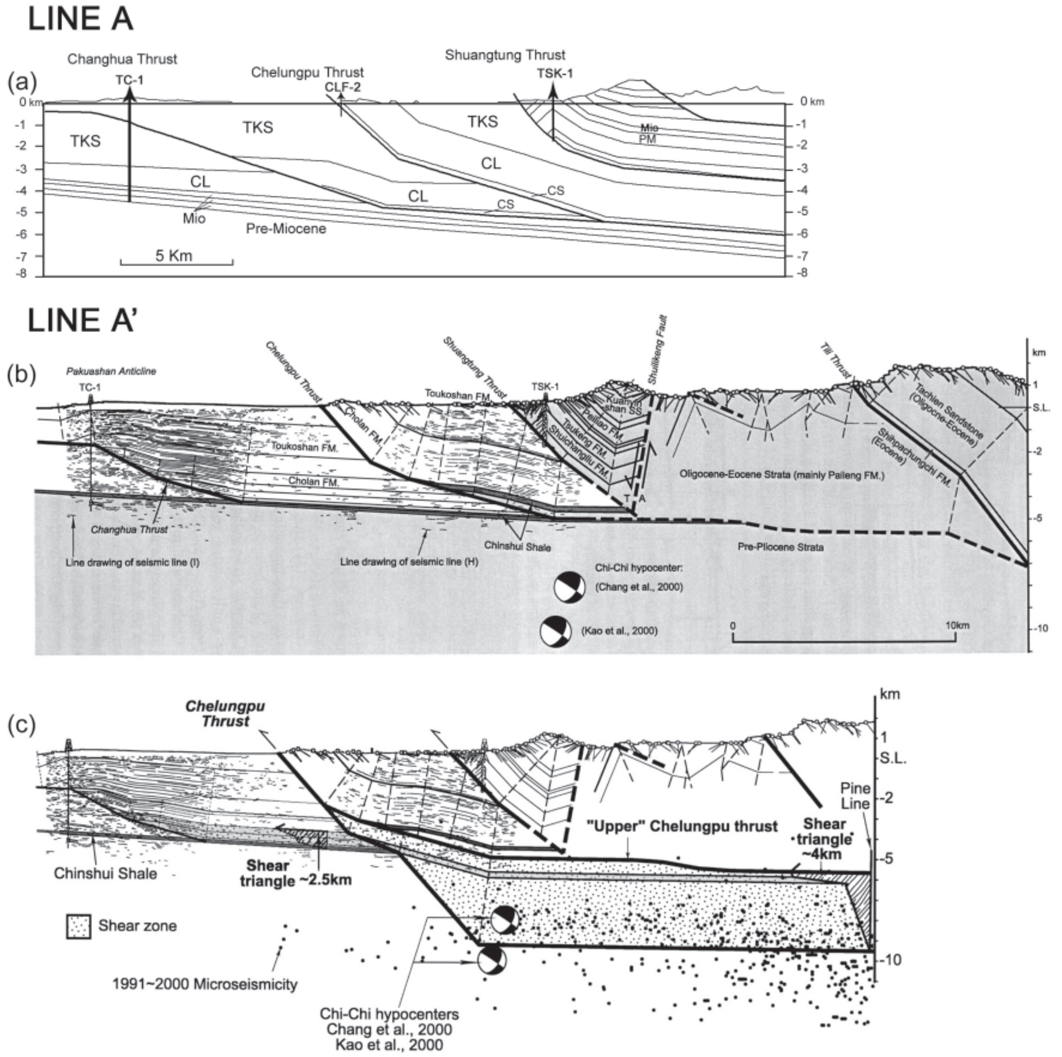

Fig. 2. (a) Suppe's (1985) balanced cross-section across the foothills belt, showing the subsurface geometry of the imbricate thrust system in central Taiwan. On the cross-section, the Changhua thrust turns into the décollement along the base of the Chinshui Shale and the Cholan Formation uniformly thickens across the Chelungpu thrust. (b) and (c) Balanced cross-sections of Yue et al. (2005), showing similar subsurface structure of the Changhua and Chelungpu thrusts with that of Suppe's (1985). The major difference between theirs and Suppe's (1985) is the interpretation of the Shuantung thrust. (c)Yue et al. (2005) proposed an alternative interpretation and depicted a high angle thrust underneath the décollement to connect with the hypocenter.

Mouthereau et al. (2001) proposed a different interpretation, in which the Chelungpu thrust bifurcates into two décollements, the shallower one merging with the Changhua thrust and the other deeper one having stair-shaped trajectory (Fig. 3a). Interpretation of the dual-décollement feature was also proposed by Wang et al. (2000, 2002b), but with the difference that the deeper décollement extends directly from the Changhua thrust (Fig. 3b). In addition, the high-angle Shuangtung-Hsiaomao and Shuichangliu thrusts that are merged with the Chelungpu thrust at the décollement in the hinterland are also interpreted in these structural cross-sections (Figs. 3a, b).

As for the Changhua thrust, some speculations gave rise to ambiguous interpretations about the structural characteristics of the surface frontal fault in the fold-and-thrust belt. Both field geology and gravity surveys indicate, in accordance with the general structural features in the foothills belt, that the fault is a thrust (Chuang et al. 1969; Hu and Chen 1969; Hu 1985), although previous seismic interpretations viewed the frontal fault as a normal fault (Hsiao 1968; Chang 1971; Wang 1974). Interpretation based on seismic data suggests that a high-angle normal fault exists underneath the low-angle Changhua thrust (Chen 1978). The magnitude of displacement along the Changhua-Tungshuhu-Chiuchiungkeng thrust, i.e., the frontal thrust, is less than that along the Chelungpu-Tachienshan-Chukou thrust.

Based on surface deformation features resulting from the Chi-Chi earthquake in 1999, several studies were carried out to examine the relationship between the Chelungpu and the Tachienshan thrusts. Lin et al. (2000b) proposed an evolutionary model whereby an originally continuous fault was segmented into the Chelungpu and Tachienshan thrusts after the Luliao fault had developed as a tear fault between them. On the other hand, surface coseismic slip distribution around this area suggests that the Luliao fault plays as a northern boundary of a counterclockwise rotating block during the coseismic event (Hung et al. 2002; Lee et al. 2002). The above alternative models for the Luliao fault reflect different roles played by the fault for long-term and instantaneous deformation.

The northern part of the study area mainly covers the HW of the San-I thrust (Fig. 1). On the surface, the exposed NNE-SSW striking San-I thrust extends northward from the Ta-An River to the San-I area and finally trends E-W. There are two trends in the structural settings of the HW for the San-I thrust. The Hsinkai fault with its southward extending Shihweichiang synclinal axis and the western limb of the syncline are striking NE-SW. The other trends in the structural settings can be manifested by the stratal boundaries that are running almost parallel with the bended fault trace of the San-I thrust. Since the San-I thrust cuts the base of the Tungkeng Formation of the Middle Miocene in its HW along its strike, the bended fault trace with parallel stratal boundaries implies that the thrust cuts at a very low angle along the base of the formation down to the subsurface. In the footwall (FW) of the E-W striking segment of the San-I thrust, the southern end of the steeply dipping western limb of the Chuhuangkeng anticline, which covers the strata from the Middle Miocene to Pleistocene, is cut off by the thrust. This indicates at least 3000 ~ 4000 meters of stratigraphic throw across this segment of the thrust. In other words, the estimated magnitude of displacement along the low-angle San-I thrust would be more than 10 km.

Meng (1963) first proposed a 3D curved feature for the continuous bended fault geometry. A seismic profile of Hu and Chiu (1984) shows gentle low-angle geometry for the San-I thrust with some normal faults in its FW in the southern part of the thrust sheet. Several balanced cross-sections were constructed to delineate the subsurface geometry of the San-I thrust (Suppe 1979; Hung and Wiltschko 1993; Lee et al. 2002). Hung and Wiltschko (1993) suggested that the bended fault trace on the surface reflects the variation from lateral ramp to frontal ramp of the fault plane. Recently, Hung and Suppe (2002) interpreted the property of the southward extension of the San-I thrust in the subsurface and suggested that the fault is in the FW of the Chelungpu thrust to south (Fig. 3).

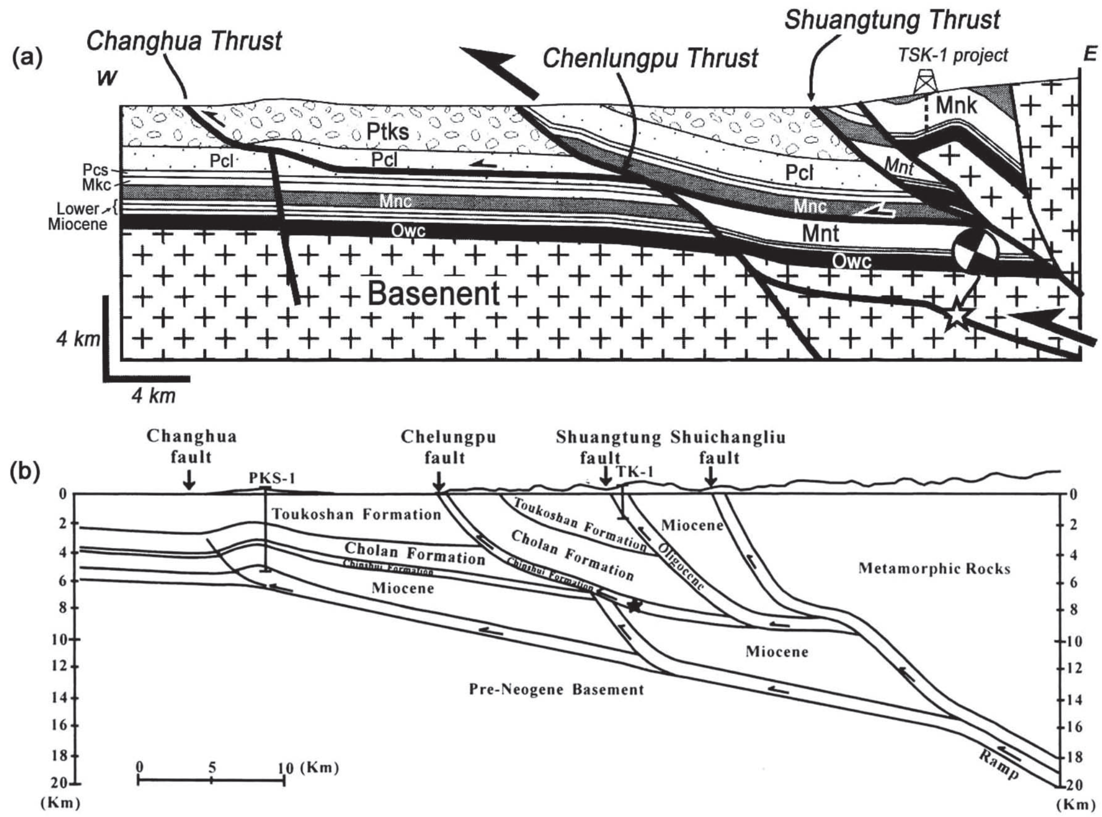

Fig. 3. Dual-décollement models for the imbricate thrust system across the foothills belt. (a) The balanced cross-section of Mouthereau et al. (2001) showing the shallow décollement of the Changhua thrust merged with that of the Chelungpu thrust. Another décollement is interpreted for the mainshock of the Chi-Chi earthquake. (b) The cross-section of Wang et al. (2000, 2002b) showing the deeper décollement of the Changhua thrust and the shallower one of the Chelungpu thrust. Both models suggest that there is a thrust ramp connecting the décollements. Such interpretation would cause some problems of balancing the cross-sections. See text for detailed discussions.

3. CONSTRUCTION OF BALANCED CROSS-SECTIONS

Based on well bore and surface geological data, nine balanced cross sections across the foothills belt were constructed to describe the subsurface geometry of the major thrusts in the foreland of the fold-and-thrust belt (Fig. 1). The space between each pair of cross-section lines narrows toward the northern and southern parts with a view to examining along-strike variation in subsurface structural geometry in the specific area. Seismic data were used as constraints in areas that lack well bore and surface geological data. Lines 1 to 3 were built to both analyze structural features in the southern part of the study area and outline the transition zone from the Chelungpu to the Tachienshan thrust. Lines 4 to 6 portray connective relationships in the subsurface among the major thrusts in the central part. Lines 7 to 9 disclose HW structures of the San-I thrust in the northern part. To construct a 3D geometry of the Chelungpu thrust in the subsurface, this study also refers to the cross-section by Hung and Suppe (2002) located between Lines 6 and 7.

In the central and southern parts of the study area, the thickness of the Pliocene at the HW of the Chelungpu-Tachienshan-Chukou thrust is more than one and half times of that of the FW (Fig. 4). The disparity in stratal thickness also implies lithofacies change on the FW and HW of the thrust and therefore some different stratigraphic systems exist (Fig. 5).

On the surface geology map by the CPC (Fig. 1), the surface trace of the Chelungpu thrust was interpreted as the southern extending lines of the exposed San-I thrust. The line is buried by recent sediments, not outcropping along the base of the Chinshui Shale. Such an interpretation creates a geological section in that the thrust cuts at higher angle through formations down to the subsurface (Chang 1971). Suppe (1985) presumed that the widespread Chinshui Shale can serve as a major slip surface and suggested that the Chelungpu thrust more likely runs along the formation base (Fig. 2a). The surface rupture of the Chi-Chi earthquake to some extent validates this presumption. Therefore, we adopted this concept as one of the rationales in constructing our balanced cross-sections.

3.1 Line 1

Construction of Line 1 is constrained by CPC MLN-1 and SKH-1 wells. MLN-1 well is located on the eastern limb of the Neilin anticline and penetrated an east-dipping fault plane at a depth of 2180 meter below sea level, where the Talu Shale of the Middle Miocene overlies the Cholan Formation of the Upper Pliocene. The penetrated fault plane has been interpreted as the subsurface Tungshuhu thrust. SKH-1 well is located on the eastern limb of the Shihkanhu anticline and penetrated from the Kuantaoshan Sandstone Member in the Kuechulin Formation of the Upper Miocene down to the Shihti Formation of the Lower Miocene.

The segment of the line in the coastal plan shows some normal faults and the strata gently dipping eastward (Fig. 6). An anticline probably relating to reactivated normal faulting appears in the FW of the Tungshuhu thrust, as constrained by MLN-1 well bore data. The Tungshuhu thrust is dipping at an angle of 34° to the east and down to a depth of about 5 km below the sea level, where the thrust turns into a décollement and dips at an angle of 10 to the east.

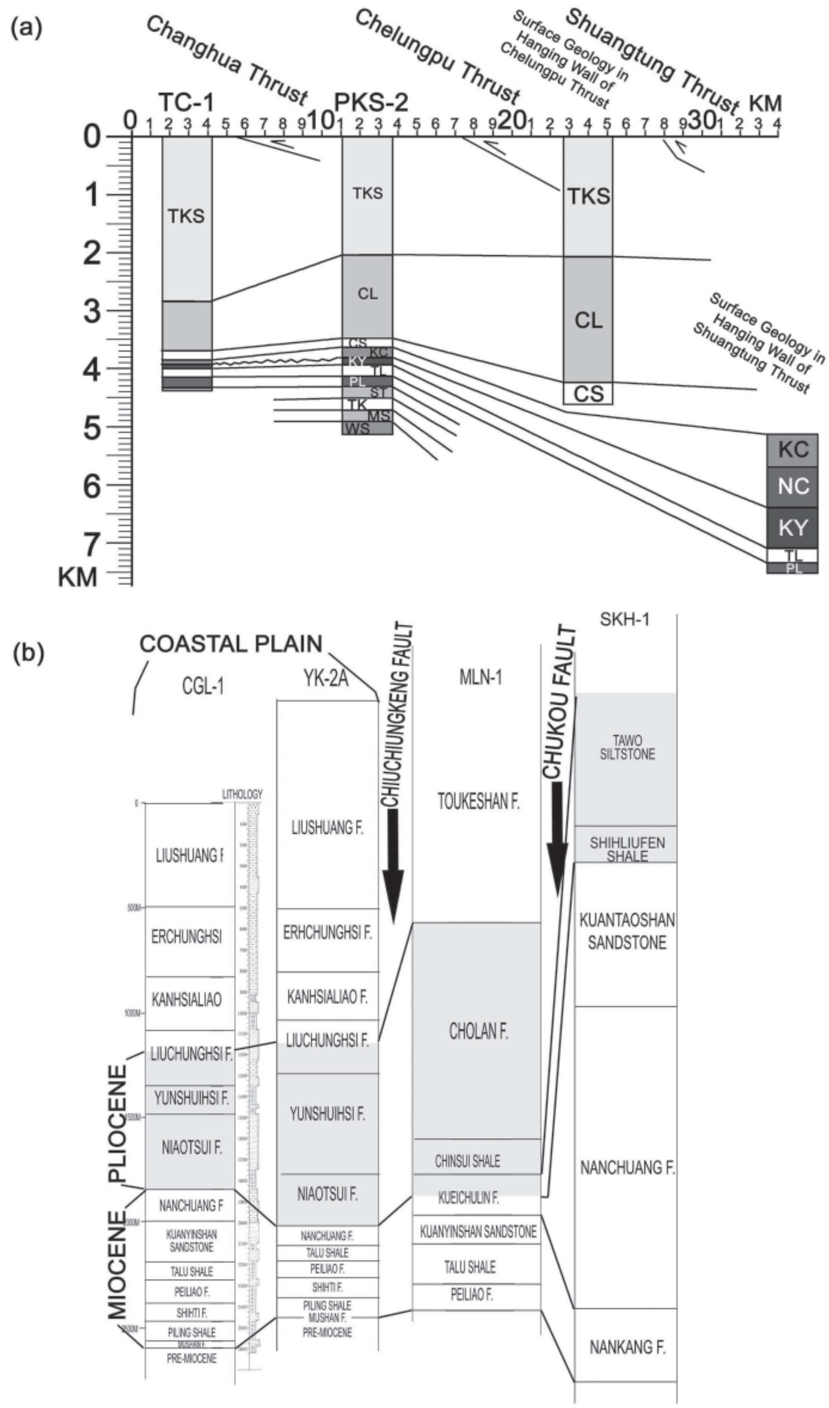

Fig. 4. Stratal thickening across the major thrusts in the (a) central and (b) southern parts of the study area.

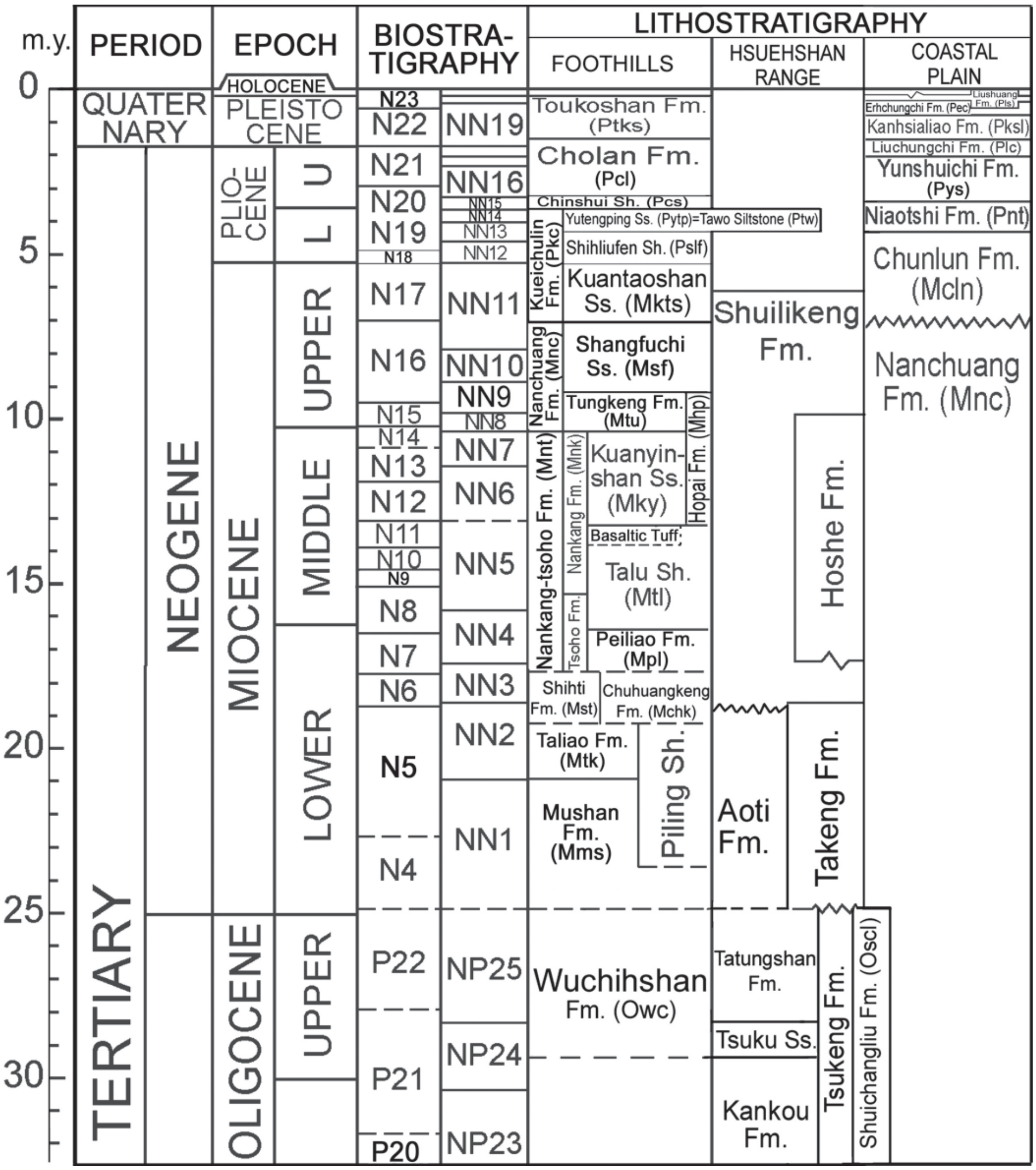

Fig. 5. Chronostratigraphic chart in Taiwan, which is modified from Chang (1975), Huang (1982), Huang and Cheng (1983), Huang and Huang (1984), Chen and Huang (1990). Biochronology follows Haq et al. (1987).

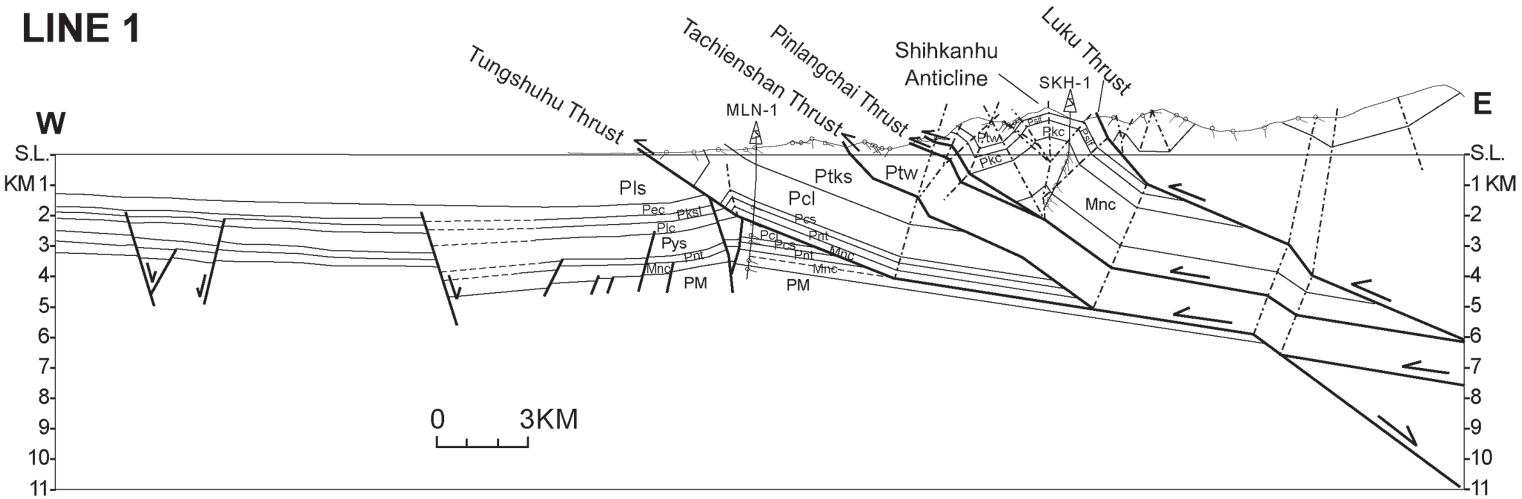

Fig. 6. Balanced cross-section of Line 1. Location of the cross sections are shown in Fig. 1. Legend of formation abbreviations, as well as the ages of the formations, is shown in Fig. 5. The Tungshuhu and Tachienshan thrusts are merged in the subsurface. The ramp behind the merging point is along the shallower part of a pre-existing normal fault, the existence of which is for stratal thickening of the Tawo Siltstone across the Tachienshan thrust and to balance the difference in stratal thickness on both sides of the Tachienshan thrust. The location of the ramp is determined by the magnitude of displacement along the Tungshuhu thrust so that the Tachienshan thrust would be lined up with the normal fault after displacement along the Tungshuhu thrust is restored.

The geometry of the Tachienshan thrust is mainly constrained by the attitudes of the HW strata of the thrust. The subsurface Tachienshan thrust is dipping at an angle of 30° in average down to the east and merges with the décollement of the Tungshuhu thrust at a depth of 5.5 km below sea level (Fig. 6). To the east, the Pinlangchai thrust is dipping to the east and almost parallel with the Tachienshan thrust. The décollement of the Tungshuhu and Tachienshan thrusts steps eastward down to another lower décollement in the subsurface east of the Shihkanhu anticline (Fig. 6). The ramp is the shallowest part of an east-dipping high-angle normal fault. The interpreted ramp and the pre-existing normal fault are to balance the difference in stratal thickness on both sides of the Tachienshan thrust. The location of the ramp is determined by the magnitude of displacement along the Tungshuhu thrust so that the Tachienshan thrust would be a straight line with the normal fault after displacement along the Tungshuhu thrust is restored.

3.2 Line 2

We used a seismic line in the coastal plane and another seismic line (S1) winding along the southern bank of the Choshui River to construct the western part of Line 2. The interpretation of structural features on S1 (Fig. 7a) is for the characteristics of the Changhua thrust and this, in turn, should be the constraint of construction for the Chelungpu thrust in the subsurface. We also referred to the well bore data from the Chushan-1 well of the CGS to infer the subsurface dipping angle of the Chelungpu thrust.

On S1 (Fig. 7a), interpretation of the Changhua thrust is based on the location of the thrust on the surface and the terminated reflectors representing the cut-off of the FW strata. The interpreted major formation tops are tied from well bore data in the adjacent areas and through other connecting seismic lines in the coastal plane and the Pakuashan areas. The interpreted cross-section shows a listric trajectory for the thrust, which is cutting downward at a high angle on the surface and flattening as a bedding slip along the base of the Miocene, or the pre-Miocene unconformity, at a depth of 3 seconds of two-way time or 7 km below sea level.

The connective relationship between the Changhua and Chelungpu thrust and the geometry of the Chelungpu thrust in the subsurface can be shown on Line 2 (Fig. 7b). The Chelungpu thrust fault cuts all the way down to the subsurface along the Chinshui Shale, which is strongly implied by the surface geology such that the fault trace is parallel with the stratal boundary between the Chinshui Shale and the overlying Cholan Formation along the entire foothills belt in the study area (Fig. 1). The bended segments of the fault plane in the subsurface are constrained by the variation in stratal dip angles of its HW on the surface. The Chelungpu thrust turns into the décollement and is merged with that of the Changhua thrust at a depth of 7.6 km below sea level. Since the stratal level for the merged décollements are different, this would imply that part of the strata older than the Chinshui Shale should be underneath the common décollement and, thus, demands a pre-existing normal fault underneath the décollement to accommodate the difference in stratal level and the different thickness of the Cholan Formation on both sides of the Chelungpu thrust (Fig. 4). The location and apparent dip angle of the interpreted normal fault are constrained by the magnitude of displacement along the Changhua thrust and the dip angle of the lowest ramp of the Chelungpu thrust, respectively. Such inter-

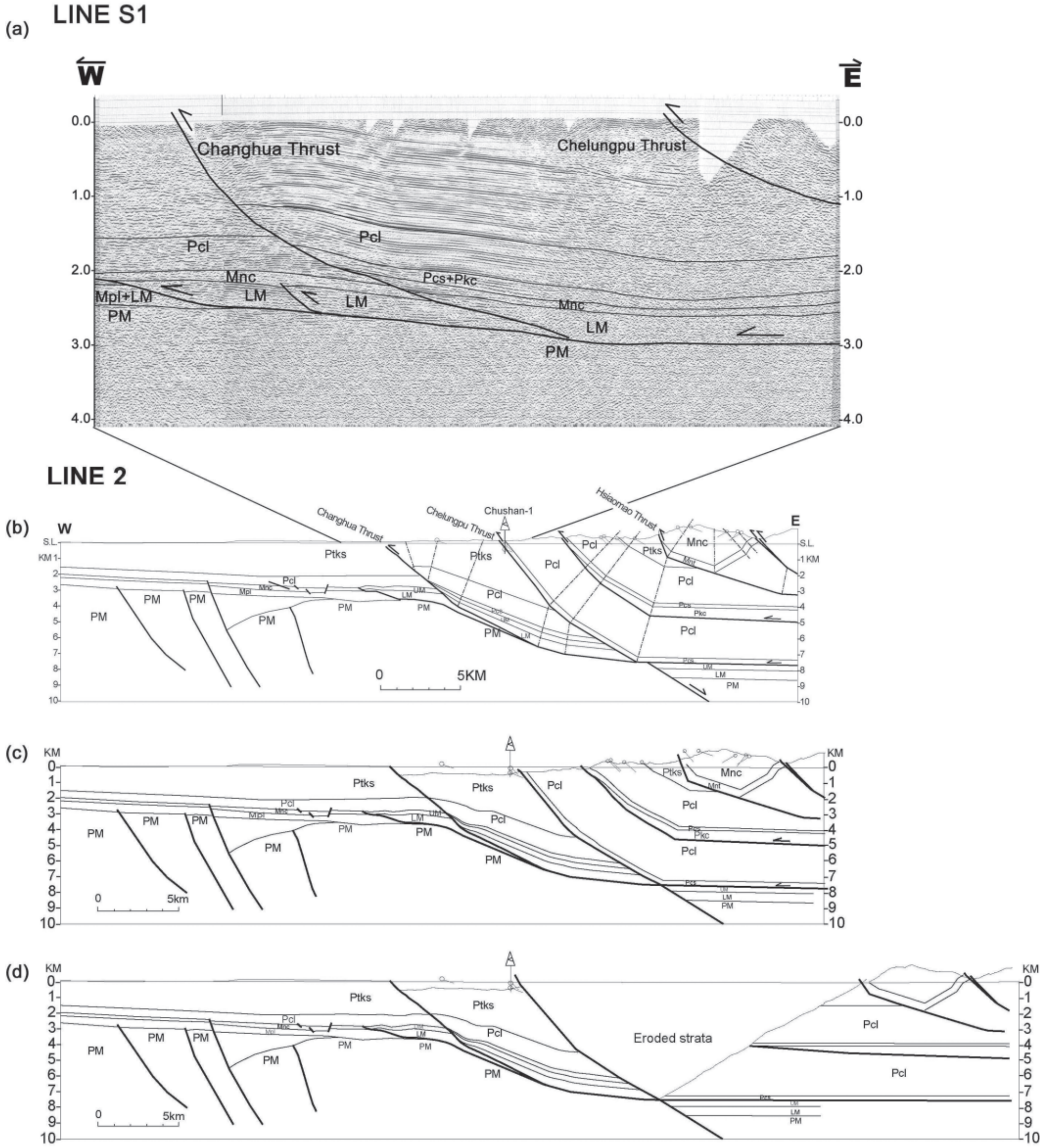

Fig. 7. (a) Seismic interpretation of Line S1. (b) Balanced cross-section of Line 2. (c) and (d) Restorations made on the slip along the Changhua thrust first and then the Chelungpu thrust, respectively. The range of Line S1 is also shown on the top of Line 2. The décollements of the Changhua and Chelungpu thrusts are along different formations but merged with each other in the subsurface. A normal fault exists underneath the common décollement and accommodates the thickened Cholan Formation in the HW of the Chelungpu thrust.

pretation would prevent any extraordinary fault geometry after displacement along the Changhua thrust is restored (Fig. 7c) so that the Chelungpu thrust fault would be restored smoothly back to its original simple low-angle geometry (Fig. 7d). The interpreted pre-existing normal fault underneath the décollement of the Chelungpu thrust also appears on the lines 3, 4, 5, and 6 to the north.

There is a splay thrust extending from the Shuangtung-Hsiaomao thrust to the Chelungpu thrust on the map (Fig. 1). The interpretations of the subsurface splay thrust and the Shuangtung-Hsiaomao thrust are based on the surface geology in that the thrusts cut off the stratal boundaries in their HWs obliquely at small angles along their strikes. The cut-off relationships on the surface indicate that the thrusts also cut off the stratal boundaries in the HWs at small angels down to the subsurface. The interpreted thrusts turn into the décollements at very shallow depth but within older strata.

3.3 Line 3

The western part of the line is identical to that of Line 2 and its eastern part is winding along the southern bank of the Choshui River. Therefore, the interpreted structural features on the western part of the line are very similar to that on Line 2 (Fig. 8). However, there are some changes in structural features on the line from that of Line 2 (Fig. 8): 1) the depth at which the décollements of the Changhua and Chelungpu thrusts are merged is 7 km and shallower than that shown on Line 2; and 2) the splay thrust cuts downward almost along the base of the Cholan Formation and turns into the décollement along the boundary between the Cholan Formation and the Chinshui Shale. The interpretation for the second feature is based on surface geology in that the line runs across the segment of the thrust where the fault trace is almost parallel with the stratal boundary in its HW (Fig. 1).

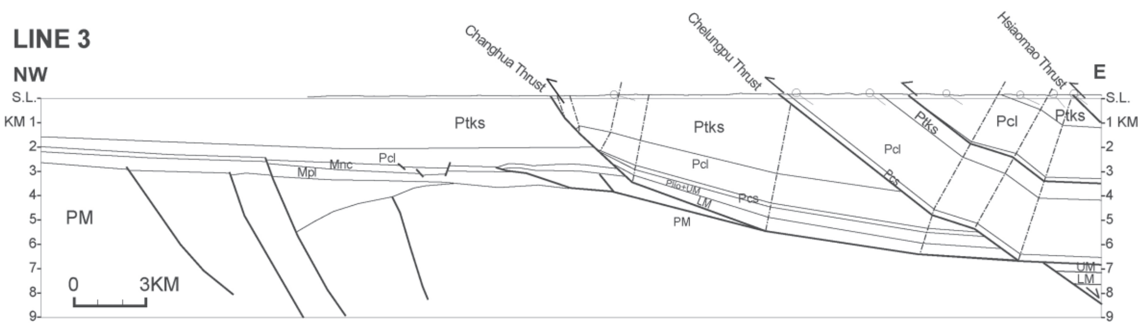

Fig. 8. Balanced cross-section of Line 3. The segment in the coastal plane is the same as that of Line 2. The structural features are very similar to that on Line 2 except that the splay thrust between the Chelungpu and Shuangtung-Hsiaomao thrusts cuts downward along the base of the Cholan Formation or the top of the Chinshui Shale.

3.4 Line 4

Line 4 is located to the north of the Choshui River and running E-W. The cross-section was constructed with well bore data from TC-1 well by the CPC for the subsurface structure of the Changhua thrust. TC-1 well is located on the crest of the HW anticline of the Changhua thrust and the well bore data shows that the thickness of the penetrated Toukoshan Formation is 1088 m thicker than that penetrated by PKS-1 well, which is located to the north, 28 km away from TC-1. We interpreted that the thickened Toukoshan Formation is due to stratal repetition resulting from slip along the Changhua thrust. Since the HW anticline of the Changhua thrust is symmetrical and similar to that shown on Line 5, as will be described below, we also referred to the interpretation of Line 5 for construction of the subsurface Changhua thrust. We presumed that the interpreted Changhua thrusts, shown on Lines 3 and 4, share a common décollement, i.e., the one along the base of the Miocene; and we interpret the Changhua thrust on Line 4 (Fig. 9) as cutting downward at a smaller angle but with greater magnitude of displacement than that shown on Line 3 (Fig. 8).

The Chelungpu thrust cuts downward along the base of the Chinshui Shale and merges with the Changhua thrust at a depth of 7 km, where the thrust turns into the décollement (Fig. 9). The splay thrust between the Chelungpu and Shuangtung-Hsiaomao thrusts cuts off the HW stratal boundaries at a greater angle down to the surface than that shown on Lines 2 and 3 (Figs. 7c, 8). Again, the interpreted cut-off angle is based on the cut-off relationships on the surface geology. The subsurface of the splay thrust is very similar to that on Line 2 in geometry but located closer to the Shuangtung-Hsiaomao thrust. The splay and Shuangtung-Hsiaomao thrusts turn into the décollements at very shallow depth but within older strata (Fig. 9).

3.5 Line 5

Line 5 runs NWW-SSW to the north of Line 4 and was constructed with well bore data from CGS Changhua-2 and CLF-2 wells and CPC TK-1 well. Changhua-2 well is located on the western limb of the Pakuashan anticline and penetrated the fault plane of the subsurface Changhua thrust at a depth of 370 m below sea level. CLF-2 and TK-1 wells were used to construct the subsurface geometry of the Chelungpu and Shuangtung-Hsiaomao thrusts, respectively. The structural features on Line 5 (Fig. 10a) are very similar to those on Line 4 (Fig. 9), except that the splay thrust has been merged with the Shuangtung-Hsiaomao thrust to the south of the line and that a local anticline occurs in the HW of the Shuangtung-Hsiaomao thrust (left-hand side of Fig. 10a). The occurrence of the anticline should be structurally related to the Tsukeng thrust in the HW of the Shuangtung-Hsiaomao thrust. In fact, surface trace of the Shuangtung-Hsiaomao thrust extends from the south and bifurcates into two branches at this location, and the Shuangtung-Hsiaomao thrust shown on Line 4 should be connected with the Tsukeng thrust on Line 5. Such a connective relationship for the bifurcated thrusts can be manifested by the different strata for the slip surface of the interpreted Shuangtung-Hsiaomao thrusts on Lines 4 and 5.

Restoration of Line 5 shows the different geometry of the normal fault underneath the décollement (Figs. 10b, c). After displacement along the Changhua thrust is restored the Chelungpu thrust would be restored eastward to meet with the terminated normal fault. In order to obtain a simple pre-translated geometry the normal fault is interpreted as a low angle fault, implying that the strike of Line 5 may not be perpendicular to that of the normal fault.

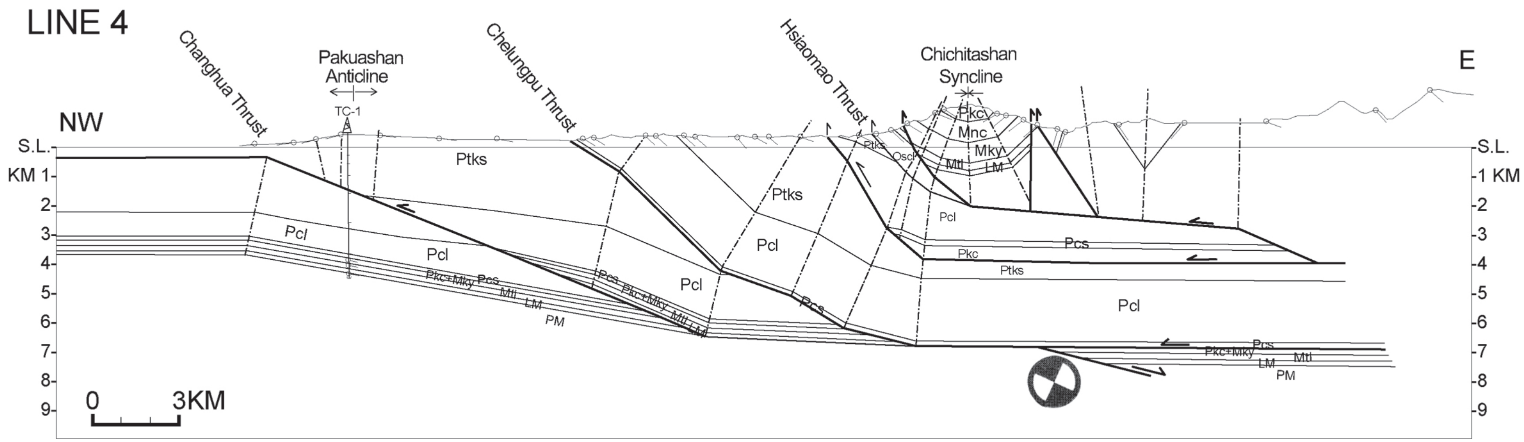

Fig. 9. Balanced cross-section of Line 4. The splay thrust between the Chelungpu and Shuangtung-Hsiaomao thrusts is cutting down through the strata and turns into the décollement with the Kuechulin Formation. The fault plane solution represents the mainshock of the Chi-Chi earthquake and is located very close to the pre-existing normal fault underneath the common décollement.

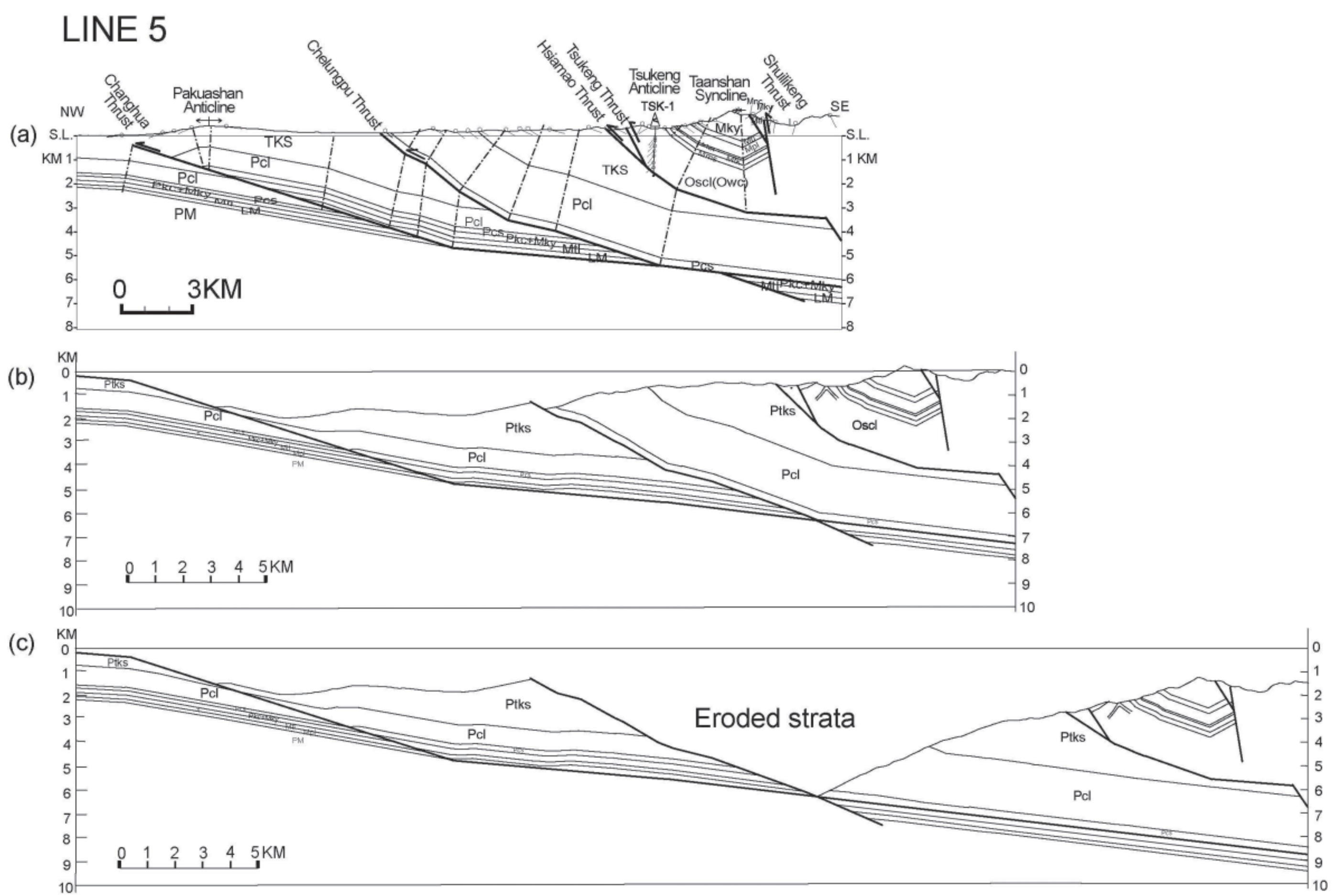

Fig. 10. (a) Balanced cross-section of Line 5. (b) and (c) Restorations made on the slip along the Changhua thrust first and then the Chelungpu thrust, respectively. The structural features on the line are very similar to that on Line 4. The splay thrust is merged with the Shuangtung-Hsiaomao thrust to the south of the line and, therefore, does not appear on the line.

3.6 Line 6

Line 6 runs E-W but winds along the southern bank of the Tatu River. Construction of the line was constrained by the well bore data of CPC PKS-1 and an interpreted seismic line S2 (Fig. 11a) for the subsurface Changhua thrust (Fig. 11b). On S2, the picked-formation tops in the FW of the Changhua thrust were tied from the CPC WG-1 well located on the coastal line and through several seismic lines. Those in the HW were from PKS-1. The fault plane of the Changhua thrust on S2 is also determined by the location of the thrust on the surface and the terminated reflectors representing the cut-off of the flat FW and east-dipping HW strata (Fig. 11a). The interpreted Changhua thrust cuts down and turns into the décollement along the base of the Miocene (Fig. 11b). There are two high-angle faults, a normal fault in the FW of the Changhua thrust and the other strike-slip fault in the HW, representing a tear fault offsetting the thrust. The tear fault is not exposed on the surface but might be buried underneath the terrace of the Tatu River.

The subsurface geometry of the Chelungpu and Shuangtung-Hsiaomao thrusts is similar to that on the lines to the south (Fig. 11b). Since the line length extends into the area where the Oligocene strata are exposed (Fig. 1) the line can display the subsurface geometry of the Shuangtung-Hsiaomao thrust to the east. The thrust is characterized by two ramp-flat structures in the subsurface, which in turn result in a series of anticline and synclines structures on the surface.

3.7 Line 7

Line 7 runs NWW-SEE and winds along the southern bank of the Ta-An River (Fig. 1). Construction of the line was constrained by the well bore data of CPC TAC-1 well and a seismic line S3, on which the picked-formation tops in turn were tied from CPC CLN-1 and TS-1 wells. The interpreted structural features on S3 (Fig. 12a) are: 1) the low-angle San-I and Hsiaonanshih thrusts (penetrated by CLN-1 well) being gently dipping down to the subsurface; 2) the Hsiaonanshih thrust terminating at the San-I thrust and not cuting upsection to the surface; 3) the strata in the FW of the San-I thrust being gently updipping to the east and offset by a set of normal faults; in addition, there being a high-angle fault with great magnitude of displacement and convex-upward geometry; and 4) there being two other undiscovered low-angle thrusts or bedding slip surfaces along the bases of the Shangfuchi Sandstone and the Chinshui Shale (these were interpreted based on termination of reflectors at the pre-Shangfuchi strata and the locally thickened Chinshui Shale, respectively).

The structural settings on Line 7 (Fig. 12b) are, from west to east, the Tiehchanshan anticline, the San-I thrust, the Shihweichiang syncline and the Hsitaopang structure. On the western part of the line, the Changhua thrust extends from the south and cuts through the western limb of the Tiehchanshan anticline. There is a syncline between the Tiehchanshan anticline and the San-I thrust. Next to the syncline is another anticline in the HW of the San-I thrust and a high-angle fault with convex-upward geometry or flower structure cutting through the axis of the anticline. The San-I thrust appears as being gently eastward dipping with a broad concave-upward fault geometry and small-scale ramp underneath the Tungshih anticline.

It structurally cuts off the eastern limb of the anticline, which is also offset by a set of high-angle normal faults. In the HW of the thrust, the eastern limb of the Shihweichiang syncline is updipping through a local anticline (the Tungshih anticline) to the east and becomes the western limb of the tight anticline of the Hsitaopang structure. In the subsurface, the San-I thrust bifurcates into two low-angle thrusts, which were penetrated by CLN-1 well. The upper one is interpreted as the subsurface segment of the exposed Hsiaonanshih thrust to the north of the line. The bifurcated thrusts extend to the east and are merged again underneath the Hsitaopang structure, where the San-I thrust turns downward into a ramp with a duplex and results in the overlying tight anticline.

The structural features on the line show that there are three structural levels for the pre-Miocene basement. We interpreted that there are three stacking wedges structures in the base-

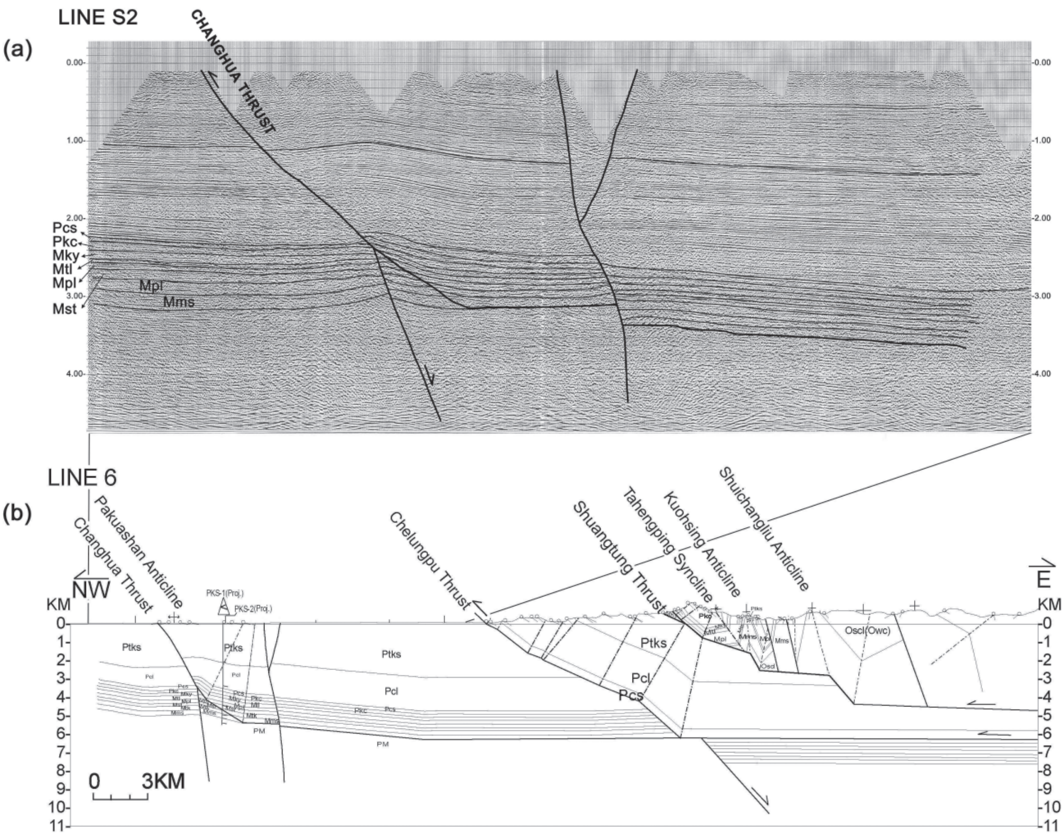

Fig. 11. (a) Seismic interpretation of Line S2. (b) Balanced cross-section of Line 6. The range of Line S1 is also shown on the top of Line 2. The trajectory of the Changhua thrust is similar to that on Lines 2 and 3. Also, the Shuangtung-Hsiaomao thrust appears as a stair-shaped trajectory in the subsurface, reflecting alternating anticline and syncline structures in its HW.

ment (Fig. 12b) that not only create the corresponding structural levels but also form the Tiehchanshan anticline and the anticline underneath the San-I thrust.

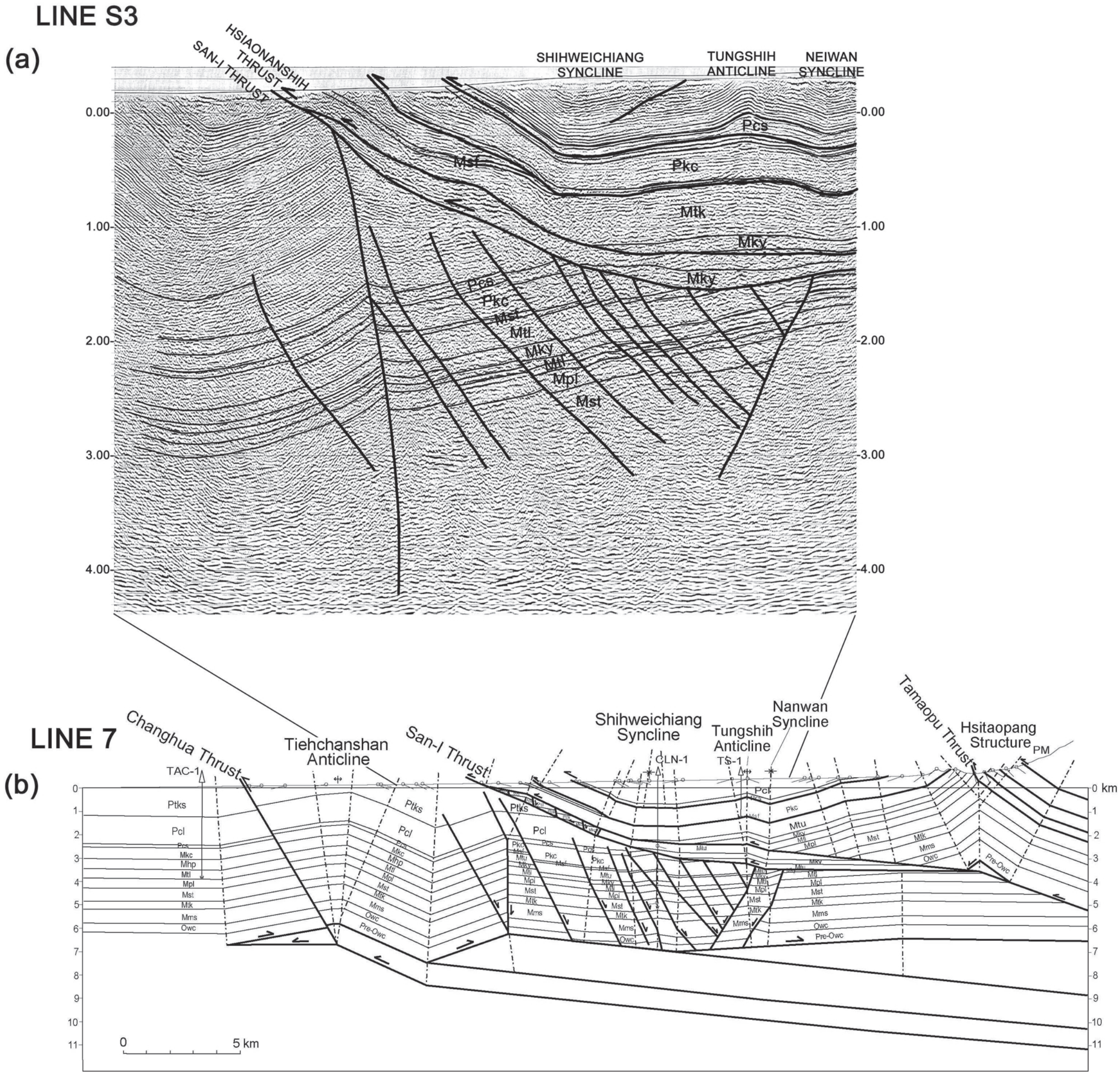

Fig. 12. (a) Seismic interpretation of Line S3. (b) Balanced cross-section of Line 7. The San-I and Hsiaonanshih thrusts appear as concave-upward low-angle thrusts. There are two other low-angle thrusts along the bases of the Shangfuchi Sandstone and the Chinshui Shale in the HW of the Hsiaonanshih thrust. Notice that thrust along the base of the Chinshui Shale is indicated by the local thickened Chinshui Shale underneath the Tungshih anticline on Line S3.

3.8 Line 8

Line 8 also runs NWW-SEE to the north of Line 7 (Fig. 1). Construction of the Tiehchanshan anticline in the western part of the line was constrained by the well bore data of CPC TCS-36, TCS-1 and HYS-1 wells. We also referred to a curvilinear seismic line S4 to interpret the subsurface geometry of the San-I thrust and the associated structures. Several structural features shown on S4 (Fig. 13a) are: 1) the subsurface geometry of the San-I thrust being a multi-bended fault plane, very similar to that shown in Meng (1963); 2) there being a convex-upward high-angle fault underneath the upper flat of the thrust [the fault is identical to the one shown on S3 (Fig. 12a)]; and 3) the steeply west-dipping strata on the western side of the high-angle fault turning into flat beddings on the eastern side of the fault. Since the eastern part of the seismic line turns into the strike intersecting at a high angle with that of Line 8, the flat beddings actually represent the steeply west-dipping strata.

The structural settings on Line 8 (Fig. 13b) are the northward extension part of that shown on Line 7; however, there are some changes in their subsurface geometry from that to the south. First, the Changhua thrust diminishes in the westernmost part of the line. Second, the eastern bifurcation between the San-I and Hsiaonanshih thrusts shifts to the location above the FW anticline and the Hsiaonanshih thrust cuts upward to the surface. Third, both thrusts are folded with the FW anticline into convex-upward fault planes and form the surface anticline. The west-dipping Hsinkai thrust cuts through the axial plane of the next syncline, which is the northward extension of the Shihweichiang syncline. Thrust might have been formed to accommodate contraction deformation along the synclinal axis. Fourth, a high-angle fault with great magnitude of displacement cuts through the western limb of the FW anticline and is characterized by a large difference in stratal thickness on both sides of the fault. Fifth, the Hsitaopang structure is a broad anticline in the subsurface, which exists as a result of balancing construction by referring to a syncline structure on the surface.

The San-I thrust merges with the Hsiaonanshih thrust. It then cuts downward, turns into a flat within the Tungkeng Formation, and extends to the Hsitaopang structure, underneath which the thrust cuts downward again as a ramp. Therefore, the San-I thrust is apparently characterized at least by three ramps in the subsurface. This stair-shaped geometry of the fault plane reflects complex features of the FW, which then were balanced by three stacking basement wedges.

The low-angle thrusts or bedding slip surfaces along the base of the Shangfuchi Sandstoneare are shown on seismic line S4 (Fig. 13a) but not online 8 (Fig. 13b). This is because the thrust only shows up and cuts down to the south in the southeastern part of the seismic line, which is located on the southern side of Line 8.

3.9 Line 9

Line 9 runs NWW-SEE and is located very close to the northern margin of the San-I thrust sheet, where the San-I thrust turns into E-W strike on the surface (Fig. 1). The construction of the line was mainly constrained by the well bore data of: CPC TCS-17, TCS-34, TCS-30 wells for the Tiehchanshan anticline; CPC KTS-1 and LLN-1wells for the San-I thrust and its associated structures; and CPC HTP-1 well for the Hsitaopang structure. Structural features

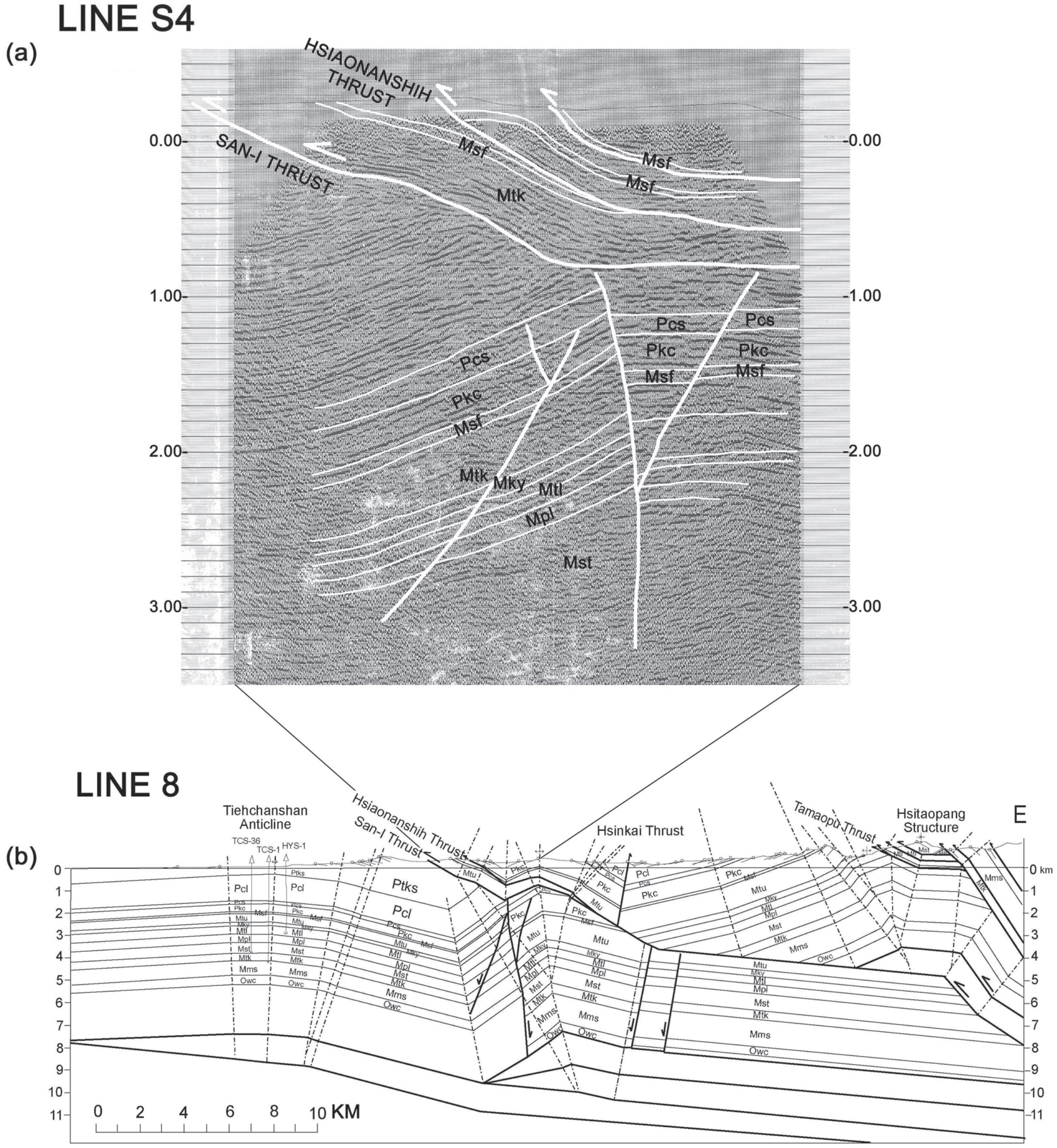

Fig. 13. (a) Seismic interpretation of Line S4. (b) Balanced cross-section of Line 8. The strike of the eastern segment of Line S4 is at high angle to that of Line 8 and the low-angle San-I thrust and strata in the FW actually are dipping to the southeast, as shown on Line 8, i.e., the thrust and strata in the FW have been upfolded.

on Line 9 (Fig. 14) are similar to those on Line 8 but with a more folded San-I thrust fault plane, as well as tighter anticline in the FW. In addition, the Hsitaopang structure is not only characterized by tight folding but also by back thrusting or a triangle zone.

4. DISCUSSIONS

4.1 Comparison of Alternative Interpretations

The location of the cross-sections of Suppe (1985) and Yue et al. (2005) are very close to Lines 4 and 5 (Fig. 1). First we compare their results with our own. As mentioned previously, the major difference between the cross-sections of Suppe (1985) and Yue et al. (2005) is in the interpretation of the Shuangtung-Hsiaomao thrust (Fig. 2). We favor Suppe's (1985) interpretation of the thrust for balancing the cross-section. As illustrated in the cross-section of Yue et al. (2005), the dip angle of the strata in the HW of the Shuangtung-Hsiaomao thrust becomes smaller away from the surface outcrop of the thrust. Such a structural feature strongly indicates that, in terms of a fault-related fold, the subsurface thrust should flatten in its deeper part so that slip along the fault plane would cause concave-upward strata in its HW. Suppe's (1985) interpretation would illustrate a longer décollement of the Shuangtung-Hsiaomao thrust extending farther to the east (Fig. 2a). As mentioned in Yue et al. (2005), their cross-section illustrates a shorter décollement of the Chelungpu thrust (Fig. 2a) than that predicted by the inversion model of surface coseismic slip distribution (Johnson and Segall 2004). Suppe's (1985) interpretation can solve the discrepancy.

Comparing our cross-sections (Fig. 9) with those of Suppe (1985) and Yue et al. (2005) (Figs. 2a, b), there are several major differences: 1) they presumed continuous thickening for the Chinshui Shale and Cholan Formation through the FW of the Chelungpu thrust to accom-

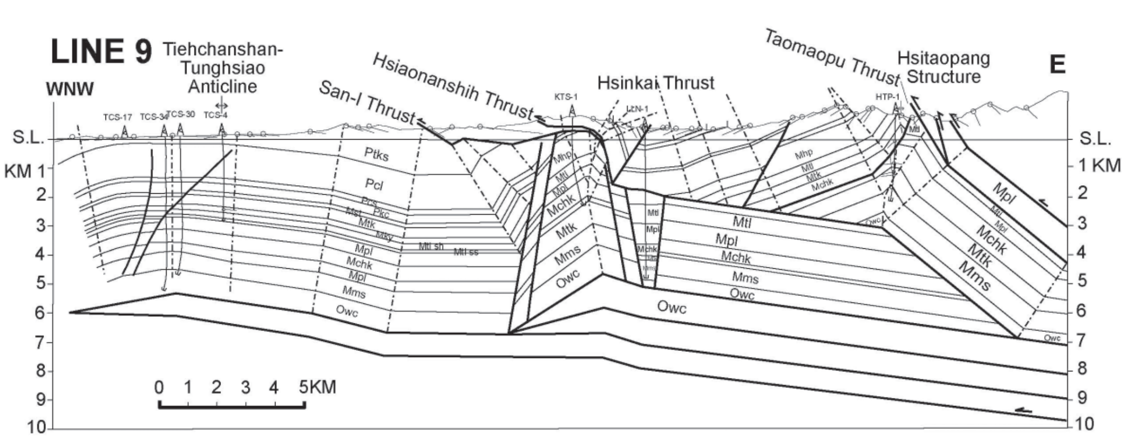

Fig. 14. Balanced cross-section of Line 9. The San-I thrust and strata in the FW have been more tightly upfolded.

modate the different stratal thickness on both sides of the thrust; 2) the Changhua thrust cuts downward all the way along the base of the Chinshui Shale; and, therefore, 3) the Changhua thrust merges with the Chelungpu thrust into the décollement along the base of the Chinshui Shale, without any pre-existing normal fault underneath the décollement to accommodate different stratal thickness in the subsurface. Yue et al. (2005) depicted a high angle fault to connect the décollement and the hypocenter of the mainshock (Fig. 2c); however, they admitted that there is no compelling evidence for the solution.

The stratal thickness for the Cholan Formation and Chinshui Shale on both sides of the Chelungpu thrust differs obviously (Fig. 4a), as constrained by the well bore data of PKS-2 well in the FW and surface geology in the HW of the thrust. In the seismic lines S1 (Fig. 7a) and S2 (Fig. 11a), parallel reflectors representing the formation top and base of the Cholan Formation show no discernible stratal thickening in the FW of the Chelungpu thrust. We believe that the difference in stratal thickness on both sides of the Chelungpu thrust should be considered a major feature in constructing the balanced cross-section and would imply different regional of the top of the Chinshui Shale on both sides of the thrust. Under such condition, the décollement along the base of the Chinshui Shale for the Changhua thrust would give rise to a complicate trajectory for the common décollement of the Changhua and Chelungpu thrusts in the subsurface. A smooth trajectory for the common décollement demands a solution that the Changhua thrust cuts downward and turns into the décollement along a formation deeper than the base of the Chinshui Shale. The slip surface for the décollement of the Changhua thrust should be determined by the difference in stratal thickness on both sides of the Chelungpu thrust and the thickness of the pre-Cholan formations of the Miocene in the FW of the Chelungpu thrust. We estimated that the most probable slip surface for the décollement is along the pre-Miocene unconformity. Such a solution can also be justified by the interpretations on the seismic lines S1 (Fig. 7a) and S2 (Fig. 13a) and has been applied to the construction of the lines across the Changhua and Chelungpu thrusts.

Mouthereau et al. (2001) referred to Chen's (1978) seismic interpretation and suggested that the décollement of the Changhua thrust is along the lower part of the Cholan Formation rather than along the base of the Chinshui Shale (Fig. 3a). In addition, the Chelungpu thrust does not cut all the way down along the base of the Chinshui Shale but through the Lower Pliocene and the Upper Miocene and turns into the décollement along the base of the Nanchuang Formation of the Upper Miocene. The depth of the décollement is about the same as that in our work and Suppe (1985). On the other hand, their interpretation did show a smoother trajectory of the thrust than in either our or Suppe's (1985) work. However, fault geometry that is cutting through the strata in the subsurface may be unlikely for the solution; as revealed and constrained by the surface geology, the trace of the thrust is along the Chinshui Shale and parallel with the formation top through the entire foothills belt (Fig. 1).

On the cross-section of Mouthereau et al. (2001) (Fig. 3a), a normal fault right underneath where the décollements of the Changhua and Chelungpu thrusts merge is depicted to accommodate the thickened Lower Miocene strata, not the thickened Cholan Formation as proposed by us. As for his interpreted FW structures of the Chelungpu thrust, Mouthereau et al. (2001) referred to the exposed Lower Miocene in the HW of the Shuangtung-Hsiaomao thrust. As yet no direct evidence indicates the thickness of the Lower Miocene underneath the décollement of the Chelungpu thrust. The balanced cross-sections of Lines 5 (Fig. 10a) and Suppe's (1985) (Fig. 2a) show a great magnitude of displacement along the Chelungpu and Shuangtung-Hsiaomao thrusts and the restored length for the cross-sections would be sufficient to accommodate gradual thickening of the Lower Miocene from the HW of the Changhua thrust to that of the Shuangtung-Hsiaomao thrust. The reason that the normal fault, if it does exist, is to accommodate the thickened Pliocene rather than the Lower Miocene is based on research on regional tectonics of the undeformed areas to the west (Yuan et al. 1989; Yang et al. 1996b, 2006; Lin et al. 2003), which suggest that predominant normal faulting did not start until the late Miocene.

Another deeper décollement connected with the shallow part of the normal fault was proposed by Mouthereau et al. (2001) (Fig. 3a) for no convincing reason related to balancing the cross-section but as a mean of connecting the hypocenter of the Chi-Chi earthquake, as determined by Kao and Chen (2000), with the Chelungpu thrust on the surface. From a long-term deformation point of view, neither our balanced cross-sections nor Suppe's (1985) predict a second deeper décollement; nonetheless, the way it is connected with other thrust and used as a long-term slip surface would induce some structural problems, which will be discussed below.

The interpretation of the connective geometry for the Changhua and Chelungpu thrusts in the subsurface by Wang et al. (2000, 2002b) (Fig. 3b) presumes that the Neogene strata thicken gradually and remarkably to the east and the décollement of the Changhua thrust is along the pre-Miocene unconformity. Therefore, on their cross-section, the décollement is not merged with but deeper than that of the Chelungpu thrust, and they depicted a ramp of thrust to connect the décollements, which forms a stair-shaped thrust trajectory in the subsurface. A similar stair-shaped thrust trajectory is also proposed in Mouthereau et al. (2001) (Fig. 3a). In terms of construction of a balanced cross-section, slip along a stair-shaped trajectory of thrust, as that proposed in Mouthereau et al. (2001) and Wang et al. (2000, 2002b), should have created some fault-related fold structures, which in fact do not appear on their cross-sections (Figs. 3a, b) or on the surface. Therefore, we believe that the subsurface geometry of the décollements should be a simple one, as indicated by that on our cross-sections and Suppe's (1985) (Fig. 2a).

Wang et al. (2002b) also made interpretation on a seismic depth section HV2 (Fig. 15a) shot by the CPC, which shows that the depth of the décollement of the Chelungpu thrust is greater than 9 km below sea level. The location of the seismic line is almost identical to that of the eastern part of Line 3. Hung and Suppe (2002) made an alternative interpretation on HV2 (Fig. 15b). Both interpretations suggest thicker Miocene strata and, thus, deeper pre-Miocene unconformity than that interpreted by us. The major difference between interpretations of HV2 (Figs. 15a, b) concerning the subsurface geometry of the Chelungpu thrust is the depth of cut-off of the Chinshui Shale in the FW of the thrust. While Wang et al. (2002b) interpreted that the base of the Cholan Formation in the FW of the thrust matches with the décollement of the Chelungpu thrust (Fig. 15a), Hung and Suppe (2002) picked a shallower reflector in the FW for the top of the Chinshui Shale with its cut-off by the ramp of the Chelungpu thrust (Fig. 15b). The interpretation by Hung and Suppe (2002) is similar to ours on this feature; however, our interpreted seismic lines (Figs. 7a, 11a) show that the thickness of the pre-Cholan formations of the Miocene in the FW of the Chelungpu thrust is uniform and not so thick as that inter-

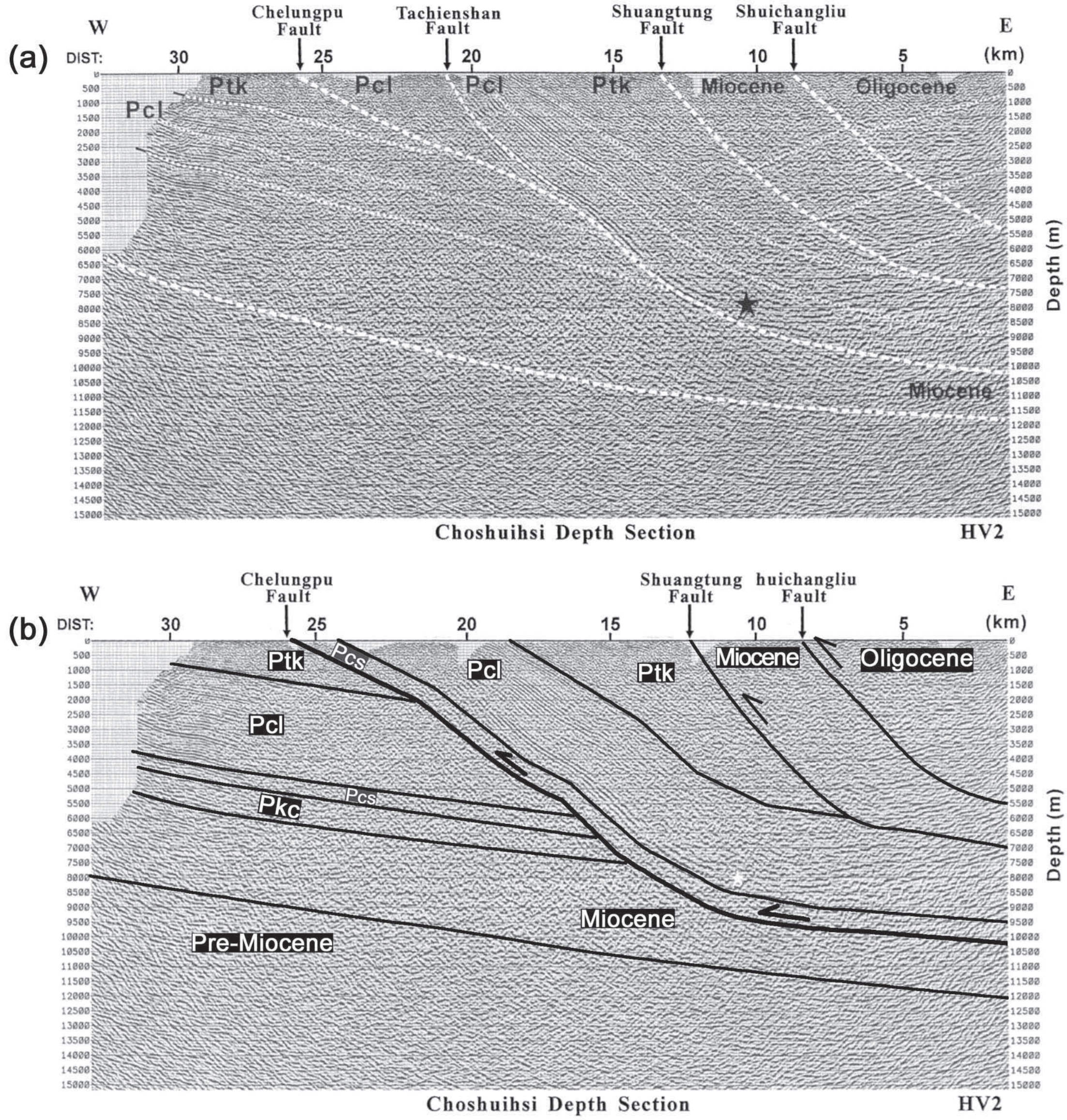

Fig. 15. Different interpretations on a seismic depth section across the imbricate thrust system by (a) Wang et al. (2002) and (b) Hung and Suppe (2002). The location of the seismic line is almost identical to that of the eastern part of Line 3. The décollements of the Chelungpu thrust are at different depth for each interpretation. Interpreted structural features by Hung and Suppe (2002) are very similar to that on Line 3 but different in depth of the pre-Miocene unconformity and of the décollement of the Chelungpu thrust.

preted on HV2. Therefore, if the Changhua thrust turns into the décollement along the pre-Miocene unconformity, as suggested by Wang et al. (2000, 2002b), it would be very probable that the décollements of the Changhua and Chelungpu thrusts may be merged in the subsurface and that a normal fault necessarily exists underneath the common décollement.

As for the difference in the interpreted depths of the common décollements, this issue ought to relate to the different methods used for interpretations, i.e., a velocity model used to convert a seismic time section into a depth section vs. a cross-section balancing method with few basic presumptions to construct a depth section. Comparing our interpretations on Lines 4 (Fig. 9) and 5 (Fig. 10a) with that by Suppe (1985) (Fig. 2a), the depth of the interpreted common décollement is determined by the dip angles of strata and the location of the axial plane of the bended strata in the HW of the Chelungpu thrust. The interpreted depth of the common décollement is at a range of 5 to 7 km below sea level; the depth shown on Suppe's (1985) (Fig. 2a) should be viewed as the shallower limit and the one on Line 4 (Fig. 9) as the deeper limit. The tectonic meaning of the interpreted depth of the common décollement will be discussed further below.

4.2 Evolutionary Kinematics of the Chelungpu Thrust

We restored the exposed Chelungpu thrust back to the heel of the ramp to show whether the original regional of the Cholan Formation can be matched with each other in the FW and HW of the thrust. The restored sections (Figs. 7d, 10c) show the structures before slip along the ramp but after that along the décollement. Therefore, the restored sections indicate the minimum displacement along the entire fault plane of the thrust. Restoration of our lines cannot provide any estimation of the maximum magnitude of displacement, nor can that of Suppe's (1985). The cross-sections showing the restored Chelungpu thrust (Figs. 7d, 10c) indicate that the estimated magnitude of displacement along the thrust is at least 13 km.

Restorations of Lines 2 (Fig. 7) and 5 (Fig. 10) provide some characteristics of tectonic evolution for the Chelungpu thrust system. During its propagation toward the foreland the Chelungpu thrust originally was a low-angle thrust before it met a high-angle normal fault (Figs. 7d, 10c), which was then reactivated and used as the frontal ramp of the thrust (Fig. 7c, 10b). In the next stage, development of the frontal thrust, the Changhua thrust, jumped forelandward along a ramp but was still extending from the décollement of the Chelungpu thrust. In the latest stage, displacement along the Changhua thrust left the normal fault behind and underneath the common décollement (Figs.7b, 10a).

4.3 Along-Strike Variation of the Chelungpu Thrust System

To the north of Line 6, the surface rupture of the earthquake turns to the east at the Tachia River (CGS 1999) and cuts across the younger Cholan Formation. On the other hand, the surface trace of the San-I thrust, the slip surface of which is along the base of the Tungkeng Formation, can be projected southward and lined up with the Chelungpu thrust on the surface. Both features indicate the uniform geometry of the Chelungpu thrust changing into what should be reflected by the surface geology (Fig. 1). Thus, from a geological structure point of view, it is intriguing to investigate the characteristics of the Chelungpu thrust extending to the north of Line 6.

The surface geology shows that, in the HW of the Chelungpu thrust, monocline structure is replaced by a syncline structure to the north of Line 6 (Fig. 1). The syncline structure extends into the HW of the San-I and Hsiaonanshih thrusts and is gradually tightened to the north where its axis is replaced in turn by the Hsinkai thrust, as shown on the surface geology (Fig. 1) and balanced cross-sections (Figs. 12b, 13b, 14). We did not provide any balanced cross-section to delineate the subsurface structural features in the area between Lines 6 and 7. We referred to one constructed by Hung and Suppe (2002) (Fig. 16), which shows a broad concave-upward trajectory for the décollement of the Chelungpu thrust in reflecting the syncline structure on the surface. The cross-section also shows that the slip surface of the Chelungpu thrust is along the base of the Chinshui Shale; however, it is merged with or is cut by the Tamaopu thrust in the subsurface to the east. They interpreted that the slip surface for the San-I thrust is within the Kuechulin Formation, stratigraphically younger than that for the thrust in the San-I area. The location where the San-I thrust merges with the Chelungpu thrust in the subsurface needs further investigation and is not the main concern of this article. The balanced cross-section by Hung and Suppe (2002) indicates that the slip surface of the Chelungpu thrust still remains along the base of the Chinshui Shale even if there are some changes happening on the surface geology. We suggest that the bedding slip even extends along the same surface to the north where the Chinshui Shale has been deformed into a tight syncline structure. Such an interpretation can be validated by the seismic section S3 (Fig. 12a), in that thrust along the base of the Chinshui Shale is indicated by the locally thickened formation.

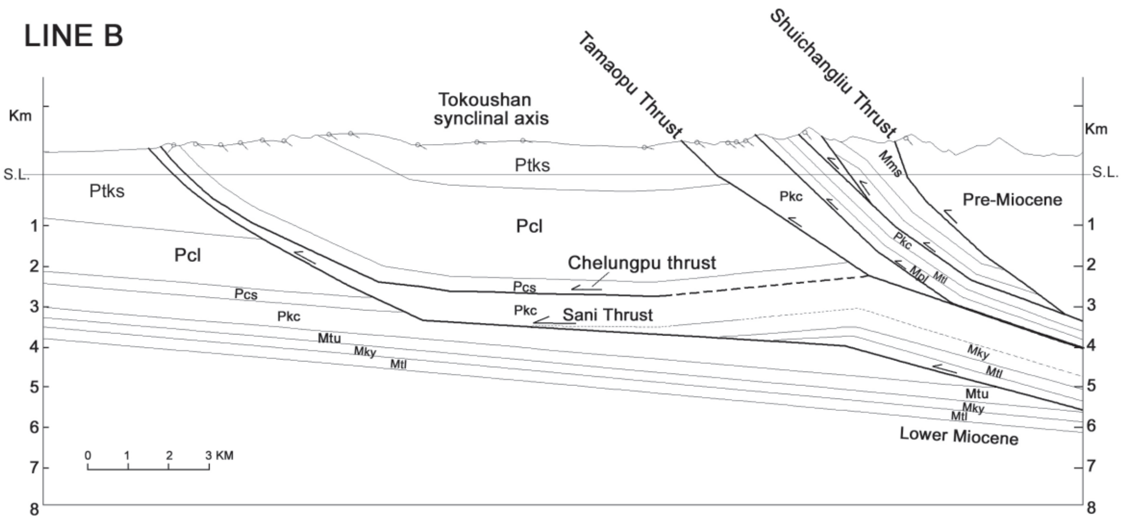

Fig. 16. Balanced cross-section of Hung and Suppe (2002). Legend of formation abbreviations and location of the cross sections are shown in Fig. 1. The ages of the formations are shown in Fig. 5.

In the southern part of the study area, not only the Changhua and Chelungpu thrusts but also the Tungshuhu and Tachienshan thrusts converge into a common décollement, which in turn cuts down through a ramp and turns back into a flat toward the hinterland (Fig. 6). The ramp is along the shallower part of a pre-existing normal fault, the existence of which is to balance the different thickness of the Pliocene across the Chelungpu thrust (Fig. 4a), and the Tachienshan thrust as well (Fig. 4b). However, the décollements of the two segments are along different slip surfaces (Figs. 6, 7b): 1) the décollement of the Tungshuhu thrust is along the base of the Nanchuang Formation, shallower than that of the Changhua thrust; and 2) the décollement of the Tachienshan thrust is along the base of the Tawo Siltstone, the upper member of the Kuechulin Formation, deeper than that of the Chelungpu thrust. Besides which, the HW structure of the Tungshuhu thrust can be viewed as a typical fault-propagation fold (Suppe 1985; Suppe and Medwedeff 1990) with its forelimb breached by the propagating thrust (Mitra 1990), while that of the Changhua thrust should be described more properly as a shear fault-bend fold (Suppe et al. 2004).

As described previously, the splay thrust between the Shuangtung-Hsiaomao and Chelungpu thrusts cuts downsection from the Cholan Formation to the Kuechulin Formation on the surface (Fig. 1). Lines 2 (Fig. 7b) and 4 (Fig. 9), which are running across the southernmost segment of the Chelungpu thrust, show that the splay thrust turns into the décollement within the Kuechulin Formation to the east. Both surface and subsurface geology indicates that the décollement of the Tachienshan thrust should joint with that of the splay thrust, although there is a tear fault, the Luliao fault, separating the thrusts on the surface. Thus, the splay thrust plays a more significant role than a secondary fault connecting the Shuangtung-Hsiaomao and Chelungpu thrusts; it represents a displacement transfer zone from the Chelungpu and Shuangtung-Hsiaomao thrust system to the Tachienshan and Fenghuangshan thrust system, maintaining a constant or gradual variation in transverse displacement between the adjacent segments of the foothills belt.

4.4 3D Geometry of the Chelungpu Thrust

The above analysis of the along-strike variation and lateral connection relationship for both ends of the Chelungpu thrust allows us to construct the subsurface geometry of the thrust, as well as that of the splay thrust. The cross-section of Hung and Suppe (2002) was included with our lines, except Line 1, for the construction of the 3D geometry of the Chelungpu thrust. The subsurface geometry of the thrust is a uniform curved plane striking N-S, with some local wavy features, and a ramp striking E-W in the northern part of the thrust (Fig. 17). The wavy features are mainly related with the curvilinear fault trace on the surface (Fig. 1). To the north of the ramp, the fault plane changes into a spoon-shaped geometry, which is in concordance with that of the Chinshui Shale. Wang et al. (2002b) also proposed something similar that was different in terms of the scale of the wavy fault plane in the northern part of the study area. What they proposed represents the structural feature of the shallowest part of the thrust though it still shows a regional trend of along-strike variation for the subsurface fault plane. Their interpreted seismic lines (profiles A, B, C, and D in their article) across the strike of the thrust indicate that the fault plane becomes shallower to the north. In the area near the E-W striking

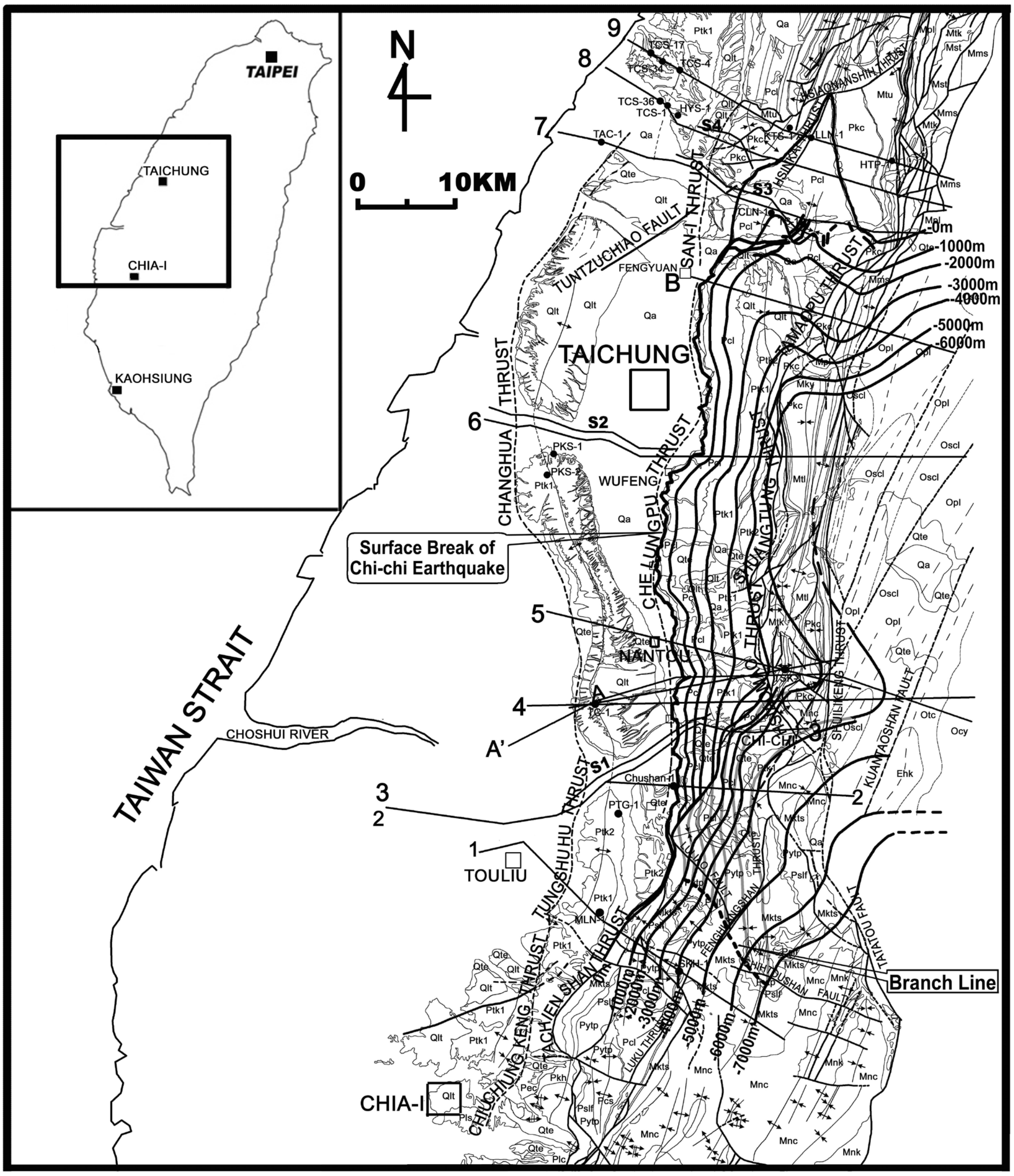

Fig. 17. 3D geometry of the Chelungpu and splay thrusts in the subsurface. The surface structural settings and the contours of the Chelungpu thrust underlying the splay thrust were drawn semi-transparent so that the structural relationships among them can be demonstrated.

surface ruptures of the Chi-Chi earthquake, the other separated but lined-up short seismic lines (S-6, S-7, and S-8 in their article) also indicate a south-dipping ramp of bedding slip for the thrust. Although their proposed geometry (Wang et al. 2002b, Fig. 10) does not show a similar curved fault plane to that shown in Fig. 17, the trend of along-strike variation of the fault plane, as indicated by their interpreted seismic lines, is consistent with that of our constructed fault geometry.

In the southern part of the studied area, we used Lines 1, 2, and 3 (Figs. 6, 7b, 8, 9) to construct the subsurface geometry of the splay thrust (Fig. 17). The fault plane strikes NE-SW and cuts off the southern end of the Chelungpu thrust in the subsurface. The cut-off line of the Chelungpu thrust, or the branch line between the thrusts in the sense of Boyer and Elliott (1982), is parallel with and located very close to the surface Luliao fault. We believe that the coincidence between the subsurface branch line and the surface Luliao fault has some implications for the characteristics of the splay thrust and the Luliao fault. To the northeast of the Luliao thrust, the stratal boundaries in the HW of the splay thrust turn from NE-SW striking, parallel with the splay thrust, into NW-SE striking, parallel with the Luliao fault (Fig. 1). The strata that strikes NW-SE are also dipping to the northeast. There are two alternative solutions for the change in subsurface geometry of the splay thrust. The slip surface of the splay thrust might follow the geometry of the HW strata and rise up to the southwest. This solution indicates that the Luliao thrust can be viewed as the lateral ramp of the splay thrust. However, the hypothetical geometry would cause a complicated or even incompatible situation whereby the deeper slip surface along shallower formation rises up to a shallower slip surface but along a deeper formation. An alternate solution suggests that the NE-dipping strata represent the front limb structures related to a SW-dipping ramp of the splay thrust which is breached by the NE-dipping Luliao thrust. If such an interpretation is valid, the branch line between the Chelungpu and splay thrusts may represent the heel of the ramp and the Luliao fault emerges upward from the intersectional line between the ramp and the shallower slip surface of the splay thrust.

4.5 Implications for Active Tectonics

Either Suppe's (1985) or our balanced cross-sections intrigue and shed light on the problem about linkage between the mainshock and the surface rupture of the Chi-Chi earthquake. The trajectory of the Chelungpu thrust shown on the balanced cross-sections indicates that the dip angle of the décollement at the hypocenter of the earthquake is much shallower than that of the mainshock (Line 4, Fig. 9), and that the depth of the décollement is at least 1 KM shallower than that of the shallowest depth estimation for the mainshock, i.e., 8 km below sea level (Chang et al. 2000). Mouthereau et al. (2001) proposed a dual-décollement model (Fig. 3a) to reconcile the discrepancy in depth between the mainshock and the décollement. We have given discussions on the model and suggested that the dual-décollement is unnecessary and inappropriate in terms of balancing the cross-section. Wang et al. (2000, 2002b) proposed a deeper décollement to link the mainshock with the surface rupture (Figs. 3b, 15a). Still, their interpretation cannot explain the discrepancy in dip angle between the mainshock and the décollement. On line 4 (Fig. 9), the hypocenter of the mainshock is very close to the normal fault underneath the décollement. Since the location of the normal fault depends on interpreted displacement along the Changhua thrust, we speculate that the hypocenter is within the range of interpretation error for the normal fault and that the connection between existence of the normal fault and the mainshock is highly implied.

The bended surface rupture of the northern part of the active Chelungpu thrust during the Chi-Chi earthquake has attracted the attention of many studies (Kao and Chen 2000; Lee et al. 2000; Lee et al. 2002). A mechanical model proposed by Lee et al. (2002) suggested that the subsurface geometry of the Chinshui Shale controls the E-W striking surface rupture. They attributed the change in the strike of the surface rupture to the variation of the northward tightened syncline of the Chinshui Shale in the subsurface, which is viewed as a strain guide for the bended surface rupture. Lee et al. (2000) first delineated the structural contour map of the Chinshui Shale in the subsurface, which represents the geometry of the active Chelungpu thrust, and proposed that slip along a local south-plunging syncline of the northern part of the active thrust created the E-W striking ramp-like subsurface rupture. Although their contour map of the Chinshui Shale was not constructed based on any balanced cross-section the geometry of the contour is very similar to that constructed in this study (Fig. 17). Both the contour map of the Chinshui Shale by Lee at al. (2000) and our constructed 3D geometry of the Chelungpu thrust (Fig. 17) give a simpler explanation for the bended surface rupture. The northward tightened syncline is a local and shallow feature that is connected with the main part of the thrust through a south-dipping and E-W striking ramp. We suggest that the ramp provides a stronger strain guide during subsurface rupture propagation thereby creating the bended surface rupture.

5. CONCLUSIONS

We constructed 9 balanced cross-sections across the foothills belt in the study area to delineate the subsurface geometry of the major thrusts in the foreland of the fold-and-thrust belt. In the central part of the study area, the Changhua, Chelungpu, and Shuangtung-Hsiaomao thrusts form a typical imbricate thrust system. The Chelungpu thrust develops and cuts down to the subsurface invariably along the base of the Chinshui Shale. The Changhua thrust develops as a high-angle thrust, turns into the décollement along the pre-Miocene unconformity, and is merged with that of the Chelungpu thrust into a common décollement at a depth of 5 to 7 km below sea level. The Shuangtung-Hsiaomao thrust also turns into a shallower décollement along the Upper Kuechulin Formation. Our interpretation is similar to that proposed in previous studies but different in that there is a pre-existing normal fault underneath the common décollement of the Changhua and Chelungpu thrusts to accommodate the thickened strata in the HW of the Chelungpu thrust. In the northern part of the study area, the Chelungpu thrust developed continuously along the base of the Chinshui Shale into a syncline structure that is gradually tightened to the north in the HW of the San-I and Hsiaonanshih thrusts.

In the southern part of the study area, the splay thrust between the Shuangtung-Hsiaomao and Chelungpu thrusts cuts downsection from the Cholan Formation to the Kuechulin and turns into the décollement within the Kuechulin Formation to the east. Both surface and subsurface geology indicates that the décollement of the Tachienshan thrust should joint with that of the splay thrust.

The restored cross-sections indicate that the estimated magnitude of displacement along the Chelungpu thrust is at least 13 km. During its propagation toward the foreland, the Chelungpu thrust originally was a low-angle thrust before it met a pre-existing high-angle normal fault, which then was reactivated and became the frontal ramp of the thrust. In the latest stage, displacement along the Changhua thrust left the pre-existing normal fault behind and kept it underneath the common décollement.

The subsurface geometry of the Chelungpu thrust is a uniform curved plane striking N-S, with some local wavy features, and a ramp striking E-W in the northern part of the thrust. To the north of the ramp, the fault plane changes into a spoon-shaped geometry. In the southern part of the study area, the fault plane of the splay thrust is striking NE-SW and cuts off the southern end of the Chelungpu thrust in the subsurface. The cut-off line of the Chelungpu thrust, or the branch line between the thrusts, is parallel with and located very close to the surface Luliao fault. We suggests that the splay thrust is a SW-dipping ramp, which is breached by the NE-dipping Luliao thrust emerging upward from the intersectional line between the ramp and the shallower slip surface of the splay thrust, and that the branch line between the Chelungpu and splay thrusts may represent the heel of the ramp.

The trajectory of the Chelungpu thrust shown on the balanced cross-sections indicates that dip angle of the décollement at the hypocenter of the earthquake is much shallower than that of the mainshock and that the depth of the décollement is at least 1 km shallower than that of the shallowest depth estimation for the mainshock. As the hypocenter of the mainshock is very close to the pre-existing normal fault underneath the décollement, the connection between them is highly implied. We also suggest that the ramp in the northern part of the Chelungpu thrust should provide a stronger strain guide during the subsurface rupture propagation to create the bended surface rupture.

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