WESTERN PACIFIC EARTH SCIENCES
Vol.2, No.4, P.411-426, 7 Figs., November, 2002

STRUCTURAL CHARACTERISTICS OF THE CHELUNGPU FAULT ZONE IN THE TAICHUNG AREA, CENTRAL TAIWAN

CHII-WEN LIN[1], RUEY-CHYUAN SHIH[2], YEN-HUI LIN[1] AND WEN-SHAN CHEN[3]

1. Central Geological Survey, Ministry of Economic Affairs
2. Institute of Seismology, National Chung Cheng University
3. Department of Geosciences, National Taiwan University

ABSTRACT

The Chelungpu fault is a relatively long active fault compared to other earthquake faults in western Taiwan. This paper is to unravel the structural and associated features of the Chelungpu fault, through field mapping, borehole and geophysical explorations between the Tachiachi and Wuchi rivers in the Taichung area. The results show that the Chelungpu fault zone is about 200 to 400-m thick and spreads up as wide as 2000-m in the Chinshui Shale and the lower part of the Cholan Formation. In general, the Chelungpu fault is bounded by the Sanyi fault and the Tachienshan fault in the north and south, respectively; the fault can be divided into 4 segments based on geological features. The major thrust fault system in western central Taiwan has been suggested as constituting of a trailing imbricate fan, and the faulting was propagated westward due to progressive foreland migration. However, within each fault zone faults are arranged in a leading imbricate fan. The secondary faults were not only branched from the hanging wall of the master Chelungpu fault but also laterally propagated toward their tips. All the fault segments were propagated along the strike direction and gradually turned to right at their northerly tip due probably to the northwestward tectonic force.

Key words: Chelungpu Fault Zone, Chi-Chi Earthquake, Imbricate Fan, Fault Segment, Central Taiwan

INTRODUCTION

The Chelungpu fault was reactivated in 1999, induced the Chi-Chi earthquake, and caused surface ruptures for about 100-km long in central Taiwan (Central Geological Survey; CGS, 1999a, b). Based on the geological maps by Chinese Petroleum Corporation (CPC; 1989a, b), the Chelungpu fault concealed and covered by alluvium deposits is situated at hundreds meters west of the surface ruptures of the Chi-Chi earthquake (herein called the Chi-Chi earthquake fault). Nevertheless, Lai *et al.* (1997) showed that the Chelungpu fault is located on and/or near the border of the plain and hills, where some of its branch faults are exposed sporadically. After the Chi-Chi earthquake, two previous locations are found not exactly coinciding with the Chi-Chi earthquake fault. Whether the new surface ruptures could represent the exact localities of the Chelungpu fault is open for discussion (Lin *et al.*, 2003), and the detail structural characteristics of the fault are still not clear.

Theoretically, the longitudinal trace and thickness of a fault is proportional to the total amount of fault slip and/or stratigraphic separation (e.g. Hull, 1988; Scholz, 2002); therefore the fault zone of the Chelungpu fault should not be confined to such a narrow band as the Chi-Chi earthquake fault revealed. This phenomenon has been observed both before and after the Chi-Chi earthquake, during our field mapping of the Chelungpu fault. Indeed, identifying the width and detail structural features of a fault zone are the key parameters to elucidate the fault behavior and faulting process. Huang *et al.* (2000) and Lin *et al.* (2003) already conducted field mapping for parts of the Chelungpu fault zone. In this paper, we will add more data from detailed field mapping, borehole logging and shallow seismic images from the Tachiachi to Wuchi river areas to unravel the structural features and kinematic development of the Chelungpu fault.

CHARACTERISTICS OF THE CHELUNGPU FAULT ZONE

Stratigraphically, the Taichung Basin lying west of the Chelungpu fault is covered by alluvium deposits, while the Fengyuan Hill to the east is covered by the Chinshui Shale, Cholan Formation, terrace and alluvium deposits (Chang, 1971). We have mapped a strip area 2-km wide on each side of the trace of earthquake fault, and the field data are combined with the results from borehole and shallow seismic imaging (Shih *et al.*, 2002). It shows that the fault zone is not confined only to the exposed traces of the earthquake ruptures, but spreads up 2000-m wide in some area. We have subdivided the study area into 3 sections, including Fengyuan to Tanzi, Takeng to Chelungpu, and Chuzikeng to Wuchi. The followings will show the detailed structural features in the three sections of the fault from north to south.

Fengyuan to Tanzi Section

North of Fengyuan, the Chi-Chi earthquake fault cut through terrace and alluvium deposits and caused the highest uplifting along the fault. In the south, the earthquake fault ran into hilly region where the Chinshui Shale and Cholan Formation are exposed (Fig. 1A). Three distinct features can be observed in this section: first, trace of the earthquake fault is in irregular shape, and the trace was not well connected southeast of Fengyuan where a jump for at least 2-km wide was found in hilly region; second, the earthquake fault spreads up 1000-m wide on the surface (e.g. in east of Tanzi); third, some branch faults with sinistral slip are found east of Tanzi. Combined with the images from shallow seismic exploration, we recognize that the leading front (westernmost) of the Chelungpu fault zone is located at the western boundary of the terrace. In addition, the Sanyi thrust fault is believed to line up with the northern extension of the Chelungpu fault (CPC, 1989a). A good outcrop is observed on the northern bank of the Tachiachi, but it is situated at more than 2-km to the west of the earthquake fault.

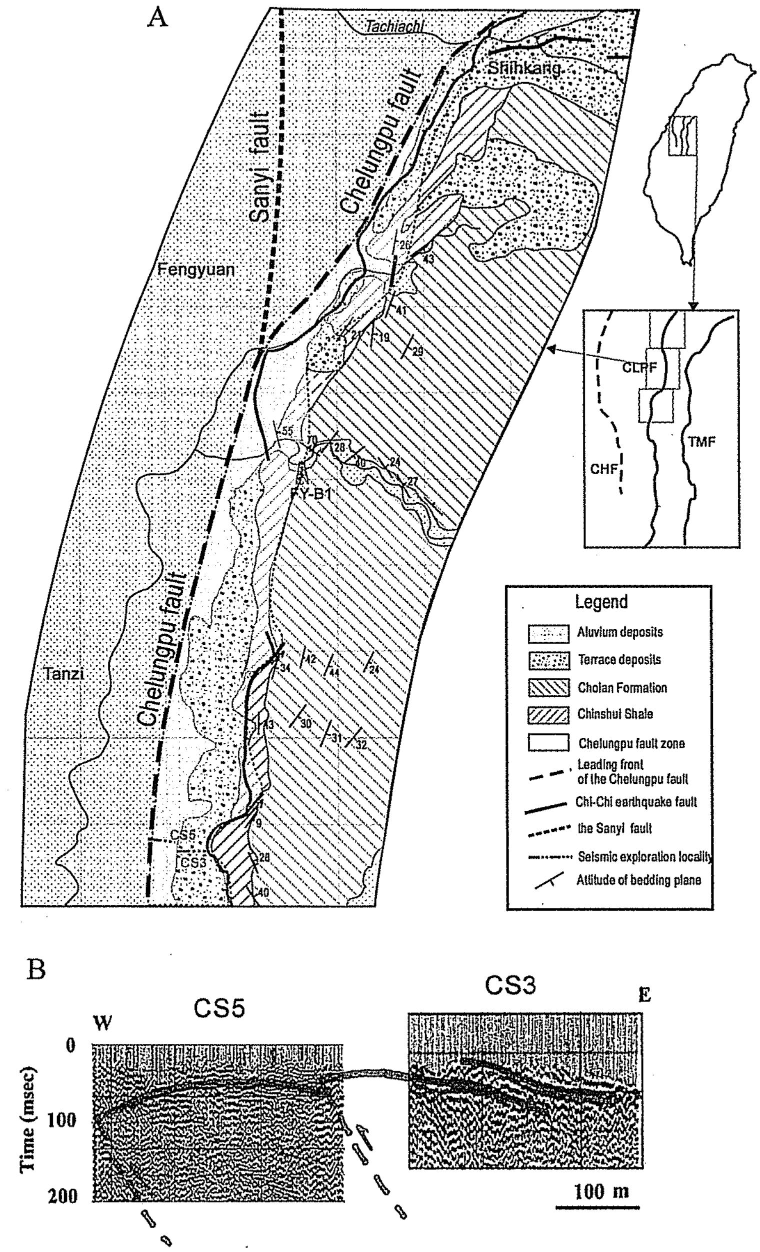

Figure 1. A. Geologic stripe map of the Chelungpu fault zone between Fengyuan and Tanzi (modified from Huang, *et al.*, 2002). FY-B1 is the locality of borehole of Tanaka *et al.* (2002); CHF represents the Changhua fault; CLPF, the Chelungpu fault; TMF, the Tamaopu-Shuangtung fault. B. A combined seismic image of the Chelungpu fault zone in the Tanzi area. CS5 is located on the lower terrace while CS3, on the higher terrace. Two proposed faults are visible in the images, which are 1000 and 700-m to the west of the Chi-Chi earthquake fault, respectively.

Fig. 1B shows a shallow subsurface seismic image combined from two profiles conducted in the Tanzi area before the Chi-Chi earthquake (Shih *et al.*, 2000). Here, two faults were interpreted to exist; one is at the westernmost part of the section and the other in between the two sections. In the western section (CS5), which is located on a lower terrace, the strata in the east dip to the east, but in the westernmost part, strata are dragged and dip toward the west. In the eastern section (CS3), which is located on the higher terrace, the strata show dipping toward the east. The location of the fault shown in the western section (CS5) matches with the Chelungpu fault that indicated by CPC (1989a). However, these two faults shown in Fig. 1B are located at about 1000-m and 700-m west of the Chi-Chi earthquake fault, respectively. Results from the electrical resistance profile in the Tanzi area (Shih *et al.*, 2000) also suggest that these fracture zones of the Chelungpu fault dips 35~65 degrees to the east.

In summary, we may find three faults in the fault system in this area, spreading more than 1000-m wide: the two faults that appear on the seismic sections might be the old faults, and the Chi-Chi earthquake fault that is situated at the joined part of the terrace and hilly region is the current active fault. All the three faults might belong to the same fault zone. Because of strain hardening, the later-formed earthquake fault migrates eastward.

Takeng to Chelungpu Section

In this section, we found the Chi-Chi earthquake fault cut into the Chinshui Shale in the Takeng area (Fig. 2A); a clear outcrop with exposed footwall and hanging wall are seen in the Talichi. Further to the south, the earthquake fault lies in between hills and plain and strikes southeast until near Buzi, where the fault strikes southwest and then extinguishes. Another rupture was found in the hilly region, which caused two steps as its ends. Several irregular surface ruptures were exposed near Sanchiao, forming the densest rupture distribution during the Chi-Chi earthquake. In addition, a NWW trending rupture with uplifting side to the north is found in Toupien Village as well. South of Sanchiao, the earthquake fault again cut into the hilly region.

There are two noticeable features found in this section: first, the surface ruptures are situated in the Chinshui Shale and the lower part of the Cholan Formation, indicating the leading front of the Chelungpu fault might be located west of earthquake fault; second, the en-echelon pattern of ruptures and steps in north of Sanchiao may indicate that the fault zone consists of several small-scale faults; and third, the fault zone in Sanchiao and Toupien areas might spread up about 2000-m wide.

A borehole of 300-m deep was drilled by CGS at the southern bank of the Talichi (TK-B1 of Fig. 2) 194-m east of the Chi-Chi earthquake fault. The core consists of 127-m thick mudstone-dominated strata of the Chinshui Shale in the upper part, with highly sheared, small-scale fracture zones locally. In the underlying 173-m thick conglomerate beds of the Toukoshan Formation, sandstone layers are highly sheared, stretched, offset and rotated. Another drilling core from a borehole in Takeng (CGS-DG-28-6) shows two fault zones of 11-m and 14-m thick, respectively. Both of the fault zones lie in the Chinshui Shale and contain foliated fault breccias and gouge. The results suggest that the main thrust is situated in the Chinshui Shale with a dip of 34- degrees to the east.

Fig. 2B shows a 960-m long shallow seismic profile of the Takeng area (DK1), in which flat and smooth strata at the middle part are disrupted by faulting, and two other faults with less separation are seen in the eastern part (Fig. 2B). Among these three faults, the westernmost one has the largest vertical offset and is located 300-m west of the Chi-Chi earthquake fault, suggesting the Chelungpu fault zone might be 300-m wide.

A

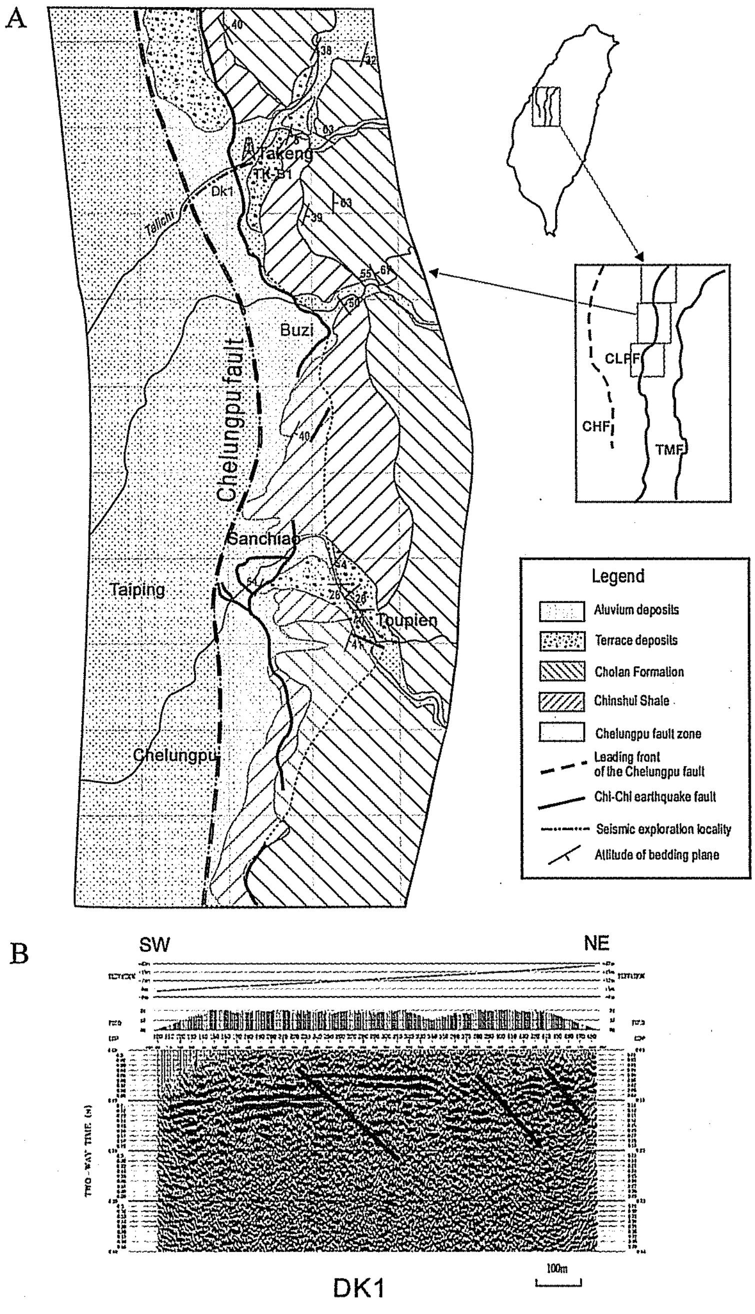

Figure 2. A. Geologic stripe map of the Chelungpu fault zone between Takeng and Chelungpu (modified from Huang, *et al.*, 2000); TK-B1 is a borehole mentioned in text. B. Shallow seismic image in Takeng area, it shows that there are three proposed faults in this image; DK1 is locality of seismic exploration.

Chuzikeng to Wuchi Section

The earthquake fault trace toward Chuzikeng strikes southward, until crosscut by a east-west trending fault, and then propagates into hilly region. A clear outcrop of the Chelungpu fault zone is exposed in a riverbed south of Tsaohuchi (TL-O1 in Fig. 3A), where fault originally thrust onto the non-lateritic terrace is new reactivated and becomes to form an uplift of 2-m high during the present earthquake. Behind the fault, many small-scale faults can be observed in the disturbed strata of the Chinshui Shale (Fig. 3B), which are also reactivated but with relatively smaller uplifts less than 10-cm. Noticeably, these faults have fault planes steeper than that of the frontal fault, and even dipping to the opposite directions occasionally. In addition, the core from a borehole of 100-m long (TL-B1) in that location shows the upper part 37-m are terrace deposits, and the lower 63-m are the Chinshui Shale. There are two fault zones found in the Chinshui Shale, each of 7 and 10-m thick, located at 75-m and 90-m depths, respectively. Both of the fault zones contain fault breccias, foliated and cataclastic structures. They extend probably to the surface at 120~170-m west of the westernmost part of the earthquake rupture. The results suggest a fault zone of more than 320-m wide, all belonging to the Chelungpu fault zone.

There are two groups of faults exposed in the riverbed of the Kanchi, one strikes northwest and the other northeast (Fig. 4). The former is extended and connected to a monocline caused by the present earthquake on the playground of Kwuanfu Junior High School. These small-scale faults are all of the reverse-type with left-lateral component. Sandstone layers in these fault zones are found folded and dragged. A borehole of 50-m deep was conducted by CGS in the Wufeng area for the supplementary needs of excavation study, unraveling two fault zones in this core, 9 and 6-m thick respectively, both with slightly sheared, foliated fabrics and cataclastic structures.

We have also obtained four shallow seismic reflections profiling in the Wufeng area after the Chi-Chi earthquake to investigate the subsurface structural features (Shih *et al.*, 2002). Two of them were deployed across the earthquake fault, one was deployed on the footwall and the other on the hanging wall (Fig. 3). The section CSW1 is 326-m long across two earthquake ruptures located at 60-m and 160-m from the western end point of this section. In this profile, three fracture zones are revealed, even though the disturbed zone is not consistent with the locations of the surface ruptures (Fig. 5A). The seismic image suggests the fault zone in shallow depth is much wider than that on the surface. In other word, the earthquake fault is only a behavior on the surface and shows only a small part of the Chelungpu fault zone. The result is also well consistent with the outcrops exposed in the Kanchi that mentioned above. The section CSW2 is 278-m long, deployed on the riverbank of the Kanchi, across the earthquake ruptures as well. Highly disturbed zones and three faults are seen in the image, and the same with the section CSW1, the largest vertical offset on the surface is not consistent with that on the seismic image (Fig. 5B). The section CSW3 is 288-m long deployed on the footwall of the earthquake fault. Slightly disturbed strata are found at about 90-msec deep and three faults are observed in this seismic section (Fig. 5C). The section CSW4 is 240-m long; the profile shows three faults existing (Fig. 5D).

In summary, two groups of earthquake ruptures were exposed and the widths spread only about 100-m wide in the Kanchi, but the fault zone might be expanded to about 400-m in the subsurface as revealed by the seismic images. Absence of sandstone layers in such a thick-bedded mudstone of the Chinshui Shale often obscures exposure of the surface fault ruptures.

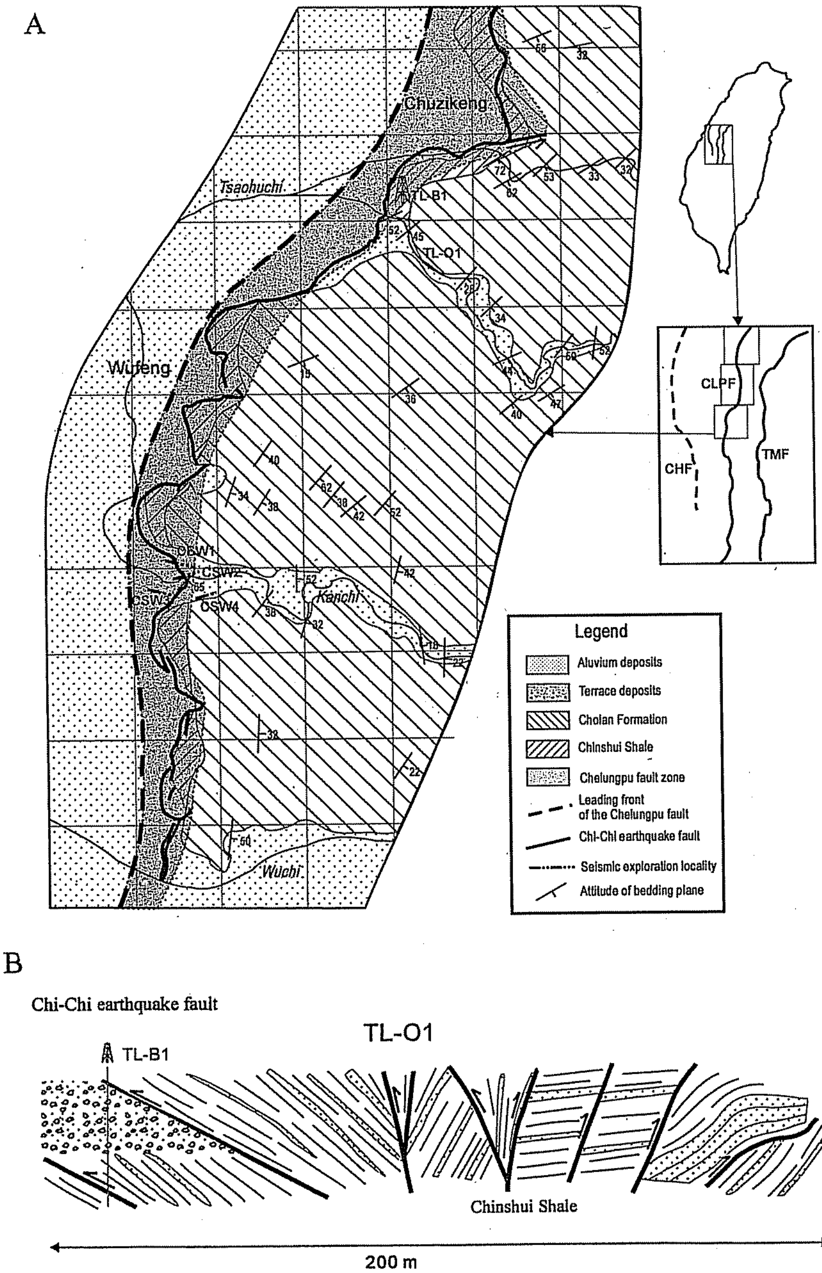

Figure 3. A. Geological stripe map of Chelungpu fault zone between Chuzikeng and Wuchi; TL-B1 represents the locality of borehole. B. A cross section combined the outcrop in south of Tsaohuchi (TL-O1) and borehole data (TL-B1), it shows that the leading front of the Chelungpu fault zone might lie at 120~170-m to the west of westernmost of earthquake rupture on surface.

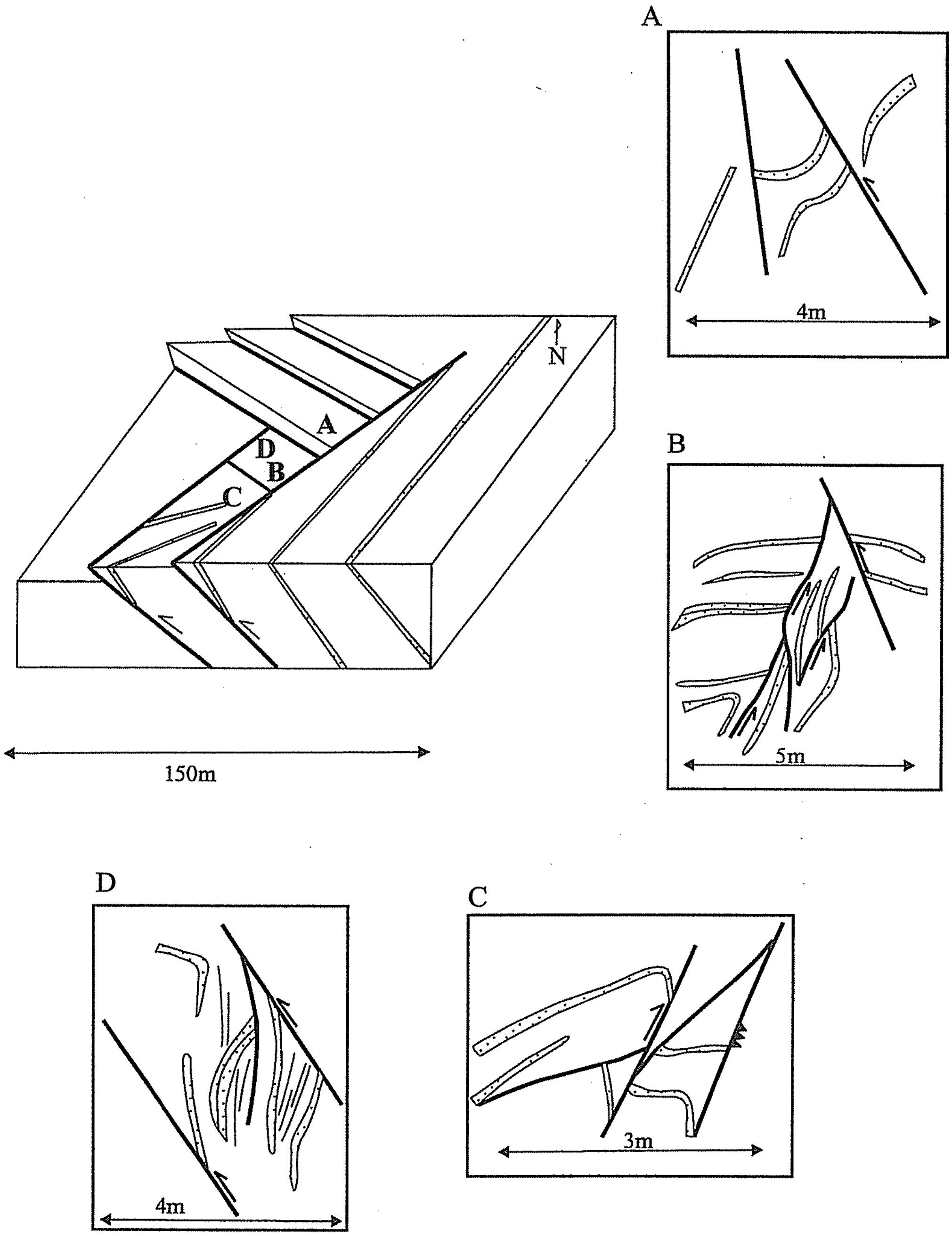

Figure 4. Small-scale structures exposed in riverbed of the Kanchi, Wufeng (plane view). One group of fault strikes northeast, and the other strikes northwest and truncated by the former. A, B, C and D are detail structures within the fault zone, which shows these faults thrust with sinistral-slip component and sandstone layers between any two minor faults are folded and dragged.

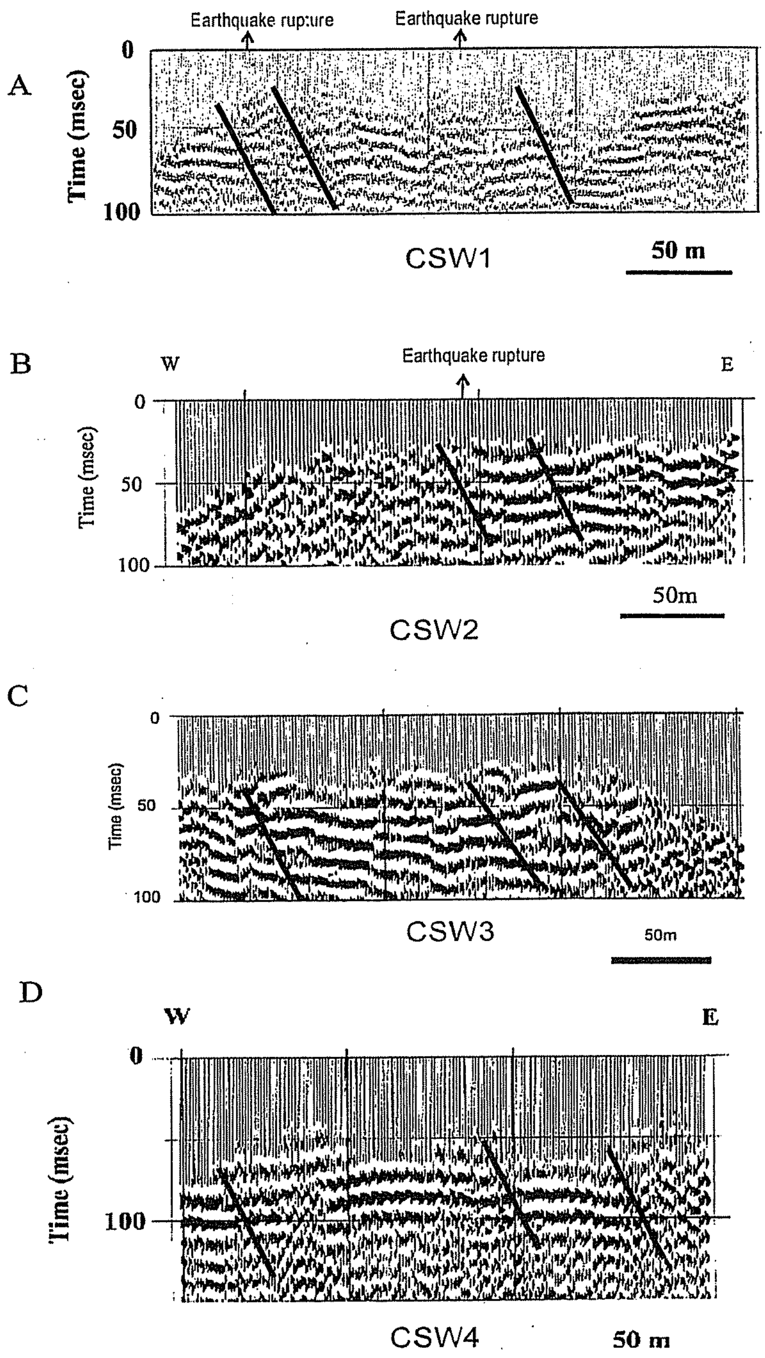

Figure 5. Seismic reflection image of the Chelungpu fault zone in Wufeng: CSC1 (A) and CSC2 (B) are at Kwuanfu Junior High School, and cross the earthquake ruptures; CSC3 (C) is located on the footwall and CSC4 (D) on the hanging wall at river bank of Kanchi.

DISCUSSION

Spread and thickness of the Chelungpu fault zone

A fault zone can be mesoscopicallly discriminated into the main gouge zone and damaged host rock according to the extent of deformation based on experimental results and field observations (Chester and Logan, 1986; Vermilye and Scholz, 1998). A main gouge zone is the one where severe deformation and more displacement occurred, while the damaged host rock includes the clustered secondary faults and displaced rock masses. Moreover, as the slip proceeding in gouge zone, stress concentration would occur in some irregularities or barriers of damaged host rock, it would eventually form secondary faults and/or induce the preexisting faults to reactivate (Vermilye and Scholz, 1998). Consequently, it may have several meso-scale faults, ranged from tens of centimeter to tens of meter wide, visible in the outcrops, drilling cores and seismic images. These faults have the same strata exposed on its hanging wall and footwall, and might be treated as secondary faults, and most of them might have become the earthquake ruptures of the Chi-Chi earthquake. As we have mentioned, many faults have been found in the outcrops, cores and seismic images around the earthquake fault, whether they are reactivated during the Chi-Chi earthquake. Wang *et al.* (2002) also proposed the sole thrust that separating the late Quaternary gravel deposits from the Kueichulin Formation would meet at a depth of 650-m. According to their proposed Chi-Chi earthquake faults that are situated at 225-m and 425-m deep to the sole thrust, supposing the dip of sloe thrust is 40-degree as indicated from drilling data in Takeng, thus the surface extension of the sole thrust should be at 660-m west of the Chi-Chi earthquake fault. All of the above results suggest that the Chelungpu fault zone might spread into a very broad area, e.g. 1000-m in Tanzi, and 2000-m in Sanchiao, or more than 300-m in Takeng and 400-m in Wufeng.

Wojtal and Mitra (1986) suggested that rock masses slides along a fault plane would accompany with strain hardening, and consequently strain softening. Strain softening usually occurs on the fine-grained strata where higher strain is concentrated (Hull, 1988). Thereafter small fractures and faults will be formed near the fault plane and eventually the meso-scale faults are clustered. However, other factors may also control the width of a fault zone, such as reactivation and displacement of a fault. Stratigraphically, the Chinshui Shale consists of thick beds of shale, occasionally intercalated with thin alternated shale/sandstone, which belongs to the Pliocene outer shore deposits (Yang, 1997). Therefore, the faults that are situated in shale beds of the Chinshui Shale and the Cholan Formation are favored for strain softening. It is concluded that the Chelungpu fault zone actually covers the whole Chinshui Shale and lower part of the Cholan Formation, and is over 400 m thick.

Imbrications and Kinematic Development of the Chelungpu fault

For a thrust fault, secondary faults will be branched upward from the main fault. They are usually clustered near surface because of the stress-free boundary condition. Consequently, these branch faults are developed on the hanging wall and arranged as an imbricate thrust system during progressive movement (Scholz, 2002). Ramsay and Huber (1987) have suggested that there are usually many slip planes in a thrust system for which the leading and trailing imbricate fans are main styles; while the former one has the largest displacement in the frontal fault, the latter one in the rear fault.

The Chi-Chi earthquake fault and associated surface ruptures actually belong to secondary faults of the Chelungpu fault. They formed on the hanging wall, in the Chinshui Shale and

Cholan Formation. Some of these faults were reactivated from old faults and others newly formed. Since the Chelungpu fault has more than 1500-m in stratigraphic separation, it might develop a several hundred-of-meter thick fault zone. Secondary faults that branched from the main thrust constitute an imbricate structure and broaden the fault zone on the surface. In this case, the Chi-Chi earthquake fault will be only a surface expression for some of the branch faults in the Chelungpu fault zone. A drilling log in the Fengyuan area was carried out by Tanaka *et al.* (2002). They show that there were two fracture zones of 3-m and 10-m thick, respectively, both activated during the Chi-Chi earthquake: the one in the bottom could be the major fault, and the one on top a new breaching fault. Additionally, based on seismic exploration, Wang *et al.* (2002) suggested that another fault gouge zone beneath the above two fractures zones would be the main thrust, which separates the Kueichulin Formation from the Toukoshan Formation. All these data support that the observed earthquake fault should be the secondary faults related to the Chelungpu fault zone. These secondary faults may not be necessarily parallel to each other; instead, and they might be branched obliquely upward from the sole thrust instead. These so-called splay faults are often exposed in southern section of the Chelungpu fault (Lin *et al.*, 2000a, 2003).

The proposed model for the faulting process of the major faults in central Taiwan is shown in Fig. 6, in which, we may see three major thrust faults, from west to east, called the Changhua, Chelungpu and Tamaopu-Shuangtung faults in the fold-and thrust belt of western central Taiwan (e.g. Lin *et al.*, 2000b). Each thrust fault was formed and branched from the detachment fault, and it uplifted the thrust sheet due to compression caused by collision. In the meanwhile, the foreland subsided and became a basin on the footwall of the thrust. Later on, the newly formed foreland basin gradually gathered the overburden and pore pressure, and was favorable for initiating faulting. Then, it developed another new thrust fault, which was branched from the decollement, and eventually caused a new thrust sheet in progressive deformation. This process was repeated for foreland basin migration and uplifting into the fold-and-thrust belt in western Taiwan. It can be identified in fact that the sediments in each footwall of thrust are younger westward and all unconsolidated and/or semi-consolidated. Based on the imbricate nature and stratigraphic separation of each major fault, one would expect a sequence of faulting as follows: the Tamaopu-Shuangtung fault that separates the outer and inner Foothills was formed first; the Chelungpu fault that separates the western plain and the outer Foothills was second; and then the Changhua fault was formed at last, which is proposed to be a blind fault concealed by alluvium deposits and built up the gentle Pakuashan anticline on its hanging wall. The sequence of faulting was formed, and the major faults were propagated toward west, thus constituting a trailing imbricate fan. Nevertheless, the faulting process within each fault zone is arranged as a leading imbricate fan (Fig. 6D) as indicated by the above-mentioned cases in Tanzi, Takeng and Wufeng. When a thrust fault becomes the leading fracture, it will have the largest displacement, while some other secondary fractures formed simultaneously and/or later on its hanging wall will have smaller displacement. As a thrust advance progressively, branch faults will slip and extend to surface eventually, either controlled by strain partitioning or competent contrast. According to the lithologic contrast or localized strain softening, we may found the Chi-Chi earthquake ruptures distributed in a broadened zone in some areas. If this is the case, it will be very hard to tell which particular secondary fault is going to slip in further event. That is, a fault with broad fault zone, such as the Chelungpu fault that is composed of many fracture zones, should be considered, as a whole, as a fault system in working on earthquake geology and hazard assessment.

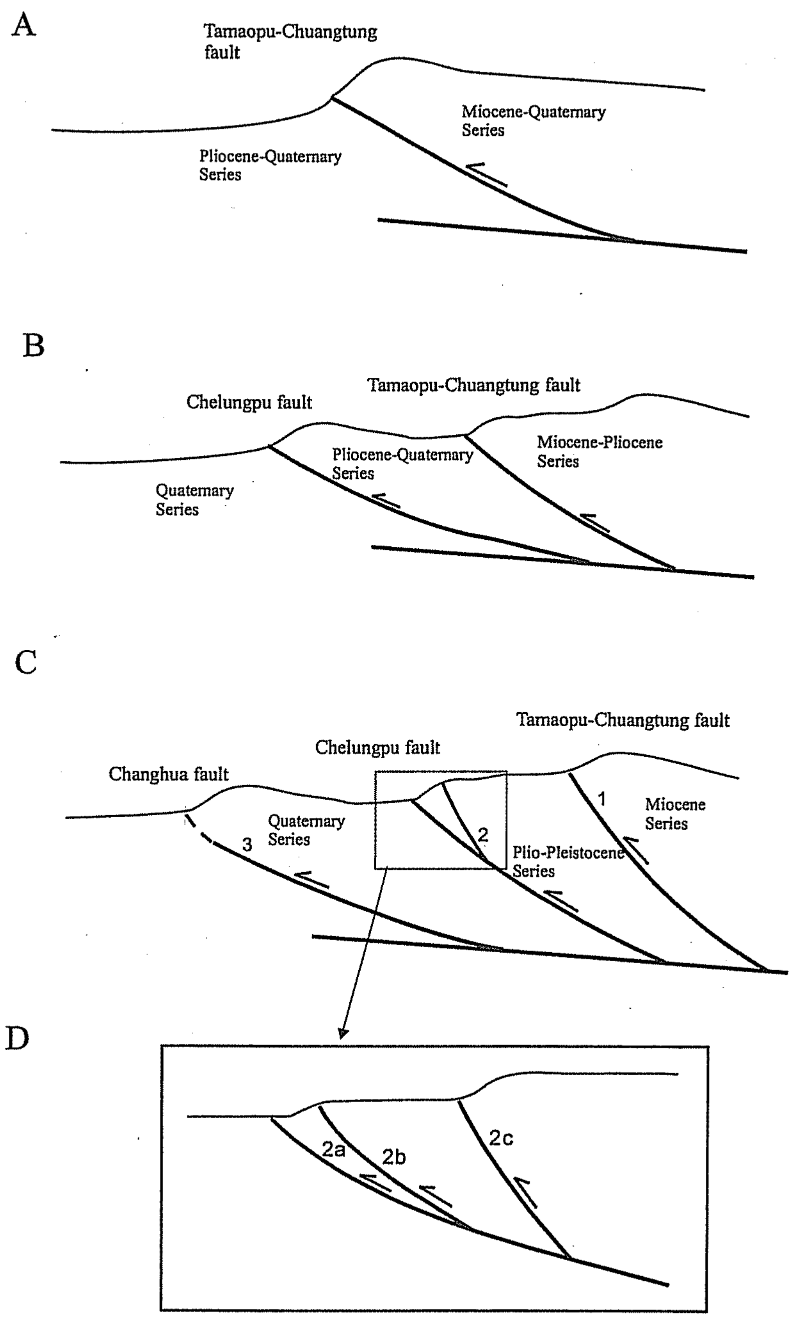

Figure 6. Imbrications and kinematic development of major faults in west-central Taiwan: Thrust sheet related to Tamaopu-Shuangtung fault (A); thrust sheet related to Chelungpu fault (B); and thrust sheet related to Changhua fault, the present situation (C). These main faults constitute a trailing imbricate fan, while imbrications within each fault constitute a leading imbricate fan (D). Numbers and characters show their sequence of development.

Lateral Propagation and Geological Segments of the Chelungpu fault

When a fault is formed and subsequently grows, its length, thickness and internal structure will all gradually change. Scholz (2002) showed that the central portion of a fault might have the largest displacement and it gradually decrease to zero at its tips. In a descending order, the strata exposed in the study area consists of the Nanchung Fm. (700-m thick), Kueichulin Fm. (800-m), Chinshui Shale (140-m), Cholan Fm. (1800-m), Toukoshan Fm. (1400-m: 1000-m thick for the lower member, and 400-m of the upper member), and the late Quaternary alluvium deposits of unknown thickness. The thickness of each stratigraphic unit or its equivalents is estimated according to Ho (1986). If we use the separation of a fault as its finite-state displacement, although the true displacement path is unknown, we could discriminate a long fault into several geological segments. To do that we must know the separation, sense of movement, structural style, and if exists, the reoccurrence feature of that fault. In this paper, we define several fault segments, or geological segments, based on a fault at where of largest separation as the initial faulting and the slip is smaller towards its two tips. In this case, the Chelungpu fault is divided into 4 segments (SC1-SC4). The SC1 segment is bounded by the Sanyi fault in the north, and the SC4 segment is bounded by the Tachienshan fault in the south (Fig. 7). The geological features of each fault segment are described as follows:

The SC1 segment may be branched from the Sanyi reverse fault but with left-lateral sense of movement. If the main slip plane of the Chi-Chi earthquake fault within the Chinshui Shale is considered, such as that suggested by Tanaka *et al.* (2002) and Wang *et al.* (2002), then beneath theses two faults, a major fault that separates the Kueichulin Fm. from the Toukoshan Fm. should be the southern extension of the Sanyi fault. It implies that the northern part of the Chelungpu fault is branched from the Sanyi fault near Fengyuan city. In addition, the latest activated event of SC1 segment is 2000-year before the Chi-Chi earthquake according to the age dated on undisturbed terrace. The SC2 segment has structural features similar to that of SC1 segment, except that the hanging wall exposed the Chinshui Shale with smaller separation. However, the lateral propagation of the SC2 segment is also eastward and this segment has the widest fault zone as mentioned before. The SC3 segment is the longest one based on lithologic similarity in the hanging wall. Recently, 3 possible reactivated events have been located in the segment in the past 1900 years by excavation (Chen *et al.*, 2003). The SC4 segment is the southernmost part of the Chelungpu fault, which is connected with the Tsushiang fault in the north and the Luliao fault in the south (Lin *et al.*, 2002b). Both of these two faults are left-lateral slip faults except that the Tsushiang fault has a reverse component. The SC4 segment constitutes a syncline with its axis trending E-W on its hanging wall; it is quite different from the homoclinal structures that are found on the hanging wall of the other segments.

The Sanyi fault has the largest separation among the main faults in western central Taiwan. The separation is largest in the middle part and gradually decreased towards its tips. This fault is not activated during the Chi-Chi earthquake, and is covered by late Pleistocene alluvium deposits based on field observation and seismic exploration (Wang *et al.*, 2002). The Tachienshan fault was however activated during the Chi-Chi earthquake, and caused 10 to 40-cm uplifts with 1 to 2-m right-lateral displacements (Lin *et al.*, 2000b). Above the fault, the Kueichulin Formation is exposed on its hanging wall and the upper member of the Toukoshan Fm. on its footwall. The dipping angle of the Tachienshan fault is about 75-degree, obtained from drilling and field data, which is in contrast to that of the Chelungpu fault of around 30~40-degree.

It is concluded that the secondary faults were not only branched from the hanging wall of each fault zone but also laterally propagated to their tips. All the fault segments propagated and turned right eastward, controlled by the northwestward tectonic force.

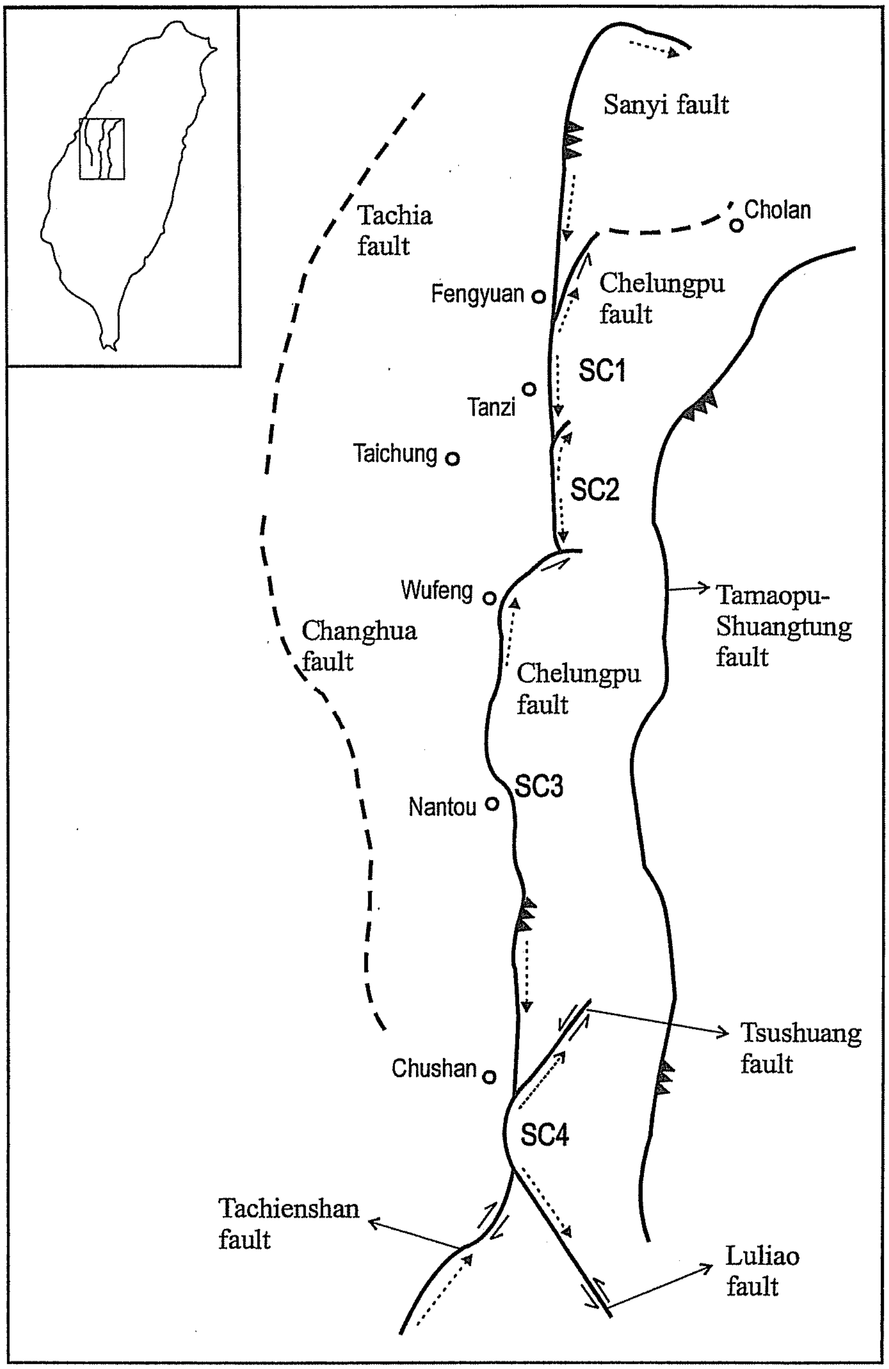

Figure 7. Propagation and geological segments related to the Chelungpu fault. Each segment has the direction for decreasing of separation (arrow with dotted line) towards to its tips, and the propagation of its northerly tip turn east.

CONCLUSIONS

The Chi-Chi earthquake caused surface ruptures that are situated on plain, the adjoining area of plain and hills, and the hilly region. Structurally, these earthquake ruptures lie on the hanging wall of the Chelungpu fault, and are distributed in a broad zone based on the lithologic contrast or localized strain softening. The Chelungpu fault zone is spread up to as wide as 2000-m and 200 to 400-m thick in the Chinshui Shale and the lower part of the Cholan Formation.

The three major thrust faults, namely the Changhua, Chelungpu and Tamaopu-Shuangtung faults in western central Taiwan, constitute a trailing imbricate fan of a faulting process that is propagating westward due to foreland migration. However, the faulting process within each fault zone is arranged as a leading imbricate fan, in which the leading fault has the largest displacement, and some secondary fractures are formed simultaneously and/or later on the hanging wall of the main fault. Besides, the secondary faults are not only branched from the hanging wall of each fault zone but also propagated toward their tips. In addition, the Chelungpu fault can be divided into 4 segments, all the fault segments propagated and turned right eastward at their northerly tips and is controlled by the northwestward tectonic force.

ACKNOWLEDGMENTS

This research is granted by the Central Geological Survey under the project of "Investigation on Earthquake Geology and Active Faults". Messrs. Wen-Jeng Huang, Zih-Yen Chen and Ms. S.Y. Liu gave assistance in field mapping, and two anonymous reviewers gave the critical suggestions, to which the gratitude is due.

REFERENCES

Central Geological Survey (1999a) *Surface Ruptures along the Chelungpu Fault during the 1999 Chi-Chi Earthquake*: Chungho, Taipei. (In Chinese)

Central Geological Survey (1999b) *Geological Reports of the 1999 Chi-Chi Earthquake*: Chungho, Taipei, 315pp. (In Chinese)

Chinese Petroleum Corporation (1989a) Geological map sheet of Taichung, scale 1:100,000, Miaoli, Taiwan.

Chinese Petroleum Corporation (1989b) Geological map sheet of Chiayi, scale 1:100,000, Miaoli, Taiwan.

Chang, S.L. (1971) Subsurface geological study of the Taichung basin, Taiwan: *Petrol. Geol. Taiwan*, **8**, 21-45.

Chen, W.S., Lee, K.J., Lee, L.S., Chen, Y.G., Chang, H.C. and Lee, Y.H. (2003) Paleoseismology of the Chelungpu fault during the past 1900 years: 2003 annual meeting of Geological Society Located in Taipei, Abstract, p6. (In Chinese)

Chester, F.M. and Logan, J.M. (1986) Implications for mechanical properties of brittle faults from observations of the Punchbowl fault zone, California: *Pure and Applied Geophysics*, **124**, 79-106.

Ho, C.S. (1986) *An Introduction to the Geology of Taiwan*: Central Geological Survey, MOEA, Chungho, Taipei, 164pp.

Huang, W.J., Chen, Z.Y., Liu, S.Y., Lin, Y.H., Lin, C.W. and Chang, H.C. (2000) Surface deformation models of the 1999 Chi-Chi earthquake between Tachiachi and Toupienkengchi, Central Taiwan: *Special Publication Central Geol. Survey*, **12**, 63-87. (In Chinese)

Hull, J. (1988) Thickness-displacement relationships for deformation zones: *J. Struct. Geol.*, **10**, 431-435.

Lai, T.C., Lee, J.F., Hou, C.H., Fei, L.Y. and Lin, C.C. (1997) Investigation of the Chelungpu fault- geodesy and drilling, Detail Planning of the MRT Net of Taichung Metropolis: unpublished report of Taiwan Government. (In Chinese)

Lin, C.W., Shih, T.S., Huang, W.C., Shih, T.S. and Chang, H.C. (2000a) The Chi-Chi earthquake fault and structural analysis of the area south of Choshuihsi, central Taiwan: *Special Publication Central Geol. Survey*, **12**, 89-111. (In Chinese)

Lin, C.W., Chang, H.C., Lu, S.T., Shih, T.S. and Huang, W.J. (2000b) *An Introduction to the Active Faults of Taiwan, Explanatory Text of the Active Fault Map of Taiwan*, 2nd Edition: Special Publication Central Geol. Survey, 13, 122pp. (In Chinese)

Lin, C.W., Shih, T.S. and Shih, R.C. (2003) Characteristics of the Chelungpu fault zone in Nantou Area, Central Taiwan: *Bull. Central Geol. Survey*, no.16. (In Chinese)(In Press)

Ramsay and Huber (1987) *The Techniques of Modern Structural Geology, Vol.2: Folds and Faults*: Academic Press, London, 700pp.

Scholz, C.H. (2002) *The Mechanics of Earthquakes and Faulting*: 2nd edition, Cambridge University Press, U.K., 471pp.

Shih, R.C., Chen, P.H., Yen, H.Y. and Lin, C.H. (2000) Geophysical prospecting in central Taiwan and Taitung area: *Central Geological Survey*, unpublished report, 126pp. (In Chinese)

Shih, R.C., Chen, P.H., Lu, M.T. and Chen, W.S. (2002) Investigation of Earthquake Geology and Development of Database on Active Faults- Geophysical Prospecting (1/5): *Central Geological Survey*, unpublished report, 166pp. (In Chinese)

Tanaka, H., Wang, C.H., Chen, W.M., Sakguchi, A., Ujiie, K., Ito, H. and Ando., M. (2002) Initial science report of shallow drilling penetrating into the Chelungpu fault zone, Taiwan: *TAO*, **13**, no.3, 227-251.

Vermilye, J.M. and Scholz, C.H. (1998) The process zone: a microstructural view of fault grow: *J. Geophys. Res.*, **113**(B6), 12223-12237.

Wang, C.Y., Tanaka, H., Chou, J., Chen, C.C. and Hong, J.H. (2002) Shallow reflection seismics aiding geological drilling into the Chelungpu fault after the 1999 Chi-Chi earthquake, Taiwan: *TAO*, **13**, no.2, 153-170.

Wojtal, S. and Mitra, G. (1986) Strain hardening and strain softening in faults from foreland thrust: *Geol. Soc. Am. Bull.*, **97**, 674-687.

Wojtal, S. and Mitra, G. (1988) Nature of deformation in some fault rocks from Appalachian thrusts: *Special Paper Geol. Soc. Am.*, no.**222**, 17-33.

Yang, Z.C. (1997) The sedimentary environments of the Chinshui Shale, Cholan Formation and Toukoshan Formation: Master thesis of Institute of Geology, National Taiwan University, 120pp. (In Chinese)