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Structure of the 1999 Chi-Chi earthquake rupture and interaction of thrust faults in the active fold belt of western Taiwan

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Abstract

We summarize the structural characteristics of the surface ruptures of the 1999 Mw 7.6 Chi-Chi earthquake in western Taiwan and discuss the geological interaction of the Chelungpu fault with adjacent faults. Based on geological investigations, seismological analyses, and GPS measurements of surface co-seismic displacements, we describe the regional 3-D fault plane and slip distribution of the Chi-Chi earthquake and compare these to the geological features of the Chelungpu fault. We find that one key feature of the Chelungpu fault is the stratigraphy-controlled slip surface: at the level of the uppermost few kilometers, the Chelungpu fault slip plane generally follows the bedding plane of the Pliocene Chinshui shale. The second key feature of the Chelungpu fault is the difference in structurally geometric configuration between its northern and southern segments. The northern Fengyuan segment shows a bedding-parallel thrust fault within east-dipping strata in both footwall and hanging wall. In contrast, the southern Tsaotun segment exhibits east-dipping strata are overthrust onto flat-lying recent alluvial deposits. These two features not only explain a hinterland imbricate thrusting on the hanging-wall of the Fengyuan segment, but also explain the change in strike of the Chi-Chi surface ruptures at the northern end. The southern end of the 1999 Chi-Chi rupture is interpreted to be linked to a series of NW-trending strike-slip faults. In particular, we propose that the Luliao strike-slip fault served as the lateral ramp of the Chelungpu fault, and the Gukeng strike-slip fault acted as a barrier to end the southern propagation of the 1999 rupture. Geomorphic features and paleoseismological data indicate that the range-front Chelungpu fault has generated large earthquakes during the last several thousand years. Alternatively, in the Miaoli area to the north and the Chiayi area to south, historical earthquakes as well as active geomorphic features are not restricted on the range-front thrust faults. Instead, more complicated structures, including tightly spaced folds, duplex structures, and strike-slip faults are involved in seismogenic processes. A more detailed investigation of regional structural characteristics is needed for mitigation against the seismic hazards in the 300-km-long active fold belt in western Taiwan, where several damaging large earthquakes have been documented during the last century.

Keywords: Earthquake fault; Thrust; Chi-Chi earthquake; Taiwan

1. Introduction

The 1999 Mw 7.6 Chi-Chi, Taiwan, earthquake provides abundant multidisciplinary data that allow for better characterization of the structural geometry of the Taiwan collision. The Chi-Chi earthquake, much like the 1906 San Francisco and 1995 Kobe earthquakes, was among the largest events to strike highly populated areas in recent human history. Severe damage caused by the earthquake includes nearly two thousand casualties and an estimated economic loss of about 20 billion US dollars. Nevertheless, substantial scientific information has been gathered because of the earthquake; abundant seismological data were obtained from a dense network of seismometers (CWB, 1999), numerous GPS measurements were made by campaign sites and continuous stations (e.g., CGS, 1999b; Yang et al., 2000; Yu et al., 2001), and detailed field investigations have been carried out along the 90-km-long surface rupture (e.g., CGS, 1999a,b; Chen et al., 2001a; Kelson et al., 2001; Lee et al., 2002a). In this paper, we synthesize

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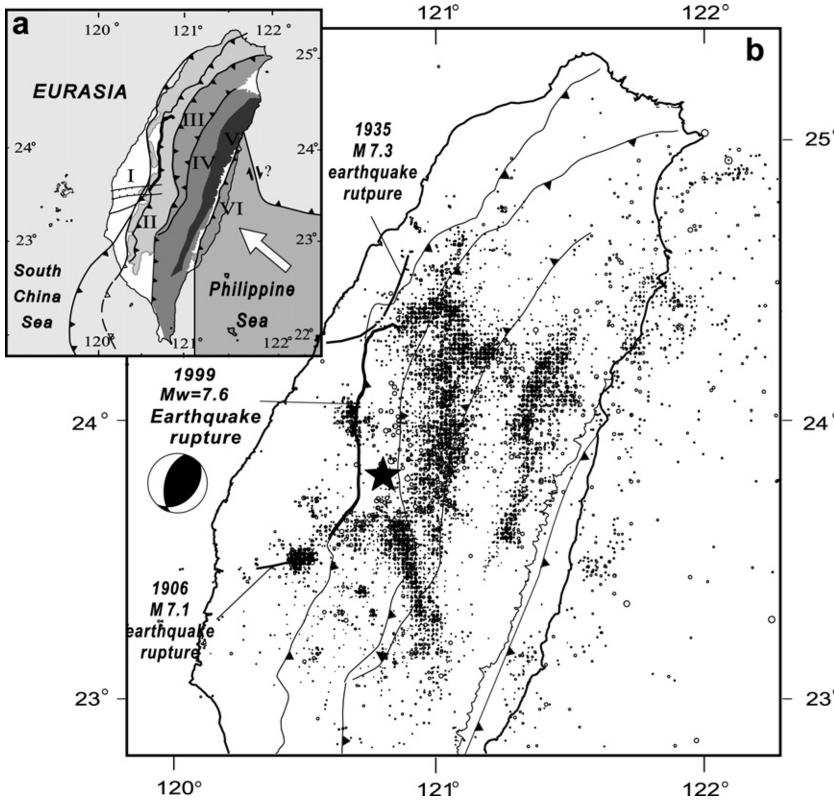

Fig. 1. (a) Tectonic framework and the general geological units of Taiwan. Rock units I to V belong to the Eurasian plate: I, Coastal plain; II, Foothills; III, Hsuehshang Range; IV, Backbone Range; V, Tananao metamorphic basement. Rock unit VI, Coastal Range, belongs to the Philippine Sea plate. The large open arrow indicates the 8.2 cm per year movement of the Philippine Sea plate with respect to the Eurasian plate. (b) The 1999 Mw 7.6 Chi-Chi earthquake sequence and the co-seismic surface rupture. Black star: epicenter of the main shock. Small dots: aftershocks from 9/21/1999 to 2/28/2000 (Kao and Chen, 2000). The surface ruptures of the 1935 M 7.3 Shitang earthquake and the 1906 M 7.1 Meishan earthquake are shown to the north and to the south of the Chi-Chi ruptures, respectively.

the structural and tectonic characteristics by combining the results of geological and geophysical studies, in order to gain insight on structural controls on the Chi-Chi earthquake.

The second portion of this paper discusses the structural relationships between earthquake and co-seismic growth of the fold-and-thrust belt, which are closely related but have not yet been fully understood (Yeats et al., 1997). The Taiwanese fold-and-thrust belt is characterized by a series of sub-parallel foreland verging thrust faults. The structural characteristics of thrust segments appear to be a result of an accumulation of large earthquakes that ruptured repeatedly on a fault patch. The structure of a segment of a thrust is often complicated at its along-strike ends where it may, or may not be linked with other faults. The complexity at the along-strike ends of the thrusts is usually due to heterogeneity in foreland rocks, or an along-strike spatial-temporal variation during the development of the thrust system. Study of the relationship between the structural characteristics of a large earthquake rupture and the long-term geological structures may thus allow us to define the history of regional structural evolution of thrust faults in Taiwan in greater detail.

The purpose of this paper is two-fold. First, we aim to synthesize the structural characteristics of the Chi-Chi earthquake rupture, in order to provide an overview in terms of geological structure. Second, we seek to provide evidence for the relationships between the structures that moved in the 1999 earthquake rupture and regional long-term geological strain, in order to give insight on the tectonic evolution of the Taiwan fold-and-thrust belt. In the following sections, we first describe the regional tectonic setting and geological background. We then summarize and compare structural behavior between the 1999 Chi-Chi earthquake and the long-term geological strain along the Chelungpu fault. We then summarize the structural characteristics of the Chi-Chi surface rupture. Finally, we discuss the interactions among the faults in the adjacent areas, by emphasizing the different long-term structural characteristics between active faults at the leading edge of the orogen.

2. Tectonic and geological setting

2.1. Plate convergence around Taiwan

The Chi-Chi earthquake occurred in the central western foothills of the Taiwan mountain range, a product of the oblique convergence between the Eurasian and the Philippine Sea plates since the Plio-Pleistocene (Ho, 1967, 1986; Suppe, 1981; Angelier, 1986; Tsai, 1986; Fig. 1). The conver-

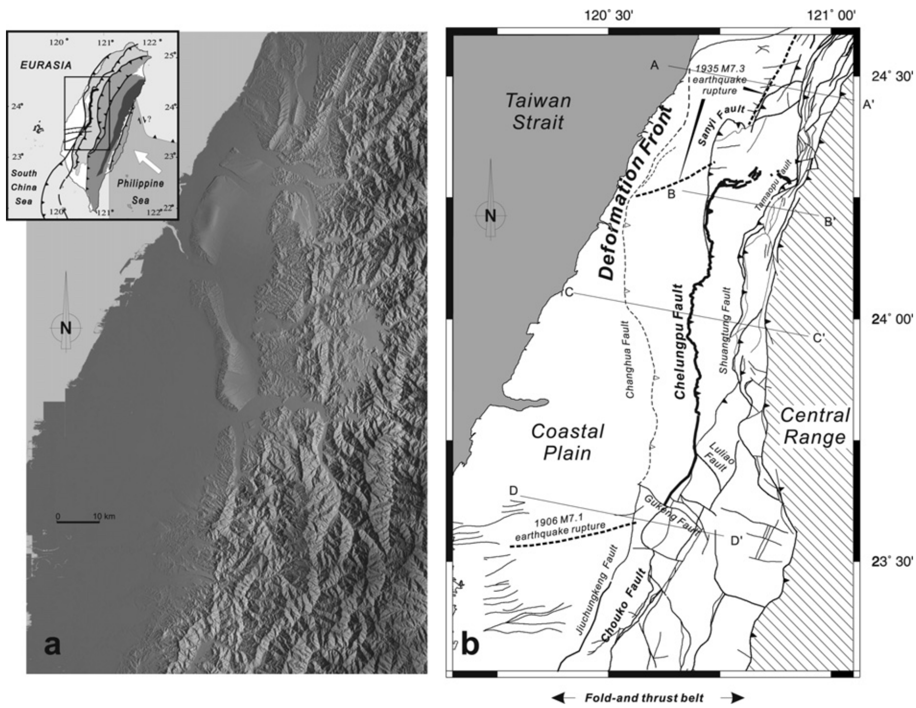

Fig. 2. (a) Shaded relief of 40-m DEM showing general topography and (b) general structures in the vicinity of the 1999 Chi-Chi earthquake area, central western Taiwan (after CPC, 1982). The 1999 earthquake ruptured the range-front Chelungpu fault (heavy curved line). The Chelungpu fault shows different structural characteristics from the Sanyi fault to the north and the Chukou fault to the south, which is demonstrated in the geological cross-sections in Fig. 3.

gence of these two plates occurs at a rate of about 82 mm/yr, according to the GPS measurements during the last 15 years (Yu et al., 1997; Yu and Kuo, 2001). The plate geometric configuration is characterized by opposing subduction zones: the Philippine Sea plate subducts northward under the Eurasian continental margin east of Taiwan and overrides the South China Sea plate (attached to the Eurasia continent margin) southwest of Taiwan. Between these two subduction zones, the Luzon island arc (located on the Philippine Sea plate) collides with the Chinese continental margin of Eurasia and produces the Taiwan mountain belt.

In addition to a record of low magnitude seismic activity along the subduction interface northeast of Taiwan, however, destructive events have also occurred in the foothills (fold-and-thrust belt) of western Taiwan according to historical accounts in the last century. The 1999 Chi-Chi earthquake was one of the largest of these damaging earthquakes and it was located in the seismic gap between the historical 1906 M 7.1 Meishan earthquake to the south and the 1935 M 7.3 Shihtan earthquake to the north (Fig. 1b).

2.2. Fold and thrust belt of western Taiwan

The fold-and-thrust belt in western Taiwan extends north to south for about 300 km and is about 20–30 km wide. It is characterized by several sub-parallel thrust faults that deform Tertiary sediments of the Chinese continental margin. In general, regional structure is characterized by anticlinal folds in the hanging walls of major thrusts and synclinal folds in their footwalls (Ho, 1967; Stach, 1957). For the area of the 1999 Chi-Chi earthquake in west central Taiwan, there are three parallel N-S striking major thrust faults (Fig. 2): (a) the Chelungpu fault, which ruptured during the Chi-Chi earthquake, and along which the Pliocene shallow marine and overlying Quaternary fluvial sediments are thrust over recent alluvial deposits (Fig. 3, section C–C′, Mouthereau et al., 2001); (b) the Shuangtung fault, located east of the Chelungpu fault, and along which the Miocene shallow marine sediments are thrust over 1 Ma Quaternary fluvial deposits (Lee et al., 1996); (c) the Changhua fault, a blind thrust to the west of the Chelungpu fault that exhibits ongoing anticlinal folding in Quaternary deposits in the hanging-wall of the thrust.

The 1999 earthquake of the Chelungpu fault is connected to the Sanyi fault and the Chukou fault, to the north and to the south, respectively (Fig. 2). The geological structure of these range-front thrusts is characterized by major east-dipping reverse faults along which Miocene or Pliocene strata are thrust over Quaternary or recent alluvium. In addition to the westward propagating thrusts, southward propagation of the fold belt was also occurred at a rate of about 90 km/My (Suppe, 1984). Assuming the initiation of faults within the range-front system mimic the southward propagation model, the Sanyi fault is interpreted to be initiated first over the last 2–3 My, followed by the Chelungpu fault, and then the Chukou fault. However, over the last tens of thousands of years, these three faults have all been active.

Structural characteristics of the fold belt vary north and south of the Chelungpu fault, as revealed by interpreted geological cross sections (Fig. 3). To the north, in the Sanyi fault region, the structure is characterized by several tightly spaced folds (Fig. 3, section A–A′, Namson, 1981). To the south, in the Chukou fault region, the structure is characterized by

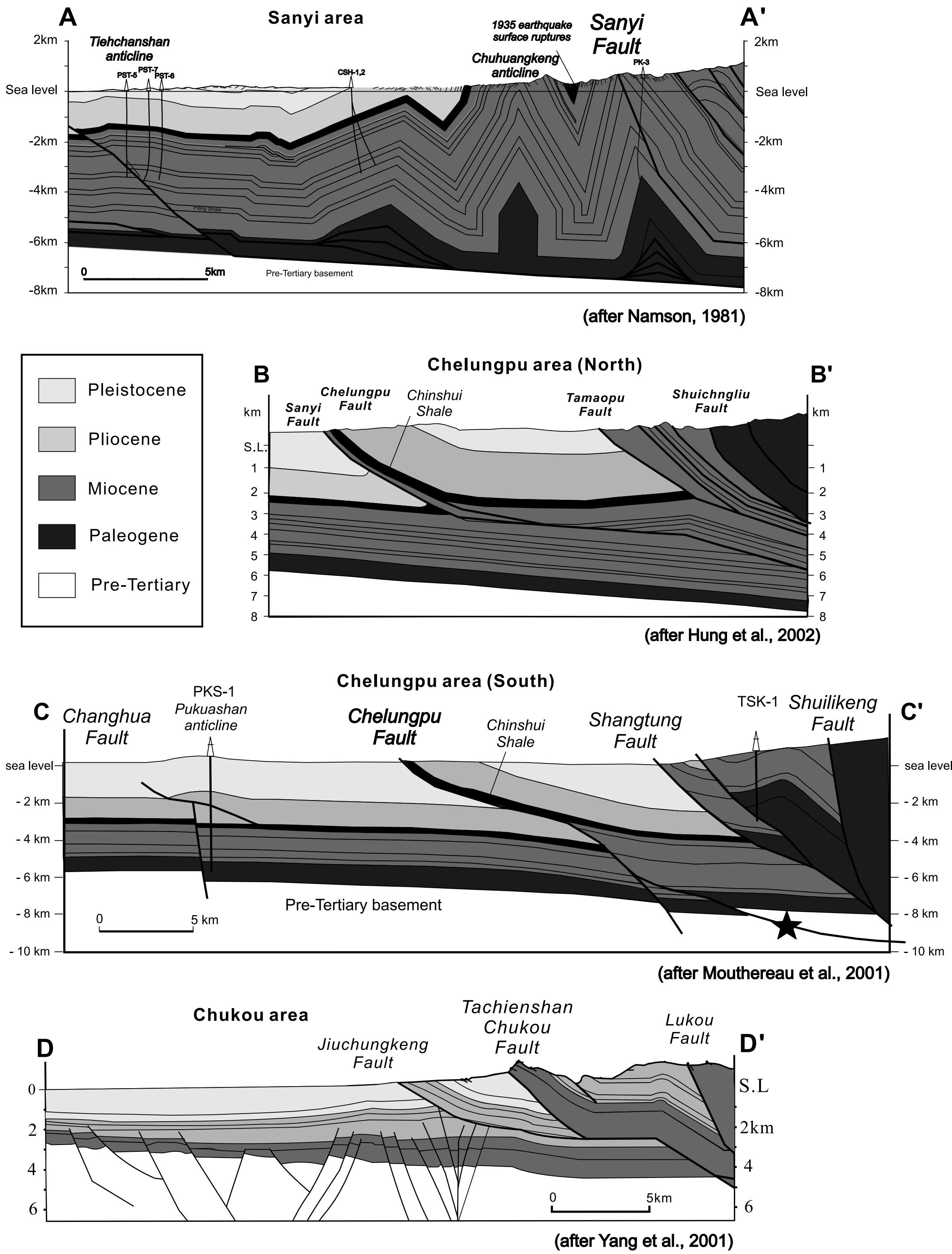

Fig. 3. Interpreted geological cross section in central western Taiwan. Location see Fig. 2. The structure of the Sanyi area (section A–A′) is characterized by tight folds, the Chelungpu area by open faults and folds (sections B–B′ and C–C′), and the Chukou area by tight faults with a duplex (section D–D′).

several parallel, closely spaced thrust faults, which include the Chukou fault (the southern extension of the Chelungpu fault), the Lukou fault, and the Jiuchungkeng fault (the southern extension of the Changhua fault). Together these form a duplex thrust system (Fig. 3, section D–D′ Yang et al., 2001).

3. The Chelunpgu fault and the 1999 earthquake rupture

In general, the earthquake ruptured the entire Chelungpu fault, according to surface observations (e.g. Chen et al., 2001a) and inversion of GPS data (Johnson et al., 2001). In

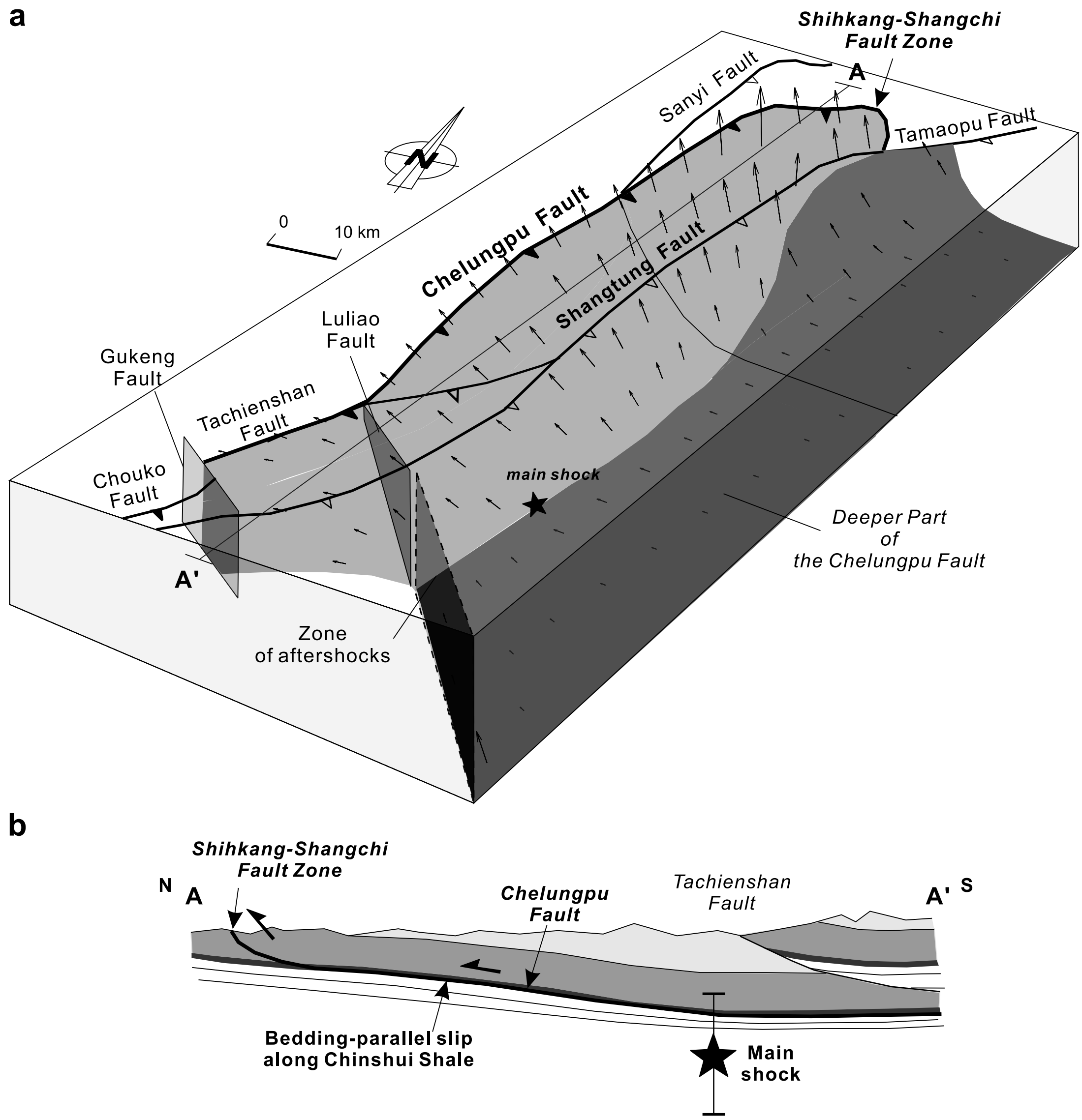

Fig. 4. (a) 3-D schematic structure of the 1999 Chelungpu rupture and its relationship with nearby major faults. The arrows on the slipped planes show the general trends of slip derived from analyses of geophysical inversion (Ma et al., 2000; Johnson et al., 2001; Chi and Dreger, 2002). (b) N-S cross section of the Chelungpu fault. The 1999 Chi-Chi earthquake nucleated in the southern part of the fault patch and propagated towards the north as the slip plane generally followed the stratigraphic beds. To the north, the 1999 rupture plane shallowed because of regional south-plunging syncline, and finally emerged at the surface (Shikang-Shangchi fault zone). To the south, the Chelungpu rupture was probably affected by a series of NW-trending strike-slip faults (e.g., Luliao fault and Gukeng fault).

Fig. 4, we constructed schematically the 3-D geometry of the Chi-Chi earthquake slip surface, by summarizing geological information of the Chelungpu fault (Chou, 1971; Mouthereau et al., 2002), focal mechanism and slip distribution from seismlogical and GPS studies (Kao and Chen, 2000; Johnson et al., 2001; Ma et al., 2000), and the information of coseismic surface ruptures (CGS, 1999a,b; Lee et al., 2002a). The main shock initiated on the southern part of the Chelungpu fault (Chung and Shin, 1999; Ma et al., 1999). The earthquake rupture propagated towards the north and west, and from depth of about 8 km to the surface (Kao and Chen, 2000). The earthquake produced nearly 90-km of continuous surface ruptures that generally followed the mapped surface trace of the Chelungpu fault (Central Geological Survey [CGS], 1999a,b; Chen et al., 2001a). The magnitude of slip on the surface increased from 1–2 m in the south to 6–8 m in the north, as revealed by fault scarp measurements (CGS, 1999b; Kelson et al., 2001; Lee et al., 2002a), GPS measurements (CGS, 1999b; Yang et al., 2000; Yu et al., 2001), and by the inversion of near-fault seismic data (Ma et al., 2000).

In 3-D geometry, the décollement in the Chelungpu fault plane gradually becomes shallower to the north and deeper to the south (Fig. 4b). The geometric configuration of the Chelungpu fault resulted in different structures at the northern and southern ends of the Chi-Chi surface rupture. To the south, the propagation of the Chi-Chi earthquake slip seemingly was affected by a NW-trending lateral ramp, the Luliao fault, a transfer structure near the southern end of the Chelungpu fault (Fig. 4). Although field evidence of surface breaks was sparse

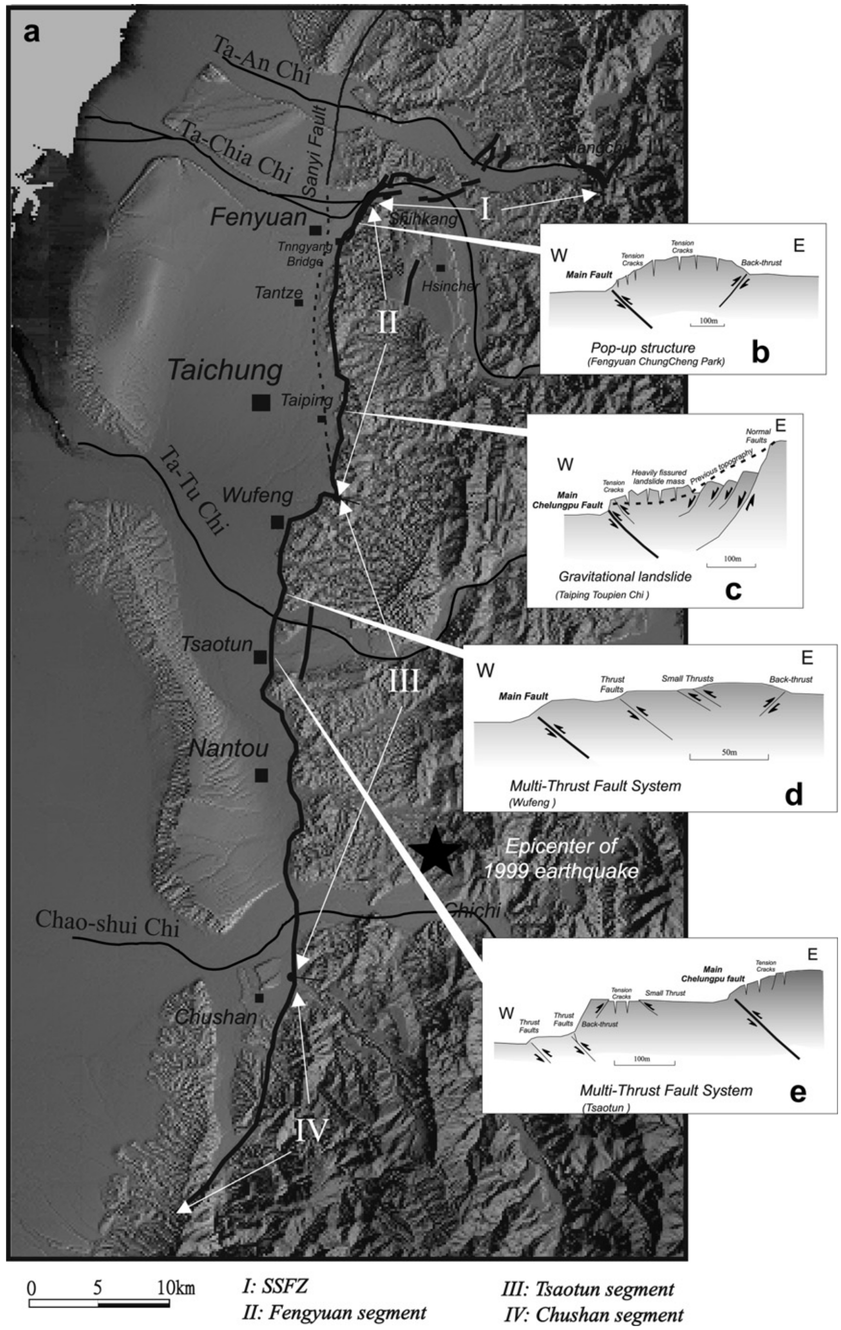

Fig. 5. Characteristic structures in the Chelungpu fault zone. The background shaded-relief map shows that the Chelungpu fault lies close to the morphological boundary between the rugged hills to the east and the flat basin to the west. However, the surface ruptures turn eastward substantially in the north and entered adjacent hills. Four segments have been defined according to geomorphic features. Typical deformation features include pop-up structures, thrust-induced large-scale gravitational landslides, and multiple thrust faults are illustrated in (b), (c), (d), and (e).

(Lee et al., 2002b), aftershocks are clearly concentrated along this NW-SE structure (Kao and Chen, 2000). To the north, the 1999 surface rupture followed the surface expression of the Chelungpu fault and entered into a regional synclinal fold structure, the Cholan syncline (Lee et al., 2002a). As the slip of the 1999 rupture propagated towards the north through this south-plunging syncline, it produced a zigzag E-W trending 15-km-long surface rupture in the northern termination.

According to its relations with the regional geology, we divided the 1999 Chi-Chi earthquake surface rupture into four fault segments (Fig. 5): the northern end (also called Shihkang–Shuangchi Fault zone, SSFZ, Lee et al., 2002a), the Fengyuan segment, the Tsaotun segment, the Chushan segment (the southern end). Among them, the Fengyuan and Tsaotun segments together represent the main Chelungpu fault. The Tsaotun segment follows closely scarps at the foot of the rugged hills. To the contrary, part of the

Fengyuan segment does not follow this morphologic boundary, but cuts hill slopes and is parallel to the scarps and lies at a distance of hundreds of meters to the east. Another important feature of the Chelungpu fault is the stratigraphically-controlled slip plane. There is a close relation between the Chelungpu fault plane and the Pliocene Chinshui shale. Data from seismic reflections and borehole drilling indicate that the bedding plane of the 150–200-m-thick fine-grained Chinshui shale served as the long-term slip surface for the Chelungpu thrust in the upper 3–4 km (Chou, 1971; Wang et al., 2002). There is a good match between the geometry of the Chelungpu fault and the Chinshui shale. Despite different geomorphic features between the Fengyuan and Tsaotun segments, the Chinshui shale is the slip surface for both segments.

The Chelungpu fault shows distinct differences in stratigraphy and structure between its northern (Fengyuan) and southern (Tsaotun) segments. In the northern part, the Fengyuan segment exhibits a bedding-parallel thrust, which slips within a series of east-dipping strata along the bottom of the Pliocene Chinshui shale over the Miocene Kueichulin Formation (Fig. 6a). In the southern part, the Tsaotun segment is overthrust onto flat Quaternary fluvial and recent alluvial deposits (Fig. 6b). Morphological differences are also observed between the Fengyuan and Tsaotun segments. As mentioned above, the Tsaotun segment coincides with the western margin of the hills, and forms the topographic boundary between the rugged foothills and the flat basin. However, the Fengyuan segment usually cuts through into the rugged foothills, implying that this segment is a relatively newly-developed segment and has not existed for a long time.

The above geological and structural differences between the Fengyuan and Tsaotun segments of the Chelungpu fault are also reflected in the structural characteristics of the 1999 Chi-Chi co-seismic rupture. First, the scarp morphology of the Chi-Chi rupture was a nearly continuous thrust scarp in the Tsaotun segment. However, the surface scarps became obscure in the Fengyuan segment, particularly where the surface ruptures bisected the foothills. Second, dip-angles of the Chelungpu fault are steeper in the Fengyuan segment and are gentler in the Tsaotun segment as observed at the ground surface (Angelier et al., 2003), and at depth by shallow seismic reflection surveys (Wang et al., 2002) and borehole data (Tanaka et al., 2002). Third, the slip on the surface ruptures showed lesser amounts in the Tsaotun segment and larger amounts in the Fengyuan segment; this could be due to either different slip histories between the north and south segments (Lee and Chan, 2005).

4. Main segments of the chelungpu surface rupture

The main Chelungpu surface ruptures consist of spectacular 2–3-m-high fault scarps with sub-equal amounts of vertical and horizontal slip, although variations exist in places. In many cases, the fault scarp has a clear expression, regardless of the nature of the surface materials (bedrock or soil cover). In some places, several fault strands were found in a relatively wide deformation zone. In other places, however, the scarp was obscured because of distributed deformation in mechanically weak surficial layers and instead formed a fold scarp (Lee et al., 2001; Chen et al., 2004).

A common feature along the Chi-Chi earthquake surface rupture is the presence of pop-up structures in the hanging wall (Fig. 5), especially at its northern end (Lee et al., 2002a). These pop-up structures are comprised by the above-mentioned, primary foreland-vergent thrust faults, hinterland-vergent backthrusts, and a gentle anticline between these faults (Fig. 5b). The pop-up structures fre-

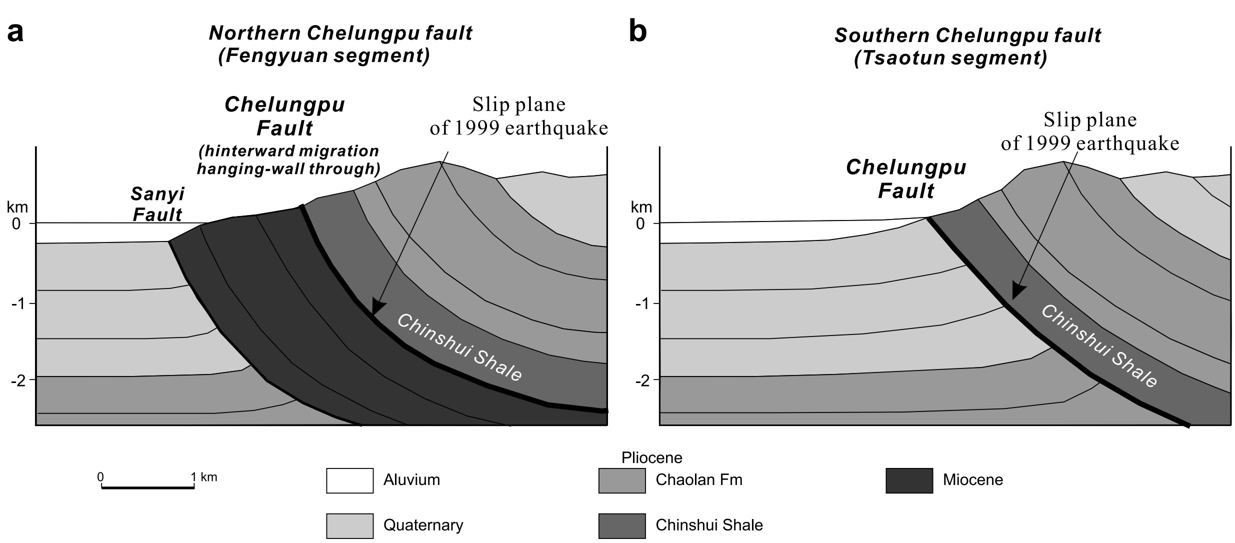

Fig. 6. Geological and structural context between the Fengyuan segment (a) and the Tsaotun segment (b) of the Chelungpu fault. The Fengyuan segment is a bedding-parallel thrust within east-dipping strata. In the Tsaotun segment, the hanging-wall strata are thrust over the flat-lying footwall. The Fengyuan segment is a relatively young fault, showing hinterland migration of imbricate thrusting and a hanging-wall breakthrough on the older, now inactive, Sanyi fault.

quently contained secondary strike-slip faults, fissures and tensile cracks, pressure ridges, and normal faults. The width of such pop-up structures varies from some tens of meters to a few kilometers (compare Figs. 5b, d, and e). At some places, fold scarps developed instead of fault scarps (e.g., the Tsaotun site in Fig. 5). The mechanism and geometry of these pop-ups probably are related to both the nature of near-surface materials (Kelson et al., 2001; Lee et al., 2004) and the change in fault dip at depth (Hung and Suppe, 2000; Suppe et al., 2000).

Outcrop measurements indicated that the surface rupture was nearly pure dip slip in most places (Kelson et al., 2001; Angelier et al., 2003; Lee et al., 2003), except in some short strike-slip transfer sub-segments. However, GPS measurements across the Chelungpu fault showed a general pattern of oblique thrusting with a significant left-lateral component (CGS, 1999b; Yu et al., 2001). En-echelon tension fissures in the hanging wall of the fault scarp provide evidence for near-surface slip partitioning, with dip-slip faulting near the surface rupture and distributed left-lateral shear on the hanging wall (Angelier et al., 2003).

Small and short segments of transfer faults were also observed, which are obliquely connected to the main earthquake fault. Most of the transfer faults are located near rivers or streams. For example, a right-lateral strike-slip fault strikes E-W along the Jian-Min Chi River north of Wufeng, and a left-lateral strike-slip fault strikes NW-SE along the Ta-Li Chi River near Taiping (Fig. 7). This implies that the development of some E-W valleys across the Chelungpu fault is related to the transfer faults. In addition, outcrop observation and fault slip analysis at the Ta-Li Chi site indicated a stress perturbation around the strike-slip transfer fault zone (Fig. 7). There exist other sharp changes in strike of the Chi-Chi surface ruptures, suggesting the presence of other strike-slip transverse faults. In the field, these transfer faults along the surface rupture were identified based on outcrop evidence, such as nearly horizontal striations on the fault surface or significant strike-slip offsets of surface markers (Fig. 7).

In addition to fault scarps, landslides were also found at several locations associated with the surface rupture. In particular, a series of nearly continuous vertical scarps extends for about 2 km long tens of meters east of the primary rupture in the Tantze area, where the Chelungpu fault emerges within hills. These 1–3 m high scarps, located near the western edge of a ridge, are likely landslide head scarps. Extensive tension fissures approximately parallel to the scarps have been found (Fig. 5c). For example, north of the Ijiang Bridge of the Taiping river, significant landslides triggered by the Chi-Chi earthquake affected an area approximately a few hundreds meters long and wide (Fig. 5c). We tend to interpret the 2-km-long vertical scarps as near-ridge extension due to hanging-wall uplift, which has also been observed and documented during the 1989 Loma Prieta earthquake (Ponti and Wells, 1991).

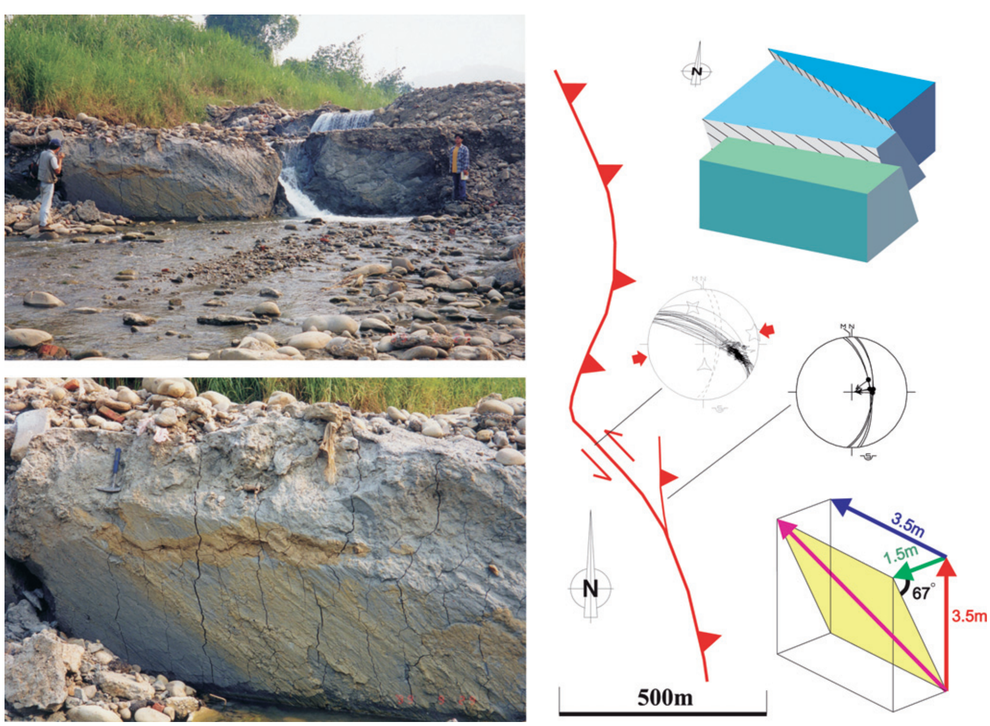

Fig. 7. Outcrop of a strike-slip transfer fault of the 1999 Chi-Chi surface ruptures in Ta-Li chi, near Taiping (location see Fig. 5). Schmidt's projection, lower hemisphere. Bedding planes shown as dashed-line great circles. Fault planes shown as thin great circles, with slickenside lineations as dots with arrows indicating the sense of motion (inward direction for reverse slip). Computed stress axes shown as stars with five branches (σ_1), four branches (σ_2), and three branches (σ_3). Method of calculation of stress tensor: Angelier (1984). Two-fault system has been observed: the major fault (strike N125°E, dip 70° to NE) is represented by an oblique reverse fault with an important left-lateral strike-slip component, and the minor one (strike N0°E, dip 70° to E) is a reverse fault. Oblique fault striations associated with the 1999 earthquake can be clearly observed on the major fault plane.

5. The north and south terminations

5.1. The northern termination

As mentioned above, the northern surface termination of the Chelungpu fault (i.e., the SSFZ) was controlled by the geometry of the Chinshui shale and the Cholan syncline. In contrast to the N-S striking fault trace of the main Chelungpu fault rupture, the SSFZ has a spoon-like shape in relation to the surface trend of the Cholan syncline and was characterized by discontinuous pop-up structures with an en echelon pattern (Fig. 8). Vertical offsets generally range from 3–6 m and were up to 8–10 m at a few locations, which are significantly larger than offsets on the main Chelungpu fault. The occurrence of multiple thrust (and back-thrust) scarps resulted in widespread damage in several villages. For example, the Shihkang Dam, which exhibited a vertical offset of about 10 m on the main body of the dam, was damaged by a complex pattern of deformation structures including a thrust fault, normal fault, and pressure ridge (Chen et al., 2000; Lee et al., 2001; Lee et al., 2002a). Secondary structures associated with the earthquake have also been observed along the SSFZ, including the arrays of fissures in the hanging wall of the thrust fault (Lee et al., 2001).

In addition to the trace of the SSFZ mimics the spoon-shaped regional trend of the strata in the south-plunging Cholan syncline, it seems that the Tamaopu fault (i.e., northern extension of the Shangtung fault), where intersects with the eastern limb of the Cholan syncline (Figs. 4 and 8), also ruptured, according to the GPS and the co-seismic analysis of the SPOT imagery (Dominguez et al., 2003). We note that both the western and eastern extremities of the SSFZ in the Cholan syncline slipped on the Chinshui shale, which was the principal slip surface of the Chelungpu fault rupture. As the 3-D shape of the Chinshui shale changes from a monoclinal east-dipping structure in the south to a synclinal structure in the north, the rupture plane also shallowed towards the north as it entered the Cholan syncline. Where the rupture plane approached the ground surface, it departed from the Chinshui shale. Measurements on the SSFZ fault scarps and near-field GPS data both indicated predominantly thrust motion with NNW-directed slip. The slip direction is consistent with the north-westward slip propagation of the Chi-Chi earthquake rupture.

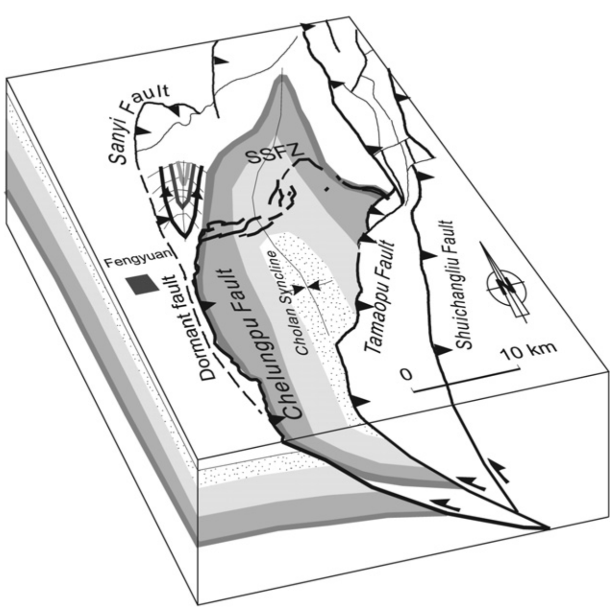

Fig. 8. Geometric configuration of the northern termination of the 1999 earthquake rupture illustrated in a 3-D block diagram. The 1999 Chi-Chi earthquake generally ruptured along the Chelungpu fault and developed parallel to bedding of the Chinshui Shale in the upper 2–3 km. Geological mapping shows that the Chinshui Shale becomes shallower to the north. The fault ruptured the surface in the Shihkang-Shangchi fault zone (SSFZ) and formed a spoon-like shape towards the core of the regional Pliocene syncline. The south-plunging Pliocene Cholan syncline controls the surface traces of the Chelungpu fault.

Many of the Chi-Chi earthquake surface ruptures on the SSFZ were superimposed on pre-existed morphological features. For example, pop-ups occurred on the Diaoshenshan anticline, a young gentle fold that deforms the Pliocene Cholan syncline and Pleistocene river terraces. This implies that the Diaoshenshan anticline is active. The long-term deformation rate and the repeat time of damaging earthquakes along the SSFZ remain unknown and need further investigation.

Another important characteristic of the 1999 rupture on the SSFZ is the surface large displacements. Both field measurements along the fault scarps and near-field GPS measurements showed an increase in the amount of slip towards the north along the 90-km long surface rupture (Fig. 5). Data from near-fault seismometers revealed not only relatively large surface displacements but also a relatively low velocity of rupture propagation on the northern part of the rupture (Ma et al., 1999). Ma et al. (2003) argue that thermal lubrication may have influenced fault rupture in its northern part. We suggest that fault lubrication and fault rock strength contrast between the north and south segments of the fault are related to differences in the style of faulting and geologic deposits in the upper few kilometers. The bedding-parallel slip between shale and siltstone on the Fengyuan segment likely yields fault of lower rock strength during earthquake ruptures. For the southern part of the Chelungpu fault on the Tsaotun segment, where shale in the hanging wall is thrust over conglomerate in the footwall, higher rock strength likely prevailed. We infer that high rock strength on the southern Chelungpu fault was associated with higher shaking frequency and small displacement; in contrast, lower rock strength on the northern Chelungpu fault was associated with low shaking frequency and large displacement.

5.2. The Southern termination

The Chushan segment of the Chi-Chi earthquake rupture is obscure because it did not rupture along the base of the foothills, but rather cut through the hills. The rupture

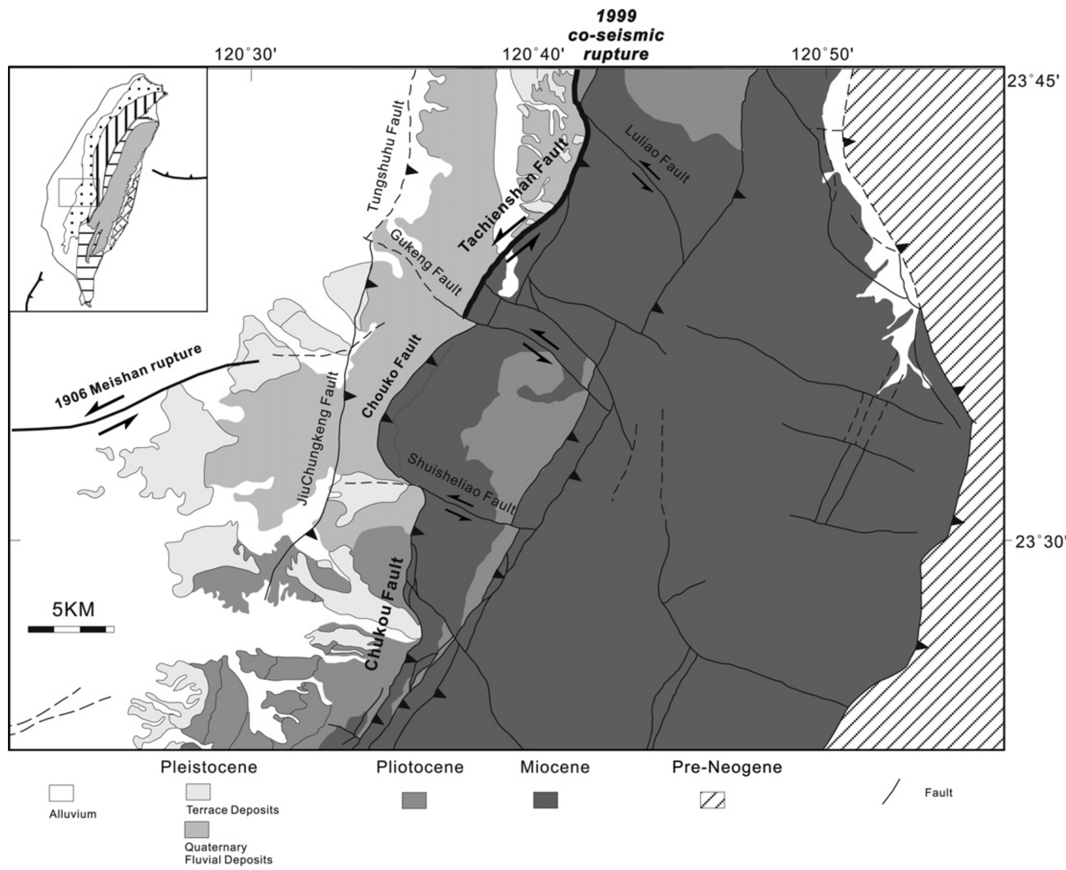

Fig. 9. General geological map in the southern end of the 1999 Chelungpu rupture and the Chukou fault area (modified after CPC, 1986). The structure of the range-front faults shows a duplex feature with three major thrust: the Jiuchungkeng fault, the Chukou fault, and the Lukou fault. A few NW- to N-W trending strike-slip faults, which likely are the reactivation on the older pre-collision normal faults, also play an important role on the structural evolution.

broke the Tachienshan fault, which is a transitional segment connecting the Chelungpu fault to the north and the Chukou fault to the south. The trend of the 1999 surface rupture turned from N-S on the Chelungpu fault to NE-SW on the Chushan segment. According to the 1:100,000-scale regional geological map (CPC, 1986), the Tachienshan fault places Mio-Pliocene marine sediments over Quaternary fluvial deposits (Fig. 9). An approximately 100-m-wide fault zone with extensively sheared rocks has been observed around the surface trace of the Chi-Chi rupture near Tungtou (Lin et al., 2000), which clearly indicates a fault with significant offset.

Observations were limited along the Chushan segment because of difficulty with access (CGS, 1999b). One exposure of the 1999 surface rupture in a tea field north of Tungtou showed right-lateral offset of about 2.5 m (Lin et al., 2000). However, the kinematics of the southern termination of the Chi-Chi rupture remains poorly understood. Two main questions are: (1) how did the earthquake rupture terminate in the south and (2) were faults other than the Tachienshan fault involved during rupture propagation at the southern end. The relatively large 2.5 m of dextral displacement at Tungtou does not suggest that co-seismic slip diminished gradually from the Tsaotun segment towards the Chushan segment. A few NW-trending strike-slip faults, which are connected obliquely to the Tachienshan fault, may have ruptured during the Chi-Chi earthquake (Fig. 9). For example, the Luliao fault cross cuts and divides the Chelungpu fault to the north and the Tachienshan fault to the south. The Gukeng fault, on the other hand, cross cuts and divides the Tachienshan fault to the north and the Chukou fault to the south. Although the field evidence of surface displacement on the Luliao and Gukeng faults remains problematic (Lee et al., 2002b), aftershocks indeed showed abundant seismicity in the vicinity of the Luliao-Gukeng strike-slip faults (Kao and Chen, 2000). The aftershock distribution suggests that the Luliao and Gukeng faults are connected to a predominant NNW-trending seismic zone, which is interpreted as the southern lateral ramp of the 1999 Chelungpu rupture (Kao and Chen, 2000; Fig. 4). This lateral ramp would result in a left-lateral slip on the Luliao fault and a right-lateral slip on the Chushan segment (Lee et al., 2002b; Hung et al., 2002).

6. Interaction between the Chelungpu fault and nearby faults

In this section, we discuss the interaction of the Chelungpu fault with nearby frontal thrust faults, based on the structural characteristics of the 1999 rupture and the long-term geological features. The potential for future large earthquakes in the fold belt of western Taiwan will also be discussed.

6.1. Westward propagation of the frontal thrust and the Changhua fault

The westward propagation of the frontal thrust can be observed in the stratigraphy of the Chelungpu area, as we described above. The Shuangtung fault, a major reverse fault east of the Chelungpu fault, can be considered the ancient range-front thrust fault. There is neither an historical earthquake nor clear geomorphic evidence that indicates recent seismic activity along the Shuangtung fault. River terraces about 30-50ky old that overlie the Shuangtung fault do not appear to be deformed.

The Changhua fault, a blind thrust west of the Chelungpu fault, is active. Unlike the Shuangtung fault, abundant evidence of deformed geomorphic surfaces has been observed along the Changhua fault (Shyu et al., 2005). Despite the fact that no large earthquakes have occurred on the Changhua fault during the last century, historical earthquakes have caused severe damage on the area of the Changhua fault, especially in 1845 and 1848 (Hsu, 1980). The future occurrence of large damaging earthquake on the Changhua fault is thus highly likely.

The long-term westward propagation of the frontal thrust fault from the Shuangtung fault to the Changhua fault is clearly shown on the stratigraphic record across these three faults. Across the easternmost Shuangtung fault, Miocene sediments are thrust over ca. 0.8–1 Ma fluvial deposits (Chi and Huang, 1981). Across the Chelungpu fault, Pliocene sediments are thrust over recent fluvial deposits. Across the westernmost Changhua fault, Quaternary deposits are thrust over recent fluvial deposits. To summarize, these faults involve younger sediments at the surface.

6.2. The Sanyi thrust and the northern Chelungpu fault

Abundant geomorphic features associated with the Chelungpu fault indicate that the fault has been active during the past few tens of thousands of years (Chen et al., 2002; Shyu et al., 2005), and likely much longer based on total offset. Paleoseismological studies on the Tsaotun segment of the Chelungpu fault revealed 4-5 large earthquake events during the past two thousands years with a repeat time of 200–400 years (Lee et al., 2001; Ota et al., 2003; Chen et al., 2004). Alternatively, geomorphic evidence for recent activity remains questionable for the Sanyi fault or the Chukou fault, the northern and southern continuations of the Chelungpu fault, respectively. Although each of these three faults represents the largest cumulative geological offset in its respective area, historical large earthquakes did not occur at these frontal thrusts, especially for the Sanyi and the Chukou faults. For example, the 1935 M 7.1 Shitang earthquake did not occur along the range-front Sanyi fault (Taipei Survey, 1936; Otuka, 1936; Huang and Yeh, 1992), and the 1906 M 7.1 Meishan earthquake also did not occur along the range-front Chukou fault (Omori, 1907). We suggest that differences in geological structure explain differences in the fault system and the location of recent large earthquakes among the areas of Sanyi, Chelungpu, and Chukou in the fold belt of western Taiwan. That is, tighter folds are present in the Sanyi area, and tighter faults with duplex thrusts and strike-slip faults are present in the Chukou area, compared to the Chelungpu area where thrust faults and the associated folds are located at greater distance from each other. We speculate that areas with more complex structures, like Sanyi and Chukou, are more difficult to predict the occurrence of the big earthquakes.

The structure of the northern connection of the Chelungpu fault with the Sanyi fault is rather complex. The Sanyi fault departs from the Chelungpu fault near Taiping and the two major thrust faults are sub-parallel northwards for about 10 km until near the Tachia river (Fig. 2). There, the Chelungpu fault turns eastward and then diminishes. Based on seismic reflection profiles (Hung et al., 2002) acquired across the Fengyuan segment, we interpret the Chelungpu and Sanyi faults to become a single fault at the depth of about 3–4 km (Fig. 3, cross section B–B′). Regionally, the Chelungpu fault is the southern continuation of the Sanyi fault during the development of the range-front thrust faults of the western Taiwan fold belt. The Chelungpu fault diverged from the Sanyi fault plane, on which Miocene rocks are thrust over Quaternary deposits. The Chelungpu fault thus cuts up section in the hanging-wall, and then cuts parallel to bedding within the Chinshui Shale as a hinterward migration from the Sanyi fault (Lee et al., 2002a).

In the northern part of the Chelungpu fault, the past several earthquakes likely repeatedly slipped along the Chinshui shale rather than the lower Sanyi fault surface. The Chelungpu fault began to break through the hanging-wall of the Sanyi fault probably about 50 ka as suggested by the smaller offset on the Fengyuan segment of the Chelungpu fault. The surface trace of the southern part of the Sanyi fault is covered by fluvial or overbank deposits and has no geomorphic expression, implying that the southern segment of the Sanyi fault is inactive during the Holocene time.

6.3. The Chukou fault and the southern Chelungpu fault

To the south of the Chelungpu fault area, the Chukou fault and its neighbors, the Jiuchungkeng fault to the west and the Lukou fault to the east, together form a duplex structure with tightly spaced faults (Fig. 3, cross section D–D′). Along this duplex, Miocene continental margin sedimentary rocks are thrust over Quaternary fluvial deposits, similar to the Chelungpu area. However, the structures are more complicated within the duplex. Stratigraphic offsets across the Chukou fault are larger than those across the Jiuchungken and Lukou faults, and the Chukou fault shows greater topographic relief. However, active geomorphic features, such as vertical offset on recent river terraces, have been observed along the Jiuchungkeng fault

(Chen et al., 2001b; Angelier et al., 2003) in contrast to the absence of active geomorphic feature on the Chukou fault (Shyu et al., 2005). Thus, geomorphology indicates that active fault slip is presently concentrated on the Jiuchungkeng fault, on the lower thrust of the duplex.

Instead of a typical thrust-dominated fold-and-thrust belt, the Chukou area exhibits a combination of structures with both thrust and strike-slip faults. Several NW- to E-W-striking strike-slip faults are present in the Chukou area (Fig. 9). Many of these strike-slip faults are reactivated normal faults, which were widespread in southwestern Taiwan during the Miocene pre-collision stage (Lin and Watts, 2002). These strike-slip faults display both left-lateral and right-lateral senses of motion (Fig. 9). For example, the Gukeng fault and the Shuisheliao fault show left-lateral offset and the Meishan fault had right-lateral slip during the 1906 earthquaket. The sense of slip of the strike-slip fault is largely influenced by the strike of the faults, which are at a small angle to the direction of regional maximum tectonic stress (Yeh et al., 1991; Kao and Chen, 2000). These strike-slip faults have the potential to produce large earthquakes, according to historical records. For example, the 1998 M 6.2 Rueyli earthquake indicated an oblique motion combining the Tachienshan thrust and the Shuisheliao left-lateral fault (Lo, 2001), and the 1999 M 6.6 Chiayi earthquake involved a N-S trending thrust fault and a E-W trending strike-slip fault (Chang et al., 2004).

7. Summary

The 1999 Chi-Chi earthquake ruptured the entire 90-km-long Chelungpu fault, a range-front thrust fault in the fold-and-thrust belt of western Taiwan. The 1999 earthquake ruptures show close relationships with the pre-existing geological structures. The slip plane of the Chelungpu fault, which slipped principally along the Pliocene Chinshui shale, is stratigraphically controlled in the upper 3-4 km. The northern Chelungpu fault, consisting of the Fengyuan segment and the SSFZ (the northern end), represents a hinterward migration of imbricate faulting in the hanging wall of the inactive Sanyi thrust. Bedding controlled slip produced the en-echelon scarps distributed in a spoon-like trend in the northern end of the 1999 earthquake surface rupture, where the Chinshui shale is folded into a regional syncline.

For the main Chelungpu fault, the northern Fengyuan and southern Tsaotun segments are different and contrast structurally. The Fengyuan segment is a bedding parallel thrust fault within a series of east-dipping strata, whereas the Pliocene Chinshui Shale in the hanging wall overlies early Miocene sandstone in the footwall. In the Tsaotun segment, the east-dipping Pliocene strata are thrust over the flat-lying Quaternary fluvial and recent alluvial deposits. This stratigraphy/geometry configuration likely results in a lower rock-strength on the fault plane for the Fengyuan segment, at least in the upper 3–4 km, and thus may be related to larger amounts of slip in the northern part of the 1999 surface ruptures. To the south, the Chushan segment of the Tachienshan fault, the southern continuation of the Chelungpu fault, is crosscut by a series of NW-trending strike-slip faults. Aftershock data indicate reactivation of these strike-slip faults.

The Chelungpu fault is structurally the simplest, compared to the northern Sanyi and the southern Chukou areas. Geological mapping indicates that the Chelungpu fault connects to the Sanyi fault to the north and the Chukou fault to the south. However, the three faults are different in terms of historically damaging earthquakes, active geomorphic expression, and long-term structural development. Deformation from the 1999 earthquake surface rupture was localized on the major thrust fault with the largest long-term offset in the Chelungpu area. In contrast, the 1935 and 1906 earthquakes did not occur on the faults with largest offset in the Sanyi and Chukou areas, respectively. Further detailed seismotectonic studies on the complex structures in Sanyi and Chukou areas are needed for mitigation against the seismic hazards in fold-belt of Taiwan.

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