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Newly found Tunglo Active Fault System in the fold and thrust belt in northwestern Taiwan deduced from deformed terraces and its tectonic significance

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Abstract

We found active faults in the fold and thrust belt between Tunglo town and the Tachia River in northwestern Taiwan. The surface rupture occurred in 1999 and 1935 nearby the study area, but no historical surface rupture is recorded in this area, suggesting that the seismic energy has been accumulated during the recent time. Deformed fluvial terraces aid in understanding late Quaternary tectonics in this tectonically active area. This area contains newly identified faults that we group as the Tunglo Fault System, which formed after the area's oldest fluvial terrace and appears at least 16 km long in roughly N–S orientation. Its progressive deformations are all recorded in associated terraces developed during the middle to late Quaternary. In the north, the system consists of two subparallel active faults, the Tunglo Fault and Tunglo East Fault, striking N–S and facing each other from opposite sides of the northward flowing Hsihu River, whose course may be controlled by interactions of above-mentioned two active faults. The northern part of the Tunglo Fault, to the west of the river, is a reverse fault with upthrown side on the west; conversely the Tunglo East Fault, to the east, is also a reverse fault, but with upthrown side on the east. Both faults are marked by a flexural scarp or eastward tilting of fluvial terraces. Considering a Quaternary syncline lies subparallel to the east of this fault system, the Tunglo Fault might be originated as a bending moment fault and the Tunglo East Fault as a flexural slip fault. However, they have developed as obvious reverse faults, which have progressive deformation under E–W compressive stress field of Taiwan. Farther south, a west-facing high scarp, the Tunglo South Fault, strikes NNE–SSW, oblique to the region's E–W direction of compression. Probably due to the strain partitioning, the Tunglo South Fault generates en echelon, elongated ridges and swales to accommodate right-lateral strike–slip displacement. Other structures in the area include eastward-striking portion of the Sanyi Fault, which has no evidence for late Quaternary surface rupture on this fault; perhaps slip on this part of Sanyi Fault ceased when the Tunglo Fault System became active.

Keywords: Tunglo Fault System; Chelungpu Fault; Late Quaternary faulting; Flexural scarp; Strike–slip faulting; Deformed terraces; Surface ruptures in 1935 and 1999

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1. Introduction

1.1. The study area and its tectonic and geomorphic setting

This study area is located in northwestern Taiwan, a folded foreland of Taiwan orogen, which is currently a tectonically active area due to on-going arc–continent collision between the Philippine Sea Plate and Eurasian Plate (Fig. 1, inset). We focused on an area between the town of Tunglo in the north and the Tachia River in the south (Fig. 1). This area is underlain by Neogene and Quaternary sedimentary rocks, which are deformed into a series of N–S to NNE–SSW trending anticlines and synclines (Chang, 1994; Lee, 2000; Fig. 2). Several faults truncate these folds. The Sanyi Fault, a major one, is known as an overthrust fault (Meng, 1963) and is previously classified as Category II active fault (late Quaternary active fault; Lin et al., 2000). Its strike suddenly turns to east at north of Sanyi as previously defined. The Sanyi Fault continues as far south as to the Tachia River. To further south (Fig. 1), the Chelungpu Fault, well-known as the seismogenic fault of the 1999 Chichi earthquake, deforms late Quaternary terraces and generally strikes N–S direction, with exceptional eastward strike change near the Tachia River. Extending the general strike of the Chelungpu Fault northward, it seems surficially to meet with the Sanyi Fault; however, they slide along different stratigraphic horizons (Hung and Wiltschko, 1993; Chen et al., 2000; Lee et al., 2003; Yue et al., 2005). Other well-known active faults in the study area are the 1935 surface ruptures (Fig. 1). One is the Tuntzuchiao Fault, striking N60°E and meets with the Sanyi Fault near the Taan River; the other is the Chihhu Fault, a back thrust and striking N25°E.

In contrast to the presence of three historical surface ruptures in the north and south of our study area, no surface rupture by historical earthquake is known from the study area, implying that this area seems to be a seismic gap. Even no direct evidence of late Quaternary deformation can be found along the Sanyi Fault. Besides, the tectonic relationship among the Sanyi,

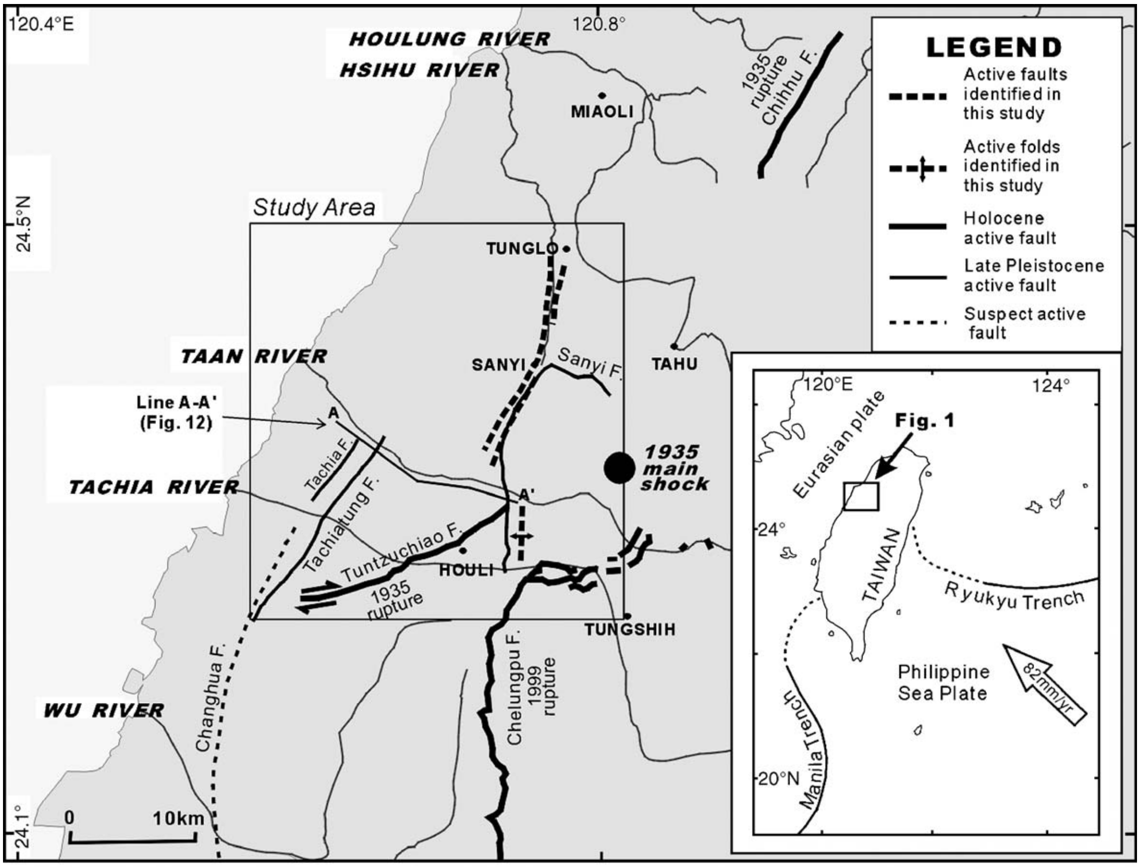

Fig. 1. Location map of the study area. Active faults are after Lin et al. (2000). Inset indicates the tectonic setting of Taiwan (after Yu et al., 1997). Newly identified active faults and fold by this study are also shown. A–A′ is the location of seismic profile line (Fig. 12).

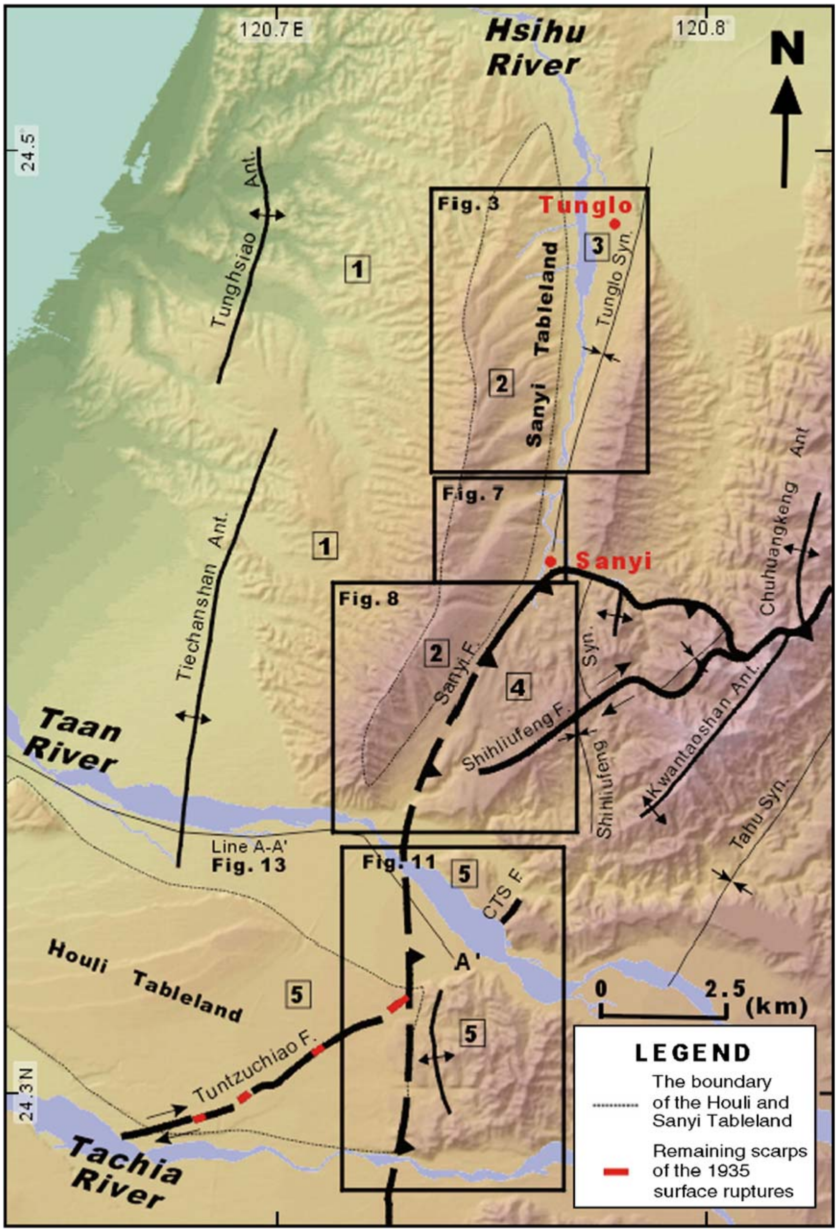

Fig. 2. Shaded relief map, constructed from DEM data (40 m in grid), shows the geomorphology of the study area. Locations of four plan view figures are shown. Known major geologic structures are from geologic maps, Tachia and Tongshi (Chang, 1994; Lee, 2000). Note the location of known Sanyi Fault suddenly bends eastward at town of Sanyi. CTS F = Chentoushan Fault. Numbers in square correspond to district numbers described in the text.

Chelungpu, and Tuntzuchiao Fault has received little attention.

The geomorphology of this area is also interesting (Fig. 2). In the eastern limb of the Tunghsiao and Tiechanshan anticlines, a nearly N–S trending sharp divide separates the study area into western and eastern two terrains. The western terrain is characterized by abundantly dissected hills, while the eastern one is characterized by widely developed fluvial terraces. The western edge of the oldest terrace descends in altitude from more than 600 m above sea level (asl) in the south to ca. 300 m asl in the north. These terraces probably originated along the course of paleo-Taan River (Chang et al., 1998). Terrace deposits overlie the upper part of the Quaternary Toukoshan Formation. The unconformity between the terrace deposits and the Toukoshan Formation, however, is very difficult to recognize because two units have similar lithology. Apparently, the eastern terraced area is higher than the western hilly area. On the eastern bank of the northward flowing Hsihu River, at least three steps of later developed narrow fluvial terraces are present. Terraces along both banks of the Hsihu River show abnormal convex profiles, suggesting considerable deformation (it will be described later). To the north of Taan River, we also found a peculiar series of bulges and lowlands, resulted from fault related strike–slip motion that previously has not been noted.

1.2. Previous work

The study of the Sanyi Fault (formerly called Sansa Fault) started in the 1930s. According to Otuka (1936), the Sansa Fault is an overthrust oriented WNW–ESE with a dip of 6° to the SW. Chang (1951) pointed out that the Sansa Fault is truncated by N–S trending Tunglo Fault in its western termination and presented a few observations of steeper dipping angle of over 20°. Meng (1963) proposed that the Sanyi Fault follows the southern part of the Tunglo Fault and bends abruptly eastward to follow the previously recognized Sansa Fault (Fig. 2). He also mentioned that there is a synclinal axis along the Hsihu River. Tang (1969) and Hung and Wiltschko (1993) suggested the abrupt strike change of Sanyi Fault be due to the preexisting Chuhuangkeng Anticline abutting in the northeast, which plays a role of resistant mass against the westward compressive stress. Based on the evidence presented by Bonilla (1975, 1977), Hsu and Chang (1979) and Lee (1994), the Sanyi Fault may have been active during the late Quaternary. Lin et al. (2000) thereafter classified the Sanyi Fault as a late Quaternary active fault (Category II), but gave no clear evidence. It is worthwhile to note here that no active fault has been previously mapped in the north of the bend of Sanyi Fault along the Hsihu River.

Chang et al. (1998) mapped fluvial terraces on both sides of the Taan River. They recognized terraces LT1, LT2 and a narrow LT4 in the western bank of Hsihu River, and reconstructed past north-flowing courses of the paleo-Taan River basing on the orientation of gravels. However, terraces distributed in the eastern bank of the Hsihu River were not mapped in detail.

The 1935 surface ruptures, i.e., the Tuntzuchiao Fault in the south and Chihhu Fault in the north, were mapped and described in the post-earthquake investigation (e.g., Otuka, 1936; Fig. 1). Another short Chentoushan Fault was later proposed in geologic map (Lee, 2000) by only geomorphic observations (Fig. 2). Nevertheless, no relation between these active faults has been ever discussed.

1.3. Purpose of the study

We use deformed terraces to investigate the middle to late Quaternary tectonics of this tectonically interesting and active district in Taiwan. We sought to map the terraces in detail and to infer the history of the terrace deformation. We thereby aim to identify various patterns of deformed landforms related to faulting and folding. We are particularly interested in examining active faults that have not been noticed before. By our own evidence, we also interpret the mechanism of faulting and infer relationship among three major faults.

1.4. Study method

To identify terraces and tectonic landforms, we extensively used aerial photos at 1:20,000 in scale. We also analyzed Taiwan Digital Elevation Model (DEM 40 m in grid) to produce shaded-relief maps and profiles. Shaded-relief maps constructed from DEM data aid in understanding the overall geomorphology, and the aerial photos help identify individual features. Fieldwork, carried out several times in 2000–2003, confirmed the deformation of terraces and the nature of covering soils of terraces.

2. Geomorphology of the study area

2.1. Outline

Fig. 2, a shaded-relief map created by 40 m DEM, shows five distinctive districts (1–5). Each one has discernible morphology and its own tectonic deformation:

(1) In the eastern limb of the Tunghsiao and Tiechanshan anticlines north of the Taan River, there are wide hilly area dissected by many small streams,
(2) East of the hilly land, there are a series of fluvial terraces, consisting of different stages. We tentatively name this area as the Sanyi Tableland,
(3) Along the eastern bank of the Hsihu River, three narrow terraces are mapped,
(4) From Sanyi to Taan River, a series of elongated flat-topped bulges and terraces are developed,

(5) Areas in both side of northern and southern bank of the Taan River are also terrace abundant. In the northern bank, only a faulted terrace is found, while complicated folded and tilted terraces are found in the south. Part of the surface rupture of the 1935 earthquake is still visible on the Houli Tableland.

As mentioned above, we can recognize a flight of terraces in this study area, especially in districts (2), (3) and (4). By aerial photograph interpretation, terraces are identified according to their geomorphic characteristics, such as the parallel distribution to modern or old rivers, and the presence of flat terrace surfaces bounded by sharp terrace risers. Also usually subrounded terrace

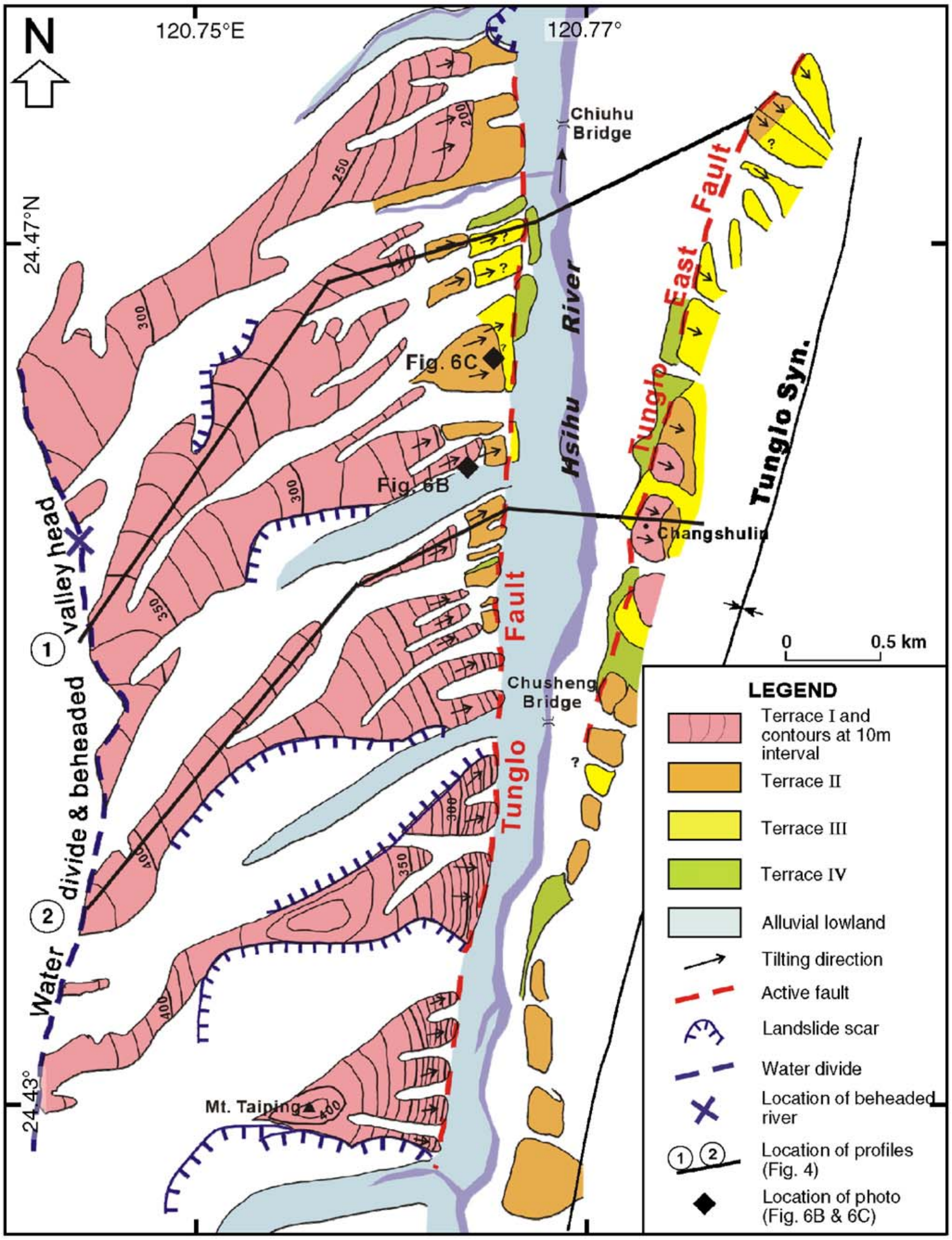

Fig. 3. Geomorphic map of the northern study area along the Hsihu River. Contours in 10-m interval on the Terrace I are derived from topographic map of 1 : 25,000. Eastward warping of Terrace I and younger terraces is clearly visible (due to Tunglo Fault). Eastward tilt of Terrace I and II on eastern bank of the Hsihu River also suggests the presence of active fault on the base of scarp (i.e., Tunglo East Fault).

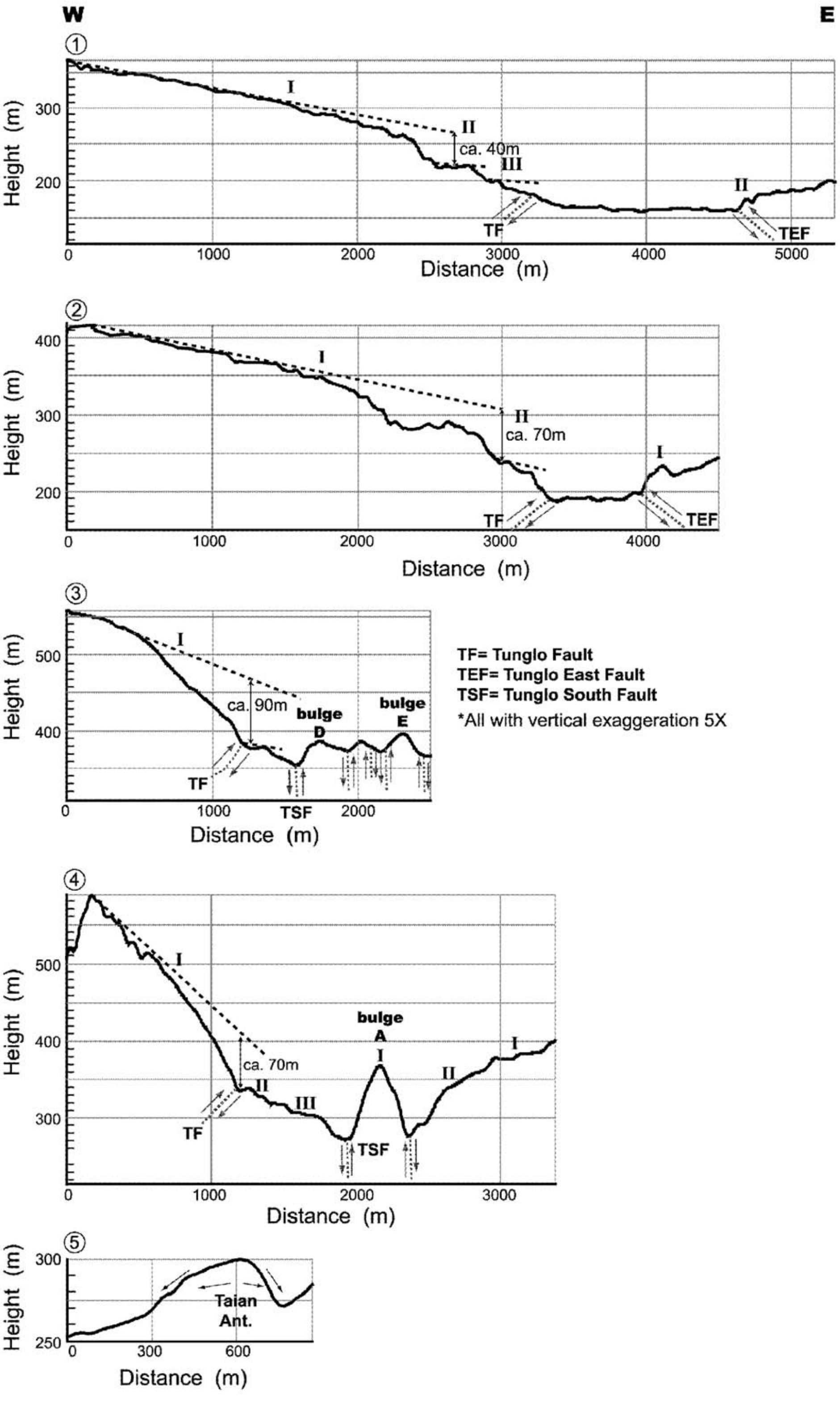

Fig. 4. Profiles constructed from DEM data show terrace deformation across terraces and main structures. See Fig. 3 for locations of profiles ① and ②, Fig. 6 for ③ and ④, and Fig. 10 for ⑤. Numbers I to III in profiles correspond to the terrace mapped in Figs. 3 and 6. Subsurface dips of the faults are only schematic. Amount of vertical offset is the minimum estimate because the height of actual terrace surface in the footwall is unknown.

gravels are seen on the top of the terrace surface, although it is difficult to recognize the unconformity between terrace deposits and underlying gravelly Toukoshan Formation.

In this paper, we tentatively classify these terraces into four stages: Terrace I to Terrace IV in descending order from the higher (older) to lower (younger) terraces distributed in the north of Taan River (Districts 2, 3, 4). To the south (District 5), we identify three terraces “a” to “c”. The groupings cannot be correlated between both sides because the terraces are not only too abundantly deformed but also lack of age control. Thus we used different symbols for terraces on both areas. Accordingly, the long-term rates of faulting remain unknown.

2.2. Description of landforms with special reference to their tectonic deformation

2.2.1. District 1

Dissected hills about 200 m asl in the south and 100 m asl in the north is underlain by lower Toukoshan Formation of Quaternary age. Many small streams dissect this hilly area and no remnant of fluvial terraces is observed (Figs. 2 and 5). Since the anticline axis is distributed in the western part of this hilly land, this area should be structurally high when Terrace I was formed. However, the hills now stand at least 100 m lower than the western edge of Terrace I of the Sanyi Tableland (Fig. 2). This results from topographic inversion: the lower Toukoshan Formation, composed of sand and silt, is more easily eroded due to its impermeability, compared with the terrace gravels and upper Toukoshan Formation (i.e., also cobbles dominant).

2.2.2. District 2: Sanyi Tableland

The prominent features of Sanyi Tableland (Figs. 2–6) include: 1) the presence of well-preserved wide Terrace I, which is higher than the western hilly district; 2) deeply dissected terraces by beheaded tributaries of the Hsihu River and by landslides; 3) remarkable northward decrease in the height of the western edge of Terrace I from more than 600 m asl in the south to only 300 m asl in the north, giving a gradient of 300 m/16 km (2%); 4) the east-facing convex scarps of both Terrace I and Terrace II, which are supposed to be concave if only erosion process works; 5) sudden height changes within Terrace I with E–W trend tear faults; and 6) different flowing directions of major tributary drainages: northeastward in the north, eastward in the middle and southeastward in the south (Figs. 3 and 8). Details of above-mentioned morphologies are given as follows:

1) Very wide Terrace I (Figs. 3–5), which has strongly laterized capping soil, is probably older than ca. 90 ka (Ota et al., 2002). This terrace is regarded as a depositional terrace by the paleo-Taan River, which flowed northward at certain early stage according to Chang et al. (1998), who divided Terrace I into two levels at north of Mount Taiping (Fig. 3). Because we did not find evidence as they proposed, we redefine Terrace I as a single depositional episode.
2) Terrace I preserves the original surface very well, but deep valleys dissect it. Several beheaded valley heads bound the Terrace I, and a water divide is clearly observed between this area and the low hills in the west (Figs. 3, 5 and 6A). This means the original divide was located in the west of its present

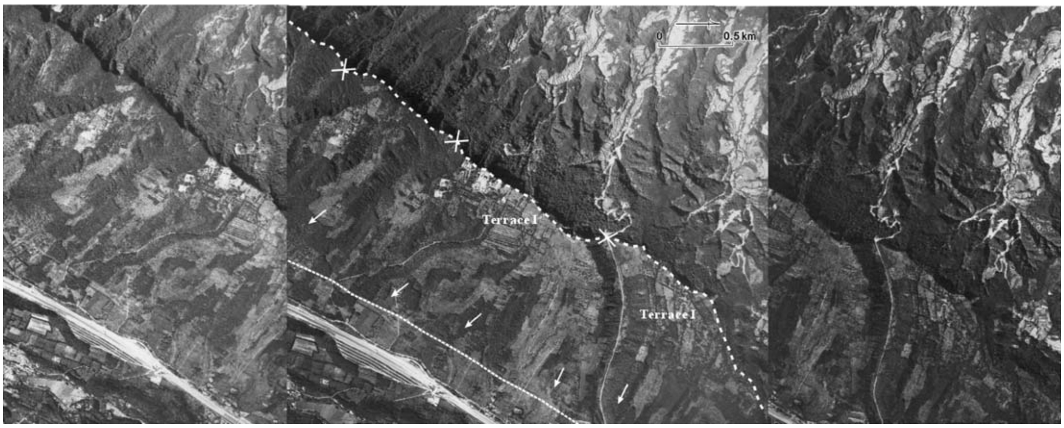

Fig. 5. Stereo-view of aerial photographs showing the well-preserved Terrace I and its deep dissection by tributaries (see Fig. 8 for location). Eastward tilting and associated flexural scarp is visible. Dashed line in the west represents the divide between the dissected hilly land and Terrace I; dotted line with arrows in the east is the Tunglo Fault. X represents the location of beheaded river.

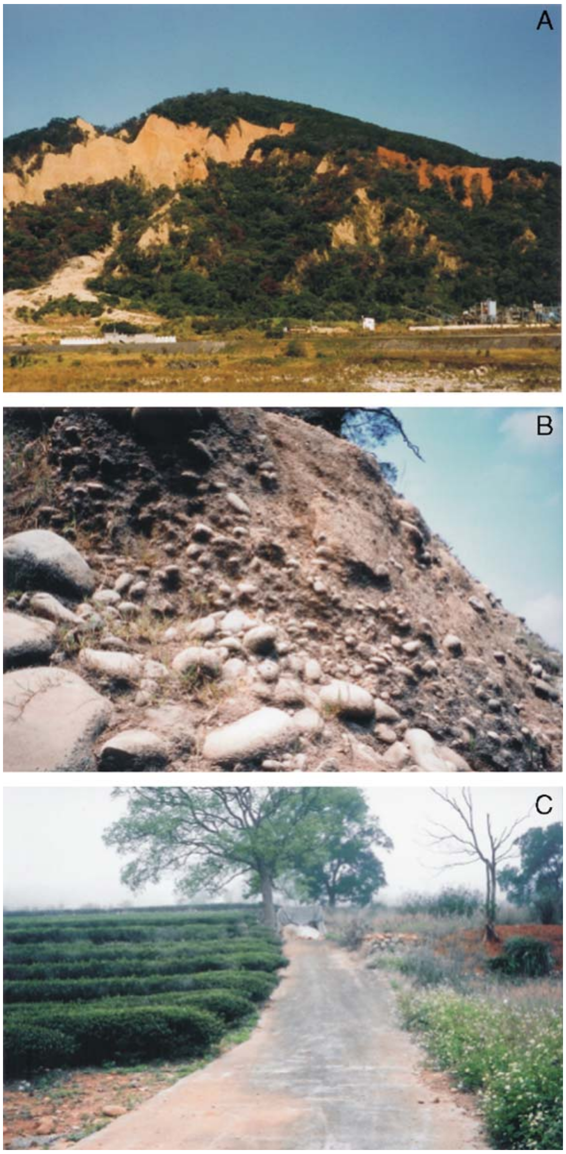

Fig. 6. (A) Eastward tilting Terrace I (right side) by Tunglo Fault in the north of the Taan River (looking northward). An irregular relief in the left (west) of the divide is a dissected hilly land, composed of the Lower Toukoshan Formation. This hilly land is lower than the terrace area due to the inversion of topography (photo by Ota, March, 2003; see Fig. 8 for location). (B) Tilted terrace gravel bed, parallel to the surface deformation direction (eastward warping) of Terrace I near Chusheng Bridge. Unconformity between Toukoshan Formation and terrace deposits is not clear here (photo by Ota, March, 2003; see Fig. 3 for location). (C) Photo showing the deformation of Terrace II by Tunglo Fault between profile lines 1 and 2, north of Chusheng Bridge. Different levels of tea garden are on the flexural slope. Lateritic soil exists on Terrace II (photo by Ota, March, 2003; see Fig. 3 for location; looking westward).

position. The presence of beheaded valley heads suggests rapid eastward erosion by streams in the hilly area.

3) The present northward gradient of Terrace I (2%) is steeper than that of the modern Taan River (1.1%). This suggests that the modern northward tilting is probably tectonic influenced and started after the formation of Terrace I.
4) In profiles, the convex slope at the eastern edge of Terrace I lacks abrupt break of an erosional scarp (Figs. 3, 4 and 5). We therefore interpret the slope as a flexural or warping scarp caused by thrust fault beneath the scarp. In Taiwan, there are many examples of such flexural scarps due to thrust faulting, such as the 1999 surface rupture along the Chelungpu Fault as well as its pre-existing fault scarps (e.g. Chen et al., 2002; Ota et al., 2004). However, the straight N–S trending 16-km-long scarp-line here may infer a high-angle reverse fault instead of a low-angle thrust (Fig. 3).
We, therefore, propose that the eastern margin of Terrace I be a flexural scarp, deformed by an active reverse fault dipping westward. We refer this fault to the "Tunglo Active Fault" (later abbreviated as Tunglo Fault). This name is adapted from the "Tunglo Fault" of Chang (1951) and Meng (1963), who mapped it as a NNE–SSW trending fault on the Tunglo Syncline. Meng's Tunglo Fault has long been ignored in recent geologic maps due to no clear evidence. We now redefine it as an active fault that strikes N–S direction and bounds the eastern margin of Terrace I because of the presence of active-fault related geomorphic features. We have not seen the fault itself, but tilted terrace gravels parallel to the scarp's surface profile were found at several sites (Fig. 6B).
The eastern margins of Terraces II and III, formed as alluvial fans by tributaries dissecting Terrace I, also show such flexural scarps. This is typically observed from the Chusheng Bridge northward (Figs. 3 and 6C). However, the eastward tilt of lower terraces is smaller than that of the Terrace I. This demonstrates that the reverse faulting has continuously acted up to recent.
This flexural scarp changes its strike at Sanyi and seems southwestward climbing up as a boundary between Terraces I and II (Fig. 8). However, human modification of the landscape makes us uncertain whether or not flexural slip has deformed Terrace II.
5) In the N–S profile, Terrace I typically descends northward, but there are two breaks located at where the strike of active reverse fault slightly changes (Fig.

7). Thus, we assume that they resulted from subsidiary tear faults. The amount of offset is ca. 25 m for the tear fault 1 and only several meters for tear fault 2.

6) Different flowing directions of the Hsihu River tributaries from north to south are probably related to different tilting directions associated with the strike changes of the fault.

2.2.3. District 3: fluvial terrace on the right bank of the Hsihu River

Three steps of fluvial terraces are developed on the eastern bank of Hsihu River (Fig. 3). Judging from the area and alignment of these terraces, younger terraces could be mainly formed by the Hsihu River. These terraces were not mapped by Chang et al. (1998). Terrace heights at Changshulin are 246 m asl (Terrace I), 230 m asl (Terrace II) and 190 m asl (Terrace III). All of the terraces have lateritic capping soils. They are difficult to observe in detail because of being obscured by human constructions, such as factories, houses and roads.

However, we still can recognize the eastward tilting on these terraces (Fig. 3), opposite to their original northwestward fluvial gradient, since they were formed by a northward flowing river. There are two interpretations for this phenomenon. One is that the eastward tilting corresponds to the growth of the Tunglo Syncline. In this case, why does the Hsihu River fail to follow the synclinal axis itself? More probably, an active reverse fault dips eastward beneath the western edge of the terraces. The convex slope of the western margin of the terraces, especially of Terraces I and II, and the straight scarp-line suggest an

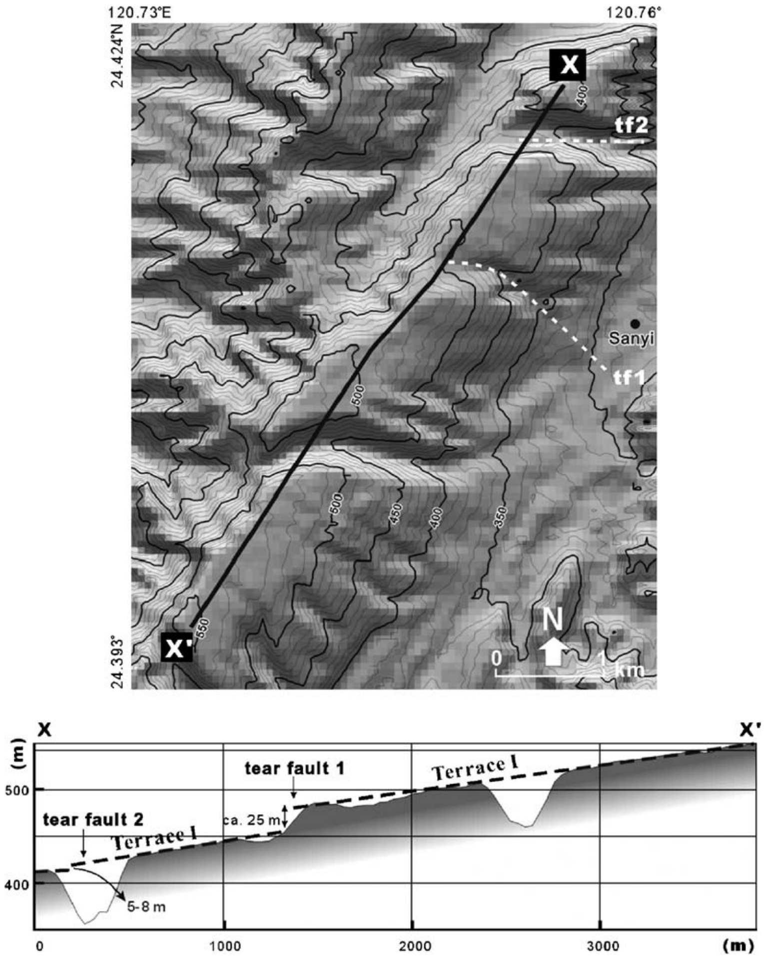

Fig. 7. Profile parallel to the main structure along the western margin of Terrace I. Two height breaks in Terrace I represent the displacement by subsidiary tear faults.

origin of high-angle reverse fault (Figs. 3 and 8). Therefore, we propose the presence of a previously unidentified active fault along the base of the scarp and tentatively name it "Tunglo East Fault". The length of this fault is rather short, only 4 km long, and scarp height is also smaller than that of the Tunglo Fault in the west of the Hsihu River.

2.2.4. District 4: High west-facing scarp, elongated bulges and minor fault scarps in the south of Sanyi town

About 50–100 m high and west-facing scarp strikes NNE to SSW in the south of Sanyi town ("b" in Fig. 8). This scarp exists to the east of Tunglo Fault and approximately follows the N–S segment of geologically known Sanyi Fault. Because its sense and apparent amount of vertical displacement is different from those of the Tunglo Fault, we now define this as the Tunglo South Fault. In the east of this fault accompanies a series of elongated bulges and intervening lowlands trending NNE–SSW between Sanyi and the Taan River (A–H in Figs. 8, 9 and 10). The bulges range from 0.2 km to 1.5 km in length. They have a flat top with gravels, suggesting that they are originally fluvial terraces, although the terrace gravel bed was not exactly identified. We tentatively correlate the top of the bulge with Terrace I, and they may have the same fluvial origin from the paleo-Taan

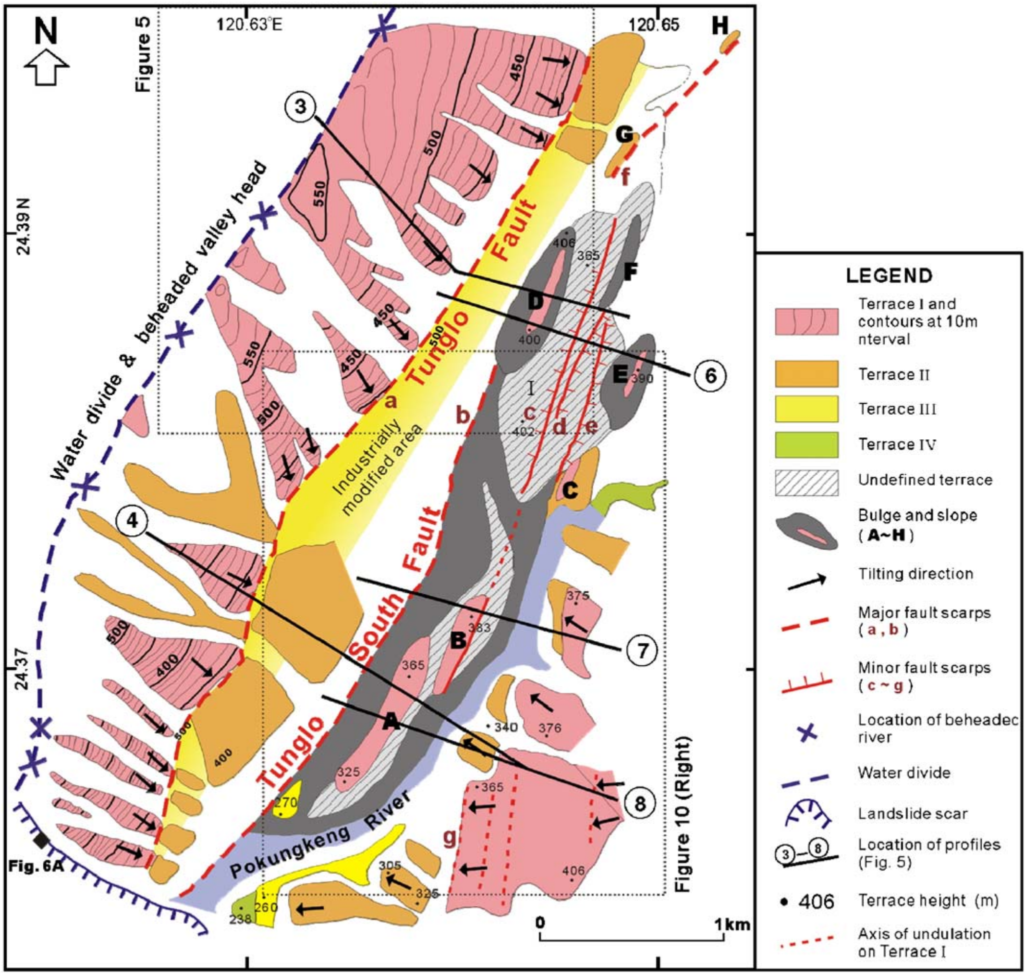

Fig. 8. Geomorphic map from Sanyi to the Taan River (see Fig. 2 for location), showing various deformation patterns of terraces. The major scarp (a) associated with Tunglo Fault limits the eastern margin of Terrace I. Scarp (b) associated with Tunglo South Fault bounds the western margin of the area predominated by tectonic bulges. A series of elongated bulges and lowland with several straight fault lines (c–f) is indicative of right lateral faulting. Westward tilting and undulation of Terraces I and II on the eastern side of Pokungkeng River is obvious. Some spot heights of the highlands are shown.

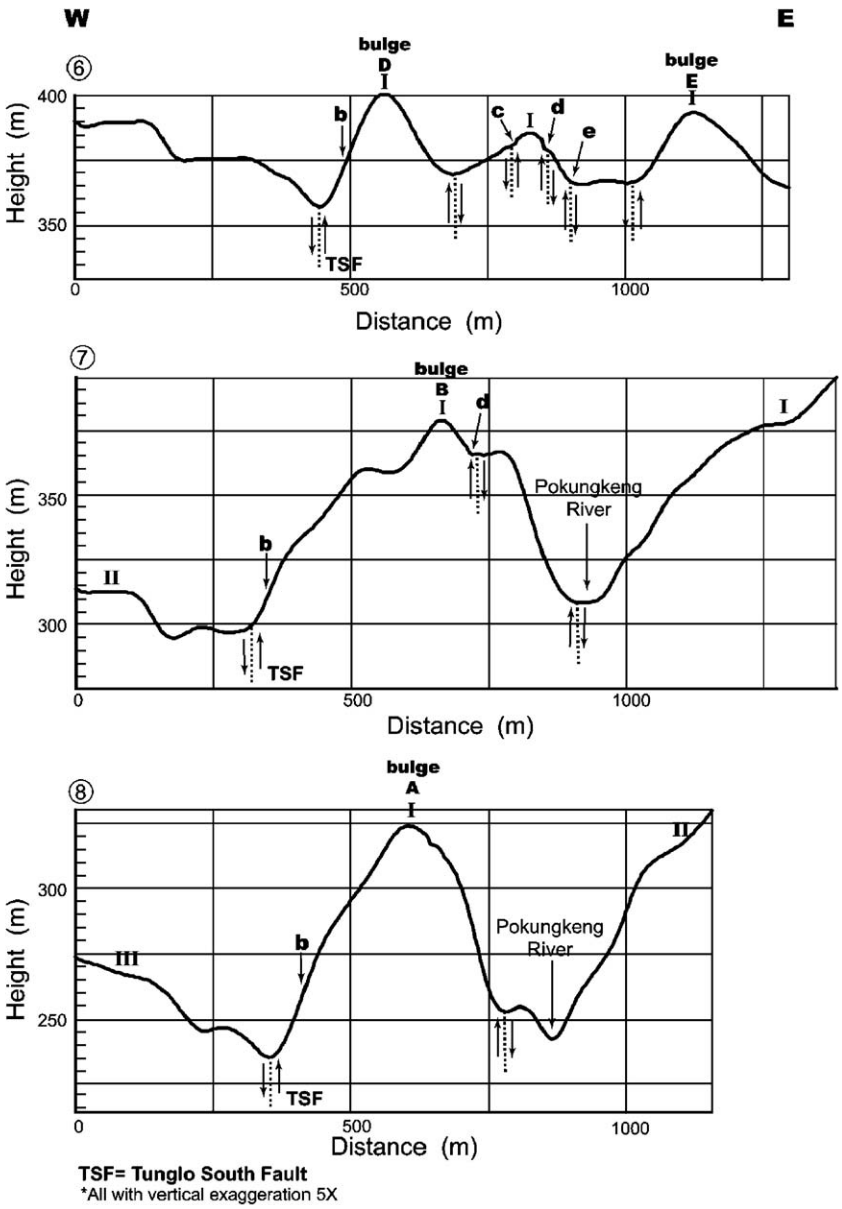

Fig. 9. Cross sections through tectonic bulges shown in Fig. 8. Dips of the faults are only schematic. I, II, III are terrace numbers.

River. However, it is difficult to correlate the intervening lowland with other terraces, because this lowland is purely tectonic origin. The height of each bulge increases northward along its long axis (e.g. bulge A, 325–365 m asl, bulge B, 340–383 m asl, and bulge D, 400–406 m asl), indicating their northward propagation associated with strike–slip movement. They also show asymmetrical cross profiles (Fig. 9). In places, the western side is steeper (bulge D); in others, the eastern slope is steeper (bulge B). Four straight small scarps (c–f in Figs. 8 and 9) strike parallel to the long axis of the bulges and dislocate the undefined terraces probably of fluvial origin. Scarp heights are as small as several meters. Consequently, we interpret these scarps as traces of minor active faults associated with the Tunglo South Fault that produced the bulges by right-lateral slip, oblique to the regional E–W stress field derived from the structure orientation.

These landforms (Fig. 10, right) resemble tectonic features shown in Fig. 10 (left), which illustrates a central part of Japan's Itoshizu Tectonic Line Active

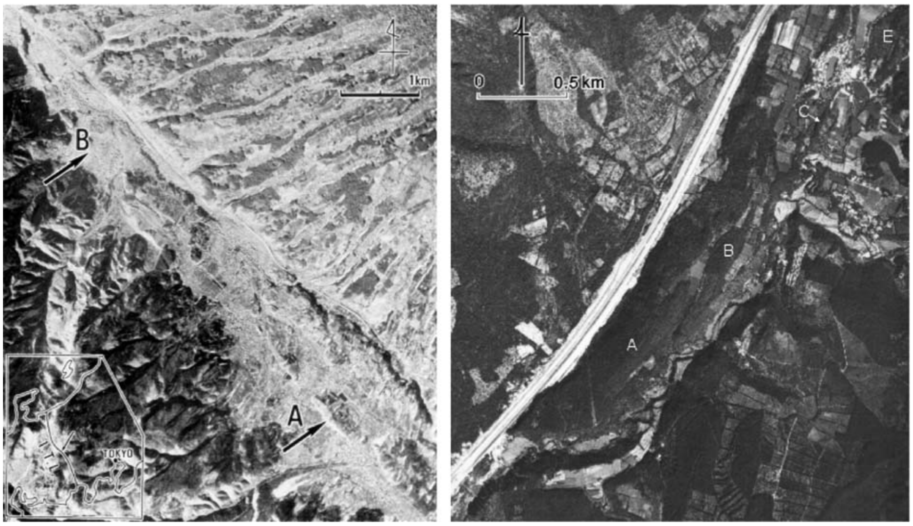

Fig. 10. Left: Mosaic aerial photograph showing the bulges and lowland due to left lateral slip of the Itoshizu Tectonic Line in central Japan, for the comparison of similar feature of this study area. Major active fault strikes NW–SE and limits the southwestern edge of tectonic bulges. Almost vertical fault planes and their repeated activities were found from trenches A and B. (Research Group for Itoshizu Tectonic Line Active Faults, 1988) Right: En echelon bulges and faulted terrace due to the Tunglo South Fault. A, B, C and E are the bulges deformed by right-lateral strike–slip fault (see Fig. 8 for location).

Fault. This fault is one of major active faults in Japan running from the Pacific side to the Japan Sea side. In this segment, its strike changes from N–S to NNW–SSE, oblique to the compressional stress field, and hence numerous tectonic bulges were formed. Trenching on the base of bulges on this tectonic line (A and B in Fig. 10, left) revealed the presence of nearly vertical fault planes and their repeated activities during the late Quaternary (Research Group for Itoshizu Tectonic Line Active Faults, 1988). Such a similarity of deformation characteristics between our study area and Itoshizu Tectonic Line Active Fault, except for the difference in sense of strike slip due to different arrangement of faults, suggests that the bulges too may have the same origin. Although we have no field evidence of fault exposure in our study area, trenching across the fault shown in Fig. 8 may eventually test our interpretation.

The bulges C–F stand as the divide to separate the Hsihu River and another stream (the Pokungkeng River) that flows southward parallel to bulge alignment. Therefore, the development of Pokungkeng River probably postdates the formation of Terrace I. In the east of this river, a wide Terraces I, II and III are present (Fig. 8). Terrace I is correlated to Terrace I across the Pokungkeng River and was formed by the paleo-Taan River, although they may be presently separated by this small stream. Terrace II and III may be also fluvial terraces, but were probably formed by the south-flowing Pokungkeng River. These terraces show remarkable undulation (Terrace I) or westward tilting (Terraces II and III). This observation further suggests that the region was under E–W compression and the bulges are developed by the stress accommodation due to the oblique fault slip.

2.2.5. District 5: deformed fluvial terrace along both banks of the Taan River and the Houli Tableland

A wide fluvial terrace on the right bank of the Taan River is shown in upper-right corner of Fig. 11. It consists of four clear levels, but the wide, upper two are considered as originally the same one and disrupted later by faulting. The scarp separating the upper two levels is sharp, straight and trending NE–SW, perpendicular to the flowing direction of the rivers beside (Fig. 11). The scarp height is ca. 70 m in the north and 55 m in the south. Judging from its straightness and orientation, this scarp is hardly formed by river erosion, but instead resulted from faulting. The scarp coincides with the location of the Chentoushan Fault (Lee, 2000), and its tens-of-meter height implies repeated Quaternary activities. Except for the sharp scarp, we cannot trace its extension northward or southward, however. Nor were we able to correlated lower terraces across the fault. Thus, we are unable to extract progressive deformation from the fault. Probably the northern and southern extension has been removed by rapid hillside and fluvial erosions.

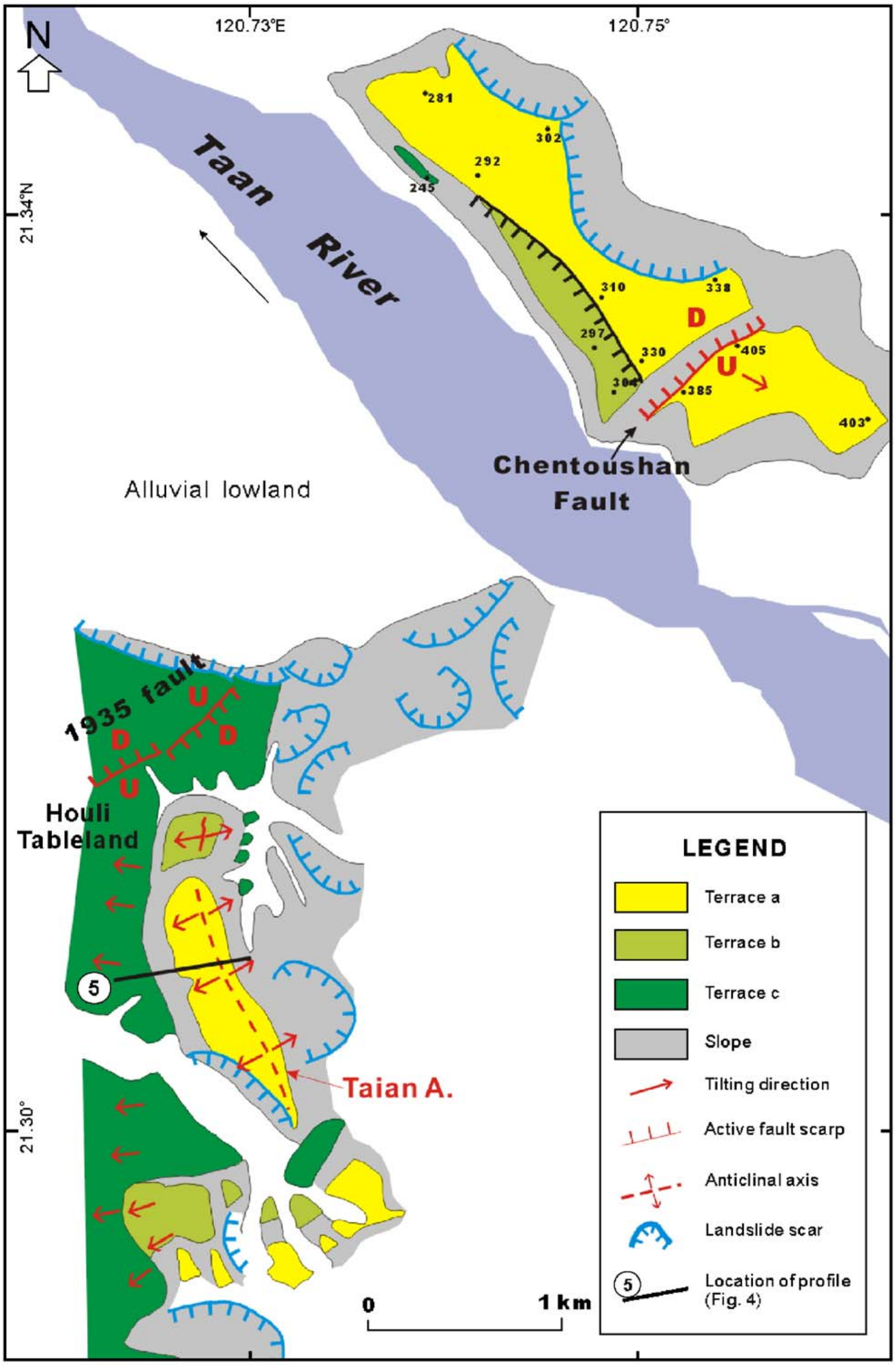

Fig. 11. Geomorphic map of the southernmost part of the study area. Correlation of terraces to the areas shown in Figs. 3 and 8 is uncertain. A high fault scarp (Chentoushan Fault) and growing Taian Anticline are shown. Surface deformation by the 1935 earthquake is partly still visible and shown in this figure.

South of the Taan River, at least three steps of fluvial terraces (a, b and c) are present in the western foot of the mountains (Fig. 11). The higher terraces, “a” and “b”, are deformed into an asymmetrical anticlinal ridge with NNW–SSE trend (Figs. 2 and 11). This growing anticline tentatively referred as Taian Anticline in this paper has not been previously mapped. The lowest terrace “c” in the west of the anticline tilts westward, indicating the late Quaternary growth of the anticline.

The M = 7.0 1935 earthquake main shock (Richter, 1958) resulted in the surface rupture (Tuntzuchiao Fault) and deformation of Terrace “c” along an ENE–WSW trend. The rupture consisted of minor fault scarps, most of which faced NW. The scarp near the Taan River, however, faces SE. En echelon cracks were common. All the ruptures and related deformations were described in detail by Otuka (1936). We traced surviving evidence of the surface rupture on the new topographic map of 1 : 25,000 and checked it in the field (Fig. 2). Although many of the surface ruptures, especially en echelon cracks, disappeared by artificial modification, we still found some of the scarps. Their height ranges from ca. 1 m to more than 3 m. Unfortunately, still no proper outcrop enables us to rule out whether the terrace deposits have cumulated the strain prior to 1935 event.

3. Discussion

3.1. Identification of new active fault system and its style

3.1.1. Identification of Tunglo Fault System

Above we have presented several active faults based on the deformation of fluvial terraces as shown in Figs. 3, 8 and 11). One of them is the Tunglo (Active) Fault, a reverse fault with assumed westward dipping fault plane, as identified by the eastward flexure of Terraces I, II and even occasionally Terrace III in the Sanyi Tableland District. It continues ca. 16 km from Tunglo to the north of the Taan River, strikes N–S in the north of Sanyi, and turns to NNE–SSW in the south. Because the downthrown side is always buried with younger deposits, the exact amount of vertical offset is difficult to determine. Also we cannot pin down the slip rate without improved dating of the terraces. However, apparent vertical offset of Terrace I, ranging at least from ca. 90 m to 40 m (Fig. 4), suggests the possible slip rate of an order of meter per millennium. The northward decrease of the vertical offset agrees with the northward down tilting of Terrace I. This indicates either the shortening rate changes due to opener structural dimension or dipping angle diminishes.

The Tunglo South Fault is distributed in the east of the southern part of Tunglo Fault, which approximately coincides with the NNE–SSW trending portion of the geologically identified Sanyi Fault. Consisting of several minor faults, the Tunglo South Fault deforms the surfaces into several bulges, which suggests the presence of dextral strike–slip because it is oriented oblique to the compressional stress (see text above). Thus, the Tunglo South Fault is likely a high angle reverse fault with dextral component, apparently independent to the low-angle Sanyi Fault. Moreover, because we found no evidence of Quaternary movement on the E–W segment of Sanyi Fault, we doubt whether the N–S segment of Sanyi Fault remains active or not.

We further propose that the Tunglo East Fault flanks the Hsihu River in the east. It extends at least 4 km along strike, shorter than the Tunglo Fault, and probably dips to the east. It produced progressive, reverse deformation on three terraces, while the apparent vertical offset is only several meters to some 10 m, smaller than that of the Tunglo Fault.

Since the narrow valley along the Hsihu River is confined in between two reverse faults with vis-à-vis vergences, it is no doubt to have a tectonic origin. Its course started to develop when these faults began activation. It is roughly after the formation of Terrace I based on the geomorphic order. The Tunglo Syncline, located further to the east of the Hsihu River valley, seems to have less influence on the development of the modern stream course and terrace deformation.

Then, we define such a complex fault system as “Tunglo (Active) Fault System”. It includes multiple active faults: the Tunglo Fault (including the N–S and NNE–SSW segments), Tunglo South Fault, demonstrated by a high west-facing scarp with an array of elongated bulges and lowlands as well as several minor faults, and Tunglo East Fault, a reverse fault in the north thrusting westward. The style of deformation within this system varies with the fault strike. Among this system, the Tunglo Fault is the major one in terms of length and vertical offset. The Tunglo Syncline shown in geologic maps (Fig. 2) predates to all these active faults, as does the E–W striking part of Sanyi Fault.

3.1.2. Other active structures

The Chentoushan Fault cuts Terrace “a” (Fig. 11) and forms a scarp height of 50–70 m, which implies repeated slips since the terrace formation. The present fault length of only 800 m is too short to have several tens of meters of vertical displacement. However, we cannot trace the extension of this fault because it projects northward into mountains and southward into a modern river.

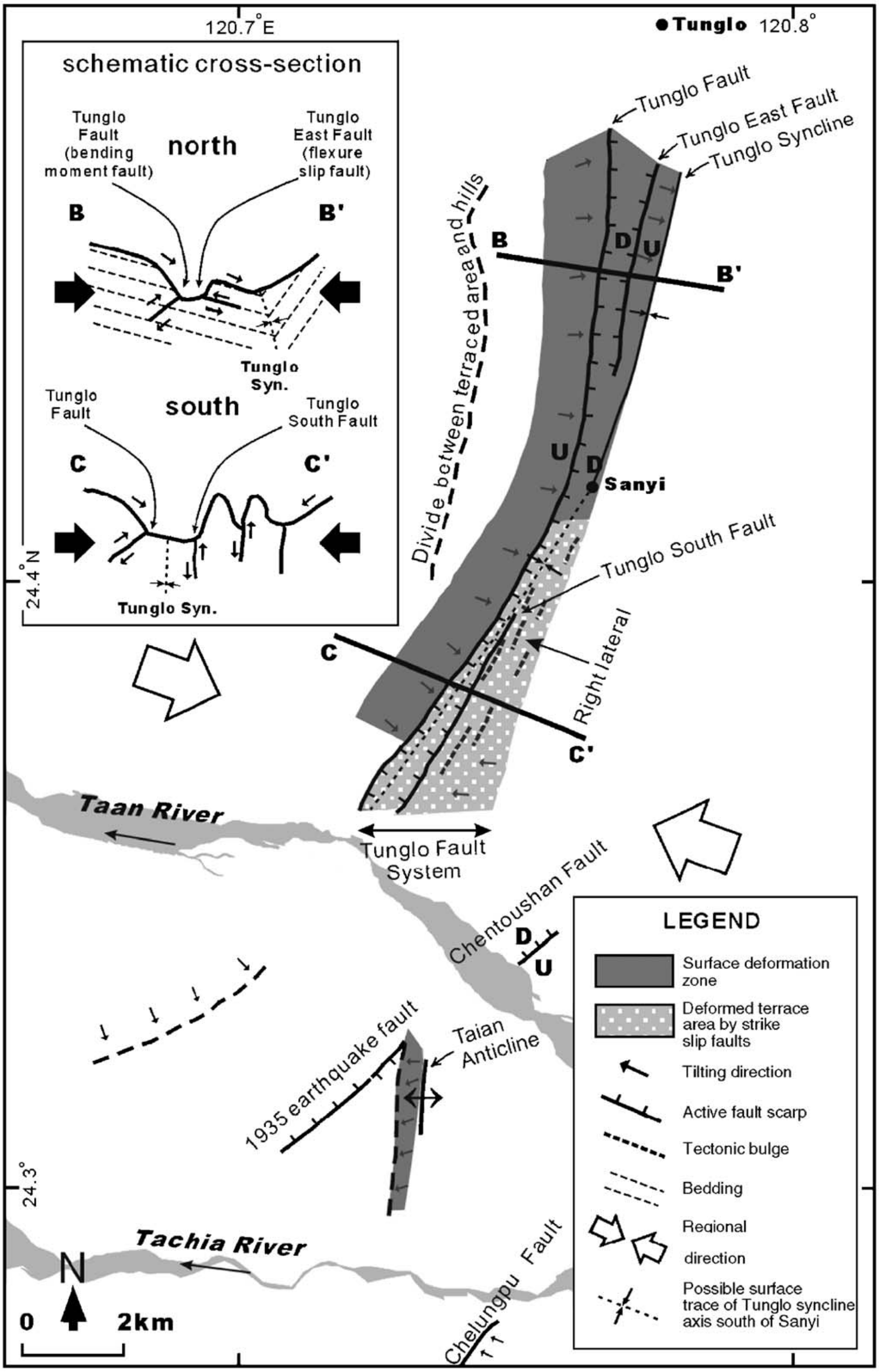

Fig. 12. Schematic map showing the Tunglo Fault System, deformation styles and possible relationships of major active faults. Inset shows the schematic cross sections showing the relationship between active faults and Tunglo Syncline.

A growing Taian Anticline (Fig. 11), showing progressive deformation, characterizes the deformed terrace between the Taan and Tachia Rivers.

The Tuntzuchiao Fault produced surface rupture the 1935 earthquake but lacks conspicuous evidence of previous activity.

3.2. Relationship of the active faults with their tectonic significance and remained problems

3.2.1. Relation of Tunglo Fault System and previously known Tunglo Syncline

Considering the distance between the Tunglo Fault and the axis of the Tunglo Syncline tapers off from north to south, the relation between the Tunglo Fault System and the Tunglo Syncline should also vary spatially (inset of Fig. 12). In the north, we prefer to interpret the Tunglo Fault as a bending moment fault, since its west-dipping fault plane transects the east-dipping strata. By contrast, the suggested east-dipping fault plane of Tunglo East Fault is parallel to the dip of the strata, implying that this fault is possibly a flexure slip fault (top of inset, Fig. 12). In this case, they would be both shallow-seated faults. However, the progressive deformation of the Tunglo Fault has proved itself not to be merely a secondary surface phenomenon, and repeated activities suggest that this may be a seismogenic fault. A published seismic profile (Hsu and Chung, 2001; Fig. 13) shows high angle strata around the west wing of the Tunglo Syncline, along with some signal discontinuity toward the axial part. We put a thrust fault here, and interpret it as a deep-seated back thrust generated by a fault bend in depth. Although the most critical portion of this profile – the shallow part – is blank, we tentatively infer this back-thrust as the root of the Tunglo Fault, for it is the only one fault in this area that shows significant surface deformation. Thus, besides the bending moment character based on its truncating relationship with the syncline as discussed above, this fault should also be a deep-rooted one, and probably promise high seismic potential in the future.

To the south, the syncline axis matches with the topographic low. The closely located Tunglo Fault and Tunglo South Fault are developed on each side of the axis. They obviously show different faulting behaviors according to the geomorphic features presented in this study. The Tunglo Fault here is similar to its northern counterpart – a back thrust – but slightly changes its strike from N–S to NNE–SSW. The Tunglo South Fault is a strike–slip dominant fault, and could be the product of strike change on the Tunglo Fault System, just like the middle segment of the Itoshizu Tectonic Line Active Fault. Nonetheless, rather than totally dominated by a strike–slip fault, the thrust-dominant Tunglo Fault still exists and accommodates a great amount of deformation. Combining the structural evolution history in this area (Hung and Wiltschko, 1993), here we proposed a model of interpretation (Fig. 14). Since Miocene, two

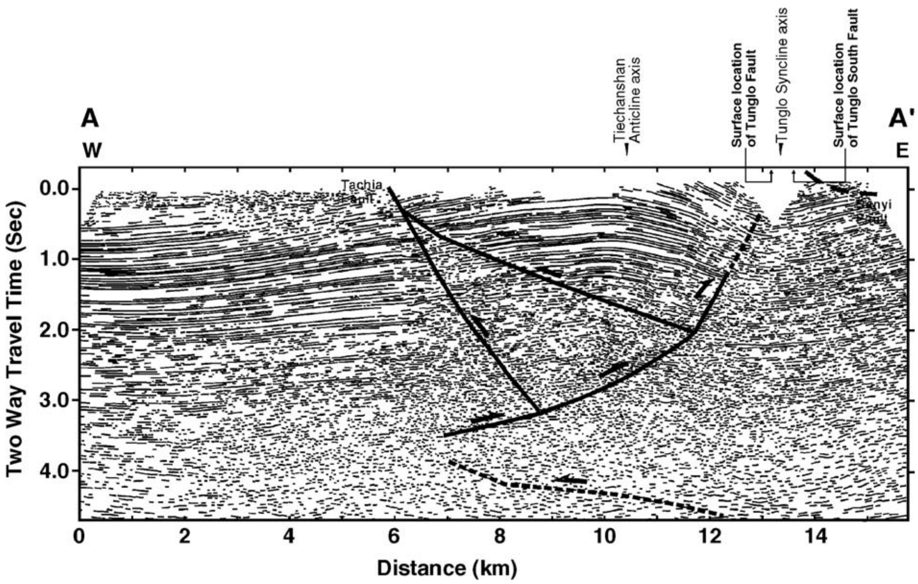

Fig. 13. An E–W profile shows re-digitized reflectors in which the Tiechanshan Anticline and Tunglo Syncline can be clearly defined (see Fig. 1 for location). We interpret that a wedge back thrust generated beneath the Tiechanshan Anticline and cut through the west limb of the Tunglo Syncline to form the anticline above due to the curved fault plane. This back thrust may be in response to a fault bend on the regional detachment (dashed line).

major folds, the Chuhuangkeng Anticline and Tunglo Syncline developed in the Sanyi area, while the Sanyi Fault gradually propagated westward. Later when it approached and overrode the Chuhuangkeng Anticline, large strain accumulated and caused the southern segment of the growing Tunglo Syncline to bend. In the meanwhile, the Tunglo Fault was formed from the south and also bended, along with the Tunglo South Fault to its east, performing strain partition to accommodated the high strain at the front of the Sanyi Thrust Fault. This model not only explains the high gradient slope of the northward dipping Terrace I, but the relationship among the old thrust fault, new thrust fault and new strike–slip fault.

3.2.2. Relation between Tunglo Fault System and other faults

By the bird view, Tunglo Fault runs southward toward the Chelungpu Fault, the major active fault in the south (Fig. 1). However, the Chelungpu Fault is a low-angle thrust dipping to the east, impossible to be the southern extension of the Tunglo Fault. Also there is almost no lateritic soil developed on the terraces in the hanging wall of the Chelungpu Fault, but the Tunglo area has abundantly developed lateritic soil on terraces, suggesting the very different slip rate for the two faults. This observation indicates the area in between Tachia and Taan rivers is an accommodation zone to separate two neotectonic domains (Lai et al., 2004; Shyu et al., 2005). In addition, surficially the Tunglo Fault System seems connecting to the Tuntzuchiao Fault. However, they are independent based on subsurface geology by seismic profiles (Yang et al., 2004). Tuntzuchiao Fault in fact is a dextral fault running beneath the Sanyi Fault plane to the northeast (Lin, 2005). It also seems that the Tuntzuchiao Fault has the same strike to Chentoushan Fault. However, no surface rupture by the 1935 earthquake was reported from the Chentoushan Fault, nor was there any evidence of dextral slip on the Chentoushan Fault. Therefore, we cannot conclude if they belong to the same fault.

Although there are some unsolved problems about the relation among the newly identified active faults, active faults certainly exist in this seismic gap area, which indicates that faulting of the Tunglo Fault System with surface rupture may occur in the future. To evaluate future faulting and faulting history of the Tunglo Fault System, it is important to obtain paleoearthquake data and compare them with those from the Chelungpu Fault.

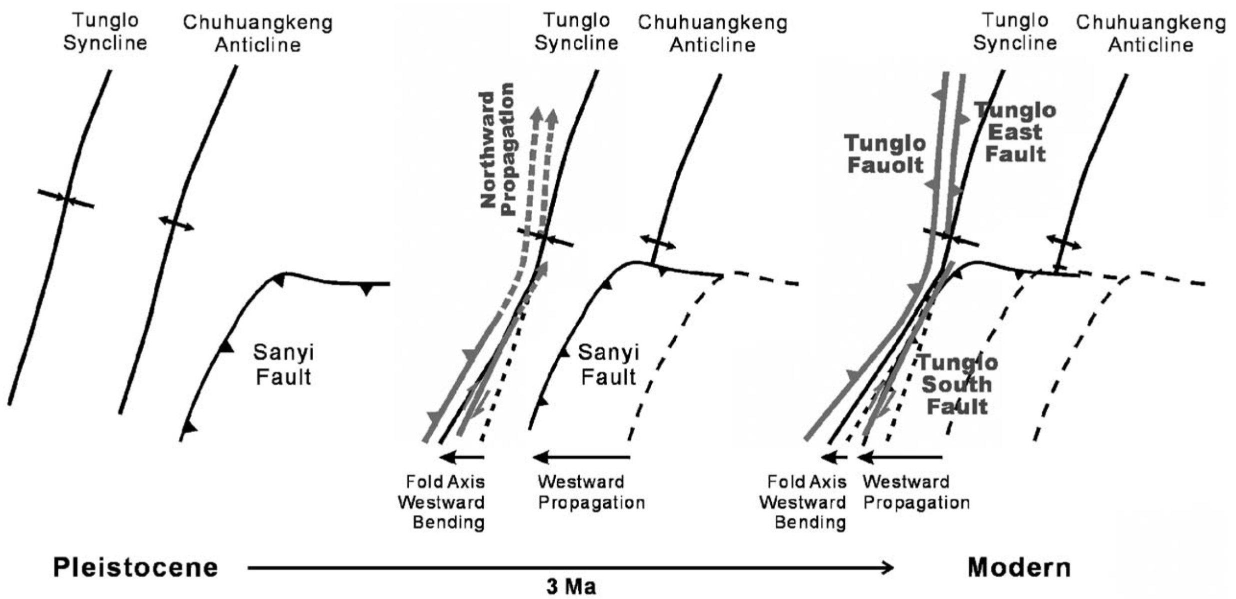

Fig. 14. Schematic model showing the evolution history of the structures in the Sanyi Area. Left: Since the beginning of the Taiwan Orogeny in Pleistocene, the Sanyi Fault has started its propagation from the east. In the meanwhile, a series of folds were formed in the west, including the Chuhuangkeng Anticline and the Tunglo Syncline. Middle: The Sanyi Fault kept propagating westward and started to override the Chuhuangkeng Anticline, which then became a huge barrier to the fault's movement in return. In response to the high stress accumulation in the front of the Sanyi Fault, two faults, one reverse fault and one dextral fault, were generated at the same time probably through the process of strain partition. Also the axis of the Tunglo Fault was westward bended. Right: As the Sanyi Fault gradually ceased movement in late Quaternary, the Tunglo Fault System then took the role of accommodating the still ongoing shortening, which was recorded by the fluvial terraces in this region.

Paleoseismic work is also needed along the N–S trending Taian Anticline and along the eastward transfer zone of the northern Chelungpu Fault.

3.3. Lithological control for landform evolution

The inversion of topography and presence of several beheaded valleys (Figs. 2, 3 and 8) resulted from serious erosion into the western hills where exposed strata are mapped as lower Toukoshan Formation. Toukoshan Formation is a Pleistocene fan–delta sequence deposited in foreland basin and composed of lower silt/sand and upper sand/cobble dominated two members. Erosion was probably facilitated by impermeable silt of the lower Toukoshan that crops out in the west hilly land. By contrast, the Sanyi Tableland is underlain by permeable upper Toukoshan and terrace gravels; thus, the landforms can be well preserved and assist to record the tectonic history.

4. Conclusions

The Tunglo Fault System, at least 16 km long, includes multiple active faults since the Quaternary. This fault system, redefined by this study, controls the drainage course of the northward-draining Hsihu River. The fault system produced additional tectonic landforms that vary with fault strike. Flexural scarp, back-tilted terrace, growing anticline are typical deformation types on the N–S trending Tunglo Fault and Tunglo East Fault, while en echelon tectonic bulges along the Tunglo South Fault in the south reflect lateral displacement on the fault that strikes oblique to the E–W compression. The east-striking segment of the Sanyi Fault shows no evidence of late Quaternary activity. The only evidence to reveal the recent activity of the Tunglo Syncline is the active Tunglo East Fault, a flexural–slip fault developed in the syncline hinge area. Tunglo Fault is a deep-seated back-thrust fault generated from the detachment in depth, which may be started in the middle Quaternary. Because of no record of surface rupture by these faults, future energy release by the faulting should be concerned. Unsolved problems include terrace ages, fault slip rates, the ages and recurrence intervals of paleoearthquakes within the Tunglo Fault System, and the relationship to other neighboring structures.

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