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Deformation front development at the northeast margin of the Tainan basin, Tainan–Kaohsiung area, Taiwan

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Abstract

The geological setting south of the Tsengwen River and the Tsochen Fault is the transitional zone between the Tainan foreland basin and Manila accretionary wedge in Southwestern Taiwan. This transitional zone is characterized by the triangle zone geological model associated with back thrusts that is quite unique compared to the other parts of the Western foreland that are dominated by thrust imbrications. The Hsinhua structure, the Tainan anticline, and the offshore H2 anticline are the first group of major culminations in the westernmost part of the Fold-and-Thrust belt that formed during the Penglay Orogeny. Structures in the the Tainan and Kaohsiung areas provide important features of the initial mountain building stage in Western Taiwan. A deeply buried basal detachment with ramp-flat geometry existed in the constructed geological sections. A typical triangle is found by back thrusting, such as where the Hsinhua Fault cuts upsection of the Upper Pliocene and Pleistocene from a lower detachment along the lower Gutingkeng Formation. The Tainan structure is a southward extension of the Hinhua Fault and has an asymmetric geometry of gentle western and steep eastern limbs. Our studies suggest that the Tainan anticline is similar to the structure formed by the Hsinhua Fault. Both are characterized by back thrusts and rooted into a detachment about 5 km deep. The triangle zone structure stops at H2 anticline offshore Tainan and beyond the west of it, All the structures are replaced by rift tectonic settings developed in the passive continental margin. On the basal detachment, a major ramp interpreted as a tectonic discontinuity was found in this study. Above the northeastern end of the major ramp of basal detachment, the Lungchuan Fault is associated with a triangle system development, while at the southwestern end a thrust wedge is present. It could be deduced that a thrust wedge intrudes northwestward. The area below the major ramp, or equivalent to the trailing edge of the basal detachment, mud diapers often occur in relation to the thickest deposits of the Gutingkeng Formation and caused by the mechanism of detachment folding.

Introduction

The fold-and-thrust belt in the Tainan and Kaohsiung area, Southwestern Taiwan, extends from the foothills in the east to the Western Coastal Plain and offshore area (Figure 1). The location of the thrust front inland of Southwestern Taiwan still remains uncertain. Accurate structural styles and their distribution between the inland and offshore still present existing high ambiguity due to the thick mudstone of Gutingkeng Formation overlying the Miocene. Therefore, this study is focused on constructing detailed balanced cross and palinspatic sections by integrating interpretation of seismic, well, and field data together. This study area is also located at the northeastern part of Tainan Basin. Overprinting of the compressional tectonics from the hinterland of Central Mountain Ranges resulted in the thick foreland mudstone cover over the pre-existing Miocene rift sequences, the deep structural framework of northeastern Tainan Basin is still a puzzle. A structural style and tectonic evolution of this area are proposed from previous documented studies (Figure 2). Generally, it is difficult to obtain good quality seismic data in the coastal plain in Southwestern Taiwan because of thick mudstone. But, in the offshore area of Southwestern Taiwan, the seismic data interpretation created from the exploration by the Chinese Petroleum Corporation and the survey by the Institute of Oceanography, National

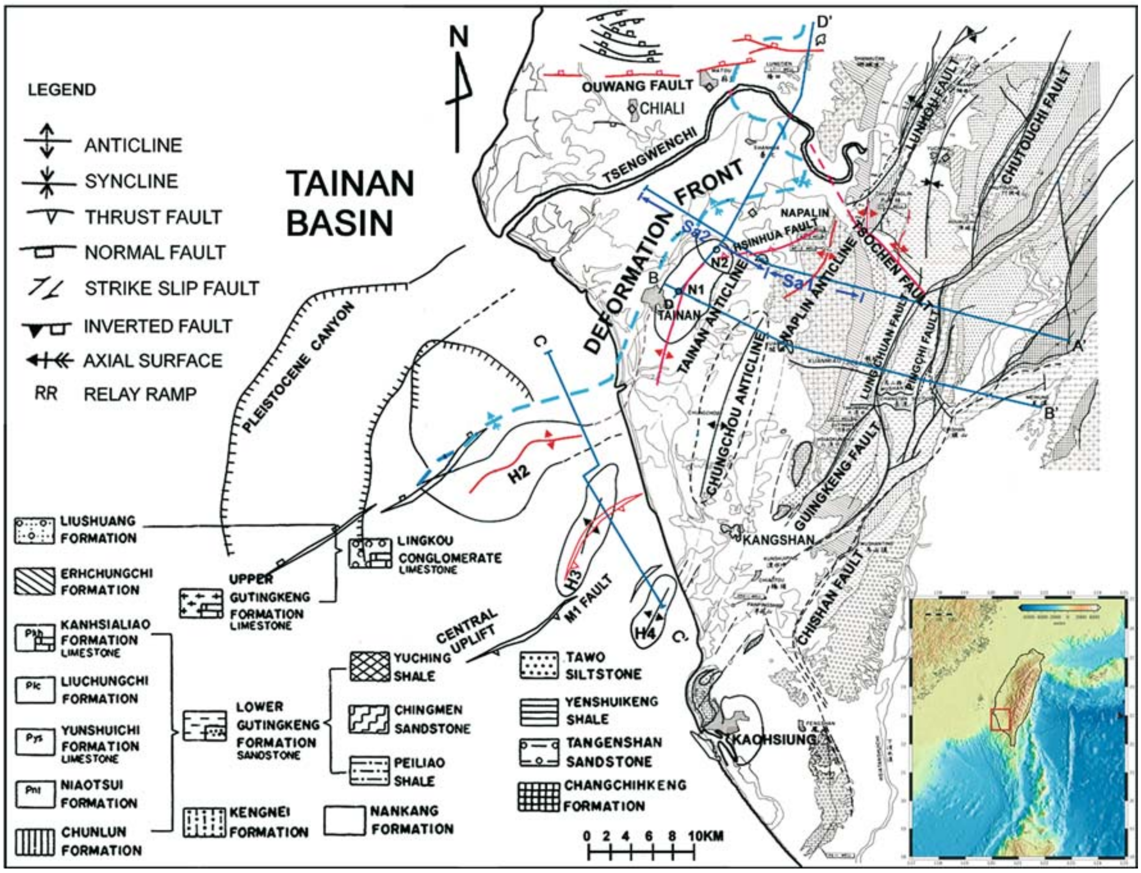

Figure 1. Studied area and shaded relief map in the Taiwan region (inland geology modified after Chou, 1971).

Taiwan University, reveal important tectonic features of the mountain front in Southwestern Taiwan. Therefore, the deformation front characteristics are always easier to observe in the offshore area than in the onshore area by the geophysical survey.

The foreland in the Western Taiwan mountain belt can be divided into three dominant tectonic units from north to south, the Taichung–Taihsi Basin, the Peikang Basement Highs, and the Tainan Basin. Tectonically, both basins were affected by contractive deformation and but remain extensional features to the west of the deformation front (Yang et al., 1991; Huang et al., 1993; Lin and Watts, 2002). The pre-orogeny tectonic settings in the foreland area in Western Taiwan can be divided into two major sedimentary basins, the Taihsi–Taichung and Tainan basins (Sun, 1982). The two basins are characterized by distinct sequences, which later affected the development of various structural styles in different segments of the fold-and-thrust belt. Thrust imbrication was considered to be the dominant folding mechanism in the previous Taihsi–Taichung Basin (Suppe, 1976, 1980, 1985; Ho, 1982; Hung and Suppe 2002), and the major synorogenic deposits sequences include the Toukoshan and Cholan Formations. The former is composed of conglomerate and fluvial sandstone. And the latter is alternations of sandstone and shale of shallow marine deposits (Covey, 1984, 1986). The depositional environment changes gradually from the southern rim of the Peikang High, and in the Tainan Basin. The foreland depositional sequences are characterized by thick and less compacted mudstone in lithology (Chou, 1971). On the same rim, structural styles also gradually changes southward from imbrication into duplex wedging and back thrusting. For examples, Suppe (1985) and Yang et al. (2003) interpreted that both Nanliao and Kuantzulin anticlines struc-

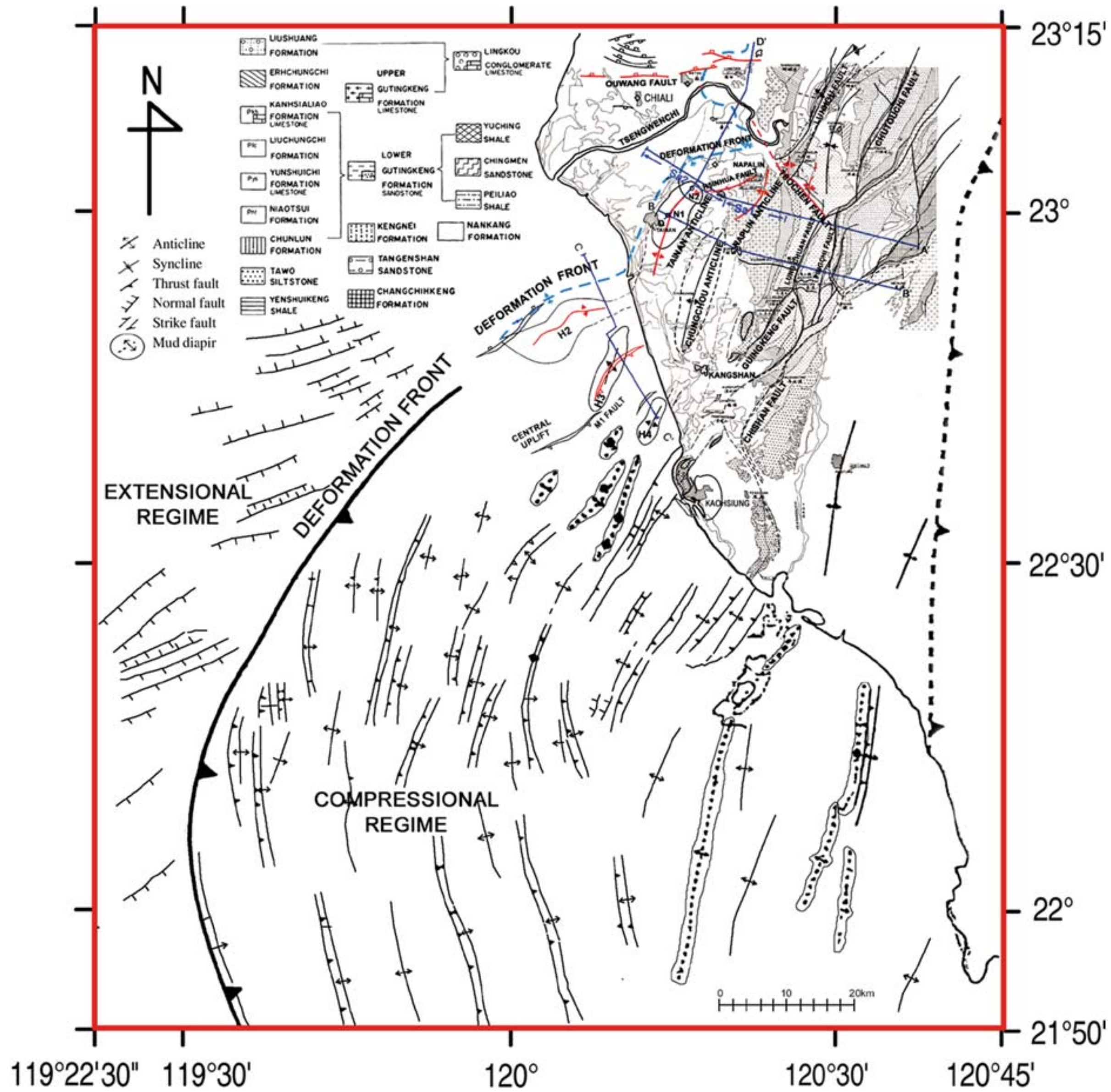

Figure 2. Structural map located in Southwestern Taiwan where the deformation front is extended from offshore into the inland area. The offshore area maintains the structural pattern of the incipient deformation of the Penglay Orogeny (modified from Lundberg et al., 1991; Huang et al., 1993; Lee et al., 1993; Yu, 1993; Fuh, et al., 1994; Chen and Yang, 1996; Liu et al., 1997; Chiang et al., 2004).

tures were underlain by duplex structures at depth, and the Nushan anticline was a triangle zone with thrusting wedge existing in the deeper part of the structure (Hung et al., 1999). Recently, some seismic profiles presented in studies on active faults in Southwestern Taiwan revealed the hinterland thrusting features. The main purpose of this study is to use the seismic data interpretation and cross-section balancing methods to perform detailed structural analysis and propose a structural model for this area.

Geological setting of southwestern Taiwan

The Southwestern Taiwan foreland is located on the southeastern Euroasian continental margin.

Table 1. Stratigraphy in Southwestern Taiwan (after Chi, 1981; Wu et al., 2002).

TIME: PERIOD	TIME: EPOCH		CALC PLAKTON NANNOFOSSIL ZONES	ABSOLUTE AGE (Ma)	CHAIYI AREA	TAINAN AREA	KAOHSIUNG, CHISHAN AREA
QUARTERNARY	HOLOCENE			0.1	TERRACE DEPOSIT	TERRACE DEPOSIT	TERRACE DEPOSIT (CHITING Fm.)
QUARTERNARY	PLEISTOCENE	LATE	NN21~NN20	0.2	LIUSHUANG Fm. (LS)	LIUSHUANG Fm. (LS)	LIUSHUANG Fm. (LS) (CHITING Fm.)
QUARTERNARY	PLEISTOCENE	EARLY	NN19	0.45	ERHCHUANGCHI Fm. (EC)	ERHCHUANGCHI Fm. (EC)	ERHCHUANGCHI Fm. (EC) (CHITING Fm.)
QUARTERNARY	PLEISTOCENE	EARLY	NN19		KANHSIALIAO (KSL)	YUCHING Sh. (YC)	GUTINGKENG Fm. (LGT)
QUARTERNARY	PLEISTOCENE	EARLY	NN19		KANHSIALIAO (KSL)	CHINMEN Ss. (CM)	GUTINGKENG Fm. (LGT)
QUARTERNARY	PLEISTOCENE	EARLY	NN19		LIUCHUNG CHI Fm. (LC)	PEILIAO Sh. (PL)	GUTINGKENG Fm. (LGT)
TERTIARY	PLIOCENE	LATE	NN18 NN17 NN16	1.8	YUNSHUICHI Fm. (YS)	CHUTOU CHI Fm. (CTC)	FAULT
TERTIARY	PLIOCENE	EARLY	NN15 NN14 NN13	3.0	NIAOTSUI Fm. (NT)	MAUPU Sh. (MP) AILIAOCHIAO Fm. (AL)	GUTINGKENG Fm. (GTK)
TERTIARY	PLIOCENE	EARLY		4.4	NIAOTSUI Fm. (NT)	YENSHUI KENG Sh. (YSK)	GUTINGKENG Fm. (GTK)
TERTIARY	PLIOCENE	EARLY	NN12	5.0	CHUNGLUN Fm. (CLN)	TANGEN SHAN S.S (TE)	MUCHA Fm. (MC) WUSHAN Fm. (WS)
TERTIARY	MIOCENE	LATE	NN11	6.6 7.0	NANCHUANG Fm. (NC)	NANCHUANG Fm. (NC): CHANGCHIH KENG Fm. (CCK)	
TERTIARY	MIOCENE	LATE	NN10 NN9	11	NANCHUANG Fm. (NC)	NANCHUANG Fm. (NC): HUNGHUATZU Fm. (HHZ)	
TERTIARY	MIOCENE	MIDDLE	NN8	12	NANCHUANG Fm. (NC)	NANCHUANG Fm. (NC): SHANMIN Sh. (SM)	

These rifted basins were formed during the Middle Eocene to Middle Oligocene periods in response to the NW–SE crust stretching and thinning of the Eurasian plate (Yu, 1993).

Generally Lundberg et al. (1991), Reed et al. (1991), and Huang (1993) studied the structural geometry of the accretionary prism offshore Southwest Taiwan based on seismic reflection profiles. A distributed, wide deformation zone comprised of folds, thrusts and piggyback basins was formed by the arc-continent collision. This structural belt is characterized by a drastic change from NW–SE, south of latitude 22° to NNE–SSW to the north. As the Manila trench extends to north and diminishes near the Central Uplift in the southern margin of the Tainan Basin, the Manila accretionary prism is replaced by the mountain building belt with its coexisting foreland basin and the trench changes into the deformation front from the fold-and-thrust belt (Lundberg et al., 1991). The zone of deformation front is characterized by the

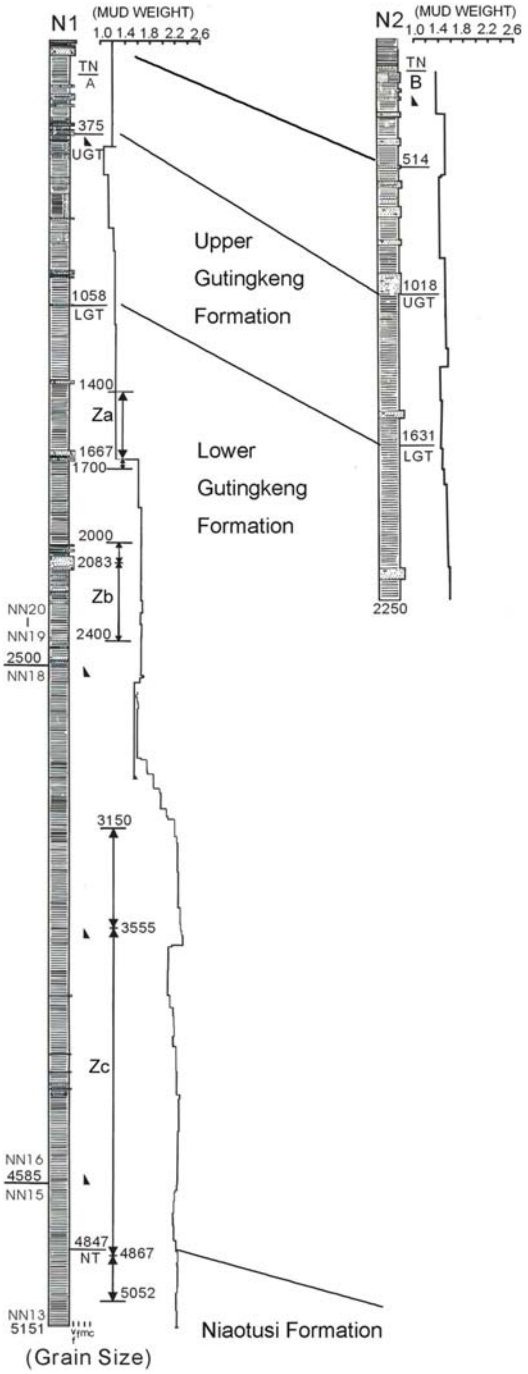

Figure 3. Typical subsurface geological column from well N1 and N2 illustrating the mudstone-dominiated facies intercracted with very few beds of very fine grain sandstone of the Plio-Pleistocene. The Tainan A and Tainan B formations are Holocene terrace deposits. Za, Zb and Zc overpressure zones are inferred from the drilling mud weight.

settings of proto-thrusts and frontal folds. Compressional structures can be observed in the eastern side of the deformation front while extensional structures and transitional settings with the alternative appearance of normal and reverse faults appear on the western side of the deformation front.

Southwestern Taiwan has been the foreland basin since the Pliocene period (Teng, 1987; Lee et al., 1999; Lin, 2001). The Neogene sandstone pinches out southward and is replaced by silty mudstone or siltstone in the Tainan–Kaoshiung area (Chou, 1971). The oldest formation outcropped in study area is the upper Miocene Changchikeng Formation The overlying Upper Gutingkeng Formation can be further divided into the Erhchungchi and Liushuang Formations in the Kaohsiung area (Table 1). The Lower Gutingkeng Formation consists of gray siltstone or mudstone intercalated with lenticular graywacke and subgraywacke while the Upper Gutingkeng Formation consists of gray sandy siltstone and sandy mudstone intercalated with lenticular graywacke and subgraywacke with abundant mollusca (Chou, 1971). The typical stratigraphic columns from the drilling well N1and N2 are shown in Figure 3. Most of the lithologic column is occupied by mudstone intercrated with fine or very fine grain sandstones. All stratigraphic boundaries are determined primarily by nannofossil analysis. The overpressure zones of Za, Zb, and Zc appear in mudstone-dominated Gutingkeng Formation and are formed by dehydration of clay minerals (Yuan, 1987).

On the southern side of the Tsengwen River and the Tsochenen Fault, the major tectonic elements include the Chishan Fault, the Pingchi Fault, and the Lungchuan Fault in the foothills belt, and the Kuanmiao Syncline, the Chungchou Anticline and the Tainan Anticline in the coastal plain area. The Tsochen fault is a tear fault served as a zone of displacement transfer between the Lungchuan Fault in the north and the Chishan fault in the south (Hickman et al., 2002). This tear fault is equivalent to the Chishan transfer zone recognized by Deffortaines et al. (1997). The Tainan, Chungchou anticlines, and the Kuanmiao Syncline geometries were constructed by using seismic data and residual gravity analy-

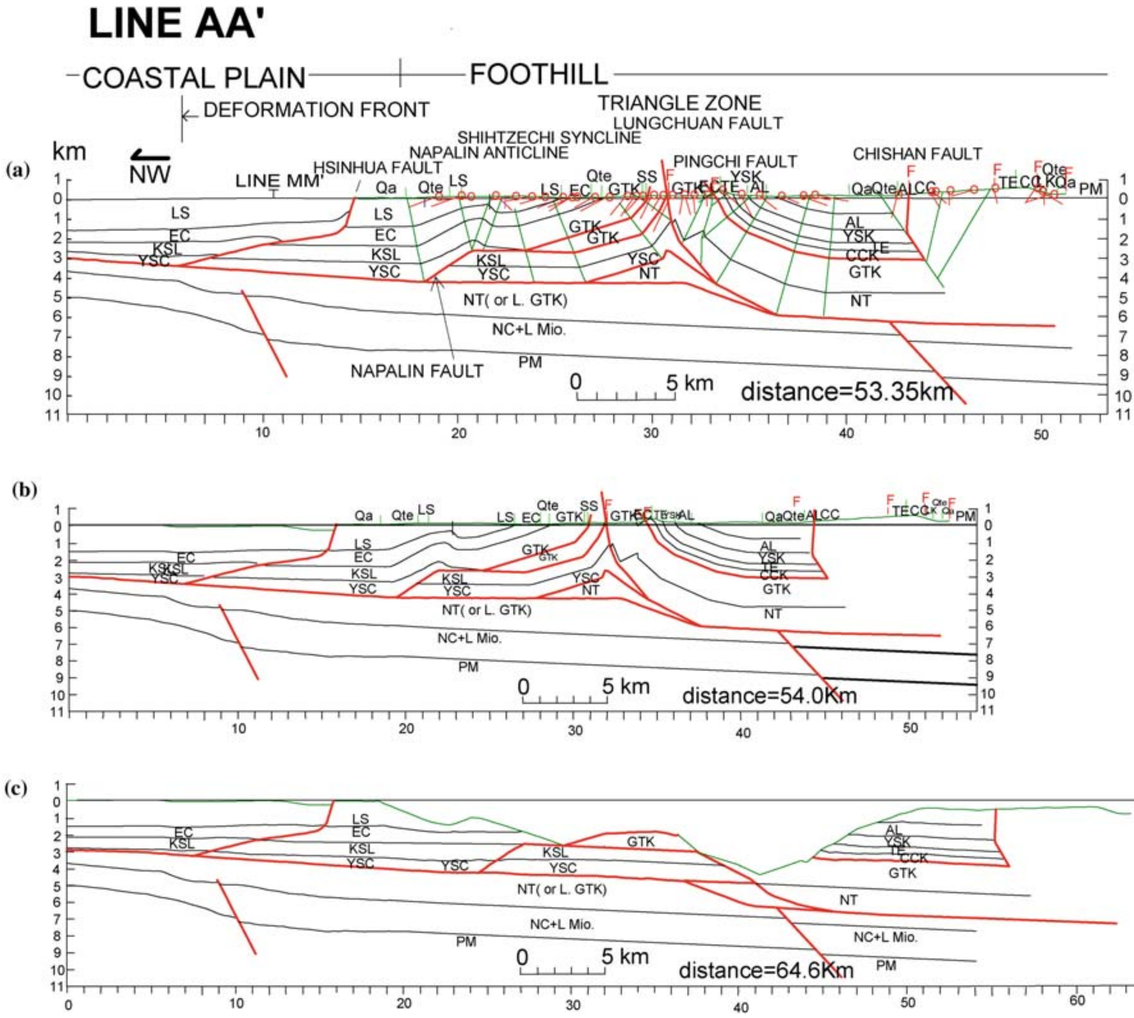

Figure 4. Sequential restoration of the Line AA′ in the western margin of the foothill belt illustrates the back-thrust signature forming the intercutaneous nappe from the hinterland. (a) Balanced dross-section AA′, (b) restored Hsinhua Fault, (c) restored triangle zone beneath the Lungchuan Fault. The contraction of hanging wall above the basal decollement is about 12.5 km at least (Hsinhua Fault: 650 m; duplex: 5000 m, Lungchuang Fault: 6850 m) (Symbol: red line, fault; green dash line, axial surface, abbreviation of formations, please see Table 1).

sis by Pan (1968) and Hsieh (1972) and a photogeology study by Sun (1964). They suggested that the en echelon arrangement of the Tainan and Chungchou anticlines and the Kuanmiao Syncline were caused by mud diapir uplift within the Lower Gutingkeng Formation under compressional stress.

Lee et al. (1999) divided Southwestern Taiwan into several piggyback sub-basins and proposed that the fold and thrust development is the main controlling factor for the pattern of basins.

Structure analysis of Southwestern Taiwan

Structural geology of the studied area can be illustrated by three geological profiles across the foothills belt and one longitudinal profile along the thrust front. Cross sections were constructed based on surface geology and subsurface well and geophysical data. Cross sections AA′ to CC′ and N–S profile DD′ will be discussed below. The correlation of the stratigraphy from north to south in the study area varies from north to south is listed in Table 1 (Chi, 1981; Wu et al.,

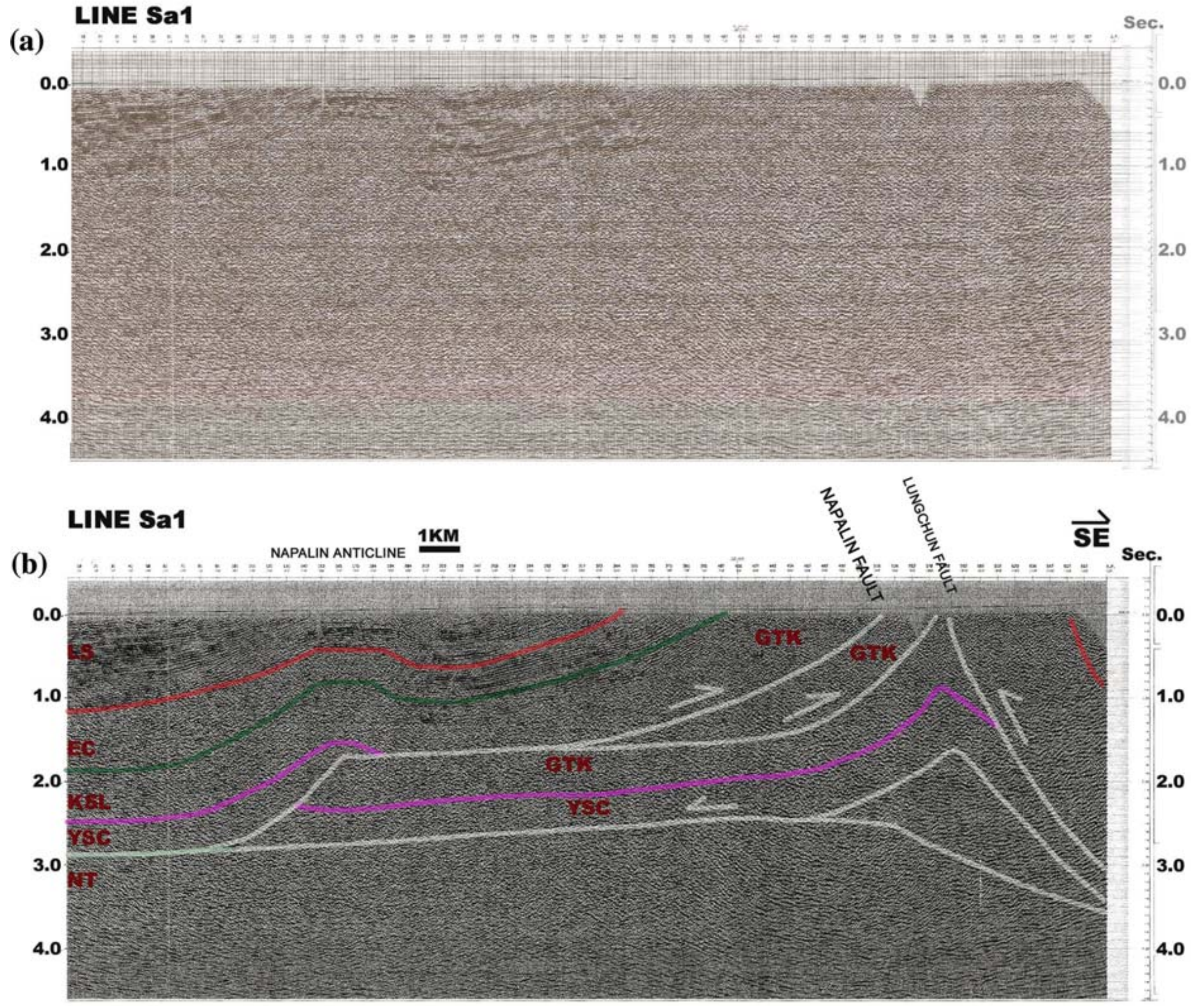

Figure 5. Seismic section Sa1 illustrating the geometry of Napalin anticline (see Figure 1 for location). Line Sa1 illustrates seismic signature of Napalin anticline with a gentle west limb and steep east limb. (a) uninterpreted seismic section Sa1, (b) Interpreted seismic section showing the Napalin anticline is formed by back-thrusting. Structures underneath the Lungchuan Fault include triangle underlying by thrust imbrication.

2002). This correlation table is composed of the lithologic, biologic, and time stratigraphy together and also exhibits the various changes of depositional environemts on the southern rim of Peikang High.

Section AA′

The major features in the A–A′ section (Figure 4) include the north–south trending and eastward dipping Lungchuan Fault detached at about 6–7 km depth. The duplex consisting of the imbrications Niautsui formation beneath the Lungchuan Fault, the Napalin anticline with a gentle western limb and steep eastern limb and associated with a blind back thrust (i.e. Napalin Fault), as shown on the seismic Line Sa1 (Figure 5). There is no reflection data at the shallow part of the southeastern side, so the deep of Hsinhua Fault must be corrected to the surface trenching features by (Lee et al., 2000). The Hsinhua Fault is a back-thrust, (or an upper detachment) with northward dipping of 17° at great depth by seismic data and at a high angle 70° near surface (Lee et al., 2000). The structural characteristics of section AA′ are partly shown

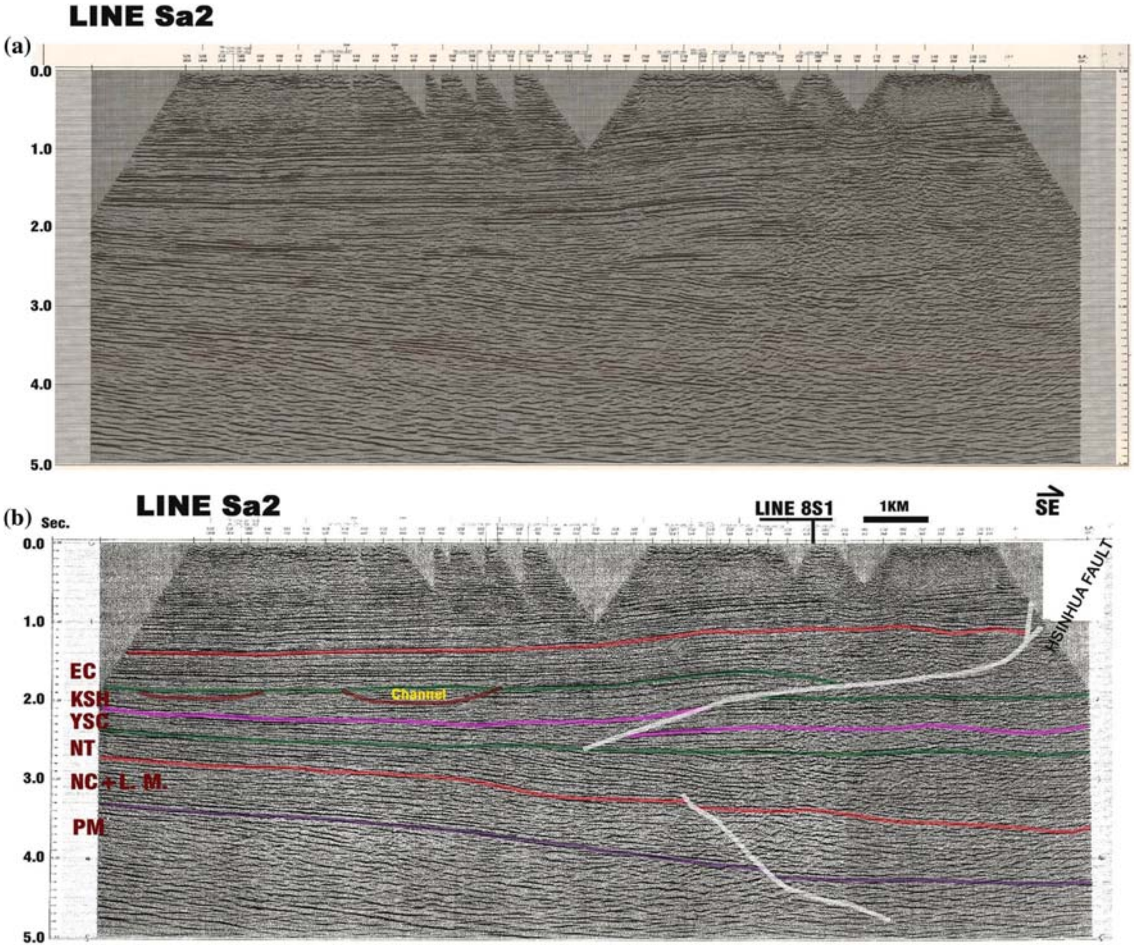

Figure 6. Seismic section Sa2 illustrating geometry of the Hsinhua Fault (see Figure 1 for location), (a) uninterpreted seismic section Sa2, (b) Interpreted Seismic profile showing the back thrusting geometry of the Hsinhua Fault and the underlying autochthonous section of sedimentary sequence of mainly Tertiary passive margin.

on the seismic profiles Sa1 (Figure 5) and Sa2 (Figure 6). Seismic section Sa1 shows that the Napalin anticline has an antiform structure with gentle west limb and steep limb in the east (Figure 5). The subsurface geometry of the Hsinhua Fault is shown in the seismic section Sa2 (Figure 6) where the geological model could be determined as a shear fault-bend fold dipping toward the south.

The Lungchuan Fault and underlying faults from a triangle zone accompany with a thrust wedging. There are two levels of detachments dipping underlying the surface of the Lungchuan Fault. The lower detachment is at 6–7 km in depth in the eastern part, and steps up on a ramp and connects the upper detachment at 4–5 km deep to the west. A duplex structure formed above the ramp with a repetition of the Niaotsui Formation.

Based on the restored profile AA′, displacement along the Hsinhua Fault is 635 m (Figure 4b). The total shortening of the Lungchuan Fault and blind thrusts underneath the Napalin Fold is about 10.6 km (Figure 4c), including 5.6 km displacement on the Lungchuan fault and 5 km slip on the restored duplex wedge (Figure 4c). The entirely restored section of AA′ (Figure 4c) indicate that the geometry of the hanging wall of the basal detachment is identical to that of the footwall. The palinspatic section from Line AA′ points out the originally geological setting and incipient ruptures of the northeastern margin of the Tainan Basin (Figure 4c). The anti-sequential kinematic restoration indicates that continuing orogenic movement has caused the eastern margin of the foothill belt to be uplifted and exposed. The palinspatic section of AA′ illustrates the geometry of the pre-orogeny and the distribution of initial thrust. A pre-existing boundary normal fault probably occurs on the western side of the Lungchuan Fault (Figure 4c). The Pingchi Fault is interpreted as a bedding-parallel fault and slip along the upper Gutingkeng Formation. The Chishan Fault and the faults to its east are generally dipping at a higher angle developed earlier than those in the outer foothill belt.

Section BB′

The BB′ section (Figure 7) is located to the south of the AA′ section and its structural features are quite similar to those on the AA′ section. Except for well LCN-2, N-1 and surface geology, there is relating few data for subsurface interpretation. The surface feature of the Chungchou Anticline was interpreted to be a monocline dipping to the east (Sun, 1964). Sun (1964) interpreted that there is a thrust in the east limb in the Tainan anticline using the geophotograph technique. Hsieh (1972) interpreted the Tainan anticline as a diapiric fold with both limbs bounded by normal faults using the seismic gravity and drilling well data to. The geomorphology of the eastern limb of the Tainan anticline shows a steep eastern limb and gentle western limb using digital aerial photograph map (Figure 8). Through repeated geodetic survey found that the Tainan anticline still active and still keep high rate of shortening with 0.4–0.5 cm/year (Fruneau, et al., 2001). By shallow seismic survey, the Houchiali Fault was previously interpreted as a normal fault on the east side of Tainan Anticline (Kuo et al., 1998). Mouthereau et al. (2002) proposed a pop-up model of a shallow decollement underlying the Tainan anticline. Recently, based on the study of trenching and paleo-earthquake study in the Tainan Tableland, Chen and Lee (2002) found that the previous Houchiali Fault is actually a regional tectonic flexure scarp modified by a sea wave rather a normal fault. The seismic lineshown by Kuo et al. (1998) can be reinterpreted that the change of bedding dip locals an axial reverse fault or nothing but an axial surface rather than a normal fault (Figure 9) due lack of clear offset between reflected horizons. Therefore, the Tainan anticline is probably associated with back thrusting mechanism at depth (Figure 7).

Section CC′

The section CC′ shows the structure in the offshore Tainan–Kaohsiung area. This geological section, constrained by time–depth conversion

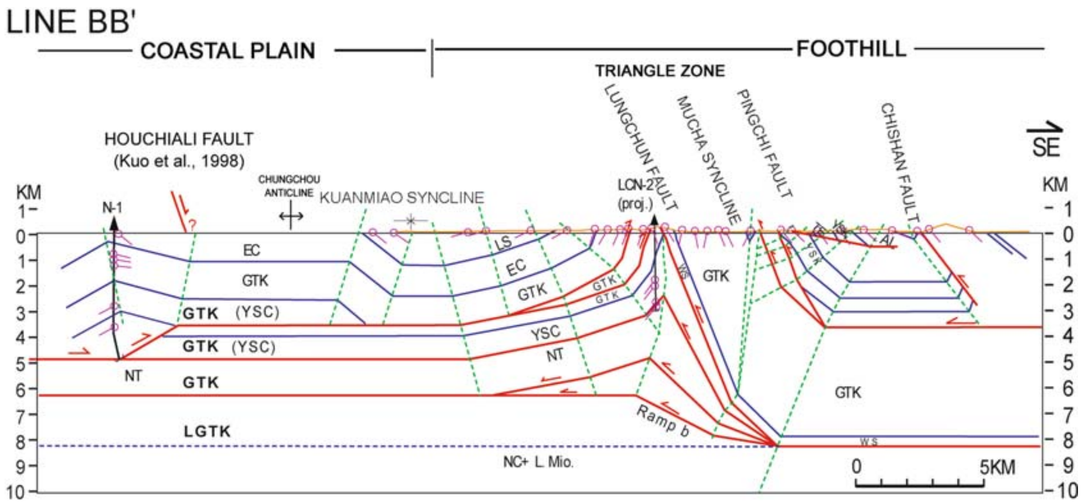

Figure 7. Line BB′ illustrating changes in structural style from east to west. Location of Line BB′ is shown on Figure 2. Line BB′ illustrates the triangle zone wedge signature moving westward.

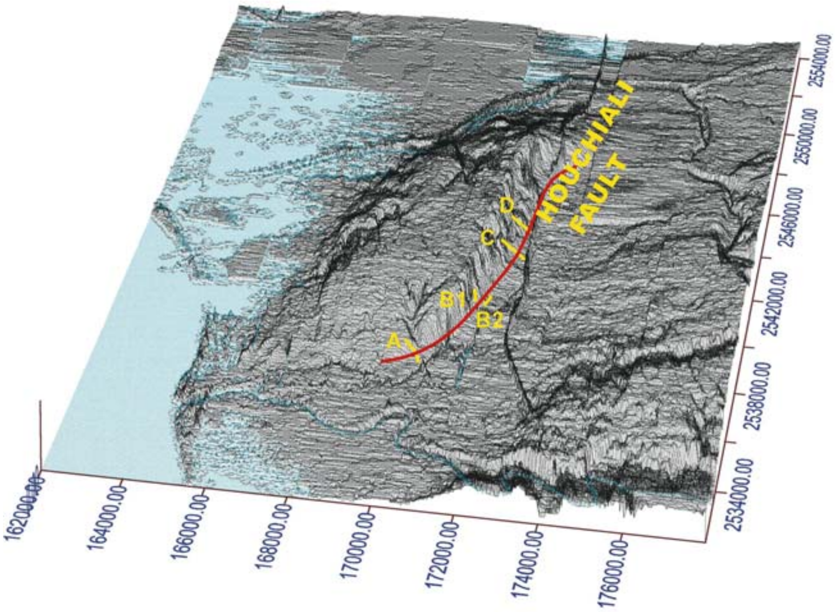

Figure 8. Digital tomography of Tainan terrace, a scarp occur at the East side of Taiwan terrace (after Kuo et al., 1998).

from seismic data interval velocity, reveals the triangle zone characteristics (Figure 10). The basal detachment (M1 fault) passes through a ramp to the northwest and then merges with a shallow detachment (B1 fault). The H3 anticline is interpreted as a thrusting wedge pattern rather than a fault-propagation fold. The H2 anticline is developed associated bending of the B1 fault. On the southern edge of section CC′, reflection-free region marks the doming of a mud diapir. A basement high located offshore of Kaohsiung City probably extends westward to the Tainan Basin Central Uplift. Generally, A bounding thrust at 7–8 km deep from southeast passes through a high angle fault ramp and flattens at about 3 km in depth. The major structure highs include H1 anticline above the basement high and draping from the Pliocene to the Pleistocene. H2 anticline is formed as a fault-bend fold with back thrust. H3 structure is recognized as a thrust wedged fold with flexure slip fault on the west-flank. The H4 anticline is formed by the mud diapir doming.

Section DD′

The pre-Miocene unconformity of the north–south direction of this area illustrates a gentle dipping southward. Horsts and grabens are the major tectonic features at the southern edge of Peikang High where the Chiali Ridge play an important role in the synrift and postrift tectonics of Tainan Basin (Figure 11). The Chiali Ridge was firstly proposed by Hu (1987) near the Chiali City. Its top is composed of crystalline limestone, dated as the age of Permian using Rubidium–Stronsium isotope method (Jahn et al., 1992). In this study, it is fond that the strike of this ridge distributes in east–west direction from coastal plain to foothill belt. The Chiali Ridge is bounded by the Ouwang Fault on the northern side while the Tsochen Fault is on the southern side. The covering formations, including Gutinkeng, Yunshuichi, Niaotsui, Nanchuang, and the lower Miocene overlie the pre-Miocene unconformity and thicken southward. The Tsochen Fault is determined as a tear fault with a flower structure in the shallow part (Figure 4). The deep part of the southern Line DD′ lacks geological and geophysical seismic data. The structural characteristics of this area will be interpreted using related crossing lines.

Discussion

Several small surface anticlines appear at the northern side of the Tsochen Fault arranging

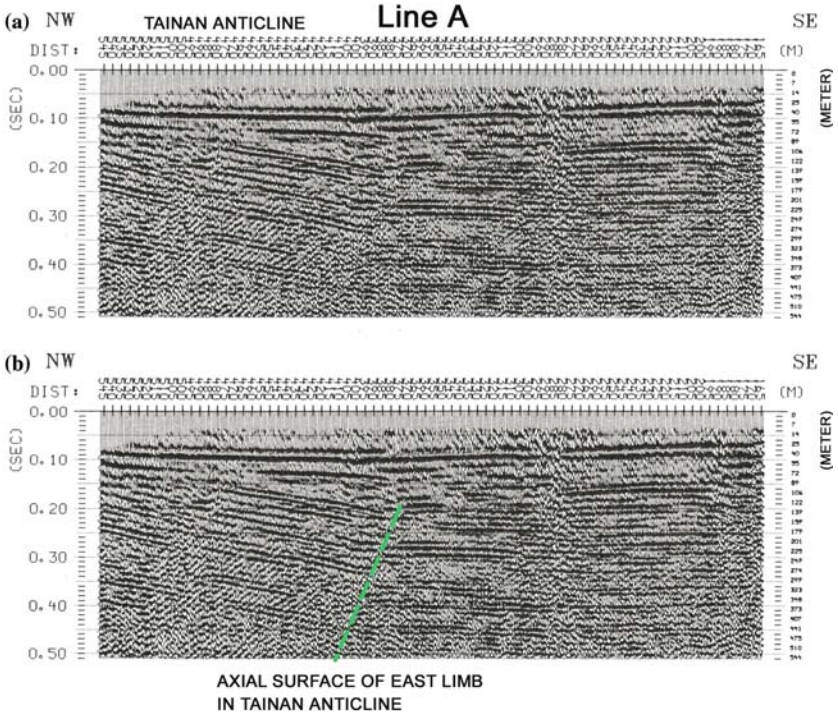

Figure 9. Seismic line A illustrating geometry of east limb of Tainan Anticline. Location of seismic line A is shown on Figure 7. (a) uninterpreted seismic section A (derived from Kuo et al., 1998), (b) Seismic line A illustrating an axial surface at the east front of Tainan terrace. The growth folding signature (Suppe, 1992) is also shown in the upper part of seismic line A.

en' echelon that verifies that the Tsochen Fault is a tear fault or a strike slip fault. The strike motion is also verified from the evidence of flower structure in the shallow part of hanging wall of Tsochen Fault from Line DD′ (Figure 4). The Tsochen Fault is thought to be the northern segment boundary of this study area. The Tsochen Fault strike-slip model is probably equivalent to the Chishan transfer fault zone (CTFZ) mentioned by Deffontaines et al. (1997).

In this study area, the southwestern margin of the foothill belt is characterized mainly by NE–SW striking and thin-skinned structural triangle zone. The triangle zone structure is significant with a series of hinterland-verging structures, such as the Napalin Thrust overlying a basal decollement that is probably lying near the conformable surface between the Niaotsui and Yunshuichi Formations. The interior of the triangle zone is commonly composed of a Niaotsui Formation passive roof duplex. The upper detachment called the Napalin Fault appears in the boundary between the Gutingkeng and Kanshialiao Formations, while the lower leading detachment appears in a weak stratigraphic horizon between the Yunshuichi and Niaotsui Formations. The trailing detachment occurs within the Lower Niaotsui Formation. The Hsinhua Fault and Napalin Fault are considered as additional back thrusts in the hanging wall of the basal detachment and finally, are rooted into this detachment surface. The Lungchuan and Pingchi Faults are foreland-verging thrusts. The Lungchuan Fault is emergent and thrusting into the adjacent foreland surface and against the upper detachment of the Napalin Fault. A shallow seismic survey by Wang et al. (1998) verified that it is difficult to find a trace of the Hsinhua Fault in places far away from the center of the fault where the fault is replaced by gentle folded structure (Wang et al., 1998). This same feature that antiform geometry dies out quickly along its strike also occurs on the Hsinhua Fault in the seismic survey of the Houchiali Fault (part of the Tainan Anticline) (Kuo et al., 1998). The Houchiali fault, which was previously interpreted as a normal fault, probably is only an axial surface running through the toe of the eastern limb

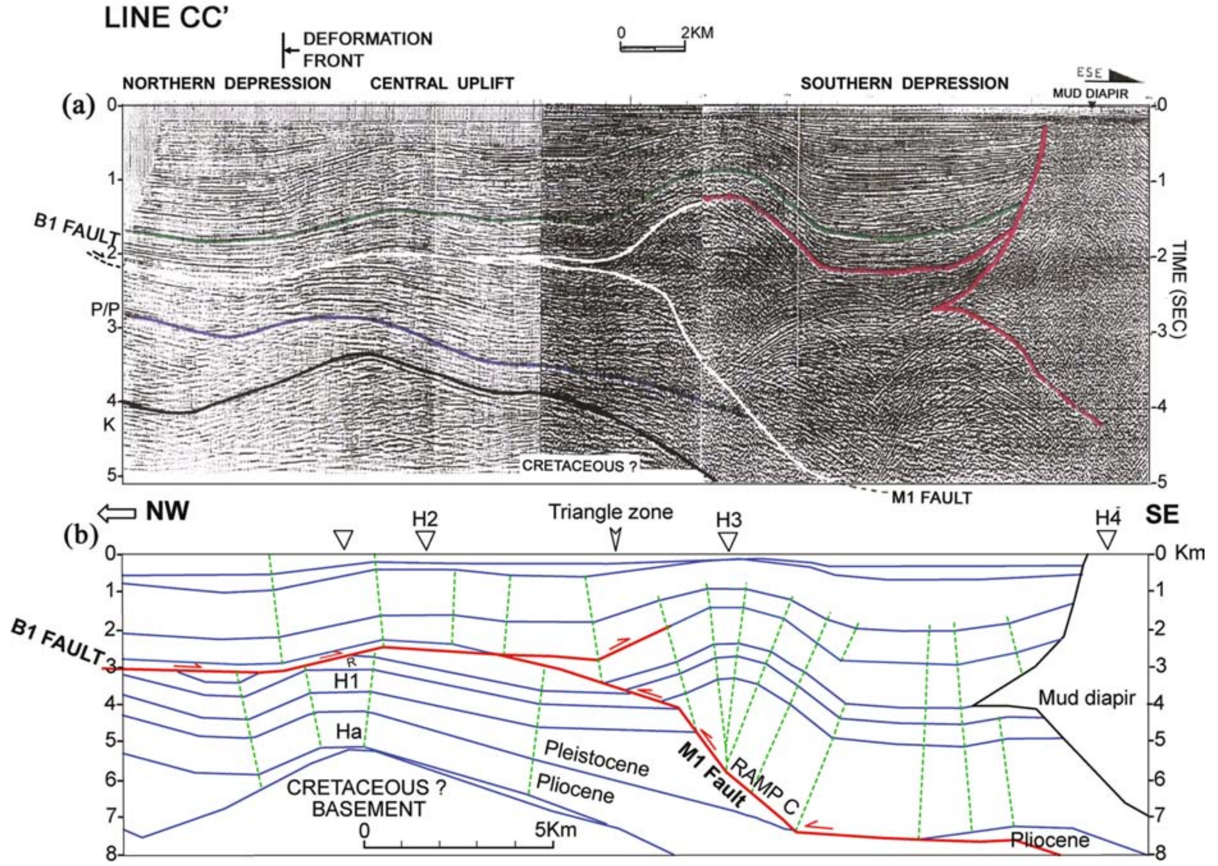

Figure 10. Line CC′ illustrating geometry of a triangle zone along the near shore of Tainan–Kaohsiung area. Location of Line CC′ is shown on Figure 2, (a) interpreted seismic section, (b) Geological cross-section CC′ illustrating changes in structural style from southeast to northwest. Figure 11 Structural change of north–south direction in the study area. Thickness of the Plio-Pleistocene and the depth of basement (pre-Miocene unconformity) are increasing southward.

of the Tainan Anticline (Figure 8). We suggest that the Hsinhua structure with its related monocline and the Tainan Anticline are very localized and are discontinuously aligned in the surface, although they probably share the same buried leading detachment, and that the back-thrust distribution is also discontinuous (Figures 2 and 10).

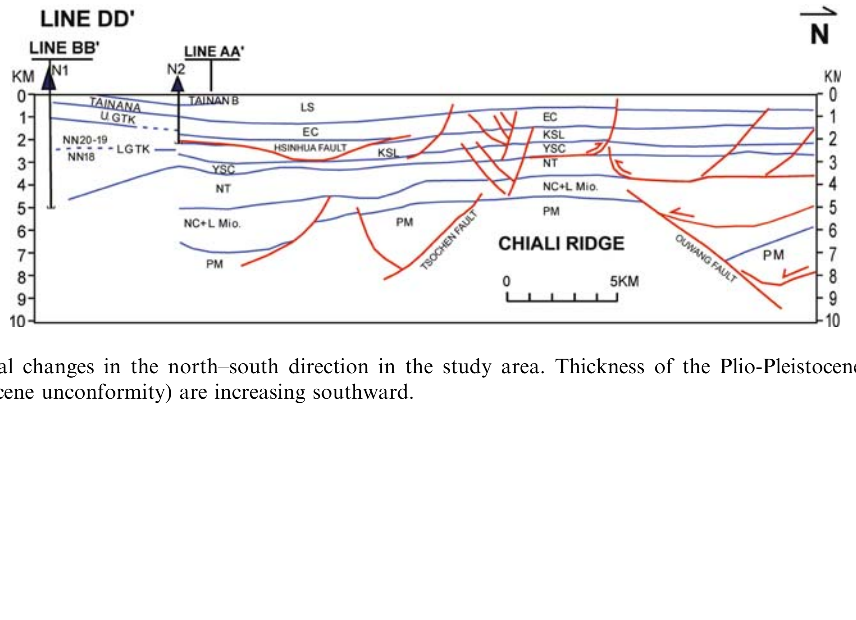

Figure 11. Structural changes in the north–south direction in the study area. Thickness of the Plio-Pleistocene and the depth of basement (pre-Miocene unconformity) are increasing southward.

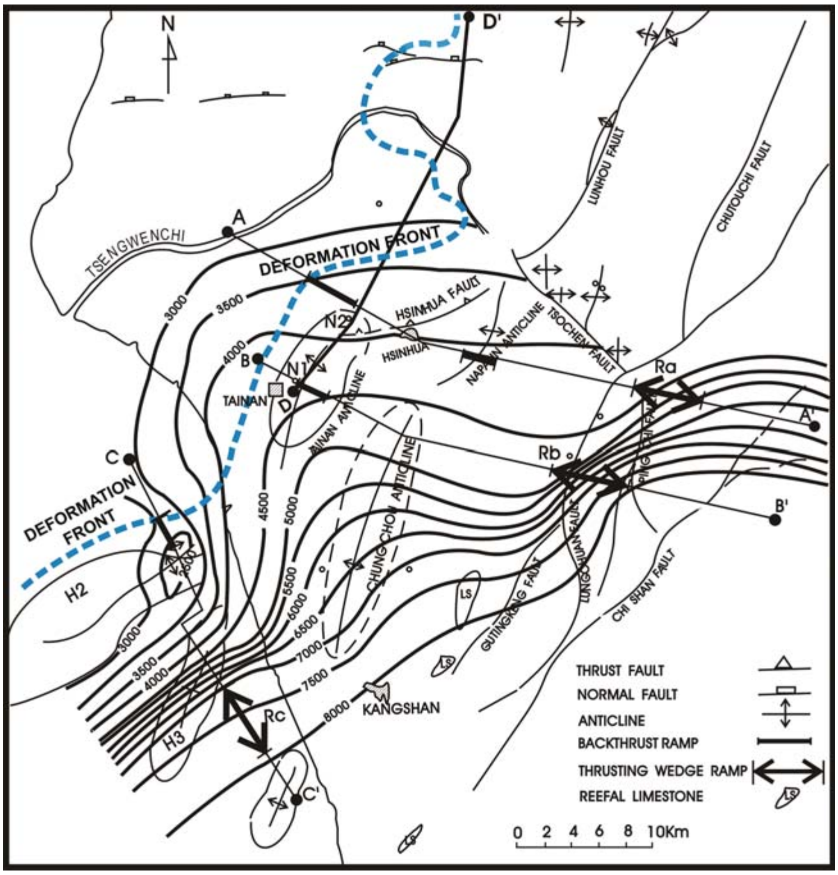

Figure 12. Depth contour map of the basal detachment illustrating the direction of the thrust wedge migration at the hanging wall.

From another point of view, the Hsinhua structure, the Tainan Anticline, and H2 Anticline are the westernmost antiforms aligned in the NE–SW linement and formed during the Penglay Orogeny. Beyond the western side of the deformation front, similar antiform structures are not observed. It could be deduced that the Hsinhua Fault, the Tainan Anticline, and the H2 Anticline (offshore) represent the incipient features of thrusting wedge that has been moving northwestward during the Penglay Orogeny. Vann et al. (1986) pointed out that in the foreland area beyond the western side of the thrust wedge there is less deformation affected by the compressional stress applied from the hinterland.

If the fault surface is correlated from geological sections such as AA′, BB′, and CC′ and then a great Buried basal detachment will be found in this area (Figure 12). Using these three sections, a depth contour map of basal detachment is constructed. The trend of the migration of this basal detachment is almost toward to the direction of northwest (Figure 12). Schematic block diagram of this area show a large ramp near the foothill belt while at the offshore and Kaohsiung area covered by thick mudstone is difficult to detect (Figure 13). The depth of the leading detachment in sections AA′, BB′, and CC′ are 3–5 km, 5 km, and 3 km, respectively. The depth of the trailing detachment on AA′, BB′ and CC′ profiles is about 7.5˜8 km. The extrusion of thrusting wedge on the hanging wall of this basal detachment will be migrate toward northwest. Therefore, the Hsinhau Fault, Tainan anticline, and H2 antiform with a hinterland dipping trend forms a liniment, aligned on the outer edge of the hanging wall of the leading detachment which is confined to the bedding horizon between the Yunshuichi Formation and Niaotsui Formation.

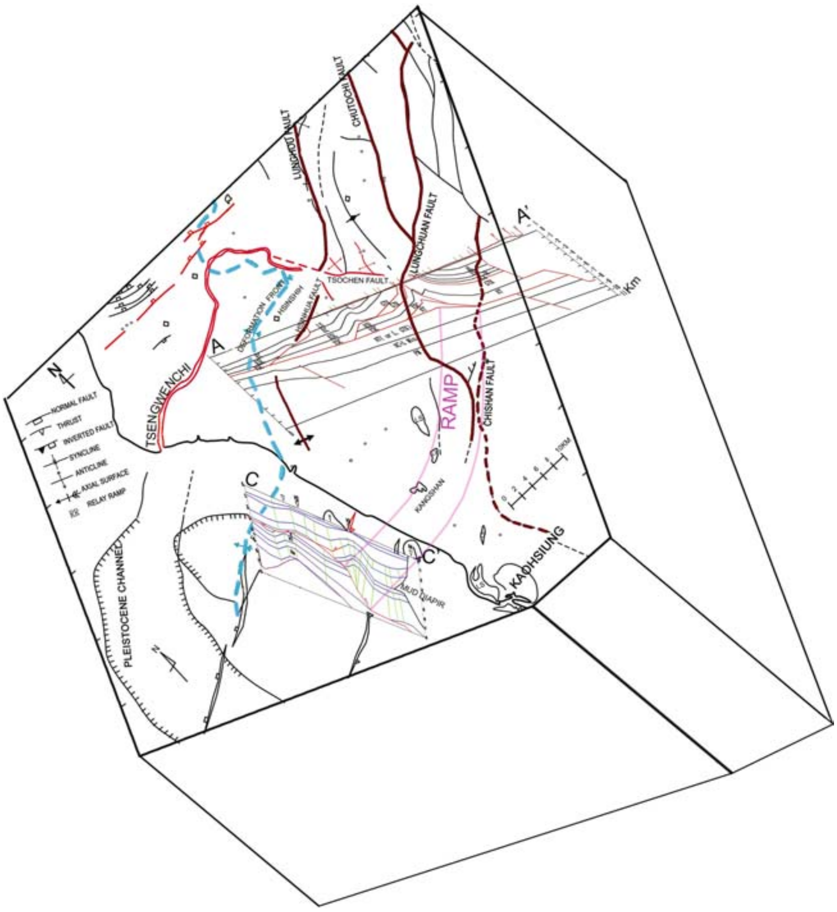

Figure 13. Schematic block diagram showing changes in structural style from north to south, cross-sections are aligned along the strike of deformation front in Southwestern Taiwan, while the zone of deformation front (dash blue line) is determined from the western most axial surface of frontal fold.

The Chungchou Anticline was determined from a gravity survey (Pan, 1968) and earlier poor seismic data analysis (Hsieh, 1972). Currently, there is still a lack of data on the deeper part. The Chungchou anticline and H3 anticline (located in the offshore area) are considered as the second deformation zone in the mountain front area. In this study, if the large ramps beneath the Lungchuan fault (ramps a and b) are correlated to ramp c of thrusting wedge H3 (line CC′), a banded ramp with the southwestern striking is formed and could be considered a pre-existing tectonic discontinuity (Figure 13). On the viewpoint, the northeastern part of the large ramp is significant with a triangle zone associated with a duplex while the southwestern end is dominated with the initial thrust wedge. It also means that the thrusting wedge above the major ramp has larger displacement and complicated structure at northeastern end rather than those at the southwestern end. The burial large ramp indicates an important deformed anticline above it. Due to lack direct evidence for the major ramp, the induced structural model will challenge to future actual data.

At the hanging wall of the lower flat in the same basal detachment, the structure pattern is dominated with mud diapirs where shallow large earthquakes do not occur due to mudstone creep (Lacombe et al., 2001). The isopach of the foreland sequences (Figure 14) reveals that the strata in the northwestern part of the Tainan Basin are much thicker than that in the Taihsi–Taichung Basin. The maximum thickness of the foreland sequence in the Tainan Basin is more than 6000 m (Lin, 2001) and is located in the offshore

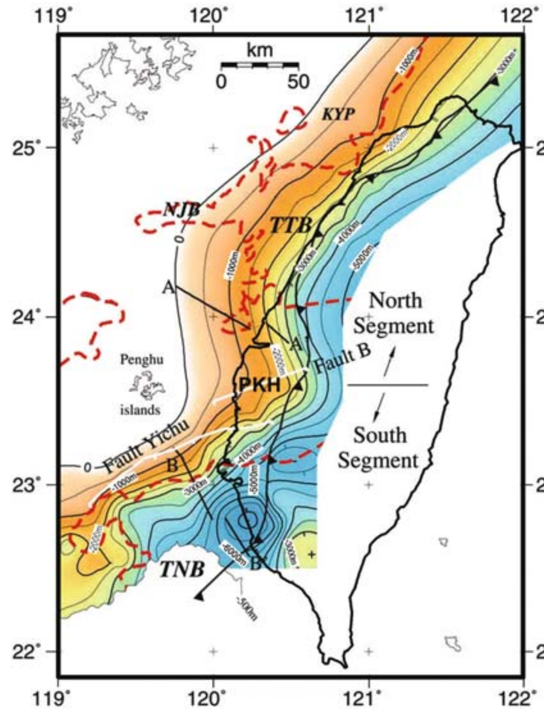

Figure 14. Isopach of the Pliocene-Pleistocene in western Taiwan illustrating two major depocenters of the foreland basin, including Taihsi–Taichung basin (north segment) and Tainan basin (south segment). Red line showing the boundaries of each basin in offshore and Western Taiwan. KYP = Kuanyin Platform, NJB = Nanjihtao Basin, PHB = Penghu Basin, PHP = Penghu Platform, TNB = Tainan Basin, TTB = Taihsi–Taichung Basin, PKH = Peikang High (after Lin, 2001).

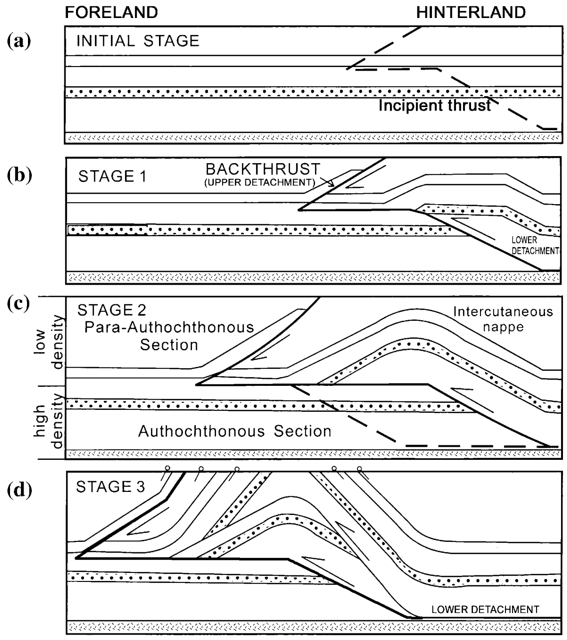

Figure 15. Schematic model illustrating the evolution of triangle zone. The autochthonous section always consists of sedimentary sequence of mainly passive margin. The contrast density plays important role in the triangle zone development (after Charlesworth and Gagon, 1985), (a) undeformed regional authochthonous strata with an incipient thrust, (b) and (c) the development of fault-bend-fold with a back-thrust, (d) triangle is formed with a Duplex. The backt-hrust keeps the similar dip angle to migrate westward.

Kaohsiung where the highest dense mud diapers occur (Sun and Liu, 1993). According to the model for generating triangle zone (Figure 15), the most important factor is the density contrast between the hanging wall and footwall of the basal detachment (Charlesworth and Gagnon, 1985). Lujan et al. (2003) pointed out that the existence of viscous material would enhance the development of a major back thrust fault and outward migration of deformation front. Jamison (1992) also suggested that thick incompetent mudstone favors the detachment-fold development (i.e., mud diapir) due to the large stress axis difference between the vertical and horizontal during compression and compaction. The Pliocene and Pleistocene mudstone has increasing thickness from north to south at the southern rim of Peikang High (Covey, 1984, 1986; Lin, 2001; Mouthereau et al., 2002), rather than frictional Miocene material. This might have enhanced the viscous property and helped in the back-thrust development. The large isopach layer of the foreland sequence in this study area exhibits a thickened southward trend with increasing mudstone. In the southern rim of the Peikang High, the structural patterns change from imbrications into a deep triangle zone or duplex wedge (Suppe, 1985; Hung et al., 1999; Yang et al., 2002, 2003) and to shallow triangle zone (Yang et al., 2003; this study). On the south side of the major buried ramp in the study area, most of the antiforms are replaced by mud diapers (in this study). The noticeable variation in structural style is matched with the increasing southward in thickness and mud content in the foreland sequences during the thrust wedge extrusion, or so-called tectonic escape model of the inland Manila accretionary wedge extension (Lacombe et al., 2001). In this study, the large buried ramp model of the basal detachment could coincidently interpret the direction change boundary of the GPS displacement field (Yu et al., 1997) in Southwestern Taiwan. The major detachment, located south of the Tsochen Fault, perhaps deeply interconnects southward with the sole decollement of Manila accretionary prism and forms a wide deformation slip surface. Actually, most of the major detachment and associated upper back-thrust sprays do not outcrop at the deformation front area, except for Hsinhua Fault and Napalin Fault, an upper back thrust in the hanging wall of the basal detachment. Therefore, the geological blind basal detachment model associated with initial deformation front with back thrusting mechanism will play an important role in mountain building in the coastal plain and foothill area in southwestern Taiwan.

The 1946 Hsinhua Earthquake with magnitude of 6.1 and hypocenter 5 km resulted in a surface rupture of 6 km long and more than 2.14 m displacement near Hsinhua City (Hsu and Lu, 1964). Therefore, the Hsinhua Fault is classified as a Holocene active fault (Lin et al., 2000). At present, it is difficult to find the relationship between the energy released and the thrusting wedge development; however, the hinterland-verging thrusting geological model in this deformation front area is very important to the earthquake hazard assessment in the coming future. This study suggests that there is a large fault ramp beneath the Lungchuan Fault, along which significant compressional energy occurs due to the westward over thrusting that has probably accumulated, or the further development of a new duplex created by a new detachment and abandoned the pre-existing triangle zone structure. Integrated correlation from geological sections AA′, BB′, and CC′ have revealed the deformed back-thrust or triangle zone features at the south rim of the Peikang High. At present, this back-thrust model associated with the triangle zone is matched with the model from Charleworth and Gagon (1985). According to their model, the back thrust will migrate to the west in the future and the para-authochthonous sections, or the younger foreland sequence will also be compelled to move westward and to be eroded. At present, this back-thrust model does not conflict with the geodetic pattern in Southwestern Taiwan (Yu et al., 1997). Hopefully, the triangle zone geological model distributed in the Tainan and Kaohsiung area will challenge the surface deformation, constructed by the GPS geodetic survey and will also contribute to an accessment for preventing earthquake hazards in the future.

Conclusions

In Southwestern Taiwan, the geological structure settings on the southern side of the Tsengwen River and the Tsochen Fault are characterized by a triangle zone and back-thrust that are quite different from those in the other part of Western Taiwan, which are dominated with thrust imbrications. A major basal detachment was determined in this area. The depth of the leading detachment is 3–5 km while depth of the trailing detachment is about 7.5∼8 km. A major fault ramp was also determined as a tectonic discontinuity. A triangle zone geological model with a duplex occurs in the northeastern part of the major ramp while in the southwest Taiwan an initial thrusting wedge occurs, and south side of the ramp has significant with mud diapers, formed by the detachment-folding model.

The Hsinhua structure, the Tainan anticline, and the H2 anticline formed a western most deformation front aligned above the leading detachment during the Pengli Orogeny in Southwestern Taiwan. The zone of deformation front in Tainan and Kaohsiung becomes an important indication of northwestern movement and delineates an incipient structural model of mountain building in Western Taiwan. The causes of the back-thrusting in the initial mountain building results from southward thickening mudstone in the Pliocene and Pleistocene sequences that increased the viscous content, rather than the friction. The other cause might be that as the density contrast increases between the underlying compacted formation and the overlying soft incompact units, the back thrusting and outward development of the mountain belt deformation front. Furthermore, at the southern area of the major ramp, mud diapers dominate the structural patterns due to detachment folding or mudstone creep in the thickest mudstone. Above all, both triangle zone and mud diapir models in Southwestern Taiwan are enough to interpret the north–south tectonic trend in the deep part of the coastal plain and foothill area in Western Taiwan.

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