Deformation patterns of an accretionary wedge in the transition zone from subduction to collision offshore southwestern Taiwan

Char-Shine Liu[1,*], Benoit Deffontaines[2], Chia-Yu Lu[3] and Serge Lallemand[4]

[1] *Institute of Oceanography, National Taiwan University, Taipei, Taiwan, ROC*

[2]*Ecole Pratique des Hautes Etudes, 15 Bd de la Mer, 35 Dinard, France*

[3]*Department of Geosciences, National Taiwan University, Taipei, Taiwan, ROC*

[4]*Laboratoire Dynamique de la Lithosphere, Universite Montpellier 2, France*

[*]*Author for correspondence (Fax: +886-2-23660881, E-mail: csliu@ntu.edu.tw)*

Keywords: morphotectonics, swath bathymetry, seismic reflection, deformation front, accretionary wedge, southwestern Taiwan

Abstract

Swath bathymetry data and seismic reflection profiles have been used to investigate details of the deformation pattern in the area offshore southwestern Taiwan where the Luzon subduction complex encroaches on the passive Chinese continental margin. Distinctive fold-and-thrust structures of the convergent zone and horst-and-graben structures of the passive margin are separated by a deformation front that extends NNW-ward from the eastern edge of the Manila Trench to the foot of the continental slope. This deformation front gradually turns into a NNE-SSW trending direction across the continental slope and the Kaoping Shelf, and connects to the frontal thrusts of the mountain belt on land Taiwan. However, the complex Penghu submarine canyon system blurs the exact location of the deformation front and nature of many morphotectonic features offshore SW Taiwan. We suggest that the deformation front offshore SW Taiwan does not appear as a simple structural line, but is characterized by a series of N-S trending folds and thrusts that terminate sequentially in an en-echelon pattern across the passive Chinese continental slope. A number of NE-SW trending lineaments cut across the fold-and-thrust structures of the frontal accretionary wedge and exhibit prominent dextral displacement indicative of the lateral expulsion of SW Taiwan. One of the prominent lineaments, named the Yung-An lineament, forms the southeastern boundary of the upper part of the Penghu submarine canyon, and has conspicuous influence over the drainage pattern of the canyon.

Introduction

Located at the western corner of the Philippine Sea plate, Taiwan is an active mountain belt formed by the collision of the Luzon volcanic arc with the passive Chinese continental margin (Biq, 1972; Bowin et al., 1978; Ho, 1986; Teng, 1990; Huang et al., 2000). Due to the obliquity of the passive continental margin with the impinging volcanic arc, this collision is propagating southward (Suppe, 1984; Byrne and Liu, 2002). At present, the most active deformation occurs in eastern and central Taiwan as revealed by GPS observations (Yu et al., 1997), whereas the offshore area south of Taiwan represents the incipient arc-continent collision zone (Lundberg et al., 1992, Reed et al., 1992; Huang et al., 1992). Further south, the oceanic crust of the South China Sea is subducting beneath the Luzon Arc along the Manila Trench (Bowin et al., 1978; Lundberg et al., 1992; Reed et al., 1992; Liu et al., 1998).

Distinctive morphotectonic features in the area offshore southern Taiwan reflect the transition from subduction to collision (Liu et al., 1998). South of 21°20’N, Manila Trench, Hengchun Ridge (accretionary wedge), North Luzon Trough (forearc basin) and Luzon Arc consist of major morphotectonic units in the subduction system (Figure 1). This simple oceanic subduction configuration evolves into a continental subduction north of about 21°30’N, and arc-continent collision on land Taiwan, as the passive Chinese continental margin enters the subduction system obliquely. The presence of the Chinese continental margin has a major impact on the deformation pattern of the subduction-collision system. A basement high (the Peikang High) in the Chinese continental margin acts as an indenter with respect to the Taiwan mountain belt and causes tectonic escape of frontal units toward southwest (Lu and Malavieille, 1994; Lu et al., 1998; Lacombe et al., 2001).

This paper presents detailed analyses of high-resolution swath bathymetry data collected during the ACT survey in 1996 (Lallemand et al., 1997) and seismic reflection profile data collected during the EW9509 and ACT surveys in the area offshore southwestern Taiwan (Figure 2). We reveal for the first time the details of sea floor morphology and structures based on the swath bathymetry data and new seismic reflection profile images. Distinctive deformation patterns and morphotectonic characteristics of the accretionary wedge in the study area provide clues to the development and geodynamic processes of the deformation front during outgrowth of the accretionary wedge. The location and structural characteristics of the deformation front are presented, several morphologic lineaments are described, and their significance and implication to the escape tectonics of SW Taiwan are proposed. Finally we discuss the geodynamic models that could explain the observed deformation patterns in this transitional deformation zone where passive continental margin enters the subduction system.

Tectonic settings

The area off SW Taiwan is the place where the accretionary wedge of the Manila Trench-Luzon Arc system encroaches the passive continental margin. South of Taiwan, the Manila Trench represents the surface plate boundary between the subducting Eurasian plate and the overriding Philippine Sea plate. However, as the tectonic configuration between these two plates transforms from subduction to collision, how this surface plate boundary evolves and where is the present location of this plate boundary on land and offshore SW Taiwan are the questions under debating. The Longitudinal Valley on land Taiwan is a major geological and tectonic boundary that separates the Coastal Range (the emerged portion of the Luzon volcanic arc) from the Backbone Range (the metamorphic basement of the passive continental margin) (Figure 1), thus has long been regarded as the plate boundary (e.g., Wu, 1978; Ho, 1986; Tsai, 1986; Angelier et al., 1997; Wu et al., 1997). On the other hand, based on the critical wedge mountain building model, Suppe (1981; 1984) treated the Taiwan mountain belt as an accretionary wedge pushed up by the Luzon Arc (the bulldozer), thus put the present surface plate boundary to the west of the Taiwan mountain belt. Teng (1990; 1996) and Huang et al. (1997) further developed tectonic evolutionary models to demonstrate how the frontal thrust of the accretionary wedge (hence the surface location of the plate boundary) migrated westward through different stages of the arc-continent collision offshore and on land Taiwan.

Offshore SW Taiwan, where the outgrowth of the submarine accretionary wedge extends westward to the Chinese continental margin, prominent morphological features are anticlinal ridges and submarine canyons (Figures 1 and 2). The Kaoping shelf and slope (Yu and Wen, 1992) are frontal portion of the submarine incipient collision zone that are separated from the Chinese continental shelf and slope by the Penghu Canyon (Figure 2). Liu et al. (1997) presented a structural framework of the area where imbricate fold-and-thrust structures are the predominant structural patterns of the submarine accretionary wedge. Distinctive fold-and-thrust structures of the convergent zone and horst-and-graben structures of the passive margin are separated by a deformation front that extends from the eastern edge of the Manila Trench and Penghu Canyon NNW-ward to the foot of the Chinese continental slope, then turns N and NE-ward across the continental slope and the Kaoping Shelf, and connects to the frontal thrust of the Taiwan mountain belt near Tainan city on land (Figure 2). The location of the deformation front was delineated by identifying the westernmost extent of the first compressive fold-and-thrust against passive continental margin sediments on seismic profiles (Liu et al., 1997). The suggested location of the deformation front is coherent with on land studies, as Deffontaines et al. (1997) proposed to interpret the Tainan ridge as the location of the deformation front that previously attributed to the Shoushan ridge (in NW Kaohsiung) in SW Taiwan. However, due to the presence of a complex submarine canyon system (the Penghu Canyon system) and inadequate seismic coverage, the exact location of the deformation front and its morphostructural characteristics across the continental slope are still in debate (e.g. Lee et al., 1993; Yu and Huang, 1998; Chiang et al., 2004).

Morphotectonic features

General morphology of the study area has been described by Liu et al. (1998) who compiled a regional bathymetric digital terrain model (DTM) with grid spacing of 500-m interval. In this study, a high-resolution digital terrain model (100-m grid spacing) was created using the full resolution of the ACT swath bathymetric data (Figure 3). Hill-shading images of the studied area generated from this high resolution DTM and illuminated from various directions are used for morphological analyses in this study (see the same methodology used on land Taiwan by Deffontaines et al., 1994). The different resulting images (such as Figure 4) were then interpreted for morphostructural features, such as local alignments of the submarine drainage and asymmetric shape of the ridges. Furthermore, 3D views of the sea floor topography are created to illustrate certain specific bathymetric features (e.g., Figure 5). We present below the two major tectonic provinces of the study area, and describe details of the morphologic and structural characters of several key morphotectonic features revealed from swath bathymety and seismic reflection data.

Major tectonic provinces

The study area can be divided into two major tectonic provinces (Figures 1 and 2) based on the structures and textures of the sea floor topography:

1. Chinese continental margin

The NW part of the study area corresponds to the Chinese continental margin characterized by a shallow continental shelf and a relatively steep continental slope. The continental shelf dips slightly to the SE with a gentle slope of less than 1°. Its southern boundary corresponds to the shelf break roughly trending N050°E at water depths between 250 and 300 m. On the shelf, few morphostructures can be observed from the bathymetry, even though it corresponds to the ENE-WSW trending Tainan basin (Sun, 1985; Yang et al., 1991). The Chinese continental slope is facing to the SE and is characterized by a 3° to 9° dip slope. It is strongly eroded by numerous NW-SE trending canyons that form tributaries of the Penghu submarine canyon system (Figures 3 and 4). The Penghu submarine canyon up-stream presents a regular drainage where tributaries flow sub-parallel to the dip slope (Deffontaines and Chorowicz, 1991). The interfluves are characterized by symmetric opposite flanks trending generally N160°E. Some aligned confluences of this submarine drainage along N080-090°E may reflect the WSW-ENE trending normal faults that bound the southern part of the Tainan Basin (Figure 2) and the passive Chinese continental margin structures (Yang et al., 1991). In the down-stream part of this area, the arcuate structural ridges were formed due to interactions between sedimentation of the passive Chinese continental margin and the active structures of the accretionary wedge dissected by submarine canyons.

The high-resolution swath bathymetry data reveal a possible large landslide on the slope of the Chinese continental margin (Figures 4 and 5). The suggested landslide covers an area about 11 by 12 km. It demonstrates the instability of the sediments deposited on this steep slope area that are subject to frequent shakes by numerous earthquakes that occurred in the Taiwan arc-continent collision belt. If this fan-shaped feature is really a large submarine landslide, it could induce tsunami in the coastal area of southwestern Taiwan. History records have shown that there were 3 to 4 tsunamis hit the Tainan and Kaohsiung area in the past 400 years (Hsu and Li, 1996). Further investigations are needed to confirm if this observed morphologic feature is the result of a large submarine landslide or not.

2. Accretionary wedge

The eastern part of the study area corresponds to an accretionary wedge characterized by generally west-verging anticlines and their associated synclines (Figures 2 and 3). From south to north, the orientation of the anticlinal ridge axes turns clockwise, from NW-SE at 21°30'N, to N-S at 22°10'N, then to NNE-SSW close to the shoreline (at about 22°45'N). Morphological offsets of the ridge axes that occurred in a few places where ridges were cut by the complex Penghu submarine canyon system may be distinguished from the high-resolution bathymetry map (Figures 3 and 4), especially in the central part of the study area. These offsets may suggest the existence of some strike-slip faults in the accretionary wedge that affected anticlinal ridges. In the eastern part of the study area, the upper portion of the Kaoping canyon crosscuts the Kaoping shelf and slope from NE to SE, then turns toward SES sub-paralleling to anticlinal ridges. The SES-trending section of the Kaoping canyon follows the trace of a major thrust fault (Liu et al., 1993).

Several prominent bathymetric lineaments are observed within the frontal portion of the accretionary wedge. The most prominent one is a N035°E trending elongated bathymetric low that we called the Yung-An lineament, as it aligns with the town of Yung-An onshore Taiwan (Figure 4). Morphologically, it is a rectilinear alignment running from the Kaoping shelf to the deformation front (delineated here by the downstream portion of the Penghu canyon). This lineament is sub-parallel to fold structures in its northern part (north of about 22°20'N), whereas downstream it is oblique to and cuts across the fold structures. Its orientation compared to the regional compression would suggest a right lateral motion. However, there is no obvious displacement of the deformation front, nor clear offsets of the different ridge axes have been observed at this scale.

Different illumination directions help to reveal the existence of other bathymetric lineaments. Figure 4B, for example, shows the existence of bathymetric lineaments that trend in N035° to N050°, N070°, N090° to N110°, N140° to N160°E, and N-S directions. Implications of those different orientations of the topographic lineaments will be discussed later.

Due to both the influx of orogenic sediments and the evolution of the collision process, the submarine Taiwan accretionary wedge is advancing westward. The hill-shading swath bathymetry maps (Figure 4) clearly reveal the northern extent of each anticlinal ridge over the lower portion of the Chinese continental slope. The anticlinal ridges that were formed by convergent tectonic processes generally exhibit long-wavelength linear topographic characters, in contrast to the short-wavelength down-slope ridges and gullies formed by erosion processes. Seismic reflection profiles running across these two topographic features confirm this observation, as will be presented below. We suggest that the northern and western boundaries of these anticlinal ridges delineate the location of the deformation front which is the boundary between the two tectonic provinces.

Morphostructural analyses

Besides the swath bathymetry data, a suite of seismic reflection profiles that run across the Chinese continental slope and the submarine Taiwan accretionary wedge were collected during the ACT cruise. By analyzing both the high-resolution bathymetry data and seismic reflection profiles, we now have a much clear view on the morphotectonic characteristics of the complex Penghu canyon system and the deformation front:

1. The Penghu submarine canyon system

Resulting from the high erosion rate of the Taiwan island, the Penghu submarine canyon system concentrates erosional flow at the southern end of the Taiwan Strait. It develops upstream across the structural boundary of the Tainan basin sitting near the edge of the Chinese continental shelf, and downstream beyond the morphostructural units of the submarine Taiwan accretionary wedge and the deformation front (Figures 2 and 3).

The Penghu canyon up-stream (Figure 4) presents a bayonet-track morphology with numerous right angle turns that are structurally guided by both the normal fault system of the passive continental margin and the fold-and-thrust system of the submarine Taiwan accretionary wedge. The normal faults generally are reactivated as right lateral transpressive strike-slip faults close to the deformation front and the Taiwan shoreline (Deffontaines et al., 1997). On the other hand, the thrust faults and anticlines of the submarine Taiwan accretionary wedge are active features as evidenced by the seismic profiles (Liu et al., 1997 and this study). The Penghu submarine canyon erodes both the passive continental margin and the accretionary wedge, guided locally by oblique fractures, such as thrust and strike-slip faults associated with the folded structures down slope (Figures 3 and 4).

2. Deformation front

Seismic reflection profiles reveal that extensional structures are observed in the Chinese continental shelf and slope region, whereas imbricate fold and thrust sheets characterize the submarine Taiwan accretionary wedge. The deformation front is defined as the most frontal contractional structure of an accretionary wedge. Offshore SW Taiwan where clear frontal contractional structure is difficult to trace, the location of the deformation front was loosely delineated by connecting the termination points of anticlinal ridges across the continental slope (Liu et al., 1997). However, by carefully analyzing detailed submarine morphology that revealed by the ACT swath bathymetry survey and closely spaced seismic reflection profile data (Figure 3), we suggest that the deformation front of the submarine Taiwan accretionary wedge does not appear as a simple contractional structure across the Chinese continental slope. Rather, a series of roughly N-S trending fold-and-thrust structures that terminate sequentially in an en echelon pattern along the Chinese continental slope act as the deformation front here.

High-resolution bathymetry data reveal clearly the anticlinal ridges of the accretionary wedge extend toward the Chinese continental slope. There are also numerous NW-SE trending ridges formed by submarine canyons that incise the continental slope. Thus, bathymetry data alone may not clearly differentiate whether a ridge is a contractional structure of the accretionary wedge or formed by submarine erosional processes along the passive continental slope. Seismic reflection profiles, on the other hand, could help to identify the nature of the ridges. Here we use 3 seismic profiles to demonstrate the structural characteristics of the deformation front in the area where the accretionary wedge moves into contact with the Chinese continental margin.

Seismic line ACT140 runs across a series of topographic ridges before it ends at the foot of the Chinese continental slope (Figure 3). The Penghu canyon dissects the westernmost anticlinal ridge (ridge A in Figure 3) of the accretionary wedge south of where ACT140 runs over the ridge. This profile (Figure 6C) clearly shows that ridge A is a fold bounded by a west-vergent thrust fault to the west. This thrust fault, though not clearly traceable on the sea floor, probably due to rapid sedimentation, indicates the location of the deformation front here.

Seismic line ACT136 lies to the north of ACT140 (Figure 3). On this profile (Figure 6B), the ridges formed by submarine erosion appear to have sharp summits while anticlinal ridges appear to have round summits and folded internal strata. From bathymetry map (Figure 3), we can easily identify ridges B, C, D and E on ACT136 (Figure 6B), however, ridge A is no longer identifiable. Ridge B appears as a broad structure consisting of 3 clustered fold-like features on seismic profile (B, B1 and B2 on Figure 6B). It is unclear whether the three fold-like features were all derived from ridge B, or they were formed by ridge B impinging against ridges of the continental slope.

Further to the north, seismic line ACT130 (Figure 6A) shows distinctive structural contrast of the passive continental margin (normal faults appeared in the left half of the profile) and accretionary wedge (fault-bend-fold structures in the right half of the profile). Underneath a slumping sediment cover, ridge C is now lying against the continental slope, and provides a constraint on the location of the deformation front on this profile.

Figure 7A presents a line-drawing interpretation of various bathymetric and structural features observed in the frontal portion of the accretionary wedge that is partially riding over the Chinese continental slope. The N140° to 160°E and N-S trending features correspond to thrusts and fold axes. On this structural map, we suggest that the anticlinal ridges of the accretionary wedge extend northward onto the Chinese continental slope, and are blocked by the continental slope and terminated one by one as the ridges progressively develope northward. The deformation front here does not appear to be a continuous simple feature. Instead it extends northward along the frontal anticlinal ridge until that ridge dies out at the continental slope, then the deformation front jumps to the next anticlinal ridge that extends further north. Figure 7B shows a model of the deformation front where accretionary wedge rides over part of the continental slope. However, due to lack of clear seismic images showing the termination of the anticlinal ridges beneath continental slope sediment, we could not rule out the possibility that the anticlinal ridges merges into a single thrust front beneath the slope sediment (Figure 7C).

Further to the north on the Kaoping shelf where no topographic ridges could be used to identify the deformation front, an anticlinal feature underneath the flat sea floor revealed by a seismic profile EW9509-36 (Figure 8) put a constraint on the location of the deformation front here. The location of the deformation front determined in this study agrees with that proposed by Liu et al. (1997). Seismic image of the deformation front on this profile appear to have the characters of a flower structure, suggesting transpressional deformation here.

Seismic line EW9509-36 also runs across the Yung-An lineament at CDPs 7900-8000 (Figure 8). The Yung-An lineament appears as a small canyon-like feature on this profile with a narrow chaotic zone underneath, but no clear faulting character could be identified. This, on the other hand, could suggest that the Yung-An lineament is a strike-slip feature.

Geodynamic implications

Escape tectonics

The collision geometry of the Taiwan mountain belt has been regarded as caused by an indentation of the Luzon arc onto the Chinese continental margin (e.g., Lu and Malavieille, 1994; Lu et al., 1997; Hu et al., 1996; 1997). Lu et al. (1998) further demonstrate that the geometry of basement highs on the Chinese continental margin has significant impact on structures observed in western Taiwan thrust wedges, as first pointed out by Biq (1992). As the result of ongoing Luzon arc colliding with the Chinese continental margin and local indentation by a basement high (the Peikang High, see Figure 9A), the SW Taiwan has undergone tectonic escape toward southwest (Lu and Malavieille, 1994; Lu et al., 1998).

Using sandbox models, Lu et al. (1998) demonstrate that south of Peikang High, the thrusts along the deformation front change their trend continuously into a curve convex to WSW, while the conjugate strike-slip fault system shows pattern of clockwise block rotation. They suggest that a large dextral transfer zone exists around the shelf-slope break of the Chinese continental margin. Along the shelf-slope break, 3 sets of systematic fractures are observed: 2 of them are conjugated fractures, the third one is parallel to the convergent direction and on the bisect direction of the previous fracture sets (Figure 9A).

In the tectonic escape model of Lu and Malavieille (1994) and Lu et al. (1998), the eastern boundary (backstop) of the SW Taiwan expulsion is the inferred left lateral Chaochou fault described by Biq (1989). The Chaochou fault in the field appears as a major straight N-S structure with a significant vertical relief as it makes the contact between the low metamorphic rocks of the southern Backbone Range to the east, and the thick alluvial Pintung basin to the west (Figure 9A).

Contrasting with the sharp and localized eastern boundary of this inferred escape structure, the western boundary is diffuse, and not clearly defined. No major structural features are seen due probably to the propagation of the oblique collision from north to south, and also from east to west. This boundary ought to move southwestward through time and therefore may not be easily identifiable from the bathymetry. The migration of the collision might also explain the distribution of the deformation among several splays with various trending, such as different orientations of the major faults offshore Tainan (e.g., Liu et al., 1997; Chow et al., 1996).

Structural models

Inversion of stress tensors from fault mechanism (e.g., Yeh et al., 1991; Angelier, 1998) indicates a fan shape direction of displacement of the onshore SW Taiwan, contrasting with the regularly N310°E direction within the collision zone in central Taiwan. Hu et al. (1997), from finite element modeling but taking into consideration of major known faults, the average lithology, and "free boundaries" in SW Taiwan, reveal the coherence of their results constrained by the GPS data (Yu et al., 1997) and the inversion of fault slip analysis. This displacement contrasts with what is seen north of the Chishan transfer fault zone (first described by Deffontaines et al., 1997) where all the folds and thrusts units migrate slowly toward the NW (Hu et al., 1997).

Lacombe et al. (2001) compiled some structural, geodetic and seismological observations for the tectonic escape model in SW Taiwan (Figure 9B), focusing on the area south of the Chishan transfer fault zone (CTFZ) where the maximum of displacement is revealed by few widespread GPS data on the SW Taiwan (Yu et al., 1997; Yu and Chen, 1998). They assume that the escaping block may be split into four rigid (small) blocks. This interpretation, which lacks detailed offshore controls, is highly debatable since new results of GPS survey done by Hu and Rau (personal communication) suggest a slow gradient of the fan-shaped displacement and the continuity of the deformation. Except small misfits due to local structures, no deformation discontinuity exists and that confirms the very regular deformation pattern described by Huchon et al. (1986), Lee (1986) and Hu et al. (1996). Thus, the assumption of rigid blocks is highly debatable and disagrees with detailed GPS survey.

The regularity of displacement in SW Taiwan could be explained by the thick (> 6 km) Gutingkeng mudstones that lie underneath the Holocene sediments in that area. Their weak mechanical properties suggest that plastic deformation ought to prevail and few discrete deformations may occur in SW Taiwan. For instance, the Tainan anticline NE of the studied area rises periodically of 1.6 cm in elevation each year, as revealed by DINSAR interferograms (Fruneau et al., 2001; Pathier et al., 2003) with a continuous velocity since 1992.

The tectonic Riedel shear (Harris and Cobbold, 1984) model was suggested by Chow et al. (1996) to explain the presence of flower structures on parts of seismic profiles. They analyzed and interpreted the observed pinch and swell of seismic reflectors along several of the seismic profiles close to the shoreline between Tainan and Kaohsiung as caused by different trending flower structures and en-echelon mud diapirs. The authors distinguished transtensional and transpressional flower structures, and argued for the right-lateral motion of the strike-slip structures. They associated mud diapirs to the en-echelon folding during strike-slip deformation. Finally they advocated the geodynamic convergence and divergence as the origin of these structures. Since the tectonic features they described are all close to the shoreline, and the seismic data they used in their study are not widely distributed, it is difficult to delineate the fault orientations from their data set. Furthermore, despite the different trending of the faults (N030, 060 and 150°E) revealed by their interpretations, they inferred a same right-lateral motion. We thus consider this model only in local scale rather than accepting the Riedel model for regional interpretation at an accretionary wedge scale.

The tectonic escape model (Lu et al., 1994; 1998) seems interesting, but not without problems: (1) The mapping of offshore structures is difficult mainly due to the complex submarine canyon morphology that makes seismic interpretation tentative; (2) The direct links between on land and offshore structures are unclear due to lack of on land and near shore seismic profiles and the flat sea floor of the Kaoping shelf; (3) The southern boundary of the Peikang High is located further to the north, thus may not explain fully the lateral escape of SW Taiwan offshore region.

We propose a simple model that explains the changing orientations of the anticline axis and faults in the frontal portion of the submarine Taiwan accretionary wedge and the development of topographic lineaments as caused by the impingement of the continental slope. The folds adapt to the shape of the continental slope that acts as an indenter here. The fold axes turns from NW to NE as the accretionary wedge rides over the continental slope northward. In the same time, the conjugated strike-slip fault associated with the fold compression turns in a clockwise sense from south to north (Figure 9C). Based on this model, in the area south of about 22°N, the left-lateral strike slip (LLSS) faults are developed along N070°E direction and the right-lateral ones trend almost N-S; in the central part of the study area, right-lateral strike slip (RLSS) faults are N060°E trending whereas the LLSS faults trend N120°E; north of 22.5°N, the RLSS are N090°E trending and the LLSS are N150°E trending. The Yung-An lineament is interpreted as formed by reactivation of several sections of the strike-slip faults and then eroded by the Penghu canyon.

Conclusions

The Taiwan accretionary wedge that extends from north of the Luzon island to the Taiwan mountain belt presents a case example of the subduction-collision tectonics. The area offshore and on land SW Taiwan is the place where the passive Chinese continental margin encroaches on the Taiwan mountain belt. Seismic reflection profile data and high-resolution swath bathymetry data, together with the recent on land geological investigation, provide new constraints on the variation of structural styles along the frontal portion of the accretionary wedge and the location of the deformation front of the subduction-collision system offshore southwestern Taiwan.

The submarine Taiwan accretionary wedge consists of a lower slope domain characterized by mostly west-vergent anticlines and thrusts, and an intensely deformed upper slope domain in the area south of Taiwan. Due to the outgrowth of the accretionary wedge as the influx of orogenic sediments increases toward Taiwan, the trend of the frontal folds and thrusts in the lower slope domain changes from a NE-SW direction north of Luzon island to a NW-SE direction north of 20^{o}N. In the area offshore SW Taiwan, the NE-SW trending Chinese continental margin prevents the westward advance of the outward growing accretionary wedge. NW-SE trending anticlines turn into a N-S trending direction and the frontal anticlines of the accretionary wedge move onto the Chinese continental slope.

Detailed swath bathymetry data reveal different morphological characters of the anticlines and the slope ridges formed by erosional processes. Seismic profiles across the foot of the continental slope confirm the different structural nature between the anticlines and slope ridges. The location and geometry of the deformation front, defined as the most frontal contractional structure along a convergent plate boundary, thus can be better constrained based on the sea floor morphology.

This study suggests that north of 22^{o}N, the deformation front can no longer be delineated along a single frontal contractional structure. It follows a series of termination points of the frontal anticlines along the NE-SW trending Chinese continental slope, and extends northeastward to Tainan onshore Taiwan. Results from recent on land geological investigations are highly coherent that the Tainan anticline corresponds to the location of the deformation front.

Various topographic lineaments have been observed on the frontal portion of the accretionary wedge in the studied area from high-resolution swath bathymetry data. One of the most prominent one, the NE-SW trending Yung-An lineament, forms the southwestern boundary of the upper Penghu Canyon. These lineaments, together with the changing orientation of the anticlinal ridges and faults in the frontal accretionary wedge, are strongly controlled by the presence of NE-SW trending Chinese continental slope and the southwestward expulsion of SW Taiwan.

Acknowledgements

This research was done within the framework of the Taiwan-France Cooperation Program in Earth Sciences supported by the National Science Council (NSC) of the Republic of China, the French Institute in Taipei (IFT), the CNRS of France, and a collaboration agreement between the University Pierre and Marie Curie and the National Taiwan University. The authors would like to thank IFREMER and the captain, crew and technical staffs of the R/V l'Atalante for their excellent work during the ACT survey. Don Reed and personnel onboard EW9509 cruise are also thanked. Philippe Schnurle processed all the seismic data used in this study, Shao-Yung Liu and Tracy Chen helped generating the DTM data set and various bathymetric maps. This manuscript benefited from discussions with S.K. Hsu, J. Malavieille and J. Angelier. L. Teng, J.C. Lee and J.D. Chou provided critical comments and suggestions. This study was supported by funds to C.S. Liu from NSC-85-2611-M-002A-005Y, NSC-90-2611-M-002-003 and NSC91-2119-M-002 -018.

REFERENCES:

Angelier, J., 1998, A new direct inversion of earthquake focal mechanisms to reconstruct the stress tensor, E.G.S. XXIII Gen. Assembly, Nice, 1998, Part I, Soc. Symp., *Solid Earth Geoph. and Geod., Annales Geophysicae*, **16**, suppl. 1, 115.

Angelier, J., Chu, H.T., Lee, J.C., 1997, Shear concentration in a collision zone: kinematics of the Chihshang fault as revealed by outcrop-scale quantification of active faulting, Longitudinal Valley, eastern Taiwan, *Tectonophysics*, **274**, 117-143.

Biq, C.C., 1972, Dual-trench structure in the Taiwan-Luzon region. *Proc. Geol. Soc. China*, **15**, 65-75.

Biq, C.C., 1989, The Yushan-Hsuehshan megashear zone in Taiwan, *Proc. Geol. Soc. China*, **32**, 7-20.

Biq, C.C., 1992, Another Coastal Range on Taiwan, *Ti-Chih*, **12**, 1-14. (in Chinese with English abstract).

Bowin, C., Lu, R., Lee, C.S. and Shouthen, H., 1978, Plate convergence and accretion in Taiwan-Luzon region, *Am. Assoc. Pet. Geol. Bull.*, **62**, 1645-1672.

Byrne, T. and Liu, C.-S., 2002, Introduction to the geology and geophysics of Taiwan, in T. Byrne and C.-S. Liu (editors), Geology and Geophysics of an Arc-Continent Collision, Taiwan, *Geol. Soc. Am. Special Paper* ***358***, 1-4.

Chiang, C.S., Yu, H.S. and Chou, Y.W., 2004, Characteristics fo the wedge-top depozone of the southern Taiwan foreland basin system, *Basin Research*, **16**, 65-78.

Chow, J.-D., Lai, T.-D., Liu, C.-S. and Yu, H.-S., 1996, Flower structures and strike-slip deformation off southwestern Taiwan. *Terre. Atmos. Oceanic Sci.*, **7**(4), 534-533.

Deffontaines, B. and Chorowicz, J., 1991, Principle of drainage basin analysis from multisource data: Application to the structural analysis of the Zaire Basin, *Tectonophysics*, **194**, 237-263.

Deffontaines, B., Lee, J.C., Angelier, J., Carvalho, J. and Rudant, J.P., 1994, New geomorphic data on Taiwan active orogen: A multisource approach, *Jour. Geophys. Res*, **99**, B8, 20243-20266.

Deffontaines, B., Lacombe, O., Angelier, J., Chu, H.-T., Mouthereau, F., Lee, C.-T., Deramond, J., Lee, J.-F., Yu, M.-S. and Liew, P.-M., 1997, Quaternary transfer faulting in Taiwan Foothills: Evidence from a multisource approach, *Tectonophysics*, **274**, 61-82.

Fruneau, B., Pathier, E., Raymond, D., Deffontaines, B., Lee, C.T., Wang, H.T., Angelier, J., Rudant, J.P. and Chang, C.P., 2001, Uplift of Tainan Tableland (SW Taiwan) revealed by SAR interferometry, *Geophys. Res. Lett.*, **28(16)**, 3071-3074.

Harris, L.B. and Cobbold, P.R.,1984. Development of conjugate shear bands during simple shearing, *J. Structural Geology*, **7**, 37-44.

Ho, C.S., 1986, A synthesis of the geologic evolution of Taiwan, *Tectonophysics*, **125**, 1-16.

Hsu, M.K. and Li, Q., 1996, Tsunami in the region near Taiwan, *Acta Oceanog. Taiwanica*, **35**, 1-16. (in Chinese with English abstract)

Hu, J.C., Angelier, J., Lee, J.C., Chu, H.T. and Byrne, D., 1996, Kinematics of convergence, deformation and stress distribution in the Taiwan collision area : 2-D finite-element numerical modeling, *Tectonophysics*, **255**, 243-268.

Hu, J., Angelier, J. and Yu, S.B., 1997, An interpretation of the active deformation of southern Taiwan based on numerical simulation and GPS studies, *Tectonophysics*, **274**, 145-169.

Huang, C.Y., Shyu, C.T., Lin, S.B., Lee, T.Q. and Sheu, D.D., 1992, Marine geology in the arc-continent collision zone off south eastern Taiwan: Implications for Late Neogene evolution of the Coastal Range, *Marine Geology*, **107**, 183-212.

Huang, C.-Y., Wu, W.-Y., Chang, C.-P., Tsao, S., Yuan, P.-B., Lin, C.-W. And Xa, K.Y., 1997, Tectonic evolution of accretionary prism in the arc±continent collision terrane of Taiwan, *Tectonophysics*, **281**, 31-51.

Huang, C. Y., Yuan, P. B., Lin, C. W., Wang, T. K. and Chang, C. P., 2000, Geodynamic processes of Taiwan arc-continent collision and comparison with analogs in Timor, Papua New Guinea, Urals and Corsica, *Tectonophysics*, **325**, 1-21.

Huchon, P., Barrier, E., de Bremaecker, J.-C. and Angelier, J., 1986, Collision and stress trajectories in Taiwan: A finite element model, *Tectonophysics*, **125**, 179-191.

Lacombe, O., Mouthereau, F., Angelier, J. and Deffontaines, B., 2001, Structural, geodetic and seismological evidence for tectonic escape in SW Taiwan, *Tectonophysics*, **333**, 323-345.

Lallemand, S., Liu, C.-S. and ACT cruise scientific team, 1997, Swath bathymetry reveals active arc-continent collision near Taiwan, *EOS Tran., Am. Geophys. Un.*, **78**, No. 17, 173-175.

Lee, C.T., 1986, Methods of stress analysis and paleostress changes in northern Taiwan due to acr-continent cossision. Ph.D. dissertation, National Taiwan University.

Lee, J.C., Deffontaines, B., Angelier, J., Chu, H.-T., Hu, J.-C., Lacombe, O., Mouthereau, F., Yeh, Y.-H., Bureau, D., Carvalho, J., Lu, C.-Y., Liew, P.-M., Rudant, J.-P., Li, F.-C., Jeng, J.-C. and Lee, C.-T., 1997, Morphotectonic Map of Taiwan, Central Geological Survey, Ministry of Economic Affairs, R.O.C.

Lee, T.Y., Tang, C.H., Ting, J.S. and Hsu, Y.Y., 1993, Sequence stratigraphy of the Tainan Basin, offshore southwestern Taiwan, *Petro. Geol. Taiwan*, **28**, 119-158.

Liu, C.-S., Huang I.L. and Teng, L.S., 1997, Structural features off southwestern Taiwan, *Marine Geology*, **137**, 305-319.

Liu, C.-S., Liu, S.Y., Lallemand, S.E., Lundberg, N. and Reed, D., 1998, Digital elevation model offshore Taiwan and its tectonic implications, *Terre. Atmos. Oceanic Sci.*, **9**(4), 705-738.

Liu, C.-S., Lundberg, N., Reed, D. and Huang, Y.L., 1993, Morphological and seismic characteristics of the Kaoping Submarine Canyon, *Marine Geology*, **111**, 93-108.

Lu, C.Y., Jeng, F.S., Chang, K.J. and Tian, W.T., 1998, Impact of basement high on the structure and kinematics of the western Taiwan thrust wedge: Insights from sandbox models. *Terre. Atmos. Oceanic Sci.*, **9**(3), 533-550.

Lu, C.Y. and Malavieille, J., 1994, Oblique convergence, indentation and rotation tectonics in the Taiwan mountain belt: Insights from experimental modelling, *Earth Planet. Sci. Lett.*, **121**, 477-494.

Lu, C.Y., Yu, S.B. and Chu, H.T., 1997, Neotectonics of the Taiwan mountain belt, In: Martin, F.J., Chung, S.L., Lo, C.H., Lee, T.Y. and Uyeda, S. (Eds.), Mantle Dynamics and Plate Interaction in East Asia, *Geodynamic Series 27*, 301-315, Am. Geophy. Union.

Lundberg, N., Reed, D., Liu, C.-S. and Lieske Jr., J., 1992, Structural controls on orogenic sedimentation, submarine Taiwan collision, *Acta Geologica Taiwanica*, **30**, 131-140.

Lundberg, N., Reed, D., Liu, C.-S. and Lieske Jr., J., 1997, Forearc-basin closure and arc accretion in the submarine suture zone south of Taiwan, *Tectonophysics*, **274**, 5-24.

Pathier E., Fruneau, B., Deffontaines, B., Angelier, J., Pai, C.C., Yu, S.B. and Lee, C.T., 2003, Coseismic displacements of the footwall of the Chelungpu fault caused by the 1999, Taiwan, Chi-Chi earthquake from InSAR and GPS data, *Earth Plan. Sci. Lett.*, **212**, 73-88.

Reed, D.L., Lungberg, N., Liu, C.-S. and Kuo, B.Y., 1992, Structural relations along the margins of the offshore Taiwan accretionary wedge: implications for accretion and crustal kinematics, *Acta Geologica Taiwanica*, **30**, 105-122.

Sun, S.C., 1985, The Cenozoic tectonic evolution of offshore Taiwan, *Energy*, **10**, 421-423.

Suppe, J., 1981, Mechanics of mountain building and metamorphism in Taiwan, *Mem. Geol. Soc. China*, **4**, 67-89.

Suppe, J., 1984, Kinematics of arc-continent collision, flipping of seductions, and backarc spreading near Taiwan, *Mem. Geol. Soc. China*, **6**, 21-33.

Teng, L.S., 1990, Geotectonic evolution of late Cenozoic arc-continent collision in Taiwan, *Tectonophysics*, **183**, 57-76.

Teng, L.S., 1996, Extensional collapse of the northern Taiwan mountain belt, *Geology*, **24**, 949-952.

Tsai, Y.-B., 1986, Seismotectonics of Taiwan, *Tectonophysics*, **125**, 17-37.

Wu, F.,1978, Recent tectonics in Taiwan, *J. Phys. Earth*, **26**(suppl.), 265-299.

Wu, F., Rau, R.-J. and Salzberg, D., 1997, Taiwan orogeny: thin skinned or lithospheric collision? *Tectonophysics*, **274**, 191- 200.

Yang, K.M., Ting, H.H. and Yuan, J.W., 1991, Structural styles and tectonic modes of Neogene extensional tectonics in SW Taiwan: Implications for hydrocarbon exploration, *Petrol. Geol. Taiwan*, **26**, 1-31.

Yeh, Y.H., Barrier, E., Lin, C.H. and Angelier, J., 1991, Stress tensor analysis in the Taiwan area from focal mechanisms of earthquakes, *Tectonophysics*, **200**, 267-280.

Yu, S.B. and Chen, H.Y., 1998, Strain accumulation in southwestern Taiwan, *Terre. Atmos. Oceanic Sci.*, **9**(1), 31-50.

Yu, S.B., Chen, H.Y. and Kuo, L.C., 1997, Velocity field of GPS stations in the Taiwan area, *Tectonophysics*, **274**, 41-59.

Yu, H.S. and Huang, E.C., 1998, Morphology and origin of the Shoushan submarine canyon off southwestern Taiwan, *J. Geol. Soc. China*, **41**(4), 565-579.

Yu, H.S. and Wen, Y.H., 1992, Physiographic characteristics of the continental margin off southwestern Taiwan, *J. Geol. Soc. China*, **35**, 337-351.

FIGURE CAPTIONS

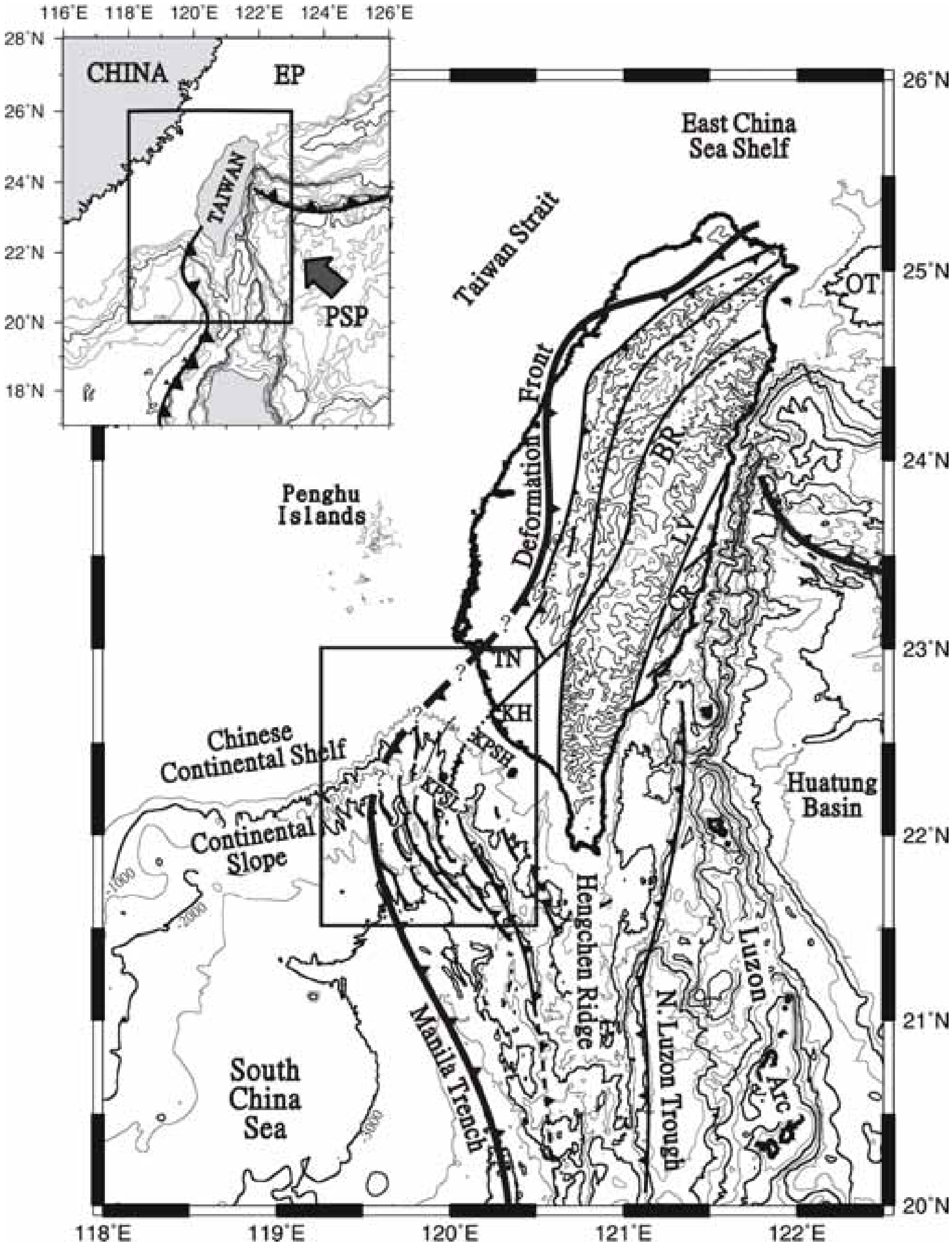

Figure 1. Geological settings of Taiwan and adjacent area. Inlet shows the tectonic setting of Taiwan and two adjacent subduction systems. Bathymetric contours in 500 m interval. Structures on land Taiwan and in the Taiwan Strait region are modified from Lee et al. (1997). Structures offshore southern Taiwan are modified from Reed et al. (1992), Lundberg et al. (1997) and Liu et al. (1997). Box indicates the study area. BR: Backbone Range, CR: Coastal Range, EP: Eurasian Plate, KH: Kaohsiung city, KPSH: Kaoping Shelf, KPSL: Kaoping Slope, LV: Longitudinal Valley, OT: Okinawa Trough, PSP: Philippine Sea Plate, TN: Tainan city.

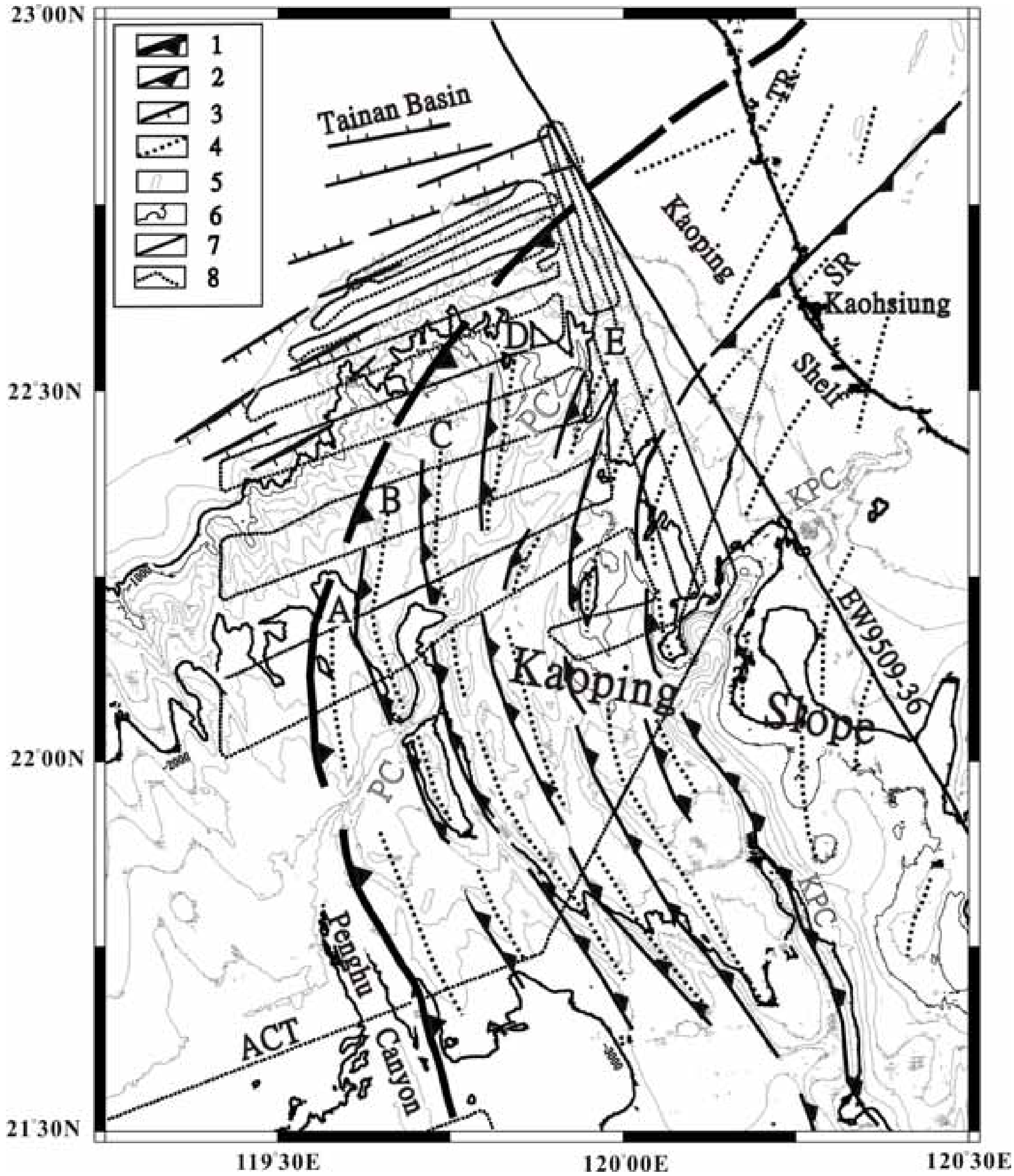

Figure 2. Structural map offshore SW Taiwan. A, B, C, D, and E are the anticlinal ridges described in the text. KPC: Kaoping Canyon, PC: Penghu Canyon, SR: Shoushan Ridge, TR: Tainan Ridge. Symbols in box: 1: Deformation front, 2: thrust fault, 3: normal fault, 4: anticlinal ridge axis, 5: bathymetric contour (interval is 200 m), 6: coast line of Taiwan, 7: EW9509-36 profile, 8: ACT ship track.

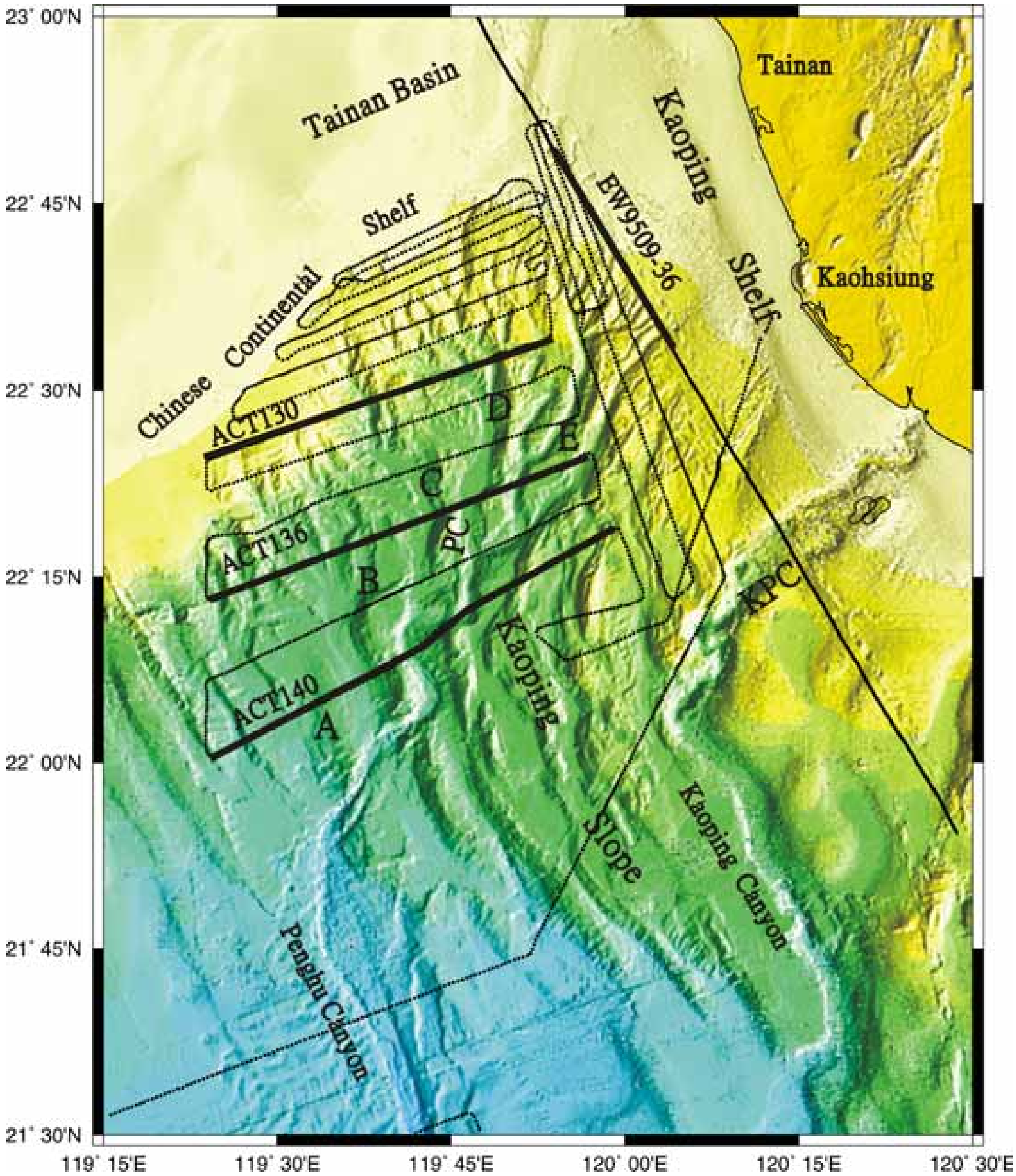

Figure 3. Hill-shading map of the study area. Solid line and dot lines show the locations of EW9509-36 profile and ACT seismic profiles, respectively. Thick lines indicate locations of the seismic profiles described in the text. A, B, C, D, and E are the anticlinal ridges described in the text. KPC: Kaoping Canyon, PC: Penghu Canyon.

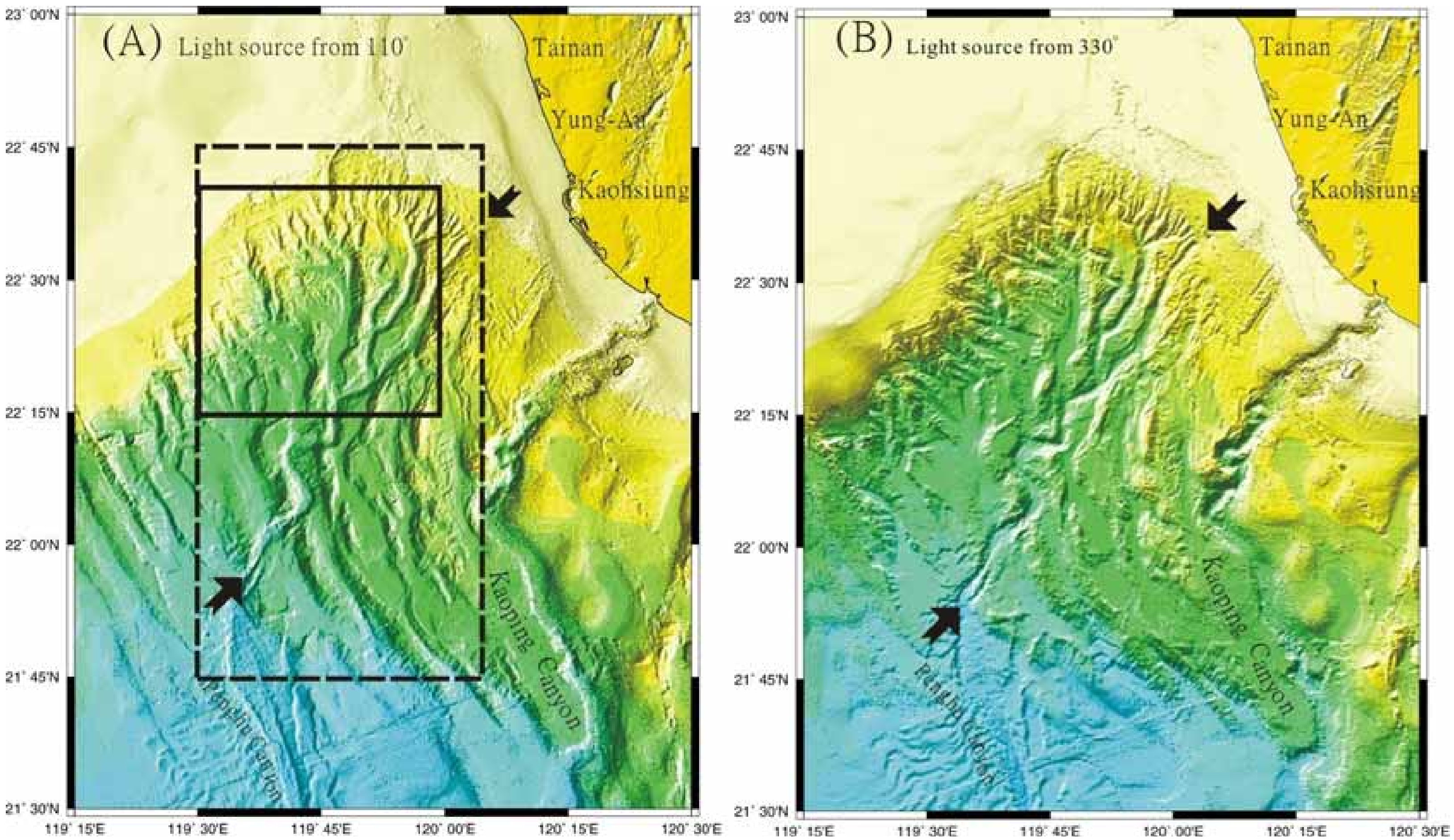

Figure 4. Hill-shading bathymetric map of the study area. Light illuminates from east (4A) and from northwest (4B) in order to highlight different topographic lineaments. Arrows indicate the N035°E trending Yung-An lineament. Solid box in 4A indicates the area covered in Figure 5. Dashed lines indicate the area covered in Figure 7A.

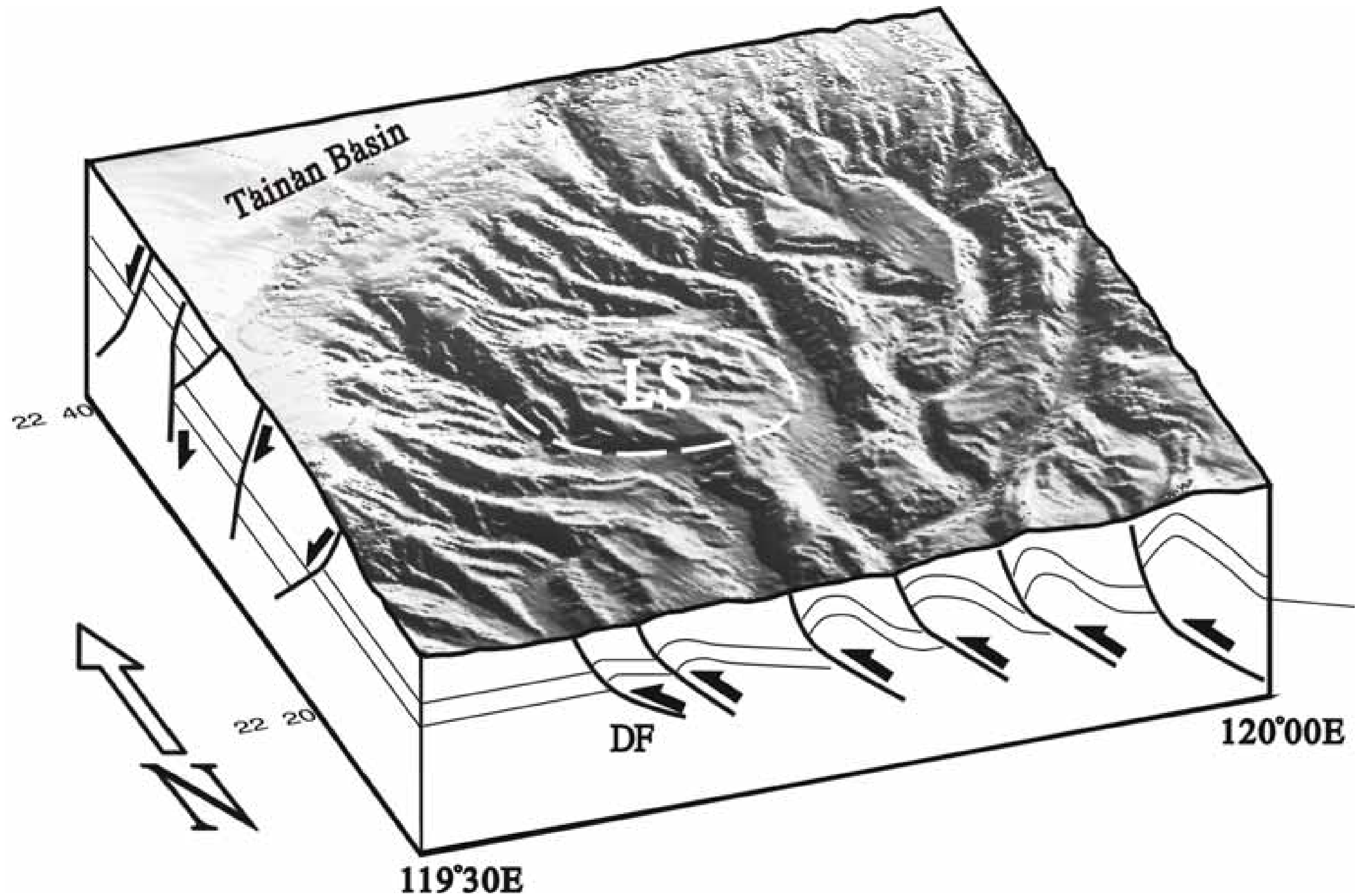

Fig. 5. A 3-D topographic expression of a possible submarine land slide (LS) characterized by a small crown and a convex downstream lobe..

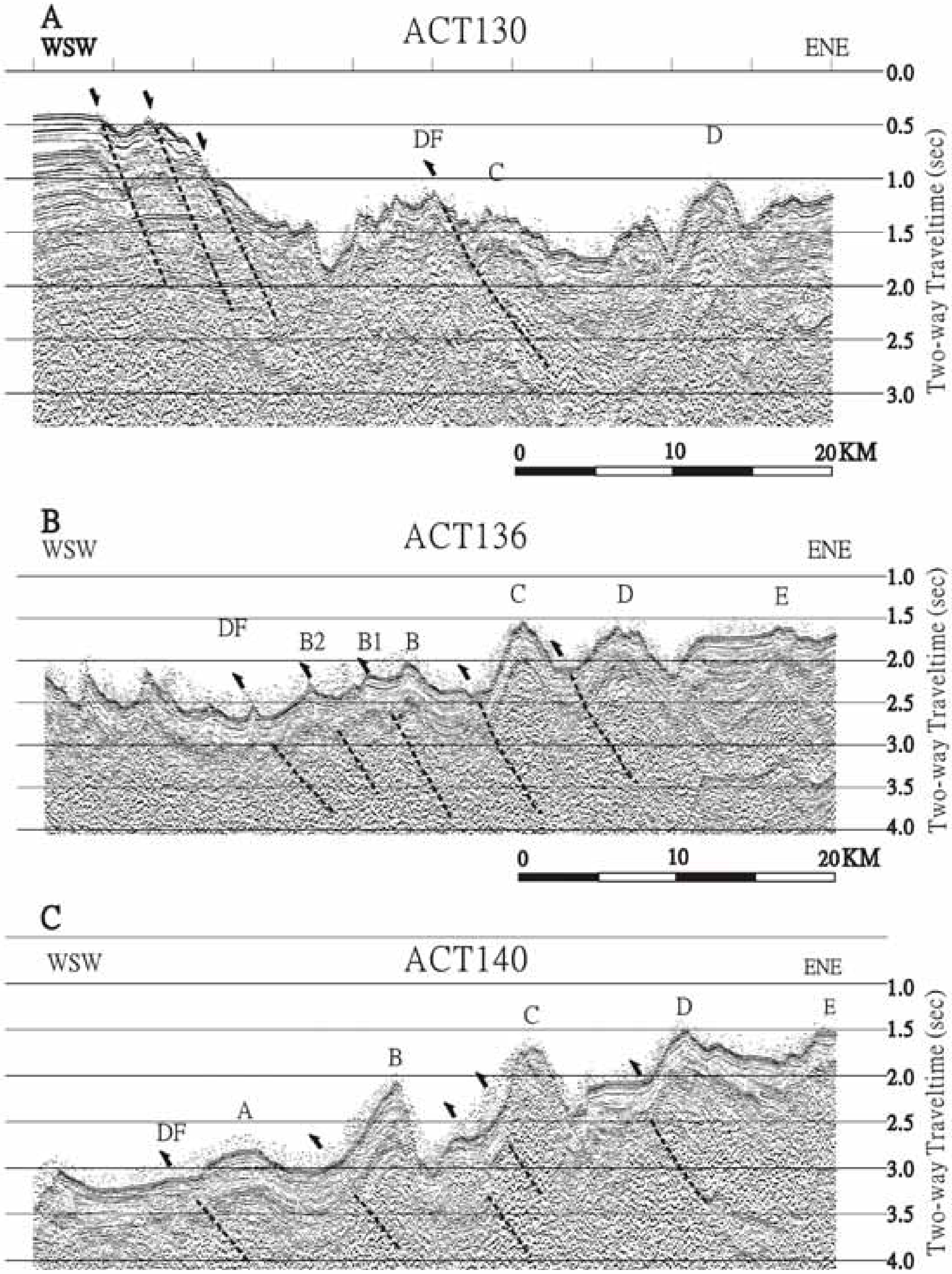

Fig. 6. Seismic reflection profiles of (A) ACT 130, (B) ACT136, and (C) ACT140. A, B, C, D and E corresponding to the anticlines identified in Figures 2 and 3 (see Figure 3 for profile locations). DF: deformation front.

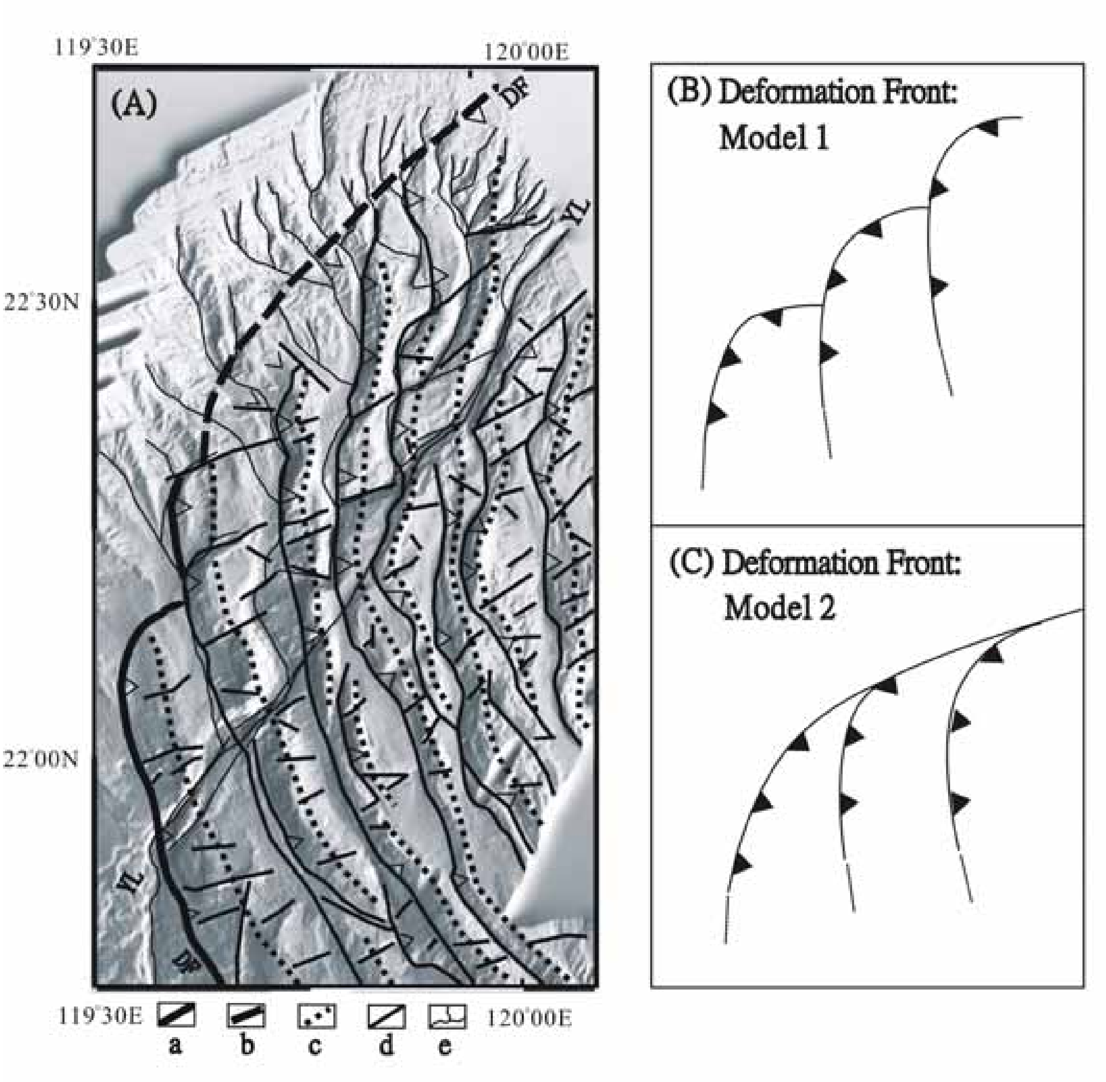

Figure 7. (A) Structural interpretation of the frontal accretionary wedge in the study area. (B) and (C) show two possible models for the geometry of the deformation front. DF: deformation front, YL: Yung-An lineament. Symbols shown below (A) are: **a**: deformation front, **b**: thrust fault, **c**: ridge axis, **d**: linear fracture, **e**: submarine canyon tributary.

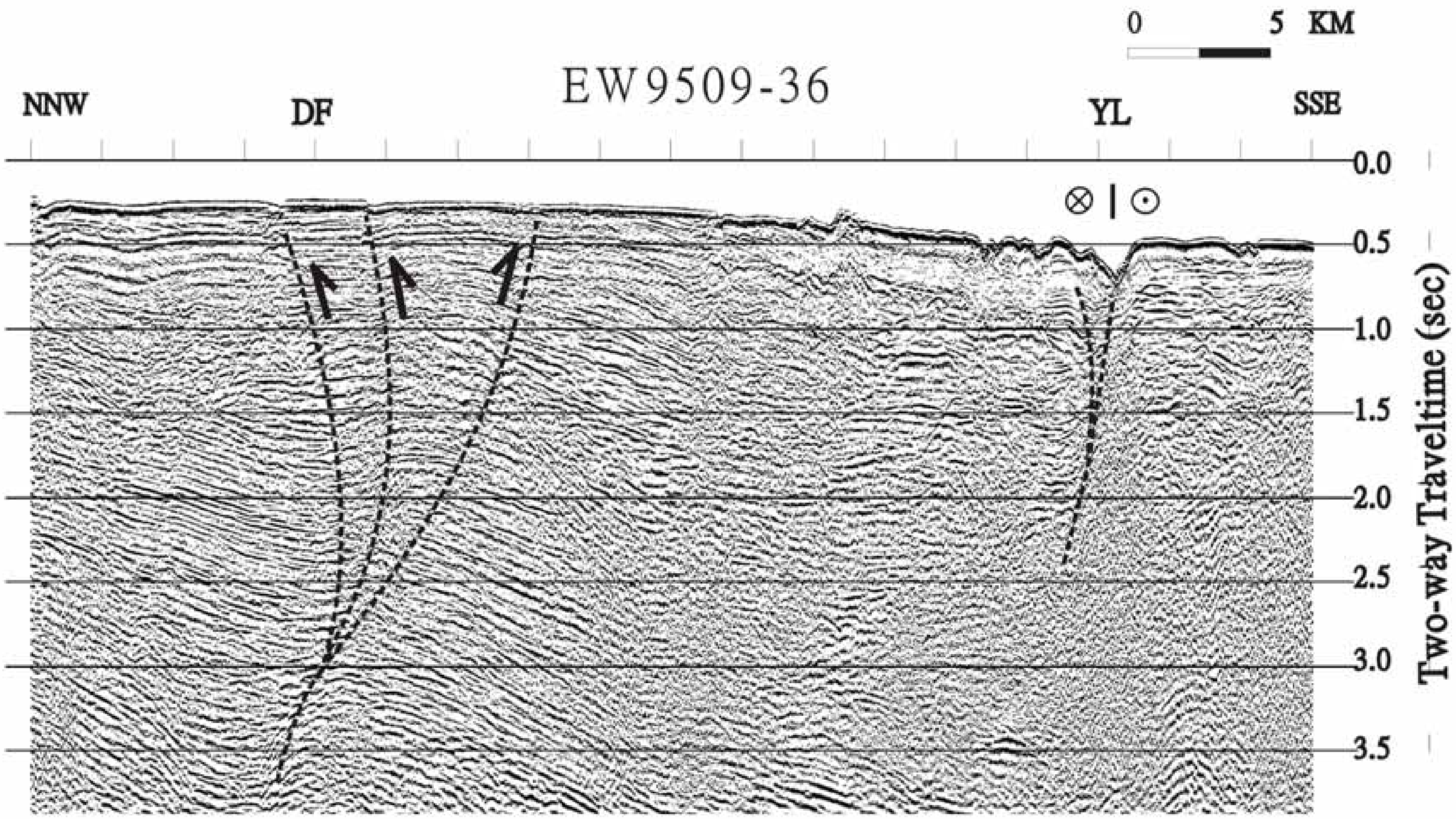

Fig. 8. A portion of the seismic reflection profile EW9509-23 showing a reactivated transpression fault that develops into the deformation front (DF) and the seismic image of the Yung-An lineament (YL) which is interpreted as a dextral strike-slip fault. See Figure 3 for location of this profile.

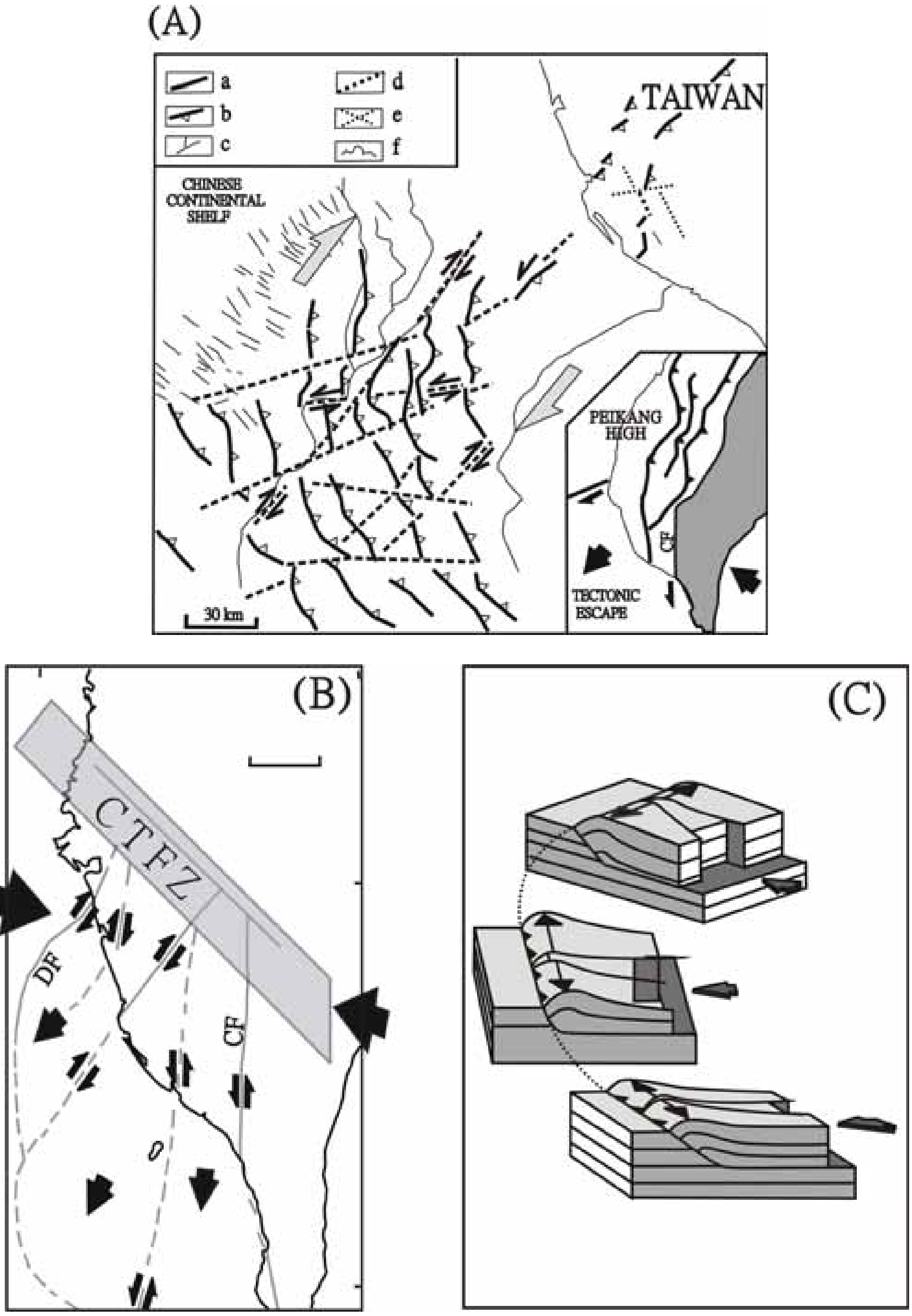

Fig 9. Geodynamic interpretations: (A) Tectonic escape model and possible mechanism for the strike-slip fault systems in the frontal accretionary wedge of the study area (modified from Lu et al., 1998). Symbols in box: **a**: coast line, **b**: thrust fault, **c**: erosional gully, **d**: strike-slip fault, **e**: on land fault, **f**: submarine canyon. CF: Chaochou Fault. (B) Block movement of the escape tectonic model suggested by Lacombe et al. (2001). CTFZ: Chishan Transfer Fault Zone, CF: Chaochou Fault, DF: Deformation Front. (C) A simple model to explain the changing orientation of anticlinal ridges and their bounding thrust faults, and the generation of strike-slip faults in different azimuths. Arrows indicate compression or extension directions.