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# Inversion of the Paleogene Chinese continental margin and thick-skinned deformation in the Western Foreland of Taiwan

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**Abstract**

New structural data, available seismicity data together with mechanical constraints on the Eurasian continental lithosphere and reconstruction of paleostress trajectories are combined in order to re-assess and discuss the dominant deformation mode (thin-skinned vs thick-skinned) in the Western fold-and-thrust belt of the active Taiwan collision zone. Serial balanced cross-sections and computed paleostress tensors suggest that structural styles and stress trajectories at the front of the Taiwan mountain belt may vary rapidly along-strike depending on the presence of pre-orogenic Paleogene troughs in the Chinese continental margin (Taihsi and Tainan basins) that are favourably oriented to be reactivated and inverted. In localities of the western foreland, where basin inversion and thick-skinned basement-involved shortening predominate, the crustal seismic activity is important and characterized by strike-slip faulting. In these domains of the fold–thrust belt, the stress deviations with respect to the regional transport direction are also important. By contrast, in domains of significant syn-orogenic subsidence, a thin-skinned style of deformation may be prominent due to the lack of available pre-existing features. The seismic activity is limited to few major faulted boundaries such as the active Chelungpu–Sani thrust, and the stress deviations are limited. The timing of deformation at the belt front seems to be independent of the structural styles, so that frontal folds are active since probably 0.5 Ma. However, in inner parts of the Western Foothills of Taiwan, where superimposed thick-skinned and thin-skinned deformation are required, out-of-sequence thrusting occurs to maintain the topographic profile. Finally, we suggest that kinematics and structural styles of the western fold–thrust belt are controlled by the mechanics of the Eurasian continental margin in agreement with a recent study. At the scale of the orogen, the limited shortening amounts across the WF and in the Central Range as well as the absence of continental HP-rocks better support a thick-skinned collision model for Taiwan.


*Keywords:* Fold–thrust belt; Thin-skinned; Thick-skinned; Continental margin; Collision

## 1. Introduction

### 1.1. Geological setting

The Taiwan orogen is the result of active accretion of a young Chinese continental margin belonging to the Eurasian plate, at the front of the oceanic Philippine Sea plate (Fig. 1) (Ho, 1976; Suppe, 1981). The collision started during the late Miocene-early Pliocene time interval (Suppe, 1981, 1984; Ho, 1986; Lin et al., 2003), i.e., only 20 Ma after the initiation of the oceanic spreading in the South China Sea (Lee and Lawver, 1995; Clift et al., 2002; Lin et al., 2003).

From East to West, several geological units are recognized across the Taiwan Island (Fig. 1); their succession reflects the collision between the northern part of the Luzon Arc, belonging to the Philippine Sea Plate, and the Chinese continental margin (Ho, 1976; Suppe, 1981). To the East, the Coastal Range (CR) represents the accreted part of Luzon Arc (Fig. 2). The Longitudinal Valley Fault (LVF) outlines the contact between the volcanic/sedimentary rocks belonging to the Luzon Arc and the units of the deformed continental margin. This fault corresponds to Philippine Sea/Eurasia plate boundary. Westwards, the Central Range comprises the exhumed Paleozoic–Mesozoic metamorphic basement (ECR), covered

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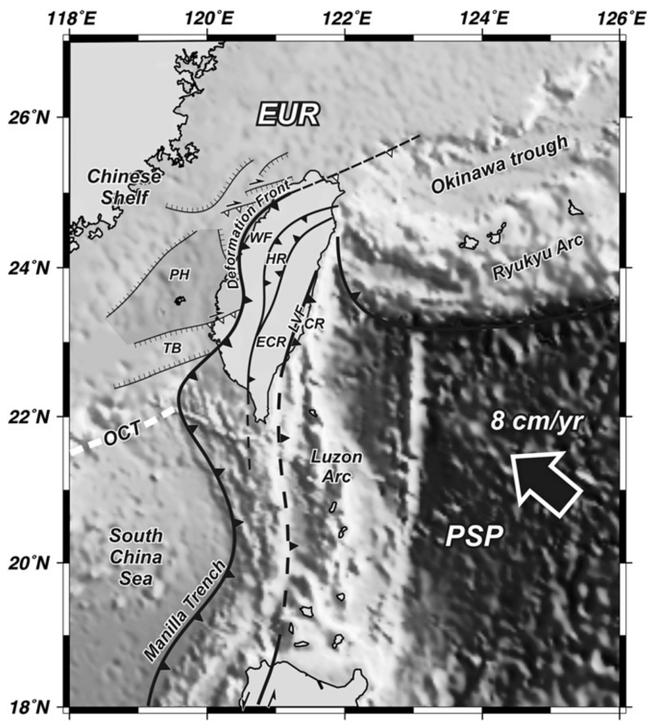


Fig. 1. Geodynamical setting of the arc-continent collision at Taiwan. Main pre-orogenic extensional basins (e.g. Tainan Basin) and basement highs (Central Peikang High and Kuanyin High) are depicted in the Western foreland. WF: Western Foothills; HR: Hsuehshan Range; ECR: Eastern Central Range; CR: Coastal Range; TB: Tainan Basin; PH: Peikang High; KH: Kuanyin High; LVF: Longitudinal Valley Fault; OCT: Ocean–Continent transition.

by Paleogene and Neogene sediments in the Backbone Range (BR) and the Hsuehshan Range (HR). The metamorphic rocks related to the Mio-Pliocene collision event mainly consist of Eurasia-derived sediments that were metamorphosed under greenschist-facies conditions (Jahn et al., 1986; Ernst and Jahn, 1987). The western, non-metamorphic belt comprises a thrust system, namely, the Western Foothills (WF), where foreland syn-orogenic deposits are involved in west-directed thrust sheets. Further west, the Coastal Plain makes the transition between the frontal thrust sheets and the adjacent foredeep basin (Fig. 2).

### *1.2. Current controversies about deformation styles and mountain building processes in Taiwan*

In an attempt at illustrating the anatomy of Taiwan in a lithospheric-scale cross-section, several geodynamic models have been proposed over the past 20 years for the Taiwan orogen (Suppe, 1984; Chemenda et al., 1995; Wu et al., 1997; Malavieille et al., 2002). A popular model, thin-skinned in style, considers the Taiwan mountain belt as the product of continuous subduction of the Eurasian Plate beneath the Taiwan Island (Suppe, 1984; Carena et al., 2002). This model implies that the Taiwan orogen kinematically belongs to the Philippine Sea Plate. An alternative, thick-skinned model predicts that Taiwan is, in fact, growing within and onto the Eurasian Plate (Wu et al., 1997).

According to the thin-skinned model, orogenic contraction is accommodated above a main basal seismogenic detachment that climbs upsection at the front of the belt in the Western Foothills domain. Large displacements and an intense deformation concentrated at the thrust front (i.e., along the Chelungpu Thrust) during the recent ($M_L = 7.6$) Chichi earthquake (21 September 1999) have been interpreted as supporting evidence for a thin-skinned style (Lallemand, 2000). Carena et al. (2002) further proposed that the distribution of micro-earthquakes that outline a nearly continuous layer of crustal seismicity defines the main detachment running beneath Taiwan Island and the Luzon Arc. Microseismicity data seem to support detailed structural studies that were first carried out in the fold-and-thrust belt of Western Taiwan, based on the assumption of a thin-skinned deformation style (Suppe and Namson, 1979; Suppe, 1980a,b, 1981, 1983; Namson, 1981, 1982, 1984). Consequently, the thin-skinned interpretation has been widely accepted for the Taiwan orogen; this, in turn, has been proposed as a case study for critical taper wedge models (Davis et al., 1983; Dahlen et al., 1984).

The alternative, thick-skinned interpretation, predicts that the seismic activity observed near the thrust front is caused by active thrust faulting distributed within the entire Eurasian continental lithosphere. According to this view, the Chichi earthquake is better explained as an intraplate collision event, rather than as an interplate subduction earthquake (Lallemand, 2000). The thick-skinned interpretation is supported by subsequent structural studies in Western Taiwan (Namson, 1984), which predict that the development of the foreland fold-and-thrust belt was largely influenced by reverse reactivation of pre-thrusting normal faults within the Chinese margin. The availability, since 1990, of new seismic profiles constrained by deep borehole data by the Chinese Petroleum Corporation, further led to generalized positive inversion models for the western fold-and-thrust belt (Chang et al., 1996; Yang et al., 1996, 2001; Lacombe and Mouthereau, 2002; Lee et al., 2002; Mouthereau et al., 2002). Gravity data (Ellwood et al., 1996) and seismic tomography (Wu et al., 1997) independently support basement involvement within the fold-and-thrust belt, i.e. a thick-skinned deformation style. In spite of increasing evidence supporting positive inversion, the alternative, i.e. thick-skinned interpretation for the structural style of the western fold-and-thrust belt of Taiwan, has received, to date, little attention.

The question of whether the western fold-and-thrust belt of Taiwan is thin-skinned or thick-skinned in style is not straightforward; yet, a more accurate definition of the deformation style of this province may have important consequences for our understanding of the development of the entire orogen in terms of quantitative estimates of shortening, strain rate determinations and inference of the exhumation/erosion paths. The conservative amounts of shortening implied by thick-skinned models seem to better fit other geological observations in Taiwan, such as the lack of HP continental rocks and the high exhumation rates in the central part of the island.

In this paper, we focus on the dominant deformation mode (thin-skinned or thick-skinned) of the western fold-and-thrust

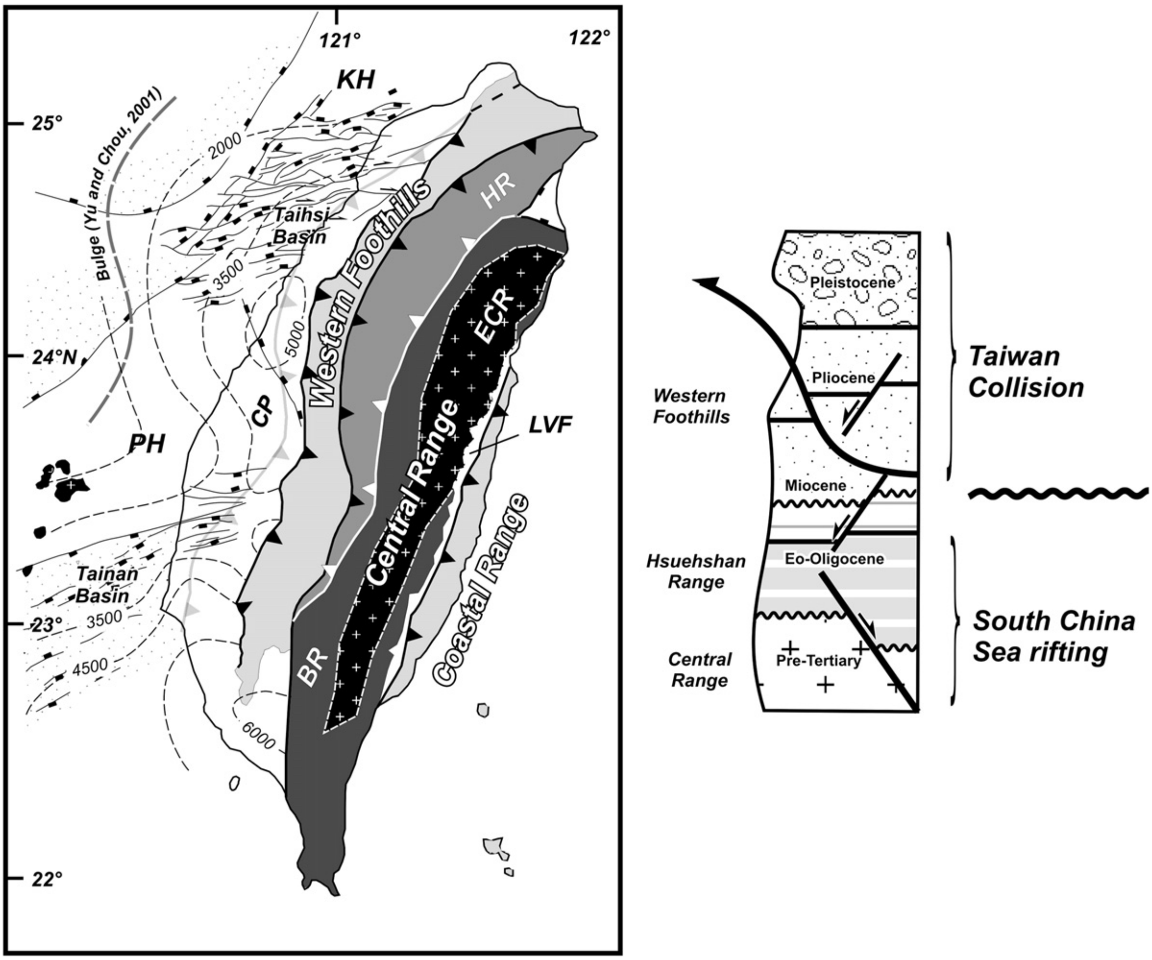


Fig. 2. Simplified geological map of Taiwan showing the main tectonic units within the Taiwan collision belt and Paleogene–Neogene inherited extensional basins and highs in offshore Western Taiwan. In the Central Range, the contact between the exhumed Paleozoic/Mesozoic metamorphic basement of the Chinese continental margin and its overlying Paleogene cover corresponding to the slate belt of the Backbone Range (BR) is outlined by a mylonitic zone shown as a white dashed line. Black dashed lines in the western foreland of Taiwan represent the isobaths of the top of the pre-Neogene basement derived from data compiled in Mouthereau et al. (2002). The position of the foreland bulge is deduced from seismic reflection data (Yu and Chou, 2001). Offshore subsurface data are based on Huang et al. (1993) for the Taihsi basin and Lee et al. (1993) for the Tainan basin. A synthetic tectono-stratigraphic log shows the timing of the major tectonic events recorded in the Chinese continental margin from rifting to collision. Abbreviation LF is for Lishan Fault; LVF for Longitudinal Valley Fault; CP for Coastal Plain; BR for Backbone Range; ECR for Eastern Central Range and HR for Hsuehshan Range.

belt of Taiwan, as inferred from the geometry of the shortened sedimentary cover, tested against its possible relations with the underlying basement in terms of structural style and plate strength. The deep structure of the belt is constrained with the aid of new structural data, integrated with available seismic data, mechanical lithospheric flexure modelling and reconstruction of paleostress trajectories.

## 2. From rifting to collision: the tectonic history of the Chinese continental margin

### 2.1. Episodes of pre-orogenic extension

Seismic profiles across the foreland (Yu and Chou, 2001; Lin et al., 2003) make it possible to reconstruct for the Chinese continental margin a history of polyphasic, positive inversion, from rifting to collision (Fig. 2). Two main types of Tertiary basins, mostly Paleogene and Neogene in age, are identified (Sun, 1982). Many of the inherited extensional features in the foreland of Taiwan were formed during the Cretaceous–Paleogene rifting of the Chinese margin, prior to spreading in the South China Sea that initiated ca. 30 Ma ago (e.g., Lee and Lawver, 1995; Clift et al., 2002; Lin et al., 2003). The Paleogene syn-rift sediments have been slightly buried during the subsequent continental collision event and now are extensively exposed in the Hsuehshan Range. These sediments are unconformably overlain by post-rift, Oligocene–Miocene deposits. The unconformity can be traced in some parts of the Backbone Range, where it is highlighted by slightly metamorphosed conglomerates. The analysis of the tectonic subsidence history reveals a second extensional event that occurred in the early–middle Miocene (ca. 20 Ma) interval, i.e. after drifting of the continental margin (e.g., Lee et al., 1993; Lin et al., 2003). Following this stage of post-rifting extension ca. 12 Ma ago an episode of uplift and associated erosion affected significantly the continental margin. The causes for this regional uplift are still unclear and controversial. Some authors have proposed that it can be related to thermal activity initiated after spreading in the South China Sea (Lin et al., 2003), whereas other authors argue that it is due to the passage of a lithospheric flexural bulge related to tectonic loading of the continental margin under compressional setting (Tensi et al., 2006).

In spite of these different and controversial interpretations, there is general agreement on the fact that the young Chinese continental margin was affected by a rapid succession of thermal and extensional events since Paleogene time. These events caused a pre-orogenic structural segmentation of the margin, outlined by intramarginal basins (e.g., Tainan or Taihsi basins) that are separated by intervening basement highs (Peikang and Kuanyin Highs). This segmentation pattern presumably was responsible for significant rheological heterogeneities along the Chinese continental lithospheric margin prior to the collisional event.

### 2.2. *Flexure of the continental margin and development of the foreland basin*

Since the late Miocene, and probably within the 12.5–6 Ma interval, a rapidly subsiding basin filled with syn-orogenic deposits developed on the flexured continental margin. The onset of the flexure event is clearly outlined in the sedimentary record by a remarkable angular unconformity of late Miocene age (Yu and Chou, 2001; Lin et al., 2003). The present geometry of the foreland basin is highly asymmetrical, with a depocentre hosting a ca. 5–6 km thick sedimentary sequence adjacent to the thrust front (Fig. 2). A rejuvenated episode of extensional deformation of probable flexural origin resulted in the reactivation of some Paleogene normal faults in the outer part of the foreland plate (Tensi et al., 2006).

The strength of a continental margin in a foreland setting largely reflects its inherited, pre-collisional history (Watts, 1992). Secondary modifications may also occur due to plate flexure but in general a previously attenuated continental lithosphere will tend to preserve its characteristic strength. For Taiwan, the age of the Chinese continental margin at the time of the onset of orogenic loading was about 50 Ma. But we can assume a younger age, of ca. 20 Ma, given that the last thermal event, associated with the second episode of extension, was responsible for a complete thermal resetting of the thermal structure of the Eurasian lithosphere. In any case, the continental margin is young and is therefore expected to be rheologically weak. Quantitative constraints on the elastic strength of the Eurasian continental margin have been recently provided (Lin and Watts, 2002; Mouthereau and Petit, 2003). Although these are based on different assumptions on boundary conditions and methods, both studies indicate low values of the effective elastic thickness (Te), between 10 and 20 km. These estimates reflect a weak behaviour for the rifted, and then flexed Chinese continental margin: this, in turn, is mainly related to its young thermal age.

## 3. Structural and seismological evidence of inversion tectonics and basement-involved deformation in the western foreland of Taiwan

### 3.1. *Irregular geometry of the Chinese continental margin and basin inversion tectonics*

Evidence for an episode of positive tectonic inversion of the continental margin in the Taiwan foreland is provided by numerous subsurface observations: these have been carried out offshore, i.e. in the Taiwan strait, and onland, i.e. beneath the Costal Plain (Chang et al., 1996; Yang et al., 1996, 2001; Lacombe and Mouthereau, 2002; Lee et al., 2002; Mouthereau et al., 2002). Critical information was collected within the Taihsi basin, north of the Taiwan foreland (Fig. 2). This is a syn-rift Paleogene basin trending ENE–WSW, i.e. parallel to the regional trend of the continental margin. To the south, the Taihsi basin bounds a major basement promontory that was only slightly affected by extension; this promontory is known as the Kuanyin High (Fig. 2). Deposition of a thick package of Oligocene–Miocene sequence occurred during a second episode of extension that took place after rifting and prior to collision and sediment loading (Mouthereau et al., 2002; Lin et al., 2003; Tensi et al., 2006).

Reflection profiles and borehole data indicate that many ENE-trending normal faults of the Taihsi basin were reverse reactivated (e.g., Huang et al., 1993). For instance, the geometry of the top-pre-Miocene basement (Fig. 2), a good proxy for the crystalline pre-Tertiary basement (Lee et al., 2002; Mouthereau et al., 2002), reveals that the deepest part of the Taihsi basin was uplifted due to positive inversion.

The Taihsi basin is bounded to the south by the Peikang basement high. This major, wedge-shaped asperity in the continental margin has strongly controlled the structural styles of the advancing thrust units. For instance, the Peikang High localizes a major transfer fault at its northern edge (Mouthereau et al., 1999) that accommodates differential advancement of the fold-and-thrust belt near the basement high. Similarly, in the southern edge of the Peikang basement high, structural inversion of the onland part of the intramarginal Tainan Basin has been documented by subsurface data (e.g., Huang et al., 1993; Chang et al., 1996).

The timing of basin inversion is constrained by the age of the youngest inverted depocentre. Inversion of the Taihsi basin probably occurred after, or during deposition of conglomerates of the Pleistocene Toukoshan Formation, as inferred from significant sediment thickness variations. Subsurface data reveal that the inversion of inherited ENE-trending normal faults south of the Peikang High affects the Liushuang Formation, dated at 0.4–0.5 Ma (Mouthereau et al., 2001b). These observations place sound constraints on the timing of tectonic inversion in the present foredeep: this episode of inversion probably began in Pleistocene time.

### 3.2. Depth distribution of crustal seismicity

The western foreland and fold-and-thrust belt of Taiwan is a very active deforming zone. More than 15,000 earthquakes with $M_L > 1$ magnitude are recorded each year (Fig. 3a) across the Taiwan orogen by the CWBSN (Central Weather Bureau Seismic Network). Of these events, about one third is located in the western foreland of Taiwan. The distribution of epicenters appears very inhomogeneous. Low seismic activity in the centre of the foreland is well correlated with the position of the Peikang basement high. By contrast, the surrounding areas exhibit significantly higher seismicity (Fig. 3a). This indicates that the foreland basement promontory behaves as a stiffer crustal portion of the Eurasian continental lithosphere, which resists subduction beneath the Western Foothills.

Hereafter, the depth-frequency distribution of seismicity recorded in 2001 in the foreland is examined along two sections. The location of both sections is shown in Fig. 3a. Uncertainties in depth location of seismic foci are typically of ca. 5 km. Based on these data one can distinguish a northern domain (section A) and a southern domain (section B). The number of events recorded in the northern domain is ca. twice with respect to the number of events recorded in the southern domain. The distribution of earthquakes in the upper crust shows that the events shallower than 20 km represent more than 97% in section B, whereas this depth category falls in the 70–80% range northward in section A. In the lower crust earthquake frequency rapidly decreases, indicating that the lithospheric mantle is essentially aseismic. This decrease of seismic activity with depth is more important in southern regions, where the lower crust is almost aseismic below 20 km. Comparison of the depth distribution of earthquakes with the location of the pre-Miocene marginal basins and highs indicates that where basin inversion has been reported, i.e., in the Tainan basin, earthquakes are restricted to the upper crust. In contrast, when moving northwards in regions where inversion tectonics has not been documented, earthquakes are located throughout the entire crust. These observations strongly suggest that the crustal seismicity is neither homogeneously nor randomly distributed in the Eurasian continent; rather, it reflects the inhomogeneities of the continental margin around the Peikang High. This inference will be examined in more detail in the discussion section.

### 3.3. Quaternary faulting and focal mechanisms of earthquakes

Many of the quaternary and active faults onshore Taiwan (Fig. 3b) are concentrated in the western foreland domain (Bonilla, 1977). For instance, the Meishan earthquake (1906, $M_L = 7.1$), whose hypocenter is located south of the Peikang High, has generated an ENE-trending fault scarp. Similarly, the Tungtzuchiao earthquake (1935, $M_L = 7.1$) located north of the Peikang High, also produced an ENE-trending fault scarp. Fault kinematics inferred from focal mechanism analysis for both earthquakes are consistent with right-lateral strike-slip faulting along an ENE trend; this is the trend of the inherited normal faults of the continental margin. Because these earthquakes are located in the Tainan and Taihsi basins respectively, they suggest a good consistency with oblique reactivation of ENE-trending inherited basins (Lacombe and Mouthereau, 2002; Mouthereau and Petit, 2003). This is further supported by the numerous moderate crustal earthquakes depicted in Fig. 3a.

In other domains of the foreland, the dominant trend of Quaternary, active faults is N–S, i.e. parallel to the regional trend of the belt. These faults are mainly thrusts, which accommodate the component of convergence normal to the edge of the continental margin. On 21 September 1999, the Chichi earthquake caused the reactivation of the Chelungpu–Sani thrust. This ruptured along a ca. 85-km-long scarp at surface (Ma et al., 1999; Kao and Chen, 2000). The hypocenter indicates a depth of $12 \pm 5$ km with a focal mechanism consistent with sliding along a ramp dipping 25° toward the east (Kao and Angelier, 2001). The error in depth location of the earthquake foci has generated a lively debate on the nature of the Chelungpu–Sani thrust. Provided that the maximum sediment thickness is 7 km in the foreland, the hypocentre may be located either at the base of the sedimentary cover or, more likely, within the metamorphic basement. This inference strongly supports the hypothesis of basement-involved thrusting (Mouthereau et al., 2001a).

### 3.4. Possible underestimate of inversion tectonics and related misinterpretations of structural styles in the Western Taiwan fold-and-thrust belt

The deformation of a sedimentary layer requires less deviatoric yielding stresses than a deeper deformation in the basement, so thin-skinned style of deformation is usually expected and more common at the thrust front of orogens, especially in the absence of well-oriented, pre-existing crustal weaknesses. As a consequence, in the absence of sound subsurface evidence for basement involvement, this mode of thin-skinned deformation is generally favoured with respect to the alternative thick-skinned mode. As for Taiwan, the structural and seismic data presented in the previous sections indicate that Paleogene normal faults are abundant beneath the foreland; hence, the possibility of reverse reactivation of pre-thrusting normal faults should necessarily be taken into account in the construction of balanced cross-sections. This inference independently suggests that the structure of the Western Foothills cannot be explained only in terms of thin-skinned tectonics. It is to be stressed that balanced cross-section restoration does not provide a unique solution for the structure of folds and thrusts. Interpretations at depth may change drastically depending on the new acquisition and improved quality of subsurface data. In Taiwan, despite some studies showing the possibility of inversion tectonics and basement-involved deformation, this alternative received little attention.

The most detailed structural studies in Taiwan were based on thin-skinned assumptions (Suppe and Namson, 1979; Suppe, 1980a,b, 1981, 1983; Namson, 1981, 1982, 1984). Namson (1984) and Narr and Suppe (1994) modified this

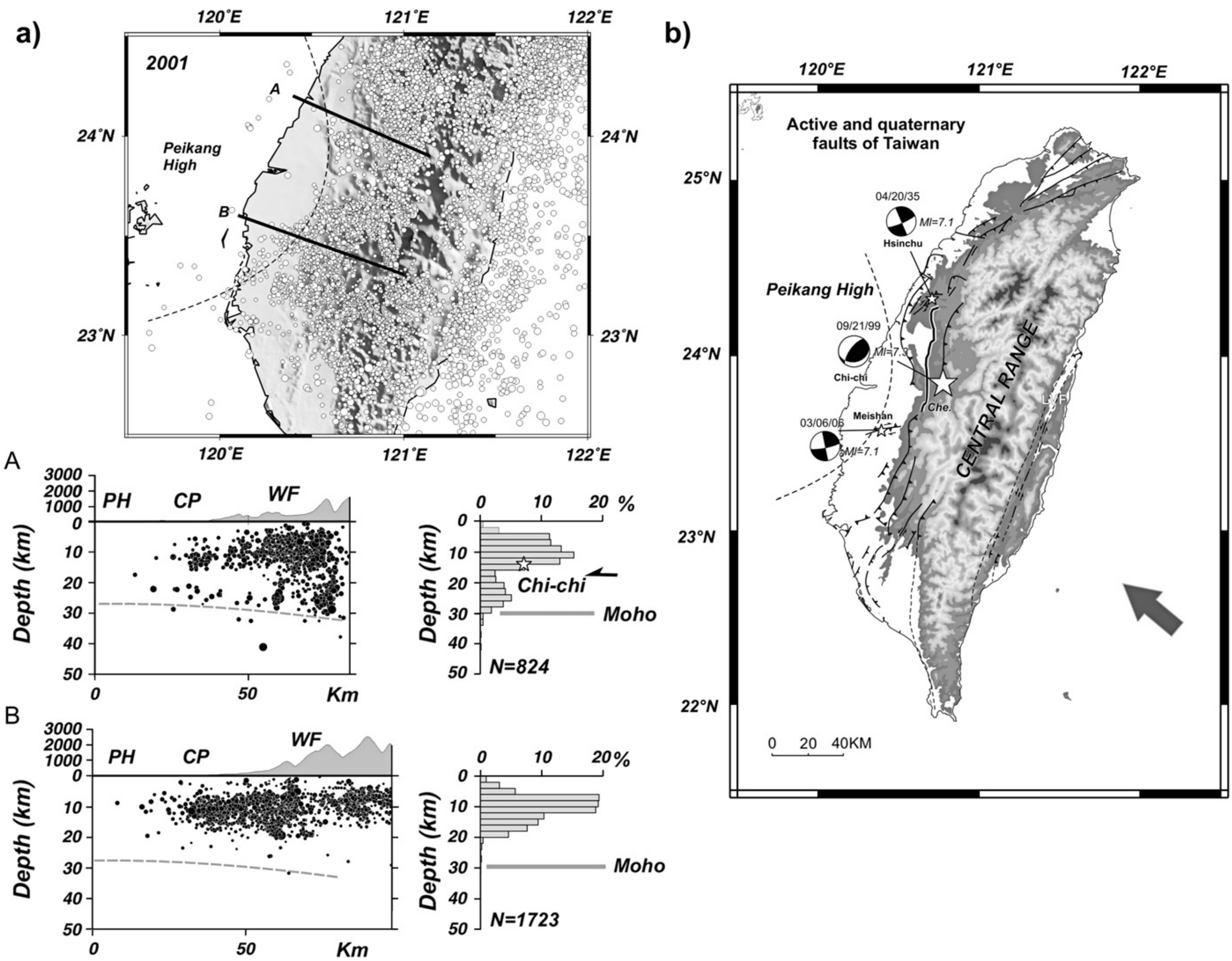


Fig. 3. Depth distribution of earthquakes and location of major active and quaternary faults in the western fold–thrust belt of Taiwan. (a) Depth distribution of earthquakes within the Eurasian crust (magnitudes $M_L > 1$). Data are issued from the CWBSN catalogue for the 2001 yearly record. Two 70-km-long seismic profiles (A and B) are investigated through (left) depth distribution of earthquakes and (right) depth-frequency distribution of seismic events. The number of earthquakes selected is shown at the bottom of each histogram. Note the concentration of shallow seismicity in section B in relation with the inversion of the inherited Tainan basin. Note that the lower crust is less seismogenic and even nearly aseismic suggesting the presence of a weak and ductile layer which may act as a crustal décollement for basement-involved deformation. (b) Active, quaternary faults and focal mechanisms of historical earthquakes (e.g., Meishan and Tungtzuchiao earthquake in 1906 and 1935, respectively). These focal mechanisms give constraints on the present reactivation of inherited extensional faults as transpressional dextral strike-slip faults consistent with basin inversion.

interpretation and proposed that some folds as related to the localization of shallow thrust ramps by inherited normal faults. In this view, the pre-Tertiary basement is not affected by contractional structures, and hence a thin-skinned deformation style is still dominant. By contrast, more recent subsurface data have been used in recent papers by the Chinese Petroleum Corporation (CPC) to demonstrate that folds are cored by basement, with no role for shallow décollements (Lee et al., 2002).

In order to further stress to what extent recently acquired subsurface data can modify the extrapolation of fold structures at depth, we illustrate the case of the Hsiaomei anticline (Fig. 4). This anticline is the outermost fold in the southern WF (see Fig. 7). The first balanced cross-section across this anticline was proposed by Suppe and Namson (1979), who interpreted the structure in terms of simple fault-bend folding. In this study, the development and growth of the Hsiaomei anticline is interpreted as due to sliding above the Miocene Talu shales, that is considered as regional basal décollement: this horizon is connected through a ramp to an upper décollement lying in the Pliocene Chinshui shales (Fig. 4a). In this model, the pre-Miocene basement of the Chinese continental margin is not affected by shortening. Based on the interpretation of a more recent seismic profile Hung et al. (1999) and Yang et al. (2001) showed that, in fact, folding may be related to the reverse reactivation of an inherited normal fault (Fig. 4b). This view requires that the basal décollement, if present, is much deeper that that predicted for the fault-bend folding model (e.g. see Suppe and Namson, 1979); however, the pre-Tertiary basement is still not deformed. Based on

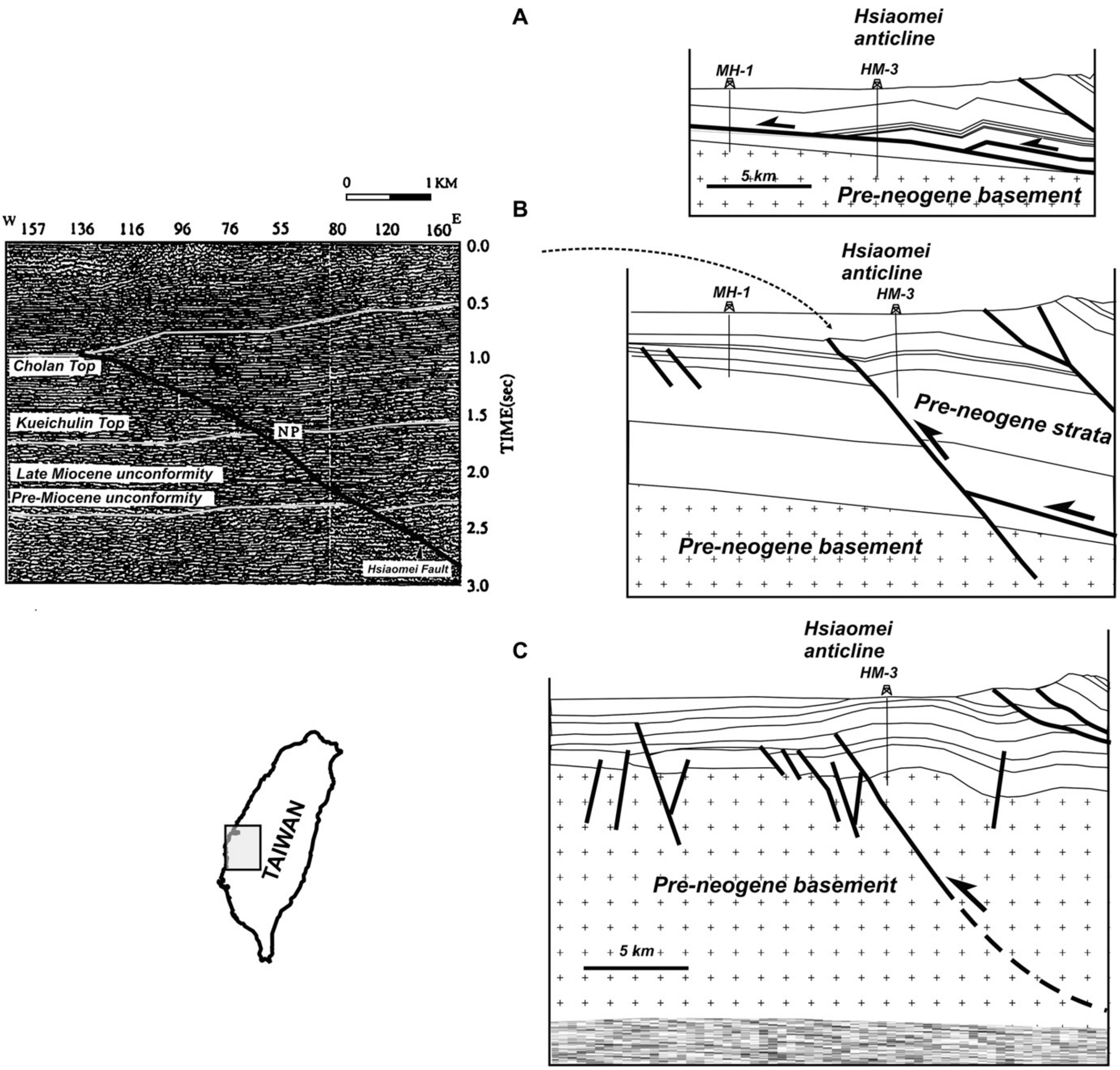


Fig. 4. Example of different structural interpretations of the Hsiaomei anticline (Chiayi area) as a function of recent seismic reflection profile in Hung et al. (1999) showing beneath the fold the reactivation of a basement normal fault belonging to the Tainan basin. (A) A preliminary interpretation suggests the presence of a décollement within the Chinshui shales at ∼3 km in agreement with a thin-skinned deformation (Suppe and Namson, 1979). (B) Based on the seismic profile, the basal décollement is moved in the pre-Neogene formation at ∼12 km (Hung et al., 1999). (C) Finally, due to the lack of significant evidence of a décollement in the pre-Neogene formation the décollement is finally located at the brittle–ductile transition ∼15 km (modified after Yang et al., 2001). The crustal shortening deduced from thin-skinned interpretation is 10 km, whereas the thick-skinned interpretation gives shortening of only ∼3 km.

new seismic lines by the CPC, constrained by unpublished borehole data, Yang et al. (2001) presented their interpretation of the Hsiaomei anticline as the result of basement-involved thrusting (Fig. 4c). Although they do not explicitly mention it, this interpretation requires that thrusting is accommodated at a deep crustal level, probably in the thermally weakened lower crust.

In summary, analysis of earthquake focal mechanisms and subsurface data strongly suggest that inversion of pre-orogenic marginal basins, and consequent basement-involved deformation, may be important processes for our enhanced understanding of fold-and-thrust structures in the western foreland of Taiwan.

## 4. Inversion tectonics and thick- vs thin-skinned structural style in the Western Foothills of Taiwan

The aim of this section is to draw an updated and completed sketch of the deformation style along the strike of the Foothills and testing the hypothesis of inversion tectonics and basement-involved deformation in the Western Foothills of Taiwan. Because of the irregular shape inherited from the pre-orogenic segmentation of the continental margin, four main morpho-structural domains are classically identified along the strike of the WF (Mouthereau et al., 2002). These are, from North to South: Northern Taiwan (Miaoli area), North-Central Taiwan (Taichung area), South-Central Taiwan (Chiayi area), Southern Taiwan (Tainan–Kaohsiung area). In the following sections we present the results of balanced cross-section restoration that was constrained by available subsurface data from the Chinese Petroleum Corporation, 1:100,000 scale geological maps (CPC, 1982) and new field observations.

### 4.1. Northern Western Foothills (Miaoli area)

This region is characterized by a complex pattern of folds that mainly trend N–S in the southern part and are progressively rotated to a mean ENE-trend northwards. The deviation of fold axes is controlled by movements along ENE-trending basement transpressive strike-slip faults inherited from the Paleogene rifting and later reactivated during convergence (Yang et al., 1996; Lacombe et al., 2003). At depth, the folds seem to be related to both thin-skinned and thick-skinned deformation. A seismic profile reveals that the Miocene and Paleogene strata are offset by normal faults (Fig. 5). These faults, as well as the base of Miocene and Paleogene strata, are tilted toward the foreland, thus suggesting that the crystalline basement was also mobilized during shortening.

The Chuhuangkeng anticline (section 1 of Fig. 5) is probably one of the most extensively studied folds in the Taiwan foreland for its hydrocarbon potential interest. It was first interpreted as a detachment-fold on the basis of its symmetric steep limbs (ca. 70° dip). Indeed, the presence of a weak layer is required in the core of this anticline. Such a layer was identified as the shaly Wuchihshan Formation (Upper Oligocene) (e.g., Namson, 1984; Hung and Wiltschko, 1993) and was consequently interpreted as a regionally important décollement. This interpretation does not take into account, nor suggests a role for normal faults in the pre-Neogene strata (Wey et al., 1992) (Fig. 6). Yet, beneath the Tiehchenshan anticline, unpublished subsurface data indicate the presence of numerous inherited faults, reactivated as strike-slip faults. This is consistent with the reactivation of normal faults described offshore west of the Miaoli–Hsinchu area (Huang et al., 1993).

The Chelungpu–Sani thrust is one of the largest faults of the WF. It strikes ca. N10°E to the south and is characterized by a pronounced bend when approaching the Chuhuangkeng anticline. Along-strike changes of structural style in relation with this fault (sections 1 and 2 of Fig. 5) illustrate a differential accommodation of orogenic shortening (Hung and Wiltschko, 1993). To the south, shortening is taken up in the hanging-wall of the Chelungpu–Sani thrust, whereas northward it is accommodated by folding within the Chuhuangkeng anticline (Hung and Wiltschko, 1993). The thrust strikes ENE in the transfer zone, known as the Sanyi transfer fault zone of Deffontaines et al. (1997); significantly, this trend is parallel to the strike of inherited normal faults of the Chinese margin. Beneath the Chuhuangkeng anticline numerous normal faults inherited from the rifting and then reactivated as strike-slip faults are observed (Fig. 6). Differences in thickness of the pre-orogenic Miocene strata across the Chelungpu–Sani thrust suggest that this is, in fact, an ancient normal fault that was later reverse reactivated (Fig. 5). This interpretation requires no shallow décollement. Consequently, a thick-skinned style, with basement-involved deformation, seems appropriate to describe the deep geometry of this structure.

### 4.2. North-Central Western Foothills (Taichung area)

The domain located a few kilometres to the south is characterized by a general decrease in elevation, and by a significant change in structural style (see Fig. 3). One main difference with the Miaoli area is the absence of ENE-structural trends (Fig. 7). Except for the N–S Chelungpu–Sani thrust, it is generally difficult to find elements of structural continuity between the two domains. Also, there is no evidence for structural features with significant topographic expression, like the Chuhuangkeng anticline. Borehole data indicate that this domain was a major depocentre during the Pliocene–Pleistocene time interval, when up to 2 km of fluvial syn-orogenic deposits were accumulated. In sharp contrast with the Miaoli domain that was significantly uplifted in response to basin inversion at that time the topography and the subsidence/uplift history of the North-Central Western Foothills suggest very different styles of deformation.

A seismic profile reveals that the frontal Pakuashan anticline grew as a consequence of thrust propagation in the Cholan formation of Pliocene age (Fig. 7). This fold defines a regional-scale curvature of the belt front that mimics the shape of the Peikang High. The analysis of tectonic features, as well as the results of kinematic modelling, indicate that the geometry of the Pakuashan anticline results from the development of an oblique ramp above a roughly N160°E inherited basement normal fault bounding the Peikang High (Mouthereau et al., 1999). This orientation, close to a general N–S trend, is not parallel to the main structural grain of the inherited basins in the Chinese margin and hence should be regarded as a local feature. The burial of the basement beneath the Plio-Pleistocene basin suggests that the basement was subsiding at that time in response to sediment loading and hinterland tectonics. As a consequence of this burial episode, inherited basement extensional features were deeper and probably less favourably oriented, and thus probably required high differential stresses to be reactivated. This may explain the dominant thin-skinned style here, in contrast with the Miaoli domain where thick-skinned style predominates. As already stressed, this style is correlated with a WF characterized by a very smooth morphology and topographic elevations that are lower than 1000 m.

Eastward, two major active N–S thrust faults, the Chelungpu–Sani thrust and the Shuangtung thrust, expose Miocene strata to the surface. The Chelungpu thrust is not directly associated to folding. Thickness variations in excess of ca. 1 km within Miocene strata are observed across this major

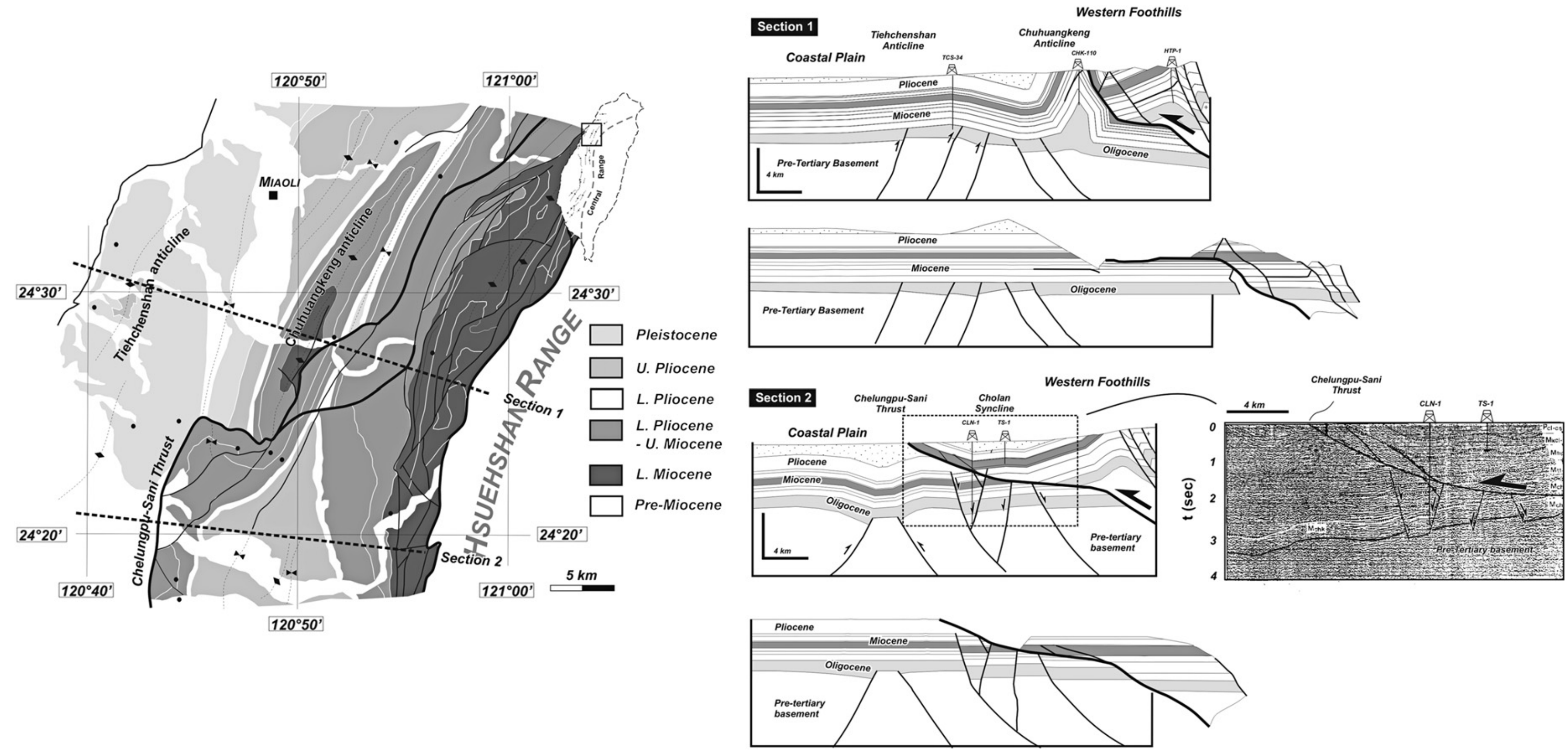


Fig. 5. Structural map of the northern Western Foothills (Miaoli area) and balanced/restored sections across the Miaoli area. An example of a seismic profile used to constrain our cross-sections is shown after (Hung and Wiltschko, 1993). Black dots correspond to locations of new sites where fault slip data have been collected and paleostress tensors computed.

thrust (Chou, 1980). These relationships suggest that the Chelungpu–Sani fault is a normal fault that was reverse reactivated during basin inversion. This history is consistent with section 2, where this main thrust is interpreted as an inverted normal fault. However, shallow seismic profiles suggest a décollement located at a 4–5 km depth within the Chinshui shales (Suppe, 1985). In order to propose a section consistent with both data, the structure of the Chelungpu–Sani fault is presented here as resulting from the reactivation of a local N–S-trending normal fault that is connected at shallower depth with a flat décollement in the sedimentary cover. The hypocenter and focal mechanism of the Chichi earthquake indicated that to the East, the Chelungpu thrust is dipping 25° eastward at a depth of $12 \pm 5$ km (Kao and Angelier, 2001). Given the thickness of Neogene strata <7 km (e.g., PKS-1 well) above the pre-Miocene basement and despite possible errors in depth location, the geometry of this structure is more consistent with deep-seated deformation than with thin-skinned deformation. So we propose that, along this transect, thin-skinned deformation predominates in the outer frontal unit whereas basement-involved thrusting likely played a major role eastward.

### 4.3. South-Central Western Foothills (Chiayi area)

Fig. 3 (see section B) shows that the average topographic elevation in the Chiayi area is significantly higher than that in the Taichung area. Indeed, altitudes across the WF increase rapidly to the east and reach nearly 2000 m at the Chukou thrust fault.

The first structural interpretations proposed for this area are thin-skinned in style (Suppe, 1976). For instance, the structure of the Kuantzuling/Chunglun anticline (section 6 of Fig. 8) was interpreted to result from an antiformal stacking of a series of duplexes in the Miocene layers (Suppe, 1976). However, the structural geometry of this domain shows remarkable similarities with that observed in the Miaoli area (Fig. 5). For instance, extensive seismic profiles in the Coastal Plain revealed the presence of ENE trending, inherited normal faults (Fig. 8). Many of these structures were reactivated as strike-slip faults (Chang et al., 1996; Lee et al., 2002). The frontal ENE-trending Hsiaomei anticline, whose subsurface structure is illustrated in Fig. 4, belongs to this family of ENE-trending folds related to basin inversion. The hypothesis of fault reactivation is also supported by historical earthquakes such as the Meishan earthquake related to dextral strike-slip faulting as well as by the abundant seismicity and strike-slip focal mechanisms (Fig. 3). Based on the interpretation of recent seismic profiles, Lee et al. (2002) proposed that the observed structures in the WF may result essentially from basin inversion. For instance, CL-2 and minor drill holes cored into the Chunglun anticline have shown a continuous pile of sediments down to 3 km above the folded pre-Miocene rocks (section 6 in Fig. 8). An other example is provided by the thickness of Miocene strata that increases by 500 m across the Chukou fault, one of the main thrusts in this domain. Lee et al. (2002) generalized this observation to all thrusts in this domain; this led

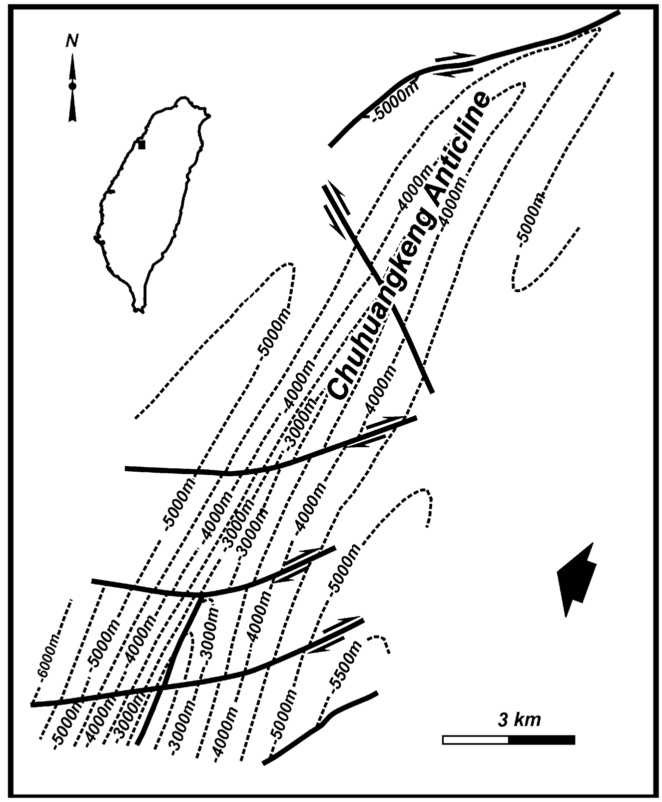


Fig. 6. Isobaths of the top of the Mushan Formation (Upper Oligocene) in the Chuhuangkeng anticline (Wey et al., 1992). This figure outlines the occurrence of inherited normal faults reactivated as transpressional dextral strike-slip faults (consistent with an average N110° compression).

us to interpret the thrusts as originating from reverse reactivation of ancient normal faults. Based on the work of Yang et al. (2001), sections 4 and 5 show clearly the same trend. These sections have been restored with respect to the base of Pliocene strata and emphasize well the increase in thickness of Miocene layers toward the east. However, shallower décollement levels in the Pliocene Chinshui shales and within Miocene layers are also locally required to accommodate surface folding. In section 6, instead of involving duplexes of Miocene layers, we propose to interpret the Chunglun–Kuantzuling anticline as the result of basement involvement in agreement with an earlier study (Lee et al., 2002). In spite of our thick-skinned view, we agree with previous thin-skinned interpretations that the growth of the fold-and-thrust belt required significant mobilization of shales in the Miocene strata. We have restored this layer in the assumption of a generally plastic–ductile, rather than a brittle behaviour. As for the Miaoli or Taichung areas, the data suggest that the structure of folds and thrusts beneath the Coastal Plain results mainly from inversion of inherited basin normal faults. The development of fold-and-thrust structures in this domain is strongly influenced by the presence of an inherited pre-orogenic trough, namely, the Tainan basin (Fig. 2). The inversion of intra-marginal basins leads to the development of a dominant thick-skinned style. But eastward into the Western Foothills, although basement-involved deformation is required at a regional scale,

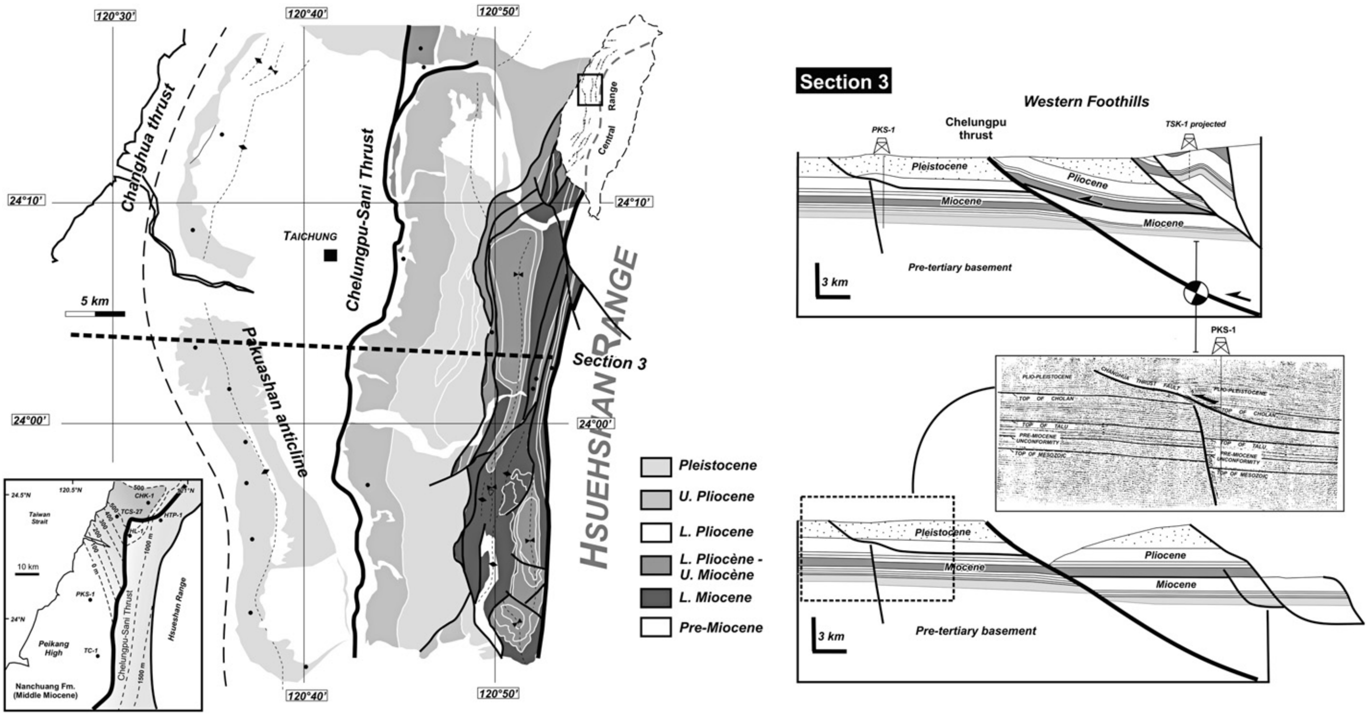


Fig. 7. Structural map of the northern-central part of the Western Foothills (Taichung area) and a balanced/restored section. An example of a seismic reflection profile across the Pakuashan anticline is shown (Chen, 1978). Insert: Isopachs map of the Nanchuang formation (Middle Miocene) from (Chou, 1980). These isopachs together with the depth of the Chichi earthquake ($12 \pm 5$ km) suggest that the thrust may be related to the inversion of an inherited basement normal fault.

complexities of surface folding suggest that multiple décollements may have been activated in the sedimentary cover.

### 4.4. Southern Western Foothills (Tainan–Kaohsiung area)

Many cross-sections constructed in the southernmost domain of Taiwan have been presented in a previous paper (Mouthereau et al., 2001b), so the main results will be only briefly summarized here. The transition from the Chiayi domain displaying high topographic elevation and this area is abrupt. The nature of sediments is also very different in relation with a much contrasted paleogeography in the Miocene–Pleistocene time interval. Lithologies are characterized by the predominance of Neogene shales of the Gutingkeng formation indicating a deep depositional environment. This area is a transitional domain toward the offshore Manila accretionary prism. It displays regularly spaced thrust and fold units involving strata of similar ages. This supports the interpretation of this part of the WF as a result of the accommodation of deformation above a single regional décollement likely lying within the Miocene strata. From the northern part to the southern part of this domain, the absence of hypocenters shallower than 20 km, as well as the low number of events, is in agreement with the folding of fluid-rich Neogene deposits within the thin-skinned Manila accretionary wedge.

To summarize, cross-sections presented above reveal that in the Coastal Plain, where pre-collisional basins have suffered no significant burial in response to flexurally driven subsidence (Miaoli and Chiayi domains), basin inversion and basement-involved shortening predominate. In other domains, a thin-skinned style of deformation may be prominent due to the lack of available pre-existing features (Taichung and Tainan/Kaohsiung domains). On the other hand, in the inner units of the WF, the superimposition of thick-skinned and thin-skinned deformation is required to fit the observed initial extensional movements at the regional-scale as well as the complexity of surface folding.

## 5. Plio-Pleistocene stress trajectories and evidence for along-strike changes in cover–basement coupling

In this section, new $\sigma_1/\sigma_3$ paleostress trajectories were computed from a compilation of more than 150 tensors homogeneously distributed in the foreland thrust system and determined from stress/kinematic indicators such as striated faults, calcite twins and pitted pebbles collected in the Plio-Pleistocene deposits of the outermost thrust units (Fig. 9a). This dataset includes more than 34 unpublished new sites (Mouthereau, 2000) that are integrated with published stress data (Lacombe et al., 1993, 1997; Hung, 1994; Rocher et al., 1996; Lin and Huang, 1997).

The Pliocene–Pleistocene stress trajectories outline a fan-shaped, curved pattern (Fig. 9b). This overall distribution has already been described and interpreted as an indenter effect due to the impingement at the rear of the growing orogenic wedge by the Coastal Range (Huchon et al., 1986). This interpretation has recently been refined with the aid of numerical modelling (e.g., Hu et al., 1997). Such a fan-shaped distribution of stress trajectories in the Foothills has been

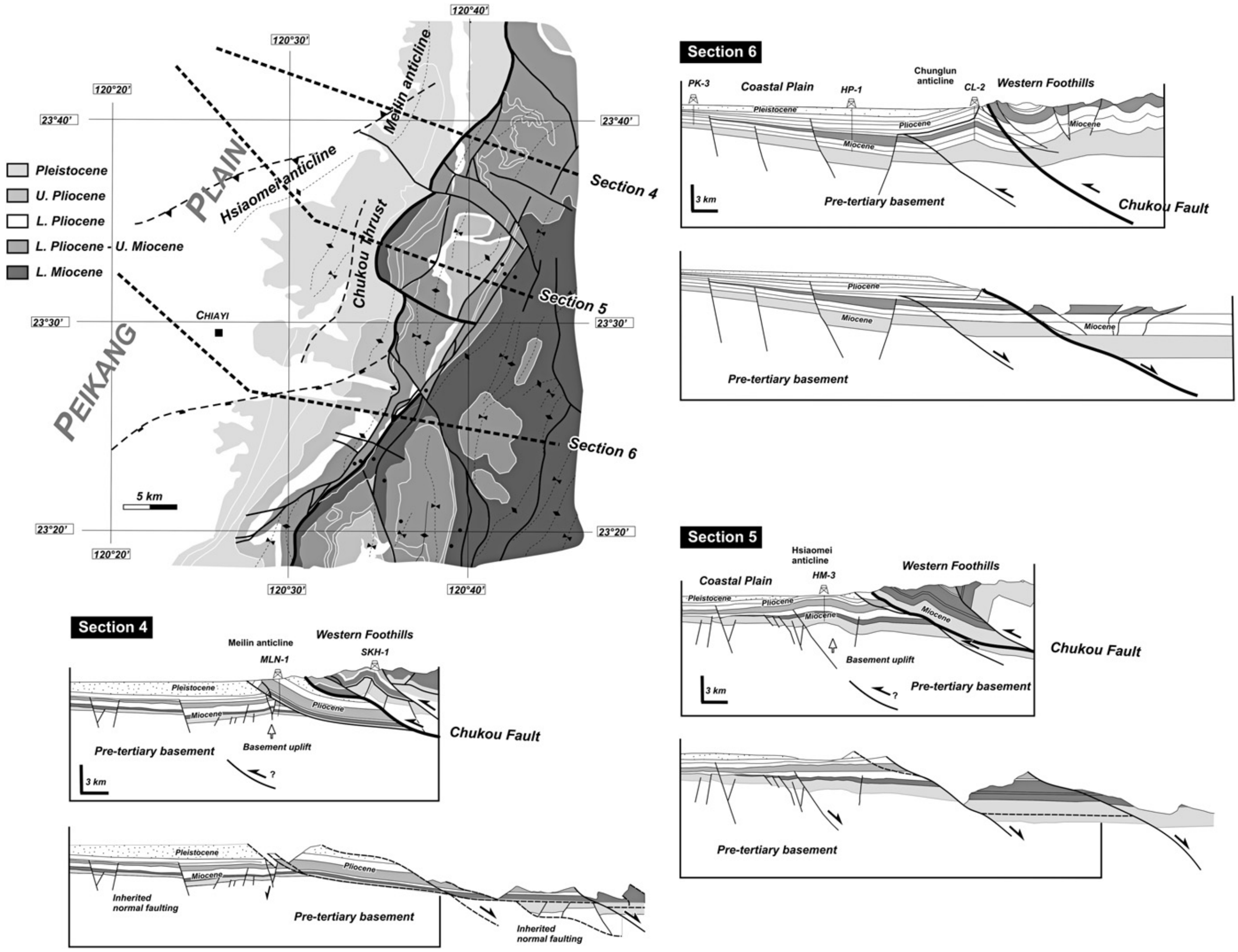


Fig. 8. Structural map of the southern-central part of the Western Foothills (Chiayi area) and balanced/restored sections.

proposed to be mainly influenced by the geometric configuration of the boundary between Eurasia and Philippine Sea Plate, the shape and rheological properties of major thrust units and, to a lesser extent, by the direction of convergence.

At the scale of the WF, the Peikang and Kuanyin basement highs have been considered for a long time as major features of the foreland controlling the kinematics of the fold–thrust belt. To the north, $\sigma_1$ stress trajectories show a large clockwise rotation on the southern edge of the Kuanyin High: the resulting NW–SE to NNW–SSE compressional trends are likely to reflect right-lateral transpressional deformation parallel to the N070°-trending structures of the margin, that accommodates the curvature of the NW Taiwan salient (Lacombe et al., 2003). In Central Taiwan, the influence of the Peikang High on the geometry and kinematics of the orogenic wedge is emphasized by the sigmoidal shape of the belt front, that reflects along-strike variations of both the thrust wedge geometry and the structural style of the frontal units (Lu et al., 1998; Mouthereau et al., 2002; this work). $\sigma_1$ stress trajectories inferred from fold axes and thrust traces around the Peikang High in sandbox models (Lin and Huang, 1998) are convergent toward the high strength basement promontory, in agreement with results of numerical models including rheological contrasts between thrust units and the Peikang High (Hu et al., 1997; Lu et al., 1998). However, the map of actual stress trajectories does not show such a distribution around the Peikang High (Fig. 9b). $\sigma_1$ is not homogeneous in direction throughout the belt front and the shape of $\sigma_3$ direction (perpendicular to the mean horizontal compression) is exactly symmetric to the curve-shaped thrust front. Stress trajectories especially undergo a slight, but significant counterclockwise rotation south of the Peikang High. Where thrust units propagate onto the rigid indentor of the Peikang High, stress trajectories show divergent trends that contrast with model predictions.

A recent numerical simulation of Jeng et al. (1996) that includes elasto-plastic properties for the outer thrust belt and the Peikang High is modelled with the aid of a stiffer material (Fig. 10). Although the rheology chosen appears more realistic, it fails to reproduce the divergence of stress trajectories in the vicinity of the Peikang High. A major limitation to this model is that it does not take into account the oblique faulted boundaries of the Peikang High and the obliquity of

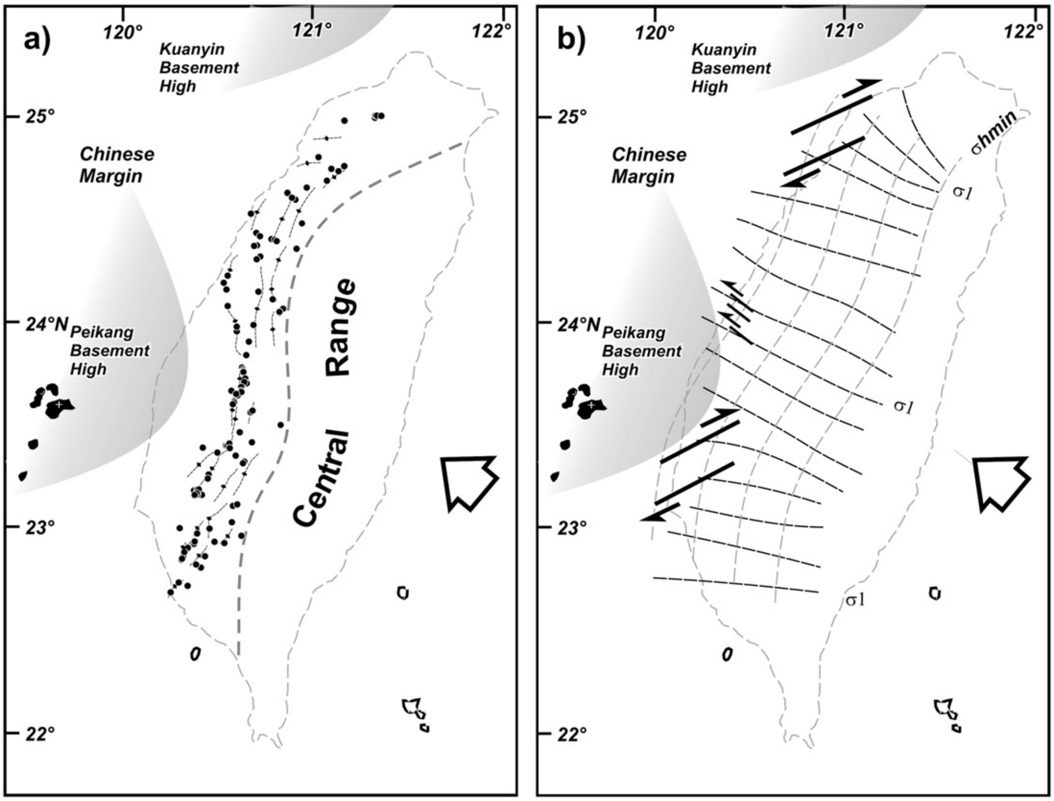


Fig. 9. Plio-Pleistocene stress trajectories of $\sigma_1$ and $\sigma_{hmin}$ in the foreland thrust system (b) deduced from interpolation of more than 150 compressional and strike-slip tensors homogeneously distributed within the Western Foothills (a). The presence of inherited faulted boundaries in the fold-and-thrust belt (Tainan and Taihsi basins) may partly explain the observed deviations of $\sigma_1$ in the vicinity of the basement promontories. See text and comparison with Fig. 10 for explanations.

the convergence. In the model, the boundaries of the Peikang High and Kuanyin High have infinite friction and therefore no movement is possible along them.

Cross-sections 4–6 of Fig. 8 illustrate that the Peikang High is bounded to the south and to the north by pre-existing Paleogene normal faults with a finite friction. These pre-existing faults underwent oblique transpressional reactivation on the southern edge of the Peikang High, where they display a right-lateral component of motion (Fig. 9b).

Based on numerical modelling of stress deviations close to strike-slip faults (e.g., Homberg et al., 1997), and as a working hypothesis, we therefore propose that the right-lateral transpressional reactivation of the bounding faults on the southern edge of the Peikang High likely induced counterclockwise deviations of stresses in the cover. The stress trajectories locally turn from an average N120 to W–E compression. In other words, the Tainan basin that flanks the Peikang High southward behaves as an inherited, weak crustal domain that allows lateral motions by reactivation of inherited faults. The important earthquakes with mechanisms consistent with right-lateral slips along ENE trends (e.g., Wu et al., 1997) in this region outline this particular deformation pattern (Fig. 3). It is worth noting that such interpretation implies that the cover is attached to the basement; otherwise the results would have been similar to sand-box models or elasto-plastic numerical models. This is in agreement with the hypothesis of a dominant thick-skinned deformation style. Additionally, counterclockwise stress deviations were probably enhanced by a phenomenon of late Pleistocene incipient tectonic escape in SW Taiwan (Lacombe et al., 1999, 2001). The contrast in type and amount of stress deviations compared to the southern edge of the Kuanyin High could be tentatively explained by a higher amount of strike-slip partitioning (i.e., the percentage of wrench component imposed by oblique transport direction and accommodated by discrete strike-slip faulting) along the pre-existing 070°-trending normal faults of the margin. On the northern edge of the Peikang High no significant deviation from the general N120 transport direction are observed. An explanation is given by the presence of newly formed tear faults in the cover that accompany folding within the left-lateral Pakua transfer fault zone (Mouthereau et al., 1999). These faults likely prevented large divergence between regional transport direction and compressional trends within the transfer zone.

The orientations of compressive stress axes outline well the mechanisms of deformation in the vicinity of the thrust front. Actual stress orientations within the advancing folded units in the vicinity of strong basement promontories are not reliably simulated by available numerical elastic models or other simulation that considers homogenous media. Where inherited basins are inverted, for instance in the Tainan basin, a counterclockwise deviation of stress axes from the regional trend of $\sigma_1$ is consistent with dextral motions along basement strike-slip faults. A more realistic model including inherited frictional boundaries in the deformed materials and faulted boundaries

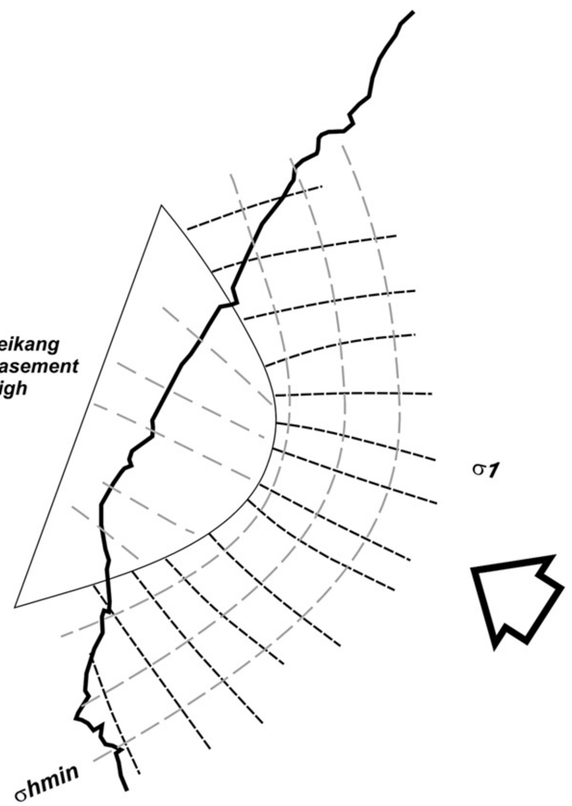


Fig. 10. Stress trajectories obtained close to Peikang High using numerical finite-element model modified after Jeng et al. (1996). Elasto-plastic behaviour for the fold–thrust belt is assumed. A Young's modulus of 60 GPa is considered for both the rigid basement promontory and the WF. The plastic behaviour for the WF is modelled by a Druker–Prager criterion with a yield stress of 240 MPa and an angle of friction of 30°. The interface between the Peikang High and the WF is modelled by a frictional angle of 15°. The discrepancies from the observed trajectories of Fig. 9 may have resulted from the interference with inherited structures such as reactivated normal faults in the Tainan basin.

south of the basement promontories is expected to better fit the stress reconstructions. This study further puts emphasis on the fact that regions with high amounts of stress deviations with respect to the regional transport direction are mainly dominated by thick-skinned deformation styles. By contrast, where the stress deviations are limited, a thin-skinned deformation dominates.

## 6. Discussion

### *6.1. Along-strike variations of structural styles in Western Taiwan and strength of the Chinese continental lithosphere*

This study has shown that structural styles (Figs. 5, 7 and 8) and reconstructed stress trajectories (Fig. 9) may vary rapidly along the strike of the belt depending on the presence of inherited pre-orogenic Paleogene troughs in the Chinese margin (Taihsi and Tainan basins) that are favourably oriented to be reactivated and inverted. These results are well correlated with the depth distribution of earthquakes and active fault mechanisms along the strike of the belt front (Fig. 3).

Subsidence/uplift history in the foreland basin during the Plio-Pleistocene shows important differences from one region to another. For instance, the inherited Taihsi basin in the Miaoli area has been uplifted and inverted during the Pleistocene while to the South, in the Taichung basin, about 2 km of Pleistocene strata were accumulated. This evolution is further attested by subsidence data. In the Coastal Plain of the Chiayi area, the unconformity of the Kanhsialiao turbiditic formation may be related to initiation of compressional deformation at the edges of the onland portion of the Tainan basin 0.5 Ma ago. All these data suggest that the foreland flexural basin has undergone a very different structural development depending on the presence or the absence of inherited Paleogene troughs.

In order to quantify the elastic strength of the Eurasian continental margin (Mouthereau and Petit, 2003) have modelled plate curvature based on a realistic brittle–elastic–ductile rheology and showed that plate rigidity may vary along the strike of the foreland. Such a result is further confirmed through the modelling of plate deflection in the West Taiwan basin (Tensi et al., 2006). From their results and the conclusions of the present study, a good correlation seems to exist between the strength of the Eurasian plate and the observed structural styles. In more detail, in regions of dominant thin-skinned style of deformation such as in the Taichung domain (Fig. 7) the continental margin is slightly stronger. By contrast, where tectonic inversion and basement-involved shortening prevail (Figs. 5 and 8), the continental margin appears slightly weaker. An explanation for the observed variations of the plate strength as a function of the structural styles is that inherited extensional basins act as weak regions within the continental lithosphere. Consequently, as the compressional deformation in the mountain belt is advancing, in-plane orogenic stresses increase within the continental margin promoting inversion of the inherited basins. In those areas, basin inversion relates to the enhancement of decoupling between the crust and mantle thus reducing the integrated strength of the lithosphere. In other areas, e.g., in Taichung area, the continental margin is relatively stronger. This study therefore suggests a strong control by the strength of the Eurasian continental margin on the way the Taiwan mountain belt is being built, a conclusion already drawn by Watts et al. (1995) in the Andes and which may apply to numerous orogens worldwide.

### *6.2. Timing of thin- vs thick-skinned deformation in the Western Foothills of Taiwan*

In section 3, we have discussed the available time constraints on the age of probable inception of basin inversion in Western Taiwan. These age constraints indicate that compressional processes leading to basin inversion in the Coastal Plain, for instance in the Miaoli area, may have occurred less than 1 Ma ago. Some tilted terraces dated ca. 0.5–0.13 Ma in the backlimb of the N–S-trending fold such as the Tiehchenshan anticline (see section 1 of Fig. 5) consistently indicate a recent fold activity. This is further confirmed by growth strata of the Pleistocene Toukoshan formation within small E–W folds, indicating an age of ∼0.5 Ma.

Because ages for large-scale uplift related to basin inversion and ages for timing of individual folds in the fold–thrust belt are similar in the Miaoli area, we suggest that both may be related to the same tectonic process and event. Surface folding and thick-skinned basement shortening, which predominates in this area, have occurred coevally about 0.5 Ma ago. Regarding the age of flexural development in the western basin dated between 12.5 and 7 Ma (Lin et al., 2003; Tensi et al., 2006) as well as the oldest thrust faulting in the fold–thrust belt recognized from tectono-sedimentary analysis (Mouthereau et al., 2001b), at 5 Ma, basement involvement has clearly occurred through in-sequence propagation of deformation. Southward, in the Taichung area, recent morphological analyses across the N–S-trending Changhua thrust have yielded an age ranging between 0.019 and 0.3 Ma (Simoes et al., 2004) consistent with earlier rough ages of 0.5 Ma estimated using tectono-sedimentary analysis (Déramond et al., 1996; Mouthereau et al., 1996). Because the Changhua thrust is clearly related to thin-skinned thrusting (section 3 in Fig. 7), deformation at the belt front has occurred coevally along the strike of the belt independently from the style of deformation involved, either thin- or thick-skinned.

We also stress that the major thrust fault in the WF, the N–S-trending Chelungpu–Sani thrust (Fig. 5) is an out-of-sequence thrust. This is shown by its recent reactivation as a basement thrust during the Chichi earthquake provided that the hypocenter is effectively located in the basement. Along this major thrust we have suggested superimposed thin-skinned and thick-skinned styles of deformation. If our interpretations are correct, it seems that the thrust front propagates preferentially as a thick-skinned structure, where inherited basins are present (i.e. in the Taihsi and Tainan basins) and as a thin-skinned structure, where these are absent (i.e. in the Taichung basin). In more internal zones of the western fold-and-thrust belt where topographic elevations are significant, the deformation involves both thin-skinned and thick-skinned styles. This internal deformation of the thrust wedge occurs by out-of-sequence thrusting (e.g., Chelungpu–Sani thrust) in order to maintain a relative balance between compressional stresses in the crust, arising from the convergence, and the topography.

### *6.3. Amounts of shortening in the Western Foothills and implications of thick-skinned deformation style for collision*

A major implication of the thick-skinned model presented in this paper is that the inferred amounts of shortening are generally lower than those reconstructed based on thin-skinned thrusting models. The estimates of shortening obtained along the strike of the WF are presented in Table 1. These values depend on the size of the portion of the WF considered. A more significant result is the percentage of shortening which roughly ranges between 10% and 35%. With respect to thin-skinned models, our results lead to lower the shortening at the WF by a factor of five. The difficulty to place these amounts of shortening in the framework of the Taiwan mountain building is related to the fact that the contraction taken up by

Table 1
Amounts of shortening and percentage of shortening relative to the length of the present cross-section

| Section | Shortening (km) | Shortening (%) | Sources |
|---|---|---|---|
| 1 | 13 (17) | 20 | Mouthereau et al., 2001a |
| 2 | 8 (10.4) | 8 | This study |
| 3 | 11 (14.3) | 25 | This study |
| 4 | 22 (28.6) | 36 | Mouthereau and Petit, 2003 |
| 5 | 20 (26) | 35 | Mouthereau and Petit, 2003 |
| 6 | 8 (10.4) | 13.5 | This study |
| 7 | 24 (33.6) | 21.5 | Mouthereau et al., 2001b |
| 8 | 11 (14.3) | 14.3 | Mouthereau et al., 2001b |

Results are shown for nine balanced sections across the Western Foothills. Only the updated sections numbered 1–6 are presented in this study. Complementary sections 7–8 and related amounts of shortening have been presented in an earlier study (Mouthereau et al., 2001b). Maximum amounts of crustal shortening and rates including 30% errors are shown in parenthesis.

structures in the Central Range and the Hsuehshan Range is poorly constrained. So these estimates are not, by themselves, representative of the total contractional shortening accommodated across the Eurasian continental margin. However, an additional structural study (Clarck et al., 1993) revealed that the magnitude of the penetrative strain in the Hsuehshan Range is low if compared with that predicted by a thin-skinned critical wedge model (Dahlen and Suppe, 1988; Dahlen and Barr, 1989). This led the authors to interpret the Hsuehshan Range as having resulted from the inversion of inherited Paleogene basin at the latitude of Taichung. Eastward, other recent tectonic studies carried out in the Backbone Range (Yui and Chu, 2000) further suggest that the exhumation process for Eurasian rocks was governed by upward extrusion that characterized the lack of asymmetry (i.e. vergence) in horizontal shortening. Together with the absence of Neogene continental HP-rocks, the limited amount of shortening we found in the Western Foothills is rather in agreement with a thick-skinned collision model (Wu et al., 1997) for which the Chinese continental margin is essentially uplifted along brittle high-angle thrust or strike-slip faults in the Western Foothills and accommodated by ductile (and aseismic) extrusion in the Central Range.

## 7. Conclusions

This paper suggests that the variations of structural style, timing of deformation, amount of shortening and stress patterns that are observed in Western Taiwan can be explained by changes in the strength of the Eurasian continental lithosphere that is controlled by the presence of inherited basins in the Paleogene Chinese continental margin. The key findings can be drawn as followed:

(1)The variations of the structural styles and the reconstructed stress trajectories in the Western Foreland of Taiwan are highly dependent on the presence of inherited pre-orogenic Paleogene troughs in the Chinese margin that are favourably oriented to be reactivated and inverted. Such variations can be correlated with changes in the depth distribution of crustal earthquakes and are consistent with the modelling of the lithospheric strength.

(2) We suggest that the thrust front preferentially propagated by thick-skinned shortening as a response of basin inversion triggered by in-plane orogenic stresses. This occurs where inherited basins are present; otherwise deformation propagates by thin-skinned shortening. In internal parts of the WF, shortening involves both thin-skinned and thick-skinned modes.
(3) A major implication of the dominant thick-skinned deformation in the WF of Taiwan is the reduction of amounts of shortening with regard to earlier thin-skinned models. We estimate Neogene crustal shortening comprised between 10% and 35% in the WF. We point out that existing geological data indicate amounts of penetrative strain in the internal belt that are too low regarding the predictions from a thin-skinned critical wedge model, which may argue in favor of a thick-skinned model for the whole Taiwan belt.

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