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Variations along the strike of the Taiwan thrust belt: Basement control on structural style, wedge geometry, and kinematics

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ABSTRACT

A model of imbricate thrust wedges based on the conceptual model of the critically tapering wedge is discussed and applied to the case of the Taiwan thrust belt. This model takes into account (1) the occurrence of compressional features located far from the foreland of the orogen and (2) the occurrence of deep-crustal decoupling that allows both the regional stress field to be transmitted in the foreland and the basement to be involved in the orogenic wedge. Accordingly, three different belt fronts are considered, a mountain front, a reactivation front, and a deformation front, based on topographic, kinematic, and mechanical criteria, respectively. The reactivation front located at the outermost reactivated extensional structure displays large curvatures in areas where structural inversion occurs. The mountain front is usually distinct from the reactivation front and localizes the emergence of a shallow décollement. Serial geologic sections of the thrust belt provide strong arguments in favor of the superimposition of deep- and shallow-décollement tectonics at the thrust-belt front in agreement with the model proposed. The along-strike structural changes are usually accompanied by changes in tectonic regimes due to local effects such as frontal contraction and lateral movement in response to indentation by the basement highs. The record of orogenic stresses in the Taiwan Strait allows us to define and locate a deformation front west of the Penghu Islands. Our results suggest that single-minded models based solely on the principles of either thin-skinned or thick-skinned tectonics may be unrealistic in the case of the Taiwan thrust belt.

INTRODUCTION

The Taiwan thrust belt has been taken as a key example for what is usually called thin-skinned tectonics (Suppe, 1976; Namson, 1981). The structure of the Western Foothills units of the Taiwan thrust belt has been investigated and described in terms of balanced cross sections based on the geometric principles of fault-related folds (Suppe and Namson, 1979). Analyses of recent structural data, however, argued in favor of basement-involved tectonics for the foreland fold-and-thrust belt (Lee et al., 1993), and new geophysical works defended the thick-skinned model for the whole thrust belt (Ellwood et al., 1996; Wu et al., 1997). Understanding the structure of the Taiwan thrust belt and the kinematic processes prevailing at depth is still an objective to be met.

The first goal of this paper is to decipher the possible in-

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volvement of the basement in the tectonics of the western frontal units. Second, we aim at relocating the thrust-belt front and determining the type of related structures. In addition, we demonstrate that along-strike variations occur in the wedge geometry. To this purpose, we have first investigated the overall structural framework of the foreland basement and established a new basement map of the western foreland. The accurate location of the thrust-belt front was first approached by a consideration of the nature and the geometry of the thrust wedge that is based on morphostructural and basement-topography analyses. These investigations provided further information on the geometry of structures and their relationship with basement-involved tectonics. On the basis of these considerations, serial geologic cross sections of the frontal thrust units have been constructed. Finally, we have carried out a kinematic analysis of thrust emplacement by means of synthetic paleostress reconstruction.

FORELAND THRUST-BELT FRONT: NATURE AND SIGNIFICANCE

Previous work on thrust-belt fronts

The study of thrust belts has been greatly spurred by the development of thin-skinned tectonics theory, especially the fundamental work of Bally et al. (1966) and Dahlstrom (1969), conducted in the Rocky Mountains of North America. These pioneering works largely contributed to the understanding of the structural framework of thrust systems as a whole (Boyer and Elliott, 1982). Furthermore, because of the increase in petroleum investigation, many structural geologists are focused on the frontal zones of thrust belts such as the one in Taiwan (Suppe and Namson, 1979).

Consequently, thrust-belt fronts (or "mountain fronts") have been described by various terminology. Basically, the terms refer to the topographic boundary of the regional foreland-dipping monocline, elevated above its initial structural level, i.e., the foreland of the thrust belt (Vann et al., 1986). This obvious morphologic frontier was regarded as the result of the emplacement of the outermost thrust. A first attempt at classifying the fronts of thrust belts, in terms of thin-skinned tectonics and based on the belts' geometries, has led geologists to distinguish two main types of fronts: (1) buried thrust fronts and (2) emergent thrust fronts. The occurrence of each of these types depends on geometric and mechanical factors, such as the lateral termination of strata suitable for hosting a décollement and/or the presence of a broad area of weakly strained rocks (Morley, 1986).

Significance of front in the critically tapering wedge model

Improvements in the understanding of thrust-belt mechanics have enabled the fold-and-thrust belt to be modeled. According to the thin-skinned tectonics theory, Chapple (1978) put emphasis on the following key assumption: most fold-and-thrust belts exhibit a basal décollement that gently dips toward the interior of the thrust belt. This basal décollement is usually sited at a relatively weak level, for example, within salt or shale units in the sedimentary cover. Above the basal décollement, compressional deformation occurs whereas in the rigid basement below, the deformation remains limited. These hypotheses led Davis et al. (1983) to describe the mechanical behavior of fold-and-thrust belts and accretionary wedges in terms of critically tapering wedges of Coulomb material (Fig. 1A). According to this model, as the critical taper is achieved, the wedge deforms internally by thrust-sheet imbrication.

In order to apply this model to mountain building, Davis et al. (1983) implicitly considered that the toe of the thrust wedge corresponds to the thrust-belt front defined by structural geologists, i.e., the topographic front. However, the thrust-belt front thus determined in the critical-taper theory (Fig. 1A) is in fact an assemblage of three distinct and fundamental boundaries. First, there is a *topographic boundary*, because one of the two parameters characterizing the critical-taper angle (γ) is the surface-slope angle (Fig. 1A). Second, a *kinematic boundary* is easily defined because as the critical taper is attained, sliding occurs along the basal décollement, resulting in the development of a new frontal thrust. Beyond this limit, i.e., at the toe, the propagation of the wedge ceases. Consequently, the front in the simple model of Davis et al. (1983) could also be viewed as a pin line (the nail in Fig. 1A) that marks the position of no movement. Third, a *mechanical boundary* can be defined between the fold-and-thrust belt hinterland (which deforms internally by faulting and folding) and the undeformed foreland domains (where low stress magnitudes prevail). Therefore, according to the critical-taper theory, defining a front in a fold-and-thrust belt must refer to these three different considerations, and three types of fronts are thus possible: a *mountain front*, a *reactivation front*, and a *deformation front*, based on topographic, kinematic, and mechanical criteria, respectively.

Hereafter, we propose an alternative model, based on the critically tapering wedge theory, in which the different fronts are distinguished and the involvement of the basement is considered (Fig. 1B). This model also takes into account the presence of inversion tectonics—usually documented in the forelands of orogens—as well as imbricate thrust wedges (Fig. 1B).

The upper thrust wedge is restricted to the cover ("thin-skinned" tectonics) and corresponds to the classical steady-state thrust wedge (Fig. 1A) considered by Davis et al. (1983). Its equilibrium depends on a critical-taper angle (γ_1 in Fig. 1B), which is controlled by the dip of the shallow décollement in the cover and the topographic slope (see Fig. 2). This thrust wedge develops by propagation of newly formed frontal thrust sheets toward the foreland; its front, the thrust-wedge front (1) in Figure 1B, corresponds to the outermost limit of the allochthonous units and is equivalent to the topographic front (= the mountain front). However, because the deformation is limited to the upper levels, the thin-skinned tectonics cannot ac-

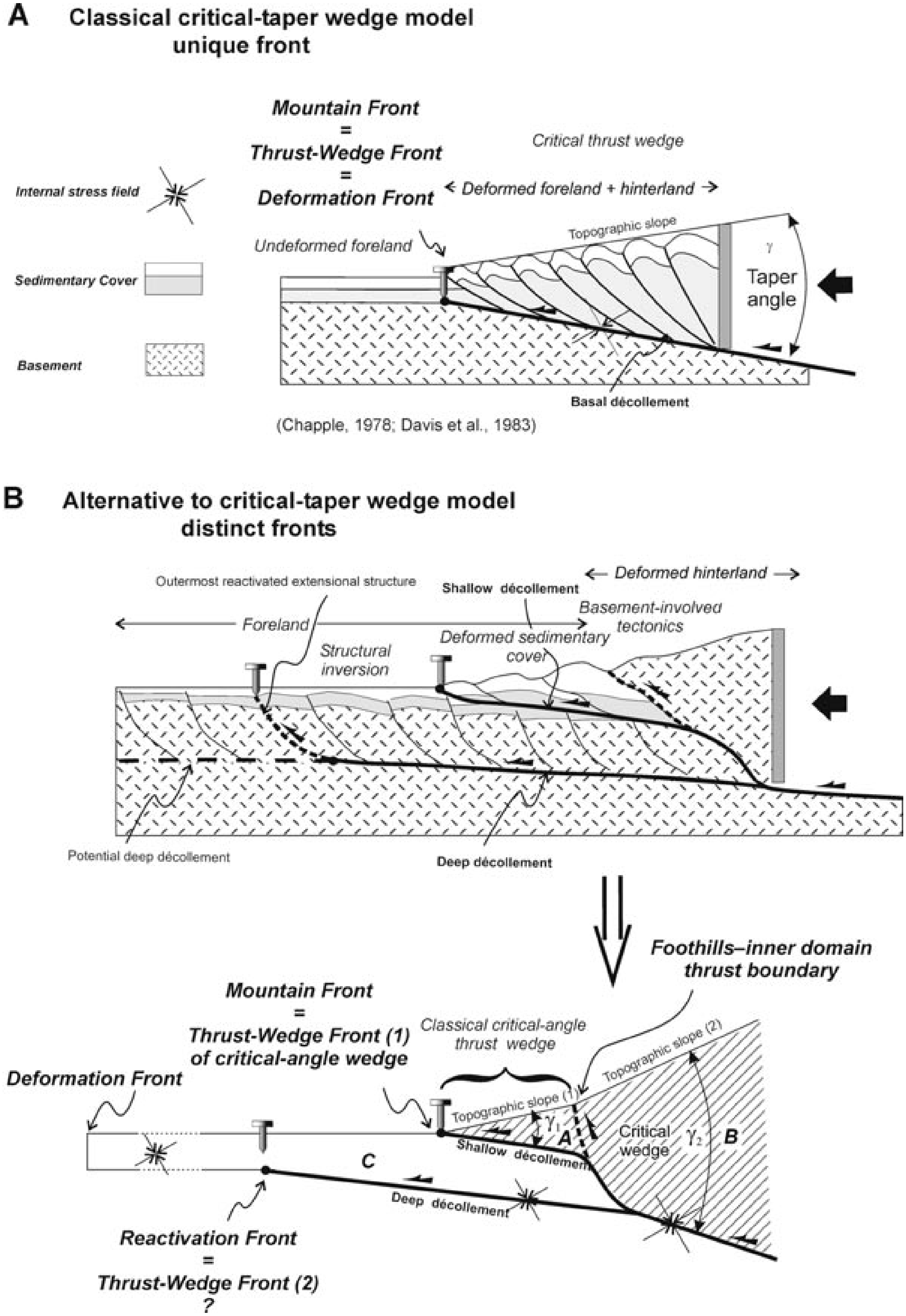

Figure 1. Determination of the different front types of foreland thrust belts on the basis of the décollement tectonics model. (A) Nature of a front in classical critically tapering wedge model after Chapple (1978) and Davis et al. (1983). (B) Alternative to critical-taper model. This alternative considers imbricate thrust wedges bounded by either a shallow décollement (thin-skinned tectonics) or a deep décollement (thick-skinned tectonics) and defines different types of structural fronts: a *mountain front* (the front of the critically tapering wedge), a *reactivation front* (the outermost reactivated preexisting extensional feature), and a *deformation front*. Differentiation of the front types is on the basis of topographic, kinematic, and mechanical criteria. A—shallow thrust wedge, B—inner domain of thrust wedge, C—outer domain of thrust wedge, γ_1—the critical-taper angle controlled by the dip of the shallow décollement, and γ_2—the critical-taper angle controlled by basement structure.

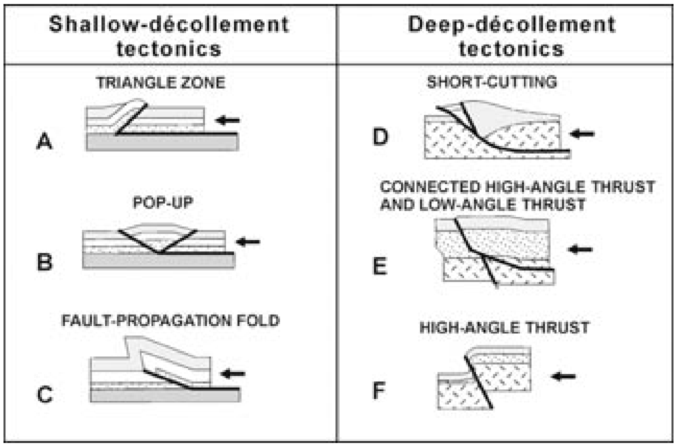

Figure 2. Main fault-related fold structures encountered at the fronts of thrust belts. (Left) Frontal structures associated with shallow-décollement tectonics; newly formed faulting is prominent. (Right) Frontal structures associated with deep-décollement tectonics; reactivation of inherited faults prevails. For details, see text.

count for the propagation of the compressional deformation far in the foreland, even though in particular cases such as the Jura Mountains, the southern Pyrenees foreland, and the Mackenzie Mountains, the occurrence of a widespread and very weak stratigraphic unit that hosts the décollement allows the thrust sheets' propagation to be observed for a significant distance from the mountain front (Vann et al., 1986).

Furthermore, the occurrence of structural inversion over large areas in the forelands of the Pyrenees and the Alps (Roure and Colletta, 1996) as well as the basement-involved tectonics in the inner part of the orogenic wedge in these areas (Roure et al., 1990) led us to consider incorporating a second, deep, basal décollement ("thick-skinned" tectonics) into the alternative to the critically tapering wedge model (Fig. 1B). Above this deep décollement, two domains can be distinguished. The inner domain (B in Fig. 1B) is characterized by a specific critical-taper angle (γ_2 in Fig. 1B) controlled by basement characteristics. As the deep décollement steps up to shallow levels, its leading edge defines the previously mentioned shallow thrust wedge (A in Fig. 1B), which can therefore be regarded as a particular frontal area of a larger critically tapering wedge (hatched area in Fig. 1B) that includes the whole thrust belt (Foothills and inner domain).

In Taiwan, to the west of the mountain front, i.e., to the west of thrust-wedge front 1 in the outer domain (C in Fig. 1B), many preexisting foreland extensional structures (provided that they had appropriate orientation with respect to the transmitted tectonic stresses) have been reactivated or inverted, resulting in the development of inverted basins. A reactivation front can thus be considered for the Taiwan example; this front corresponds to the outermost reactivated extensional structure. It marks the boundary of the activated part of the deep décollement, i.e., the position of no movement (the second outer nail in Fig. 1B). According to this definition, this reactivation front is the external boundary beyond which stresses are not sufficient to create newly formed compressional structures such as folds and faults identifiable at a regional scale. Note that the low-slope and low-strength domain (i.e., the outer domain, C in Fig. 1B) that is subject to orogenic stresses and in which structural inversion occurs above a deep basal décollement also constitutes a thrust wedge limited by the reactivation front (= thrust-wedge front 2 in Fig. 1B). However, as it is not (not yet) at steady state, it therefore cannot be discussed in terms of a critically tapering wedge in the sense of Davis et al. (1983).

Abundant microtectonics studies based on fault-slip data or calcite-twin data (e.g., Letouzey, 1986; Bergerat, 1987; Craddock et al., 1993), as well as additional numerical modeling (Sassi and Faure, 1997), have extensively demonstrated the existence of far-field stresses in the foreland of orogens. In the case of the western foreland of the Taiwan orogen, present-day stress measurements based on borehole breakouts (Suppe et al., 1985) and paleostress reconstructions based on brittle microstructure analysis (Angelier et al., 1990) have revealed that offshore areas far from the mountainous regions have recorded the orogenic stresses responsible for the formation of the orogen. Therefore, a deformation front can be located farther to the west, at least as far west as the vicinity of the Penghu Islands (see Fig. 3). The record of compressional stress regimes in foreland basins does not systematically imply that such areas should be included in the thrust wedge as claimed by some authors (Craddock et al., 1993). In fact, as previously mentioned, the recognition of a thrust wedge is principally related to the occurrence of a basal décollement and not to the sole presence of far-field compression.

Ahead of the thrust-wedge front where the activity of the basal deep décollement has stopped, the part of the foreland subject to an intraplate regional-scale stress field could be viewed as a continually stable province (Fig. 1B). The deformation front could be situated far away from the first orogenic relief: for instance, orogenic stresses have been recorded by microstructures as far as 1700 km away from the Appalachian-Ouachita orogenic belt (Craddock et al., 1993) or more than 700 km away from the Pyrenees (Lacombe et al., 1996). These findings suggest that the "deformation front" can always be defined and that it is obviously distinct from the mountain front and reactivation front (Fig. 1B). The location of the deformation front depends on the spatial attenuation rate of the stress and strain magnitudes. In fact, the maximum horizontal magnitude decreases gradually from the interior of the propagating foreland thrust belt to the stable foreland (Lacombe et al., 1996). Hence, because of the strain release, the stress regimes evolve from compressional to strike-slip, and then to extensional regimes (Letouzey, 1986; Sassi and Faure, 1997). Because this change is in many cases progressive, defining a "deformation front" requires consideration of some arbitrary limit in the amount of deformation.

Summarizing, one is led to define and distinguish three

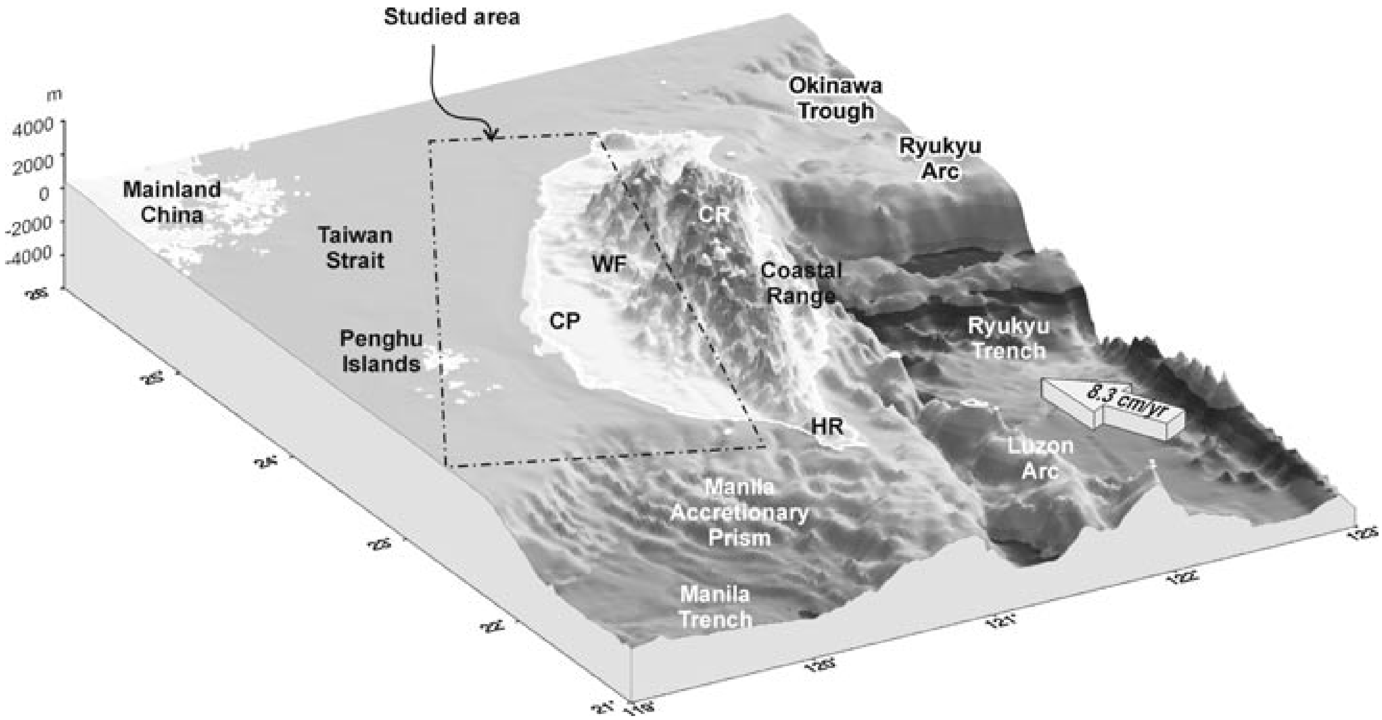

Figure 3. Block diagram of the Taiwan thrust belt in the context of Arc-continent collision. Abbreviations: CP—the Coastal Plain, the WF—the Western Foothills, CR—the Central Range, HR—the Hengchun Ridge.

fronts (Fig. 1B): the mountain front (the front of the critically tapering wedge), the reactivation front (the outermost reactivated preexisting extensional feature), and the deformation front. These fronts are based on topographic, kinematic, and mechanical criteria, respectively.

TYPES OF FAULT-RELATED FOLDS AT THRUST-BELT FRONTS

Hereafter, we focus on the style of compressional structures encountered at the front of thrust belts with regard to the depth of the basal décollement. Numerous studies in thrust belts have demonstrated that deformation of thrust sheets may reveal major complexities, especially in areas where basement-involved tectonics becomes a significant process in mountain building, such as in the Andes (Winslow, 1981) or in the Rocky Mountains (Dechesne and Mountjoy, 1992). This view has been documented by many authors who have pointed out that preexisting extensional basins were incorporated into thrust belts by structural inversion in which the slip on inherited faults has been reversed from normal to thrust movement, such as in the Canadian Cordillera (McClay et al., 1989) or the Pyrenees (Berastegui et al., 1990). Furthermore, basement-involved tectonics has also been described at the front of a thrust wedge, for instance in the Andes (Zapata and Allmendinger, 1996; Colletta et al., 1997). At the scale of the Taiwan thrust belt, new geophysical evidence, such as gravity anomalies (Ellwood et al., 1996) and seismic tomographic data (Wu et al., 1997), has recently led to discussion of the orogen in terms of basement-involved tectonics. This raised some questions about the mechanics of the orogen. In this paper, we intend to provide confirmation that both thin- and thick-skinned tectonic mechanisms are likely to have contributed to the development of the wedge in both the interior and the frontal zone of the Taiwan thrust belt.

We next focus our structural analyses on a limited area in the vicinity of topographic front. Furthermore, to prevent misunderstanding about the type of tectonic style involved, we chose to refer only to the depth of the basal décollement involved in the deformation under discussion. Consequently, we use the terms “shallow-décollement tectonics” and “deep-décollement tectonics” instead of the terms “thin-skinned tectonics” and “thick-skinned tectonics.”

The generic model of a thrust wedge (Fig. 1B) is based on topographic (geometric), kinematic, and mechanical assumptions, but it does not predict the structural styles inside the wedge or at the thrust-belt front. Nevertheless, the type of thrust-related structures in the mountain belt can be divided into two main classes depending on the depth of the décollement (Fig. 2).

Shallow-décollement tectonics

Three main types of frontal structures may usually be identified within the framework of shallow-décollement tectonics.

First, triangle zones (Fig. 2A) are likely to be in a frontal position in most fold-and-thrust belts, mainly because such structures require the presence of mechanically weak units (Cousens and Wiltschko, 1996). Second, pop-up structures that develop above a flat décollement distinguished by low friction (Huiqi et al., 1992) are typically found in accretionary prisms where high pore pressure prevails (Fig. 2B). Note that pop-up structures and triangle zones are frequently associated with buried thrust fronts characterized by a broad zone of low strain (type 1 front of Morley, 1986). Third, fault-propagation folds (Fig. 2C) are common at thrust-belt fronts because in such structures, the foreland-directed displacement is compensated at the tip of the thrust by folding (Suppe and Medwedeff, 1990). These remarkable structures are related to the thrust-wedge front by localizing the basal décollement emergence. Because they are usually subject to significant erosion, they sometimes correspond to a smooth topography in the onshore foreland.

Deep-décollement tectonics

As previously mentioned, reactivation and/or inversion of preexisting extensional structures may be a prominent deformation process in the frontal part of orogen. We distinguish herein three main geometries for frontal thrusts affected by a deep décollement. First, basement shortcutting (Fig. 2D) can generate low-angle thrust faults at the hinge fault of an inverted basin. This geometry has been encountered in nature and reproduced in analogue models (McClay, 1992; Letouzey et al., 1995). A fault-propagation fold and an ancient normal fault could interact, because the décollement zone, necessary for the deformation to propagate, is abruptly terminated (Morley, 1986). Similarly, the nucleation of a high-angle thrust at the upper part of a reactivated normal fault could be expected, as pointed out by Suppe (1986) in northern Taiwan (Fig. 2E). Basement involvement in passive roof thrusting has been also suggested as an alternative model for frontal triangle zones and was described in the Andean front of western Venezuela (Colletta et al., 1997). High-angle thrusting (Fig. 2F), resulting from the simple reactivation of planar normal faults (Cooper and Williams, 1989; Mitra and Islam, 1994) could also be a relevant expression of inversion tectonics in the foreland of thrust belts. Most of these structures have been described and defined in inverted basins (C [the outer domain] in Fig. 1B), where the deformation occurs along a steeply dipping fault characterized by a limited amount of reverse displacement; therefore this geometry does not contribute to significant topographic elevation. However, we can expect to find some of these structures in the vicinity of or associated with the topographic front. Deciphering the particular structural patterns in the front of the Taiwan fold-and-thrust belt will enable us to determine whether shallow-décollement or deep-décollement tectonics is involved at the front of the propagating thrust wedge.

A CASE STUDY: THE WESTERN FOOTHILLS OF THE TAIWAN THRUST BELT

The tectonically active Taiwan mountains are a Neogene thrust belt resulting from the oblique collision between the Philippine Sea plate and the Eurasian plate (Fig. 3). According to the NUVEL-1 model of relative plate motion (De Mets et al., 1990), the present-day convergence of the Philippine Sea plate relative to Eurasia occurs in a N50°W direction at a velocity of ~7 cm/yr (Seno et al., 1993). Results from the Taiwan GPS (Global Positioning System) network surveys, on the other hand, favor a greater velocity, 8.3 cm/yr (Yu et al., 1997). This higher velocity is probably more realistic, because the value of 7 cm/yr neglected the relative motion of the South China block with respect to Eurasia.

In the Taiwan mountains, the initiation of a collision-type tectonic setting has been dated by the beginning of the flexural subsidence in the early Pliocene (Chang and Chi, 1983). The evolution of the collision belt postdated the Oligocene–Miocene continental rifting and spreading associated with the opening of the South China Sea (Ho, 1986). The Taiwan orogen is divided into several tectono-stratigraphic belts, striking N10°–20°E. To the east, the Coastal Range (Fig. 3), mainly composed of Neogene volcanic rocks interbedded with intra-arc Pliocene basin deposits (Huang et al., 1995), is the northern extension of the Luzon arc. It acts as a buttress for the overall thrust belt. Farther west, the rocks exposed in the Central Range belong to either of two metamorphic belts (Tananao Schist, Backbone Range) or a slate belt (Hsuehshan Range). The Central Range results from the exhumation and emplacement of a complex assemblage of ancient sedimentary basins, volcanic deposits, and oceanic materials (Ho, 1986; Teng, 1990). The Western Foothills of Taiwan (Fig. 3) are a typical foreland fold-and-thrust belt, involving east-dipping imbricate sheets being thrust onto the Chinese continental margin.

In detail, the thrust sheets of the Western Foothills are composed of pretectonic Miocene shelf deposits of the Chinese platform secondarily incorporated into the thrust wedge and currently exposed above major thrusts. In addition, Pliocene–Pleistocene synorogenic sediments derived from the erosion of inner domains were deposited and incorporated into the propagating thrust units. To the west, the Coastal Plain consists of alluvial deposits in which compressional structures are nearly insignificant. Offshore southern Taiwan, the Manila accretionary prism is the result of subduction of the South China Sea beneath the Luzon arc.

Since the Pliocene, the emplacement of the thrust belt occurred under an average west-northwest–east-southeast compression deflected to the north in northern areas and to the south in southern ones so that a fan-shaped distribution of trajectories results (Angelier et al., 1986). The recent and present-day stress field interpreted from in situ measurements of borehole breakouts (Suppe et al., 1985), inversion of earthquake focal mechanisms (Yeh et al., 1991), and Holocene faults is also dominated by west-northwest–east-southeast compression, consistent with the present-day direction of convergence.

BASEMENT GEOMETRY IN FRONT OF THE TAIWAN THRUST BELT

Tertiary basins of western Taiwan

The foreland of the Taiwan thrust belt, i.e., the Chinese platform and the Taiwan Coastal Plain, displays numerous Tertiary basins. Two categories of Tertiary basins, mostly Paleogene and Neogene in age, are distinguished on the basis of a widespread early Miocene unconformity (Sun, 1982). First, the lithosphere was stretched in response to the opening of the South China Sea during the Oligocene to the early Miocene. The resulting early Paleogene extensional basins trend northeast and are filled with shelf sediments, tuffs, and lava flows revealing the volcanic activity at this time. Extensional tectonism continued to the early Neogene, but changes of stretching directions occurred with time as revealed by the geodynamic reconstructions and microtectonics data (e.g., Angelier et al., 1990). This period of rifting resulted in the development of a series of northeast-trending horsts and grabens, overprinting the Paleogene basins. The Taiwan orogen developed mainly since 5 Ma, which is the time of the beginning of the flexural subsidence in the foreland (Chang and Chi, 1983). The resulting foredeep basins are superimposed onto the precollisional basins and strike N10°–20°E, nearly perpendicular to the direction of convergence. These basins migrated toward the outer part of the belt and were progressively filled in with synorogenic deposits.

Basement structural framework

Before investigating the subsurface structures of the foreland and discussing the involvement of basement rocks in the compressional deformation, the age, composition, and stratigraphic significance of the so-called "basement" deserve discussion.

First, in the foreland, the major part of the collision-related deposits unconformably overlie the pre-Neogene rocks. This unconformity can be regarded as reflecting a major stratigraphic boundary separating the part of the cover made of synorogenic deposits from the underlying preorogenic rocks. The preorogenic rocks were displaced by normal faulting related to the earlier episodes of extension along the Chinese margin; these rocks behaved in concert with the deeper crust during the subsequent orogenic contraction.

Second, for the Taiwanese petroleum geologists, this unconformity, i.e., the top of the pre-Neogene rocks, is a good seismic reflector that separates the upper sedimentary cover from the acoustic (or seismic) basement (Hsiao, 1974). In the literature, the pre-Neogene rocks have therefore been extensively referred to as the "basement" of the overlying sedimentary cover.

Third, the corresponding pre-Neogene rocks have been drilled in a few places in the vicinity of the Peikang Plain and beneath the Penghu Islands at an average depth of 1000 m (Chiu, 1973). They are Eocene to Cretaceous to Eocene in age and are mainly composed of arkoses and arkosic sandstones; locally some mineral assemblages point to contact metamorphism due to plutonic intrusion (Chiu, 1973). Consequently, even if the pre-Neogene rocks could not strictly be considered as a true crystalline basement, their lithology is nevertheless at least partially crystalline. Therefore, the bottom of the Miocene section can be regarded as a good proxy for the top of the true basement.

In summary, the pre-Neogene rocks might be regarded (1) as an orogenic basement in the sense of tectonic cycles, (2) as an acoustic basement according to the definition of geophysicists, and (3) at least as the lower part of the cover attached to the crystalline basement. Consequently, hereafter, we call "basement" all the pre-Neogene and especially the pre-Miocene undifferentiated rocks.

We have produced a contour map of the pre-Miocene rocks (Fig. 4) based on data collected in the literature for 70 onshore and offshore wells (Chou, 1971; Chou, 1980; Shaw, 1996). This map differs significantly from the previous ones in that it covers the whole frontal part of the foreland thrust belt and the southwestern structural domains. We especially consider the basins and highs, both onshore (Coastal Plain) and offshore (Taiwan Strait). Recognizing basement highs in the frontal Western Foothills will provide indirect evidence for basement-involved tectonics at the belt front.

The basement map clearly highlights the occurrence of two major intrabasinal highs underlying the Taiwan Strait and the Coastal Plain: the offshore Kuanyin high to the north and the partly onshore Peikang high in central-western Taiwan (Fig. 4). In order to characterize the basement topography beneath the foreland and the location of Tertiary basins, we have constructed a longitudinal stratigraphic profile (Fig. 5) based on the available wells drilled in the Coastal Plain and the outer part of the Western Foothills. In this profile, we focus on the stratigraphic characteristics of each province that are relevant in the study of the thrust-belt front. Consequently, we have constructed this profile to fit with the relevant wells rather than considering the orientation of the normal faults that define the basins. In this profile, along-strike variations of basement depth and thicknesses of Neogene deposits are clearly emphasized (Fig. 5). Hence, five different basins could be determined according to their ages and structural frameworks.

The location of the different Neogene basins is likely to be dependent on the occurrence of a basement uplift in the frontal part of the foreland thrust belt (Figs. 4 and 5). The transitions between highs and basins are marked by major boundary faults (labeled in Fig. 5) that are sites of abrupt longitudinal changes in the topography of Neogene and pre-Miocene rocks. These

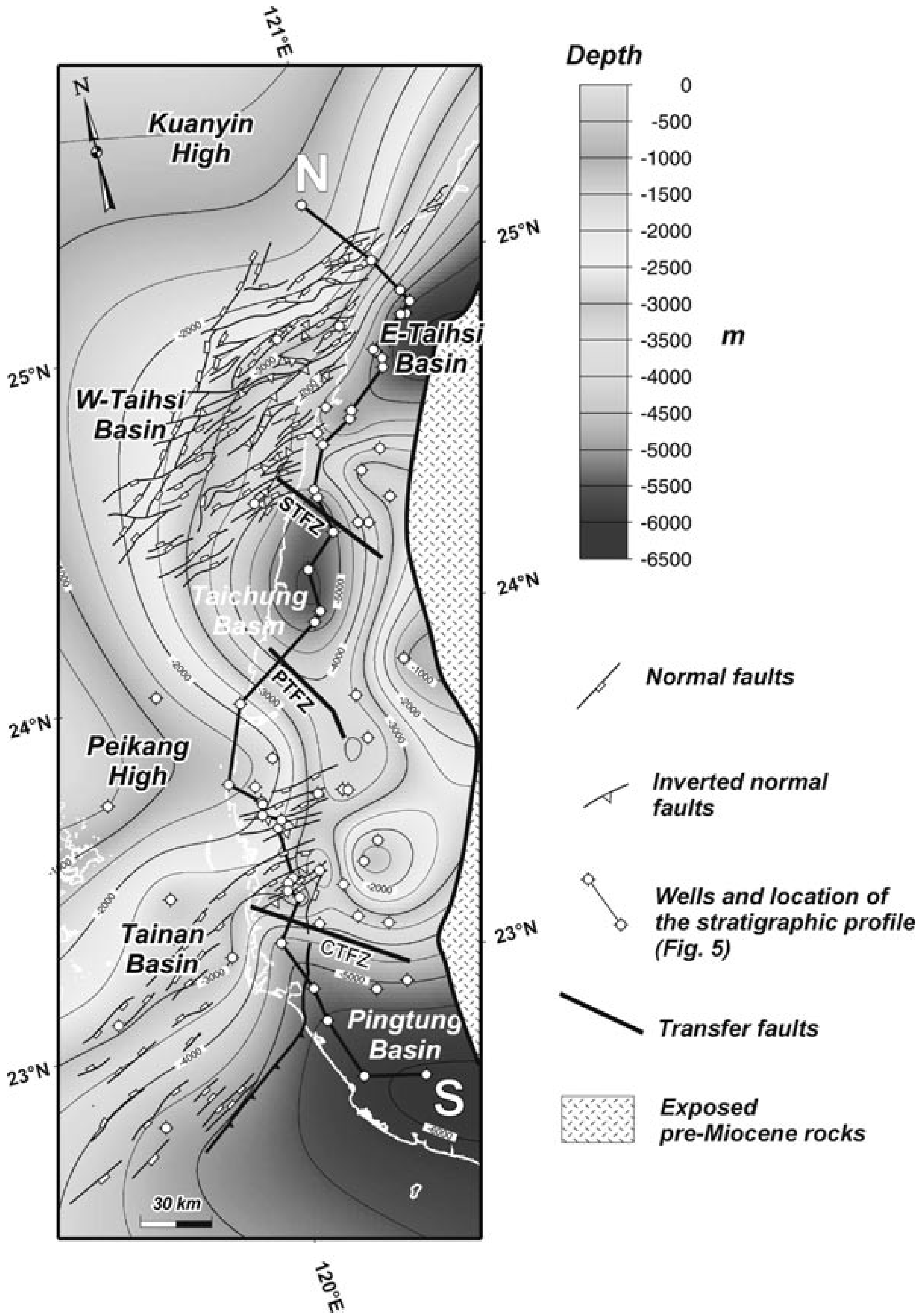

Figure 4. Contoured map of pre-Miocene rocks ("basement") and the structural framework of the Taiwan mountain-belt front. Contour interval is 500 m. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

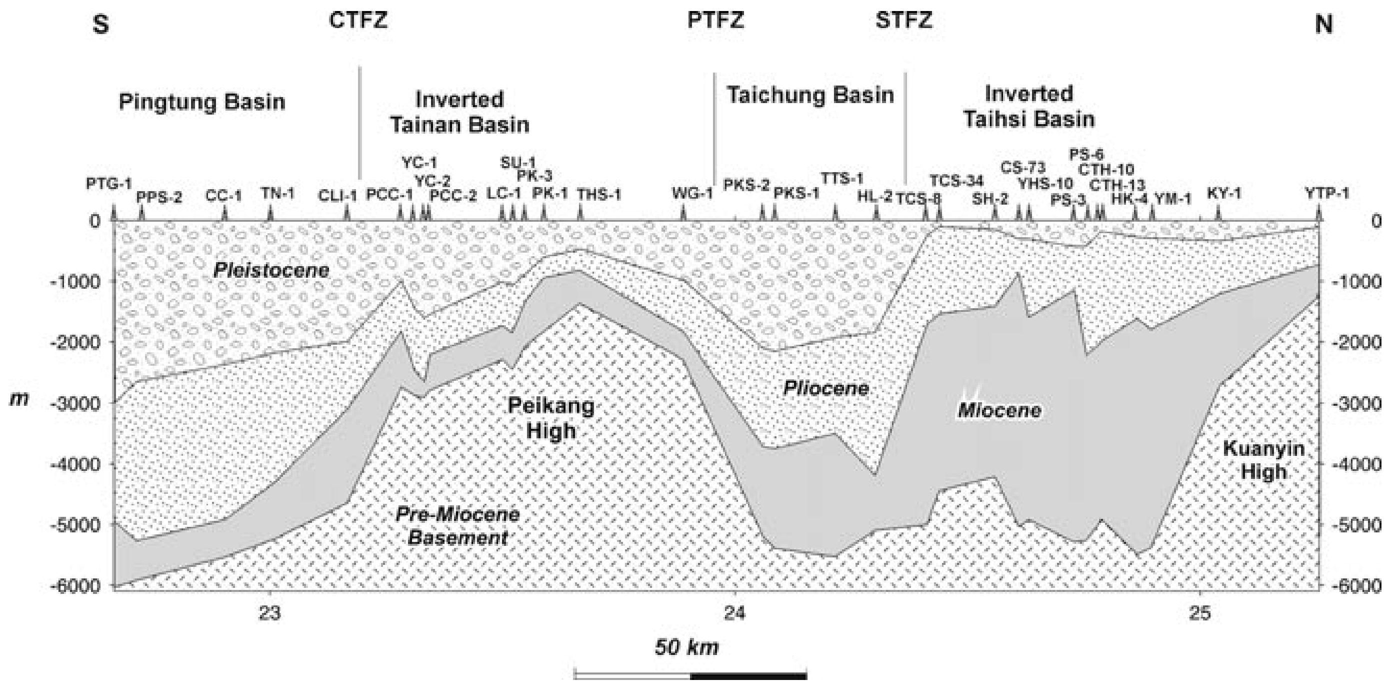

Figure 5. Along-strike stratigraphic profile of the foreland showing the location of basins and highs. Inverted basins are located on the southern edges of the major highs such as (1) the western Taihsi Basin and the Kuanyin high and (2) the Tainan basin and the Peikang high. The major oblique transfer-fault zones delineate the different parts of the foreland. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

major steps in the topography of the pre-Miocene basement are enhanced by the occurrence of major north-northwest–trending transfer faults oblique to the profile (Fig. 5). These faults have been recognized in the cover as major transfer-fault zones on the basis of morphologic analyses and distribution of earthquakes (Deffontaines et al., 1997).

We begin investigating the basement structural framework by distinguishing the precollisional Taihsi and Tainan Basins, which are both located on the southern edge of the main structural highs (Figs. 4 and 5). As revealed by Figure 5, the Taihsi Basin corresponds to the northern Miocene depocenter. Both the pre-Miocene basement of the Taihsi Basin and the entire overlying Neogene sedimentary cover have been uplifted (Fig. 5). The seismic studies of the geologists of the Chinese Petroleum Corporation have extensively demonstrated that the northern Taihsi Basin is an inverted basin (Huang et al., 1993; Shen et al., 1996) in which the pre-Neogene rocks have been offset by numerous high-angle reverse faults with a strike-slip component (Fig. 4). According to the basement map, the Taihsi Basin can be divided into a western inverted basin and an eastern noninverted basin (close to Hsinchu) where the pre-Miocene basement has probably not undergone uplift but rather lateral extrusion accommodated by strike-slip faulting, an important mechanism in this northern region (Lu et al., 1995). Inversion tectonics in northern Taiwan prevails from the southwestern edge of the Kuanyin high area to a basement transfer fault located south of Miaoli (Deffontaines et al., 1997); the Sanyi transfer-fault zone (Fig. 4). Moreover, in the eastern part of the Tainan Basin along the profile shown in Figure 5 (Chang et al., 1983), inversion tectonics have also been demonstrated by the presence of reactivated inherited extensional features and inverted the slip direction on originally normal-slip faults that offset both the Neogene sedimentary cover and the pre-Miocene basement in the southern flank of the Peikang High (Fig. 4). Most of the inverted structural features encountered in the foreland of the Taiwan orogen are represented by high-angle reverse faults that offset the pre-Neogene rocks but die out into the basement. The Neogene Taichung and Pingtung Basins show important foredeep subsidence as suggested by the thick series of syntectonic deposits of continental origin (Fig. 5). The development of these basins appears to have been controlled by the two major oblique transfer faults located north and south of the Peikang high, the Pakua transfer-fault zone and the Chishan transfer-fault zone, respectively (Fig. 4 and 5). The northern one is an ancient normal fault that locally controlled the propagation and geometry of frontal thrust sheets (Mouthereau et al., 1999). Evidence of basement uplift east of the Taichung Basin in inner domains of the Western Foothills is suggested in Figure 4.

In summary, major extensional Tertiary basins located beneath the Coastal Plain and offshore have undergone inversion tectonics during the Pliocene–Pleistocene collision. As evidenced by the reactivation of pre-Neogene normal faults and inversion of their sense of motion, the basement is likely to be affected by the inversion. Moreover, the basement-involved tectonics was also controlled by the reactivation of ancient transform faults that have acted as oblique transfer faults during the contractional episode.

LOCATION OF TAIWAN THRUST-WEDGE FRONT, WEDGE GEOMETRY, AND RELATIONSHIP WITH BASEMENT-INVOLVED TECTONICS

Remote-sensing and morphologic analyses have been successfully applied to the Taiwan mountains (Deffontaines et al., 1994; Lee, 1994). In this section, we mainly aim at locating the different fronts by a method based on the previous discussion on the depth of décollement involved and the resulting thrust-wedge geometry. In order to obtain new constraints on the frontal structure and topography, we performed a morphostructural analysis in the outermost part of the Western Foothills and the Coastal Plain. This study includes the use of (Satellite Pour l'Observation de la Terre) SPOT-Panchromatic scenes (10 × 10 m ground resolution) as well as the onshore hill-shading Digital Elevation Model (DEM) of Taiwan (40 × 40 m ground resolution) performed by Taiwanese colleagues. Both these complementary methods have enabled us to recognize small-scale structures and detect small variations in topography. This study was combined with structural information provided by available geologic maps (Chinese Petroleum Corporation, 1974) and complementary field observations and measurements. For offshore investigations, we referred to the published results of the Chinese Petroleum Corporation (Huang et al., 1993).

These combined morphological and structural analyses demonstrate the occurrence of major transfer-fault zones in the Western Foothills (Deffontaines et al., 1997). These transfer faults delineate several structural areas of distinct morphology and thrust-sheet geometry. Therefore, in this study, we distinguish five morphostructurally based regions in the thrust-wedge front from south to north: Tainan (region 1), Chiayi (region 2), Taichung (region 3), Miaoli (region 4), and Hsinchu (region 5). All are named according to the main cities in the region (Fig. 6). From the DEM data, we constructed five topographic sections across the Western Foothills and the Coastal Plain, perpendicular to the direction of the main relief (Fig. 6). Each topographic section is compared with a section of the basement top, which has been calculated from the contoured map (Fig. 4). This indirect method provides constraints and gives a good estimate of the geometry of the thrust wedge, in accordance with the model presented in Figure 1B that allows one to predict whether the basement is involved in the compressional deformation of the considered frontal areas. Our results are summarized in a general structural sketch map of the Western Foothills of Taiwan (Fig. 7).

Tainan area (region 1)

This province is located between the offshore Manila accretionary prism and the Chishan transfer-fault zone (Fig. 6). Preliminary photogeologic studies (Sun, 1964) and analyses of a recent DEM reveal that the frontal fold-and-thrust systems propagate away from the mountainous areas of the Central Range far to the west into the Coastal Plain (Fig. 6). The observation of continuous deformation in the Coastal Plain associated with the low-angle topographic slope and the low-angle, hinterland-dipping, basement-surface slope defines a wedge shape of the sedimentary cover. This result suggests that, instead of deep-décollement tectonics, shallow-décollement tectonics occurs and involves the sedimentary cover (Fig. 6). Locally, in the vicinity of the city of Tainan, the occurrence of a pop-up structure, which is usually found above shallow décollements (Fig. 2), seems to support this conclusion. Consequently, we define a thrust wedge with a low taper angle (Fig. 6), probably consistent with a low-strength area. This interpretation is in agreement with the occurrence of thick series of Pliocene–Pleistocene mudstones in this area, which by definition are characterized by low internal friction. Finally, these results confirm that the basement is not involved in the frontal deformation and that the basal décollement of the thrust wedge is presumably shallow and located above the pre-Miocene basement ("thin-skinned tectonics") in the sedimentary cover.

In summary, the Tainan area exhibits a prominent shallow-décollement tectonics. On the basis of the theoretical model proposed in Figure 1B, the deep basal décollement may be absent or poorly active. In this case, a reactivation front could not be defined whereas a mountain front is observed (Fig. 7).

Chiayi area (region 2)

This region extends from the Chishan transfer-fault zone to the north of the city of Chiayi (Fig. 6). In this region, the frontal thrust sheets exhibit various structural trends ranging from N20°E in the Western Foothills to N60°–70°E in the Coastal Plain (Fig. 7). Furthermore, numerous folds were identified farther west in the Coastal Plain through the use of photogeologic studies (Sun, 1965). Subsurface data (Chang et al., 1983) suggest that the main explanation for the changes in structural trends of frontal units and the occurrence of compressional deformation in the Coastal Plain is the reactivation and/or inversion of N60°–70°E-directed preexisting extensional features belonging to the Tainan Basin. In Figure 6, the topographic section indicates an abrupt increase of the average surface slope with regard to the southern topographic section of the Tainan area. This along-strike topographic change is correlated at depth with the uplift of the basement (Fig. 6). This result suggests the deepening of the basal décollement toward the interior of the belt and thus argues in favor of the internal thickening of the tectonic wedge by basement involvement. Moreover, the presence of inverted structures in the foreland

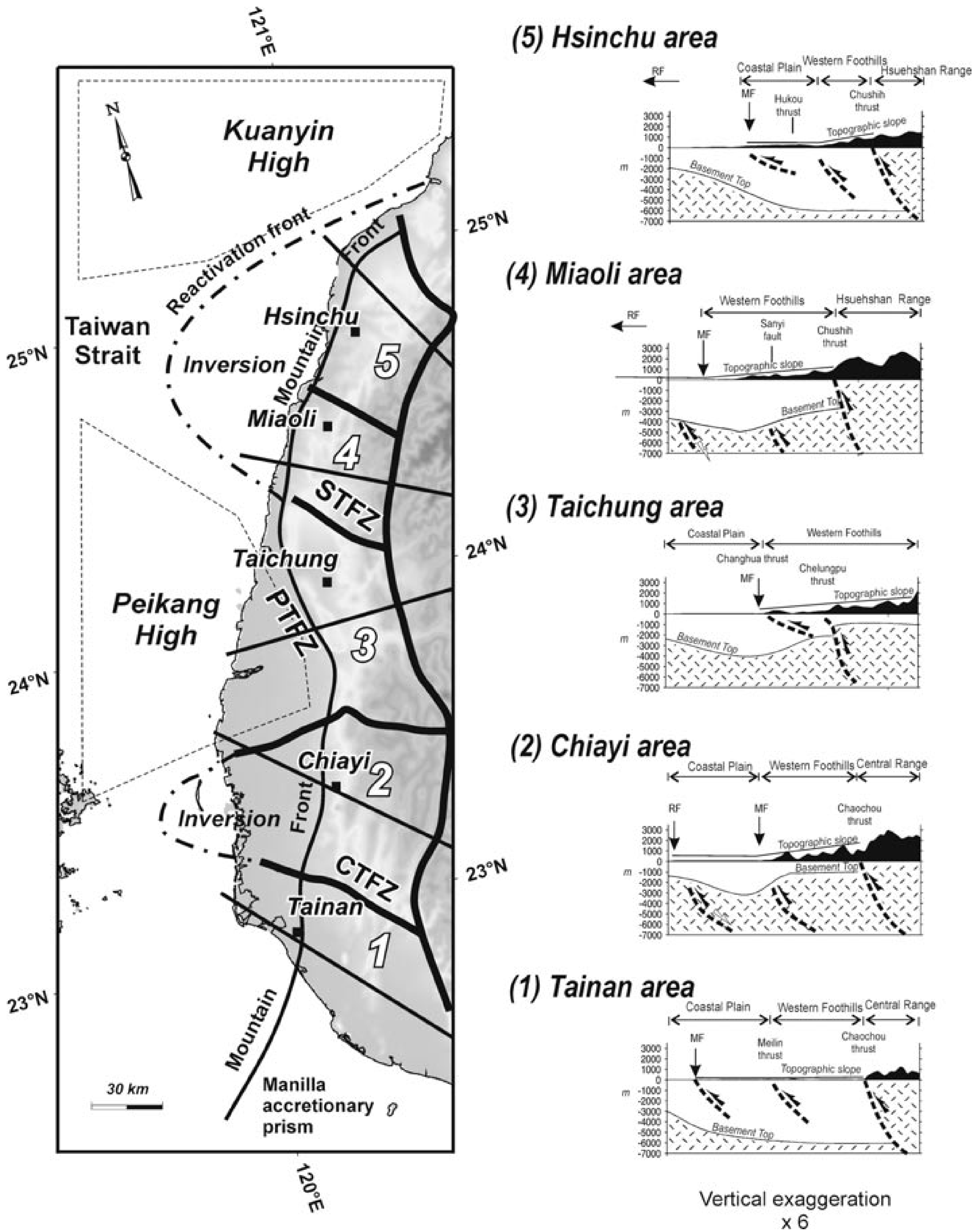

Figure 6. Superimposed profiles of the surface topography and basement top for the five morphostructurally based regions investigated in the Western Foothills. The locations of the mountain front (MF) and reactivation front (RF) are on the basis of considerations developed in the model presented in Figure 1B. Lateral changes in the topographic elevation in the Western Foothills are generally well correlated with basement highs; therefore these sections provide indirect information on the wedge geometry and whether the basement is involved in the frontal tectonics. The thick dashed lines correspond to the major thrusts and inferred frontal thrusts. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

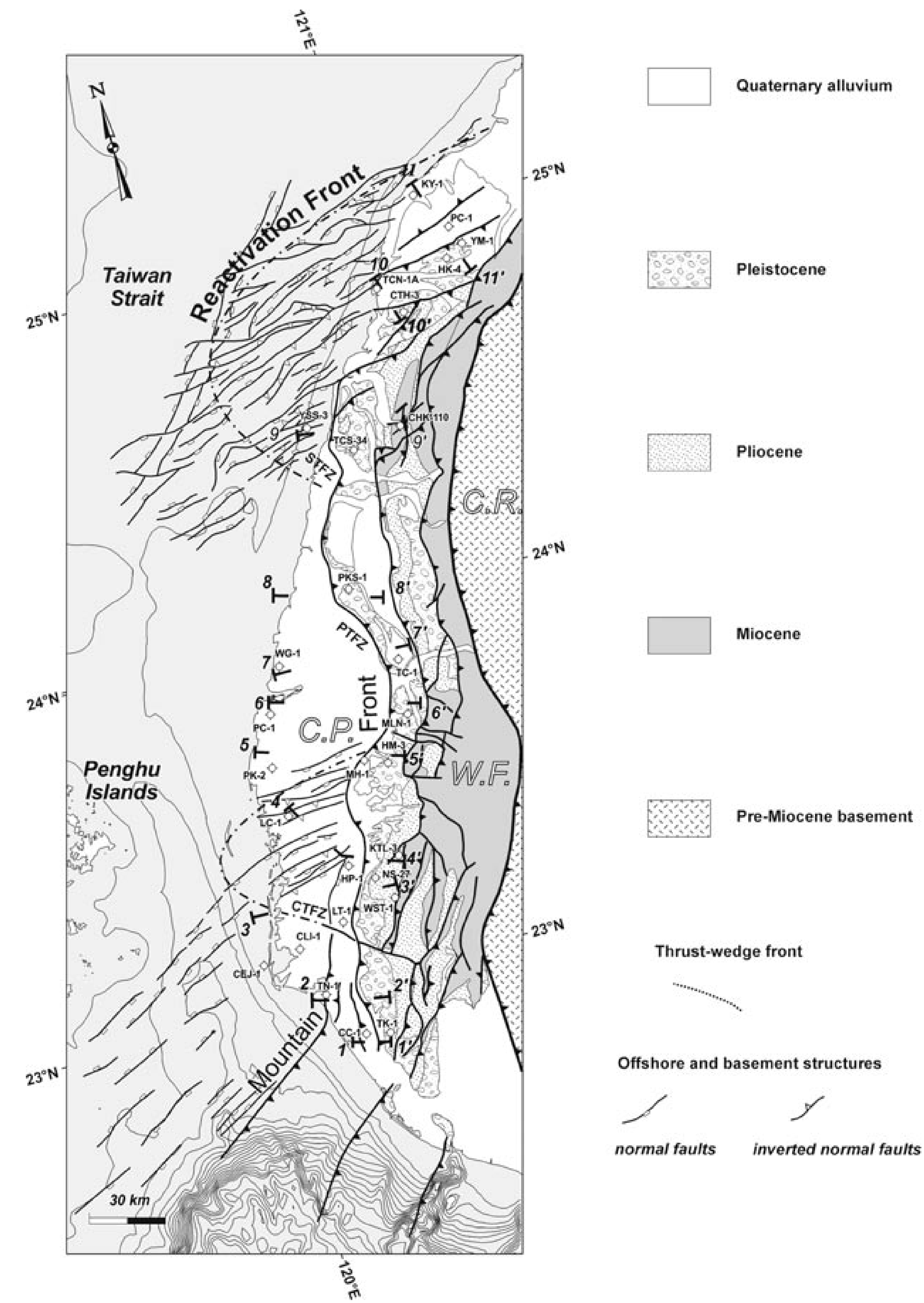

Figure 7. Structural sketch map of the Western Foothills and offshore Taiwan. The Taiwan reactivation front (dash-dot lines) curves between the basement highs and the domains where structural inversion dominates. Numbers give the locations of 11 serial geologic sections shown in Figures 8 to 12. CP—Coastal Plain, CR—Central Range, WF—Western Foothills. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

reveals (Fig. 6) that the thrust wedge has propagated westward through the Coastal Plain in favor of the activation of a deep décollement. East of the Chukou-Lunhou thrust, the thrust wedge is characterized by a significant topographic slope, and the major part of the deformation is accommodated by basement involvement that occurs above a deep décollement (Fig. 6). West of this major thrust, the thrust wedge incorporates the inverted Tainan Basin. Consequently, according to the model presented in Figure 1B, imbricate wedges controlled by a deep décollement and limited by a mountain front and a reactivation front must be considered.

In summary, the propagation of the tectonic wedge probably occurs over a deep décollement. We propose to enlarge the thrust wedge through the Coastal Plain and relocate a reactivation front that corresponds to the outermost reactivated extensional structure 20–30 km away from the mountainous areas, which are limited by the Chukou-Lunhou fault (Fig. 7). Furthermore, we notice that, according to these data, a shallow thrust wedge cannot be defined.

Taichung area (region 3)

The central part of the frontal Western Foothills in the vicinity of Taichung is outlined by a remarkable regional-scale curvature (Figs. 6 and 7). In this area, the bending of the thrust-belt front has been interpreted as the result of the activity of a major transverse fold, the Pakua transfer-fault zone (Deffontaines et al., 1997). The analysis of the DEM failed to show any compressional structures west of this transverse fold. This result shows that the thrust-wedge propagation is stopped in the vicinity of the Pakua transfer-fault zone, which thus localizes the mountain front. The occurrence of such oblique structure is due to the basement control, by an oblique inherited normal fault, on the geometry and kinematics of a frontal shallow décollement and associated frontal deformation and thrust emplacement (Mouthereau et al., 1999). The first evidence of basement involvement in the thrust wedge occurs backward in the vicinity of the Chelungpu-Sanyi thrust (Fig. 6). However, in comparison to the previously discussed section in the Chiayi area, the basement uplift in the inner part of the Taichung area is not accompanied by a significant topographic elevation. In contrast, the Western Foothills of the Taichung region display a broad zone having a low-dipping surface slope, which is correlated with an increasing spacing between major thrust sheets (Fig. 6). Such lateral structural changes are usually observed in association with a transfer-fault zone, as has been shown by analogue modeling (Calassou et al., 1993). Moreover, one of the main factors that controls the thrust-wedge propagation is erosion, which is especially important in the frontal part of the Western Foothills, as suggested by the occurrence of thick unconsolidated conglomeratic and sandy syntectonic deposits that fill the Pleistocene depocenter.

In summary, on the basis of the model presented in Figure 1B, we distinguish an inner domain and an outer domain within the critically tapering wedge. One is located to the east of the Chelungpu-Sanyi thrust and is controlled by a deep décollement. As the deep décollement steps up at shallow depth, shallow-décollement tectonics occurs. The mountain front thus defined corresponds to the thrust-wedge front of the critically tapering wedge. It is likely that the deep décollement continues westward, but its activity has probably decreased because of local indentation by the Peikang basement high.

Miaoli area (region 4)

This region is located in the middle of the large curvature of the topographically defined mountain front and corresponds to a transitional structural domain of frontal areas of the Western Foothills where structural trends change northward from predominantly N10°–20°E to N70°E. Both the bending of the front due to the Pakua transfer fault and the transfer faulting along the Sanyi fault transfer motion of the northern thrust sheets with respect to the propagation of the southern thrust sheets blocked onto the Peikang basement high. As a consequence, the related frontal relief delineates the coastline near Miaoli (Figs. 6 and 7).

The structural analysis of the basement (Fig. 4) and further seismic reflection data published by the Chinese Petroleum Corporation (Huang et al., 1993; Shen et al., 1996) have revealed that the offshore western Taihsi Basin was affected by inversion tectonics during the Pliocene–Pleistocene collision. This result implies that the compressional stresses have been transmitted away from the hilly regions in the Chinese platform in favor of the activation of a deep décollement. Consequently, according to the model examined in Figure 1B, we propose to enlarge the interpreted size of the thrust wedge offshore and thus locate the reactivation front about 60 km westward from the mountain front into the Taiwan Strait, in order to include the western edge of the Taihsi Basin in the deformation. To the east of the mountain front, onshore, the profile of the basement top yields no clear evidence of basement involvement at the front (Fig. 6). However, the pre-Miocene rocks exhibit a foreland-dipping slope, which seems to indicate that basement involvement, even though limited, occurred in relationship to the Sanyi thrust activity (Fig. 6).

Moreover, recent reflection seismic profiles (Hung and Wiltschko, 1993) have shown that normal faults have been incorporated into the frontal part of the thrust wedge, implying that basement-involved tectonics is the prominent deformational mechanism in the Miaoli region. This result led to us consider a thrust wedge controlled by a deep décollement in agreement with the model proposed (Fig. 1B). The western area is subject to orogenic stresses producing structural inversion in the foreland. Little reverse displacement occurs, resulting in low topography. East of the Sanyi thrust, the basement is involved in the deformation of the tectonic wedge. On the basis of complete structural study, the reactivation front is extended toward the east and displays a remarkable curvature similar to the shape of the mountain front (Fig. 7).

Hsinchu area (region 5)

The Hsinchu area is the northernmost province investigated in this study. Northward, the structures of the belt front progressively turn and become parallel to the inherited normal faults of the southern edge of the Kuanyin high, trending N60°–70°E (Fig. 4). Accurate topographic data of the DEM highlight the presence of a broad zone of elevated terraces in the Coastal Plain (Figs. 6 and 7). Moreover, these terraces are affected by thrust faulting (Hukou thrust in Fig. 6), demonstrating that compressional deformation has propagated farther in the Coastal Plain from the mountain front in favor of the activity of a shallow décollement. Moreover, the profile of this region reveals the deepening of the basement toward the inner part of the belt. This result shows that basement involvement is absent or limited, which leads us to interpret a typical wedge shape for the sedimentary cover. Such a geometry has been also recognized in the southernmost frontal areas of the belt. As it was noticed earlier, this region is the site of important lateral motion due to escape tectonics (Lu et al., 1995). Consequently, out-of-section transport probably occurs, which makes difficult the observation of reverse motion along faults in the basement.

To conclude, we observe a single wedge of sedimentary cover in this frontal region of northern Taiwan, demonstrating that the deformation is probably controlled by a shallow décollement. Finally, we relocate the thrust-wedge front farther north and close to the shoreline, i.e., distant from the mountain front. The geology of the frontal thrust sheets and the location of the different fronts is summarized in Figure 7. Basically, the Taiwan mountain-belt front (reactivation and mountain fronts) exhibits large curved zones (Fig. 7) that are related to the occurrence of inherited basement reentrants and salients in the foreland and to the location of ancient major oblique-transfer faults reactivated during the Pliocene–Pleistocene compression. The areas of structural inversion located south of the basement highs (Peikang and Kuanyin) are observed in association with basement-involved tectonics near the mountain front.

GEOLOGIC CROSS SECTIONS OF THE BELT FRONT

In order to determine the structure of the frontal units at depth, we have constructed 11 serial geologic sections controlled by 30 Chinese Petroleum Corporation drill holes and field measurements. When available, we have also used several onshore and offshore short seismic profiles, helped by published data (Chen, 1978; Huang et al., 1993; Yang et al., 1996). Each section cuts through the mountain front and is extended in the foreland of the Coastal Plain (see location of sections in Fig. 7). In addition, the geologic sections presented here were constructed by taking into account the conclusions on the thrust-wedge geometry in the preceding section and the location of the different fronts in agreement with the model presented in Figure 1B.

Tainan area (region 1): Sections 1–1′ and 2–2′

On the basis of the previously described results on the thrust-wedge geometry (Fig. 6), we have determined that the deformation in the southern frontal part of the belt is accommodated within a shallow thrust wedge, i.e., in the syntectonic Pliocene–Pleistocene strata deposited in the Pingtung foredeep basin. In this region, the best strata for hosting a décollement is a thick Pliocene–Pleistocene turbiditic formation (2–3 km) composed mainly of mudstones. Moreover, seismic reflection data (Fig. 8) suggest that the development of the frontal Tainan anticline (TN-1 well) is the result of the activity of a shallow thrust that dies out at depth into the Pliocene–Pleistocene mudstones. Both geologic sections constructed in this region (sections 1–1′ and 2–2′) display a series of west-verging imbricate thrust sheets that propagate toward the Coastal Plain (Fig. 8). The deformation occurs above a shallow, gently east-dipping décollement (2–5 km deep) (Fig. 8). These structural patterns match the types of fault-related folds, such as fault-propagation folds (Chungchou anticline, CC-1 well) and pop-up structures (see the line drawing of the Tainan anticline, TN-1 well) (Fig. 8) usually found in shallow-décollement tectonics (Fig. 2). In this region, the front of the shallow thrust wedge (the mountain front) is located at the emergence of the shallow frontal thrusts (Chungchou thrust and Tainan thrust). Different factors could be invoked to account for the thrust wedge to propagate far in the foreland. One is the occurrence of weak internal friction within the thick Pliocene–Pleistocene mudstones, and the other is the presence of overpressured fluids in these deposits, as illustrated by the presence of mud volcanoes in the vicinity of major thrusts. Therefore, the southwestern foreland thrust belt appears to be very similar to structures already described in the Manila accretionary prism (Reed et al., 1992), and the Tainan region may be regarded as the onshore northern extent of the Manila accretionary prism.

Chiayi area (region 2): Sections 3–3′, 4–4′, and 5–5′

The frontal deformation in the Chiayi area is characterized by thrust wedging associated with structural inversion in the outer part and basement-involved tectonics in the inner part. Compared to the previously mentioned southern area (Fig. 8), there are major changes in the thickness of Neogene formations as well as in the age of rock materials involved in the deformation. Moreover, both sedimentary and structural changes are localized across the oblique Chishan transfer-fault zone (Fig. 7). The frontal geologic sections constructed for the Chiayi region (sections 3–3′, 4–4′, and 5–5′) highlight the northward thinning of the Neogene sedimentary deposits onto the southern flank of the Peikang basement high and the increase of the early

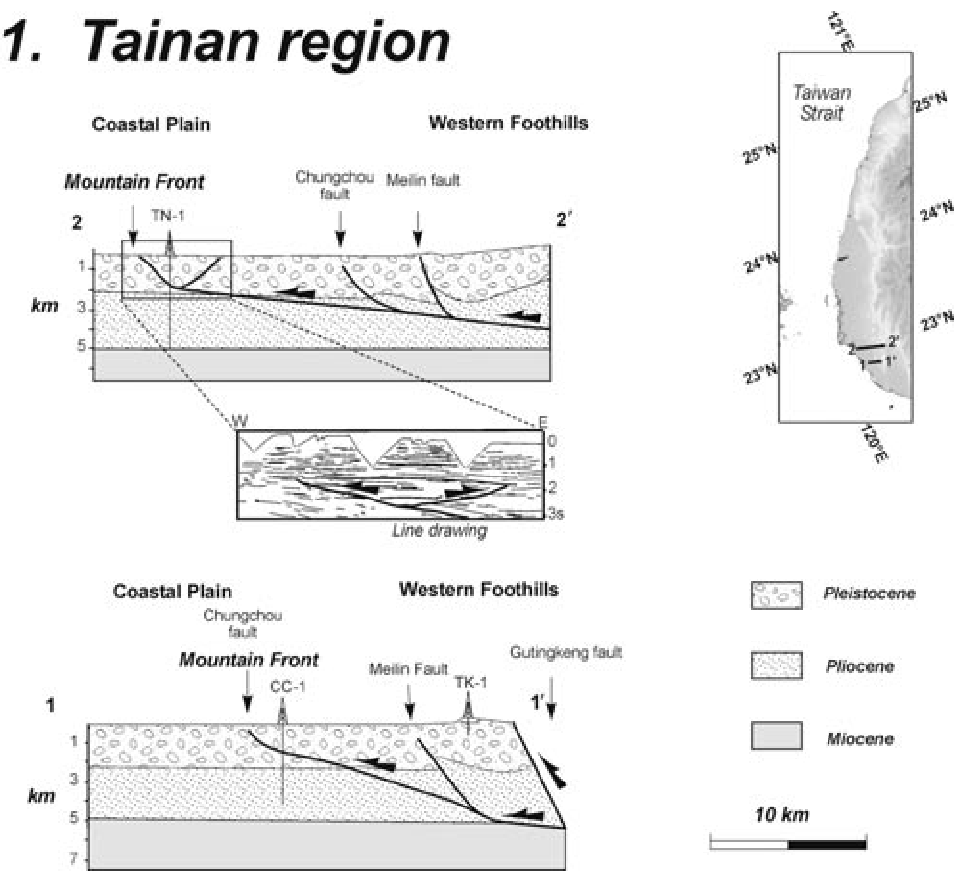

Figure 8. Frontal cross sections in the Tainan area (region 1). These two sections show a dominant shallow-décollement tectonics style affecting a significant thickness of Pliocene–Pleistocene sedimentary deposits. A reactivation front is absent, and the mountain front corresponds to the emergence of the shallow décollement.

Miocene unconformity toward the center of the basement high (Fig. 5). Little structural inversion occurs beneath the Coastal Plain according to section 3–3′ whereas basement involvement becomes much clearer in section 4–4′. With regard to the previous structural interpretations (i.e, based on thin-skinned tectonics; Suppe, 1980; Wiltschko et al., 1997) of the Niushan and Wushantou anticlines (NS-27 and WST-1 wells, section 3–3′) and Kuantaoshan anticline (KTL-3 well, section 4–4′), recent seismic reflection data have led Chang et al. (1996) to reinterpret these frontal structures in terms of simple basement involvement. For instance, seismic reflection profiles across the Niushan anticline (Hsiao, 1974) and Hsiaomei anticline (HM-3 well in section 5–5′) (Wiltschko et al., 1997) have revealed that both the Meilin fault and the Hsiaomei fault are high-angle reverse faults that are probably the result of the reactivation of inherited extensional features. Hereafter, we propose an alternative interpretation for the frontal structures that is based on the superimposition of both a shallow and a deep décollement in the vicinity of the mountain front.

In section 3–3′, the frontal fault-propagation fold geometry of the Niushan anticline (steep forelimb) is interpreted as the result of combined reactivation of an ancient normal fault due to slip along a deep décollement and the abrupt termination of the shallow basal décollement (Fig. 9). This structure has strong similarity with the case described by Suppe (1986) in the northern part of the thrust belt (see also Fig. 2E). The deep décollement extends westward as suggested by the structural inversion in the Coastal Plain. Moreover, it is probably deeper than 9 km. In section 3–3′, the shallow décollement is localized at the base of the Miocene strata (Suppe, 1980) near 5–6 km. The mountain front that corresponds to the emergence of the shallow décollement is distinct from the reactivation front.

To the north, the frontal deformation exhibits structural inversion in the Coastal Plain (Chang et al., 1983), and a broad foreland-dipping syncline (section 4–4′) is observed in the western part of the Western Foothills. Its eastern limb is affected by backthrusting, arguing in favor of the development of a major triangle zone resulting from the imbrication of the pre-Miocene basement beneath the Kuantaoshan anticline (KTL-3 well) (Fig. 9). In the case of superimposed shallow and deep décollement tectonics, and in order to fit with the result of Suppe (1980), a possible alternative to explain the formation of the Kuantaoshan anticline is the result of shortcutting by a reactivated normal fault whose sense of motion has been inverted to thrust slip (Fig. 2D). On the other hand, the deep-décollement surface is located much deeper than commonly assumed at nearly 10–15 km.

Section 5–5′ is located farther north and exhibits the same structural framework as section 4–4′ but structural inversion in the Coastal Plain is absent. The frontal triangle zone evolves

2. Chiayi region

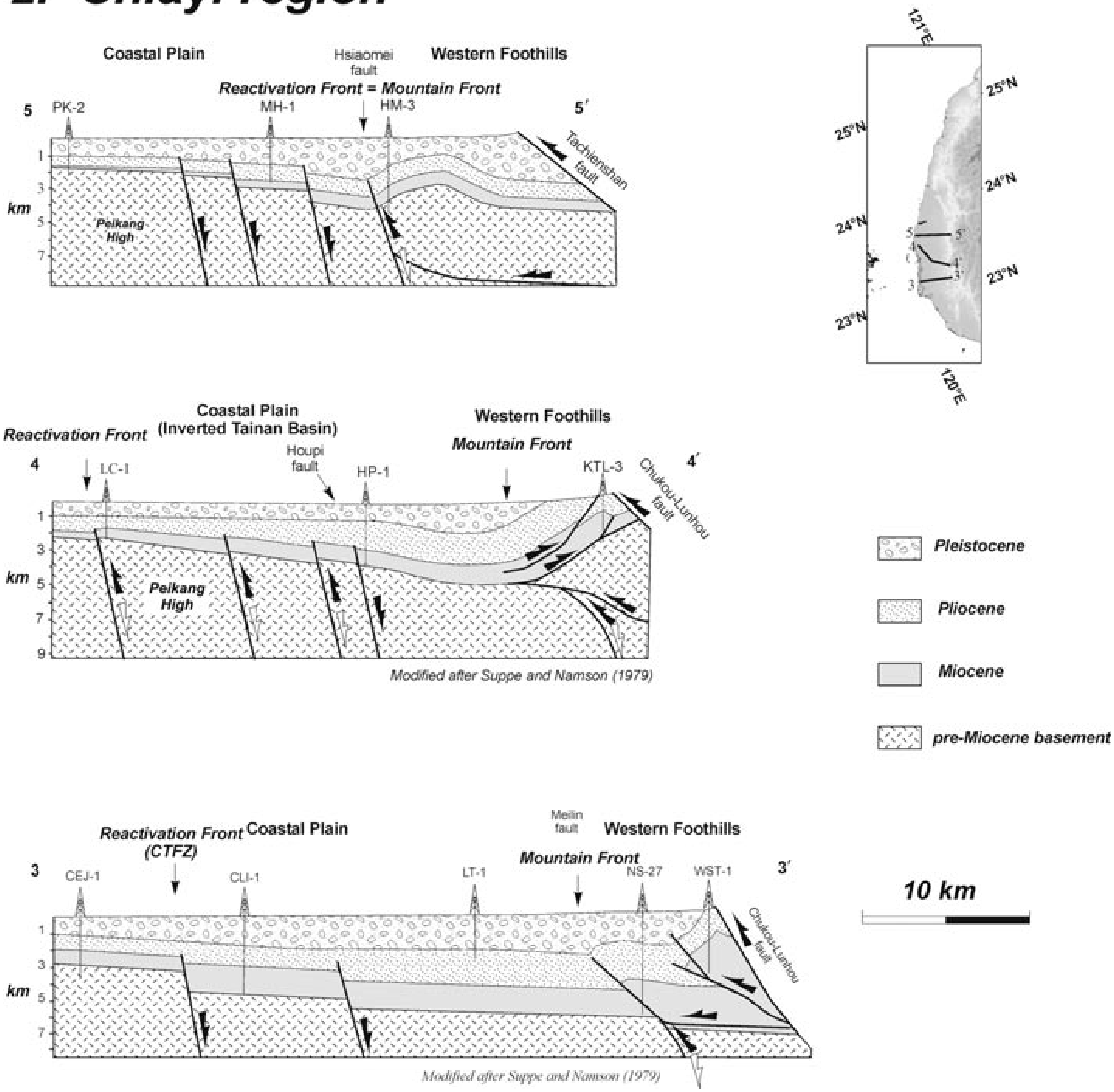

Figure 9. Frontal cross sections in the Chiayi area (region 2). These sections highlight the occurrence of inversion tectonics in the Coastal Plain and basement-involved tectonics in the Western Foothills. Beneath the Chukou-Lunhou fault, the basement involvement occurs by roof thrusting to create a major triangle zone. The reactivation front (the outermost reactivated extensional structure) is distinct from the mountain front. Frontal structures in the vicinity of the mountain front show the superimposition of shallow- and deep-décollement tectonics. CTFZ—Chishan transfer-fault zone.

into a broad anticline in the Hsiaomei anticline (HM-3 well), and the pre-Miocene rocks are also involved in the frontal deformation. Furthermore, the connection between high-angle thrusting (that merges at depth into a deep décollement according to our interpretation) and the shallow décollement (similar to that of section 4–4′) occurs.

Considering results already obtained concerning the geometry of frontal structures in the vicinity of the mountain front (Fig. 6), the structural analysis carried out in the Chiayi area provides support to the interpretation in terms of superimposed shallow-décollement and deep-décollement tectonics.

Taichung area (region 3): Sections 6–6′, 7–7′, and 8–8′

From north to south, the frontal deformation in the Taichung area is controlled by the hinge fault of the Peikang high (Fig. 10). In the cover, this fault has induced the development of a major transfer zone (Mouthereau et al., 1999).

The type of frontal folds in the Taichung area corresponds mainly to fault-propagation folding. In detail, moving southward, the fold limbs flatten, e.g., the Meilin anticline (section 6–6′; MLN-1 well) exhibits a narrow fault-propagation fold with steep limbs (Suppe and Namson, 1979), whereas to the north, the Pakuashan anticline (section 8–8′; PKS-1 well) displays almost flat limbs, as shown in a seismic reflection profile (Chen, 1978). Moreover, the frontal deformation occurs above a shallow décollement (3–4 km deep) that, from north to south, cuts through the Miocene (section 6–6′) and then the Pliocene strata (sections 7–7′ and 8–8′). The atypical, gently dipping limbs shown in section 8–8′ have been probably enhanced by the syndepositional folding when the sedimentation rate became higher than the fold's uplift rate. Effectively, the evolution of fold limbs in this region is characterized by a high deposition rate in the Taichung Basin (Figs. 4 and 5) during the Pleistocene (Mouthereau et al., 1999). In summary, the thrust-wedge front in the Taichung area corresponds to shallow-décollement tectonics, although the thrust location is controlled by a preexisting major normal fault that cuts the basement, as evidenced by a seismic reflection profile (Chen, 1978).

Miaoli area (region 4): Section 9–9′

For many years, the Miaoli and Hsinchu areas of northern Taiwan (Fig. 7) have been investigated by structural geologists in terms of gas and oil exploration potential. The geometry of major anticlines was firstly described as validating the thin-skinned tectonics concept (Suppe and Namson, 1979; Namson, 1981). As a consequence, these previous structural models did not consider the complex array of basement normal faults and the roles of reactivation and structural inversion that have been documented by more recent onshore and offshore seismic reflection profiles (Huang et al., 1993; Shen et al., 1996) (Fig. 7). The geometric study of the thrust wedge reveals that this region exhibits a thick tectonic wedge in which basement is involved and structural inversion occurs (Fig. 6). In the past few years, some authors have entirely reinterpreted this area in terms of thick-skinned tectonics and have omitted any reference to shallow-décollement tectonics (Lee et al., 1993).

The section 9–9′ (Fig. 11) cuts through the frontal broad and symmetrical Tiehchenshan anticline gas field (TCS wells) and, in its eastern part, the tight and symmetrical Chuhuangkeng anticline (CHK-110 well). The latter has been interpreted by Namson (1981) in terms of décollement folding in the shallow-décollement tectonics style. However, evidence of backthrusting in the core of the anticline associated with a foreland-dipping syncline gives constraints on the occurrence of a basement triangle zone. This type of structure has been already encountered in the Chiayi area (section 4–4′; Fig. 9). We propose an alternative hypothesis for the development of the fold that combines shallow and deep décollements. The décollement folding might thus have been generated at the tip of a reactivated normal fault as the result of the activation of a shallow décollement. Some seismic reflection data from the Chinese Petroleum Corporation (personal commun.) reveal that beneath the outermost Tiehchenshan anticline, high-angle thrusts and backthrusts affect the pre-Miocene basement and the sedimentary cover (Fig. 11). Consequently, inversion of deep-seated inherited normal faults could be a mechanism for the development of the outer Tiehchenshan anticline, which localized the mountain front. In summary, even though deep-décollement tectonics is probably the main deformational mechanism in the frontal domain of the Miaoli area, superimposed shallow- and deep-décollement tectonics are likely to have occurred.

Hsinchu area (region 5): Sections 10–10′ and 11–11′

Sections 10–10′ and 11–11′ trend N20°W, perpendicular to the direction of the frontal thrusts. In section 10–10′ (Fig. 12), the relationship between the deep-décollement and the shallow-décollement tectonics is well evidenced. On the basis of seismic sections, Suppe (1986) and Yang et al. (1996) demonstrated that the Chingtsaohu frontal anticline (Fig. 12, CTH-3 well) results from the superimposition of connected low-angle and high-angle reverse faults, in agreement with the model of Figure 2E. Seismic reflection profiles further indicate that the basal décollement lies within the pre-Miocene basement at a depth of 4 km on average. The basal décollement dies out and becomes steeper in the vicinity of the reactivated normal fault. In the same section, the westernmost anticline (TCN-1A well) is interpreted as being the result of the inversion of an inherited extensional feature of the Chinese margin (see Fig. 2F). In section 11–11′, the Yangmei-Hukou anticline (YM-1 and HK-4 wells), which was first interpreted by Suppe and Namson (1979), is the result of fault-bend folding, and the shallow basal décollement lies at 5 km depth. By taking into account these former studies and the occurrence of underlying inherited normal faults bounding the southern part of the Kuanyin basement high, we reinterpret this fold by a similar geometric model that

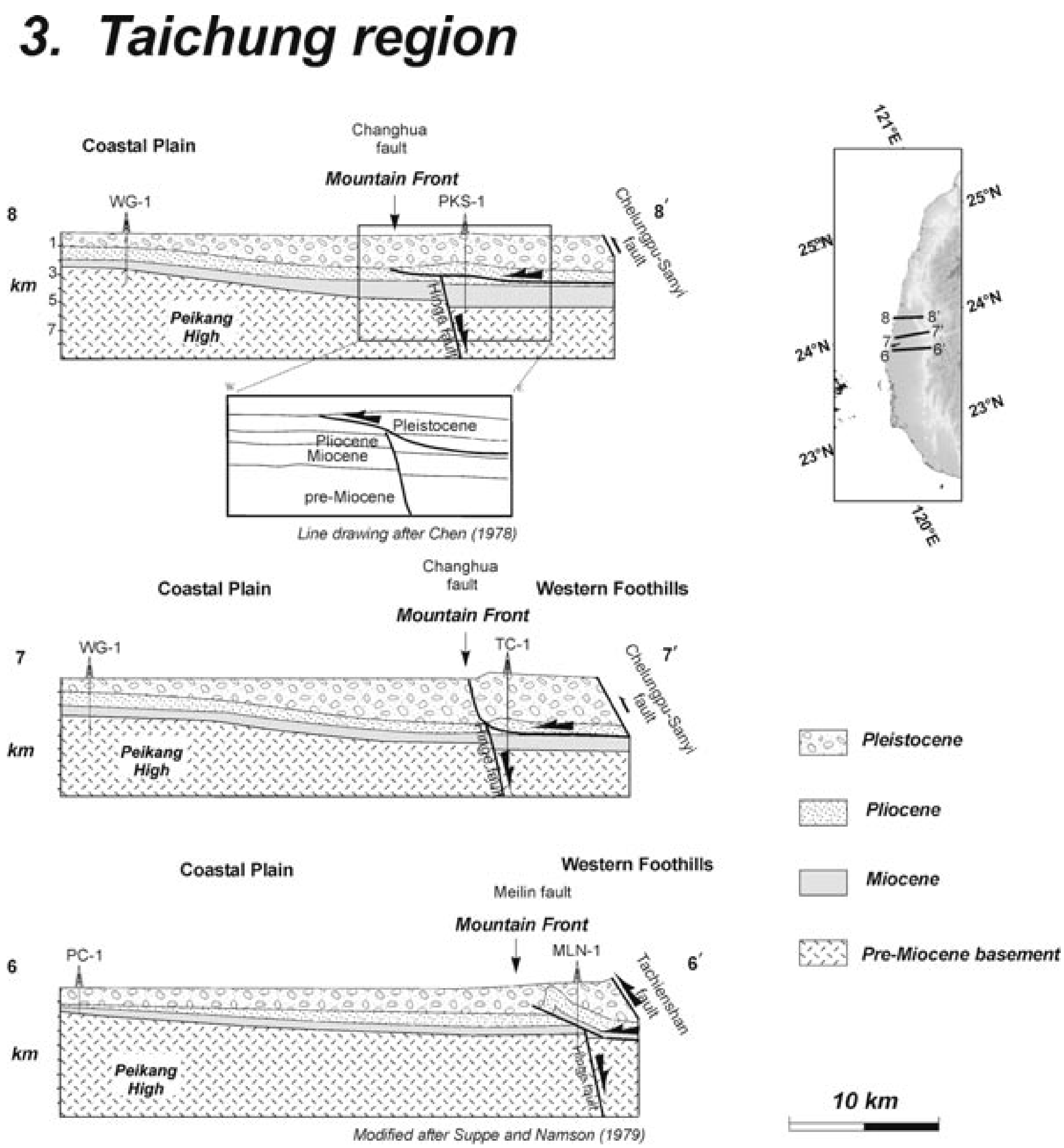

Figure 10. Frontal cross sections in the Taichung area (region 3). The reactivation front is absent. The location of the mountain front (emergence of the shallow décollement) is controlled by a preexisting normal fault that cuts the basement.

was proposed for the Chingtsaohu anticline. Nevertheless, the pre-Miocene basement rocks are probably not involved in the wedge. Therefore, the shallow basal décollement deepens toward the south and displays major steps by localizing ramps above underlying normal faults. Farther west, the thrust wedge propagates in the Coastal Plain above the shallow décollement. A seismic reflection line reveals that the western limb of the Pingchi anticline (PC-1 well) is affected by backthrusting that probably merges at depth with a flat and shallow décollement, thus defining a remarkable frontal triangle zone in the unconsolidated Pleistocene conglomeratic deposits. The western extremity of the triangle zone delineates the mountain front.

To summarize, the compressional structures in this northernmost province exhibit dominant shallow-décollement tectonics. Locally, particular structural styles highlight the superimposition of both shallow- and deep-décollement tectonics, the latter being largely controlled by oblique reactivation of inherited normal faults so that the basement involvement remains limited.

The structural analyses of the serial geologic sections complement the previous investigations of the geometry of the

4. Miaoli area

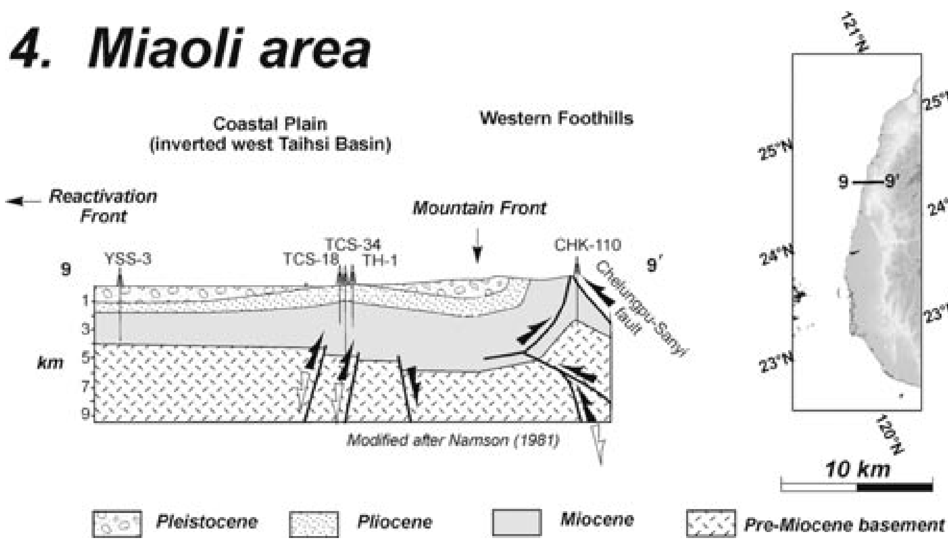

Figure 11. Frontal cross section in the Miaoli area (region 4). This section is marked by structural inversion, i.e., high-angle thrusting along preexisting normal faults. It also shows the basement involvement in the vicinity of the mountain front. In this area, the reactivation front is distinct from the mountain front.

5. Hsinchu area

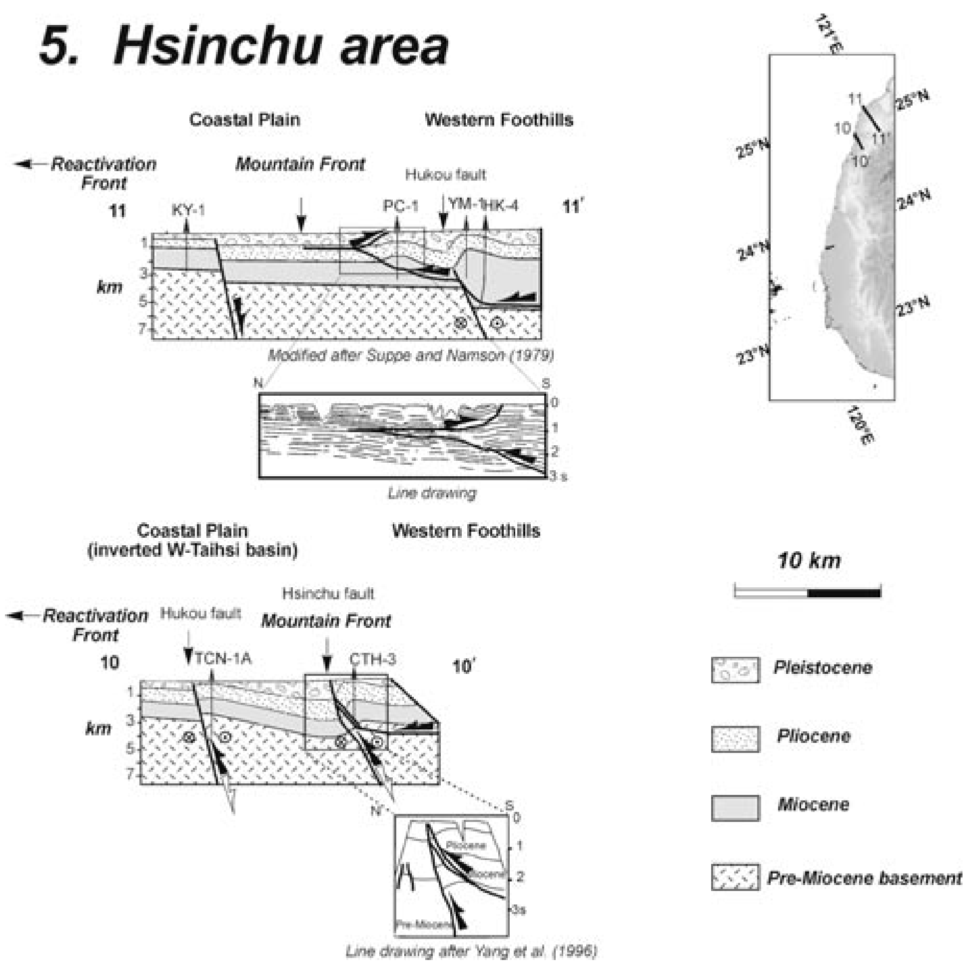

Figure 12. Frontal cross sections in the Hsinchu area (region 5). These sections show the superimposition of shallow- and deep-décollement tectonics. The reactivation front is distinct from the mountain front.

thrust wedge based on study of the surface slope and the topography of the basement. Superimposition of shallow- and deep-décollement tectonics consequently appears as an important tectonic process during the emplacement of frontal thrust sheets.

COMPRESSIONAL TECTONIC REGIMES AT THE TAIWAN THRUST-BELT FRONT

The geometry of the Taiwan thrust-belt frontal zone was highly influenced by the presence of precollisional normal-fault patterns. We consequently attempted to determine the nature and orientation of the tectonic forces prevailing during the Pliocene–Quaternary emplacement of the frontal units. This study is based on kinematic indicators such as striated faults, calcite twins, and impressed pebbles; we collected data as far away as possible from the major faults in the Pliocene–Pleistocene deposits of the outermost thrust units (Angelier et al., 1986; Lacombe et al., 1993, 1997; Hung, 1994; Rocher et al., 1996; Lin and Huang, 1997; this work).

A statistical analysis of the distribution of reconstructed principal paleostress axes (Angelier, 1990) has been performed for each of the regions previously discussed (Fig. 13). A striking result, taking into account the statistical distribution compared with the uncertainties on paleostress reconstructions, is the relative homogeneity of the N120°E orientation of the maximum principal stress axes σ_1. Variations exist, but remain limited considering the along-strike structural complexity (σ_1 distribution diagrams in Fig. 13). Of particular interest is the distribution of tectonic regimes, as a function of the plunges of σ_2 and σ_3 axes (Fig. 13).

The σ_2 axes are predominantly vertical in regions 1 and 3, indicating that strike-slip regimes prevailed in southwestern Taiwan and the Pakuashan area during the thrust emplacement. This geometry may be explained by the obliquity of the trend of the mountain front relative to the regional compression and/or to a decrease in north-south confining stress probably related to incipient lateral extrusion. In addition, the σ_2 and σ_3 axes tend to form a girdle perpendicular to the compression, which argues in favor of stress permutation between pure compressional and strike-slip coeval regimes during the Pleistocene.

In contrast, in regions 2 and 4, steep plunges are predominant for σ_3 axes, suggesting that a purely compressional regime (reverse-faulting type) prevailed during the Pliocene–Pleistocene. This regime is related to the inversion of preexisting features in the Tainan basin at the southern edge of the Peikang and Kuanyin highs, even though some scatter along a girdle in the distribution of σ_2 and σ_3 axes again suggests the possible occurrence of stress permutations.

The data acquired to the north (region 5) are scarce so that no stereo plot is shown. However, they suggest that the dominant regime is of strike-slip type in the northernmost province of the Western Foothills, in relationship to transcurrent faulting along preexisting N60°E faults (Lu et al., 1995).

Thus, the analysis of kinematics markers reveals that (1) regionally σ_1 is approximately parallel to the plate-convergence vector (Fig. 13) and (2) locally strike-slip or reverse-slip compressional regimes dominate, depending on factors such as frontal contraction and lateral movement, in response to indentation by the Peikang and Kuanyin highs.

CONCLUSIONS

The conceptual model of critically tapering wedge (Davis et al., 1983) has been discussed in order (1) to explain the occurrence of inverted extensional features located far into the foreland of an orogen and newly formed microstructures induced by far-field compression related to a deep-crustal décollement, which allows the orogenic stresses to be transmitted within the foreland, and (2) to take into account the basement involvement in the orogenic wedge. On this basis, we propose a model of imbricate thrust wedges.

This model considers three different thrust-belt fronts, a mountain front, a reactivation front, and a deformation front, which are distinguished on the basis of topographic, kinematic, and mechanical criteria (Fig. 1B). This model is applied to the case of western Taiwan (Fig. 14, A and B), and on the basis of these principles, we have redefined and relocated the different fronts.

From south to north, the study of the foreland thrust-belt wedge geometry has been supported by analysis of serial sections in which the basement and the surface topography are compared and discussed (Fig. 6). We have thus distinguished areas where prominent shallow deformation occurs and those where basement involvement dominates. According to this preliminary geometric analysis of western Taiwan, we have shown that a reactivation front exists and corresponds to the termination of the activated part of a deep décollement, i.e., the outermost reactivated extensional structure (Fig. 7). The reactivation front exhibits large curvatures extending offshore in the Taiwan Strait (Fig. 14A). These features are related to the occurrence of inherited basement reentrants and salients in the foreland and to the location of ancient major oblique transfer faults, e.g., the Chishan transfer-fault zone and Sanyi transfer-fault zone, reactivated during the Pliocene–Pleistocene contraction (Fig. 14, A and C). South of basement highs (Peikang and Kuanyin), structural inversion occurs. Such an inversion is commonly found, in the case of the Taiwan mountain-belt front, in association with basement-involved deformation in the inner domains, demonstrating that deep décollement occurs and is continuous beneath the foreland. According to the model shown in Figure 1B, the mountain front delineates the emergence of the shallow décollement and is equivalent not only to the front of a shallow thrust wedge but also to the critical tectonic wedge made of both allochthonous sedimentary and basement units according to the classical critically tapering wedge model of Davis et al. (1983). Because both the present-day stress measurements and the paleostress reconstructions based on brittle microstruc-

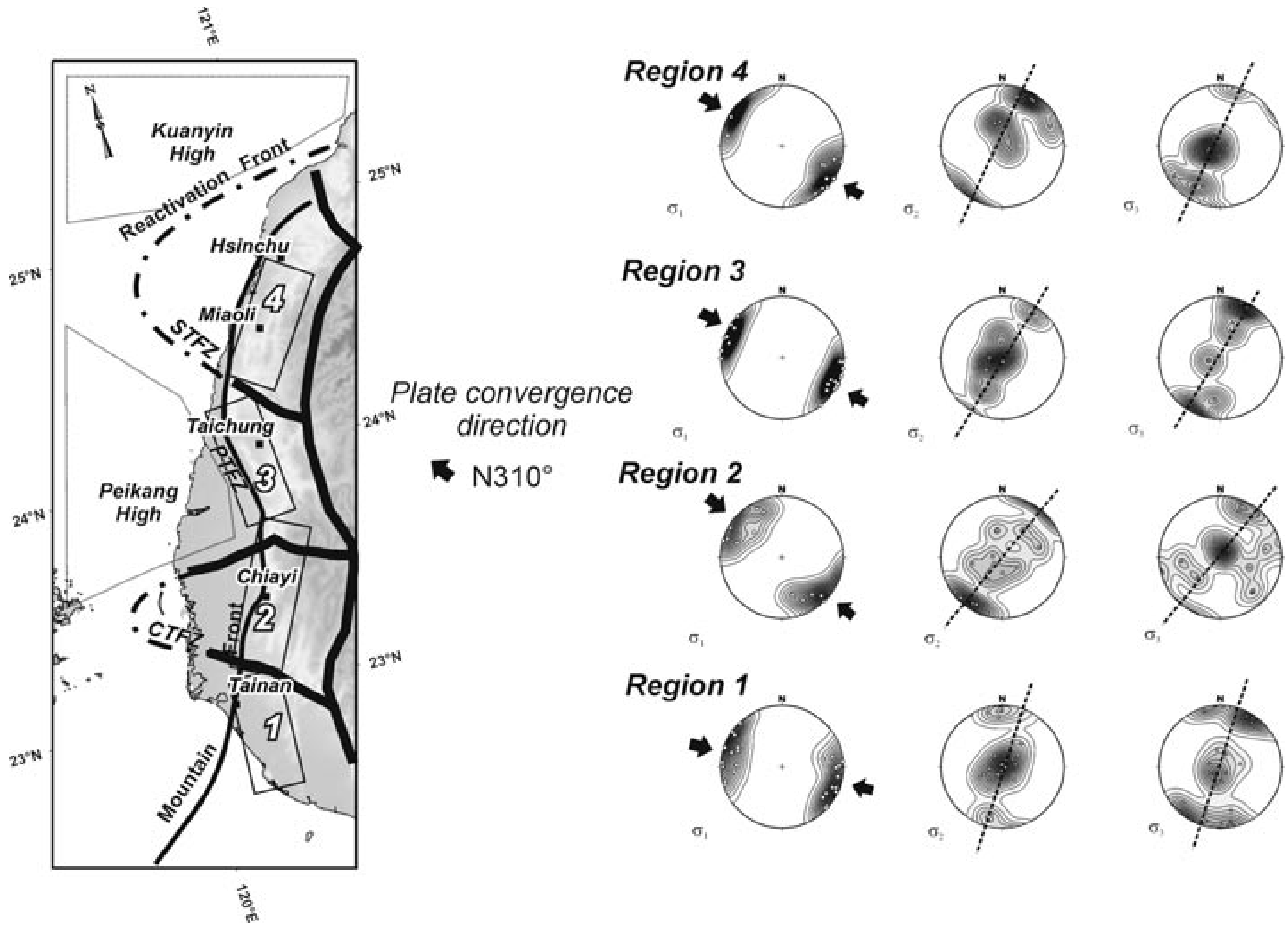

Figure 13. Stereo plots of compiled stress patterns in the studied areas (data are scarce in region 5 so no plot is presented; see text). Each plot represents the statistical distribution of σ_1, σ_2, and σ_3 for a given population. Results are based on original data and others sources (Angelier et al., 1986; Lacombe et al., 1993, 1997; Hung, 1994; Rocher et al., 1996; Lin and Huang, 1997; this work) collected within the frontal part of the thrust belt through the Pliocene–Pleistocene deposits. Dashed lines on σ_2 and σ_3 stereo plots indicate that permutation may have occurred between these two axes. The average compression azimuth is N120°E. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

ture analysis have revealed that the orogenic stresses have been recorded in the Taiwan Strait near the Penghu Islands, we define a deformation front located west of the Penghu Islands (Fig. 14A) according to the model proposed in Figure 1B.

At the local scale, the structural styles of the frontal structures have been examined through the construction of serial geologic sections (Figs. 8–12) and provide strong support to the presence of deep- as well as shallow-décollement tectonics. For instance, shallow-décollement structures dominate in southern Taiwan (region 1), as illustrated by pop-up structures and low-angle thrusting. Northward, such shallow-décollement structures are locally superimposed on deeper-décollement structures, which results in the development of basement triangle zones, whereas offshore, simple high-angle thrusting dominates (regions 2 and 4). Preexisting extensional features (regions 2 and 5) might also localize the emergence of shallow décollements.

The along-strike structural changes are followed by variations in the recent kinematics of the deformation in frontal areas, which reflect local effects such as frontal contraction and lateral movement in response to indentation by the Peikang and Kuanyin highs (Fig. 14A).

Investigation of the western Taiwan mountain-belt front has revealed high levels of complexity emphasized by the along-strike variations in the thrust-wedge geometry, structural styles of frontal units, types of décollement-involved tectonics, and faulting mechanisms at the front. This high structural complexity is amplified by the diachronous evolution of tectonic and kinematic domains evolving northward from subduction to collision, in an oblique-convergence setting. Moreover, our re-

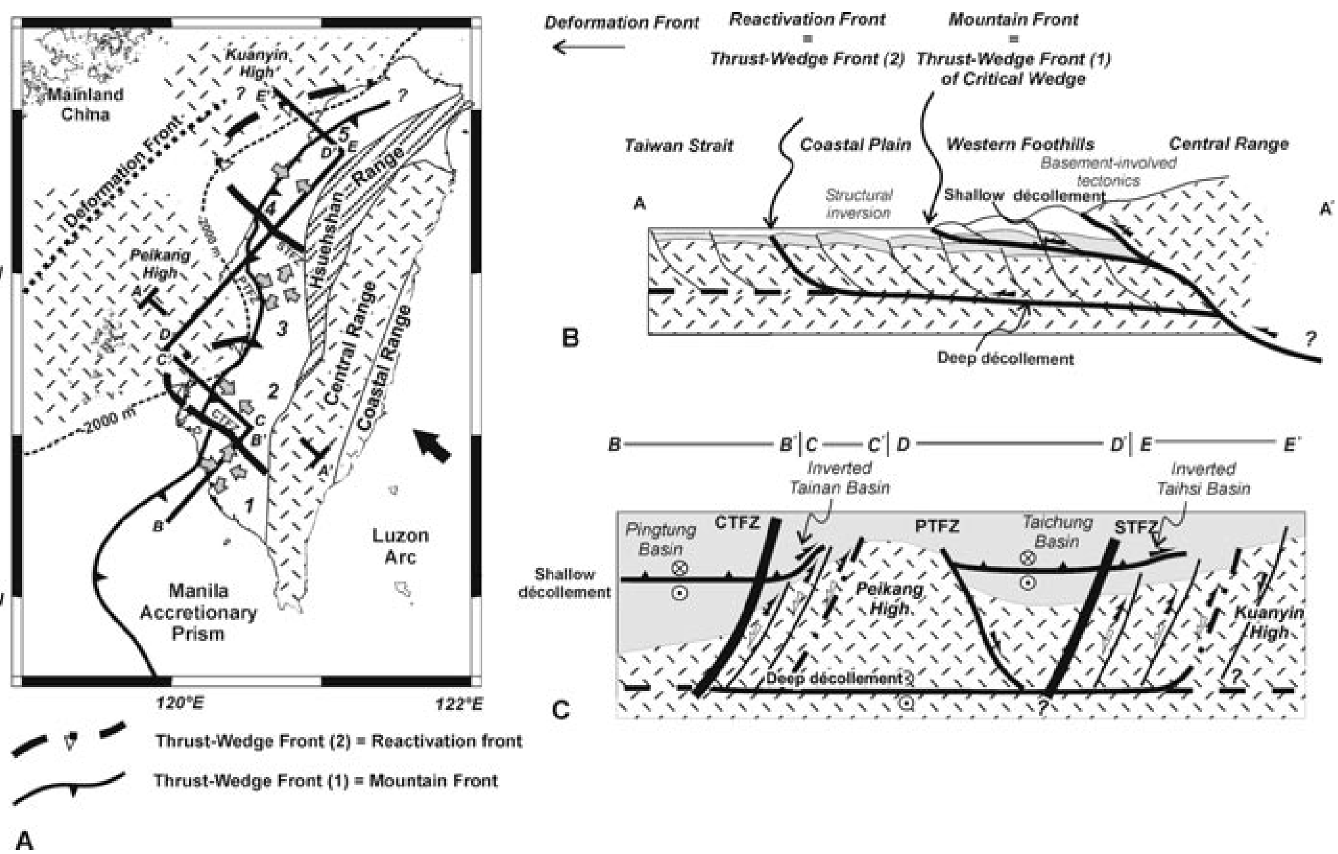

Figure 14. (A) Structural sketch map of the Taiwan thrust belt, showing locations of the different types of thrust-belt fronts in western Taiwan and their relationship with the shape of the pre-Miocene basement (the –2000 m contour). Regions where the reactivation front overlaps the –2000 m contour on the pre-Miocene basement correspond to inverted-basin areas. The along-strike variation of structural style is correlated with along-strike variations in the main stress regimes and demonstrates the evolution from prominent strike-slip regimes, i.e., the Tainan (1) and Taichung (3) areas, to purely compressional regimes especially in areas where basin inversion occurs, i.e., the Chiayi (2) and Miaoli (4) areas. (B) Schematic northwest-southeast cross section of the Western Foothills (example from the Chiayi area) highlighting the superimposition of both shallow- and deep-décollement tectonics according to the model of imbricate thrust wedges presented in Figure 1B. (C) Structural section of the basement showing basins, highs, and transfer faults that compose the basement structural framework. This section outlines the control of the structural inheritance on the deformation style and the kinematics of the thrust sheets. CTFZ—Chishan transfer-fault zone, PTFZ—Pakua transfer-fault zone, STFZ—Sanyi transfer-fault zone.

sults on the Taiwan mountain-belt front suggest that single-minded models such as either thin-skinned or thick-skinned tectonics may be unrealistic in the case of the Taiwan thrust belt and should be considered with care prior to any structural and kinematically consistent reconstruction of reversibly deformable cross sections in the Western Foothills.

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