Cenozoic tectonics of the China continental margin: insights from Taiwan

LOUIS S. TENG[1] & ANDREW T. LIN[2]

[1]*Institute of Geosciences, National Taiwan University, 1 Roosevelt Road, Sections 4, Taipei, Taiwan, ROC (e-mail: tengls@ntu.edu.tw)*

[2]*Institute of Geophysics, National Central University, 300 Jongda Road, Jongli, Taiwan, ROC (e-mail: lin@earth.ncu.edu.tw)*

Abstract: The continental margin to the east and south of China comprises an active margin in the East China Sea, a collision mountain belt in Taiwan, and a passive margin in the South China Sea. These three segments were generally regarded as separate tectonic entities and their interrelations have long been the subject of debate. Here we synthesize available information to outline the tectonic and geological background of the China margin, examine the link between Taiwan and the neighbouring China margins, and thereby establish a Cenozoic evolutionary model.

The China margin is floored with a pre-Cenozoic continental basement covered with an up to 10-km-thick pile of Cenozoic sedimentary strata. The continental basement has been invariably stretched and moulded into a series of northeast-trending horsts and grabens. Except in the Okinawa Trough of the East China Sea, the Cenozoic sedimentary cover typically exhibits a two-tier tectonostratigraphic structure, with narrow Palaeogene rift basins draped by a blanket-like Neogene–Quaternary sequence. The two-tier structure prevails in the entire inner part of the China margin, including the Taiwan Strait off western Taiwan. In the outer China margin, however, the two-tier structure persists only in the South China Sea, and is in stark contrast with the collisional orogen of Taiwan and the Ryukyu arc of the East China Sea.

By untangling the contractional deformation of the northern Taiwan mountain belt, it has been possible to reconstruct a precollisional tectonostratigraphic section with a distinctive two-tier structure shown by a Palaeogene half-graben covered with a Miocene drape sequence. When put together with Palaeogene rift basins of the Taiwan Strait, it becomes clear that the precollisional continental margin of Taiwan resembles that of the South China Sea, characterized by two lines of Palaeogene rift basins. Hence before the collision started in Late Miocene times, Taiwan was part of the passive South China margin that extended northward to the southern Ryukyu area.

Ever since the end of the Cretaceous, the China continental margin has been dominated by extensional tectonics, regardless of the presence or absence of subduction zones. In the Early Cenozoic, extensive crustal attenuation resulted in region-wide subsidence and formation of rift basins. Extension in the South China Sea culminated in Late Oligocene times, when part of the outer margin was drifted away by the opening ocean basin. In the East China Sea, the margin remained intact and became separated from the South China Sea margin by a transform fault. From the Miocene onwards, the South China Sea margin has been passively subsiding, sporadically punctuated with basaltic volcanism. In the East China Sea margin, the Okinawa Trough has opened and the Ryukyu volcanic arc thrived. The NE edge of the South China Sea margin was deformed as the Taiwan orogen.

China consists of a mosaic of continental blocks and accretionary complexes that had undergone a prolonged history of subduction, collision, and terrain accretion since the Proterozoic (Sengor & Natal'in 1996; Zhao *et al.* 1996). By Late Mesozoic times, the process of terrain amalgamation was completed, and China has since been an integral part of the Eurasian continent (Hsü *et al.* 1990; Enkin *et al.* 1992; Li 1998). In the Cenozoic era, continental China has not remained stable, but rather has been strongly influenced by plate interactions around the southern and eastern edges of the Eurasian plate (Fig. 1). In western China, indentation of the Indian subcontinent at the SW Eurasian margin has caused extensive contractional defor-

From: MALPAS, J., FLETCHER, C. J. N., ALI, J. R. & AITCHISON, J. C. (eds) 2004. *Aspects of the Tectonic Evolution of China*. Geological Society, London, Special Publications, **226**, 313–332.
0305-8719/04/$15

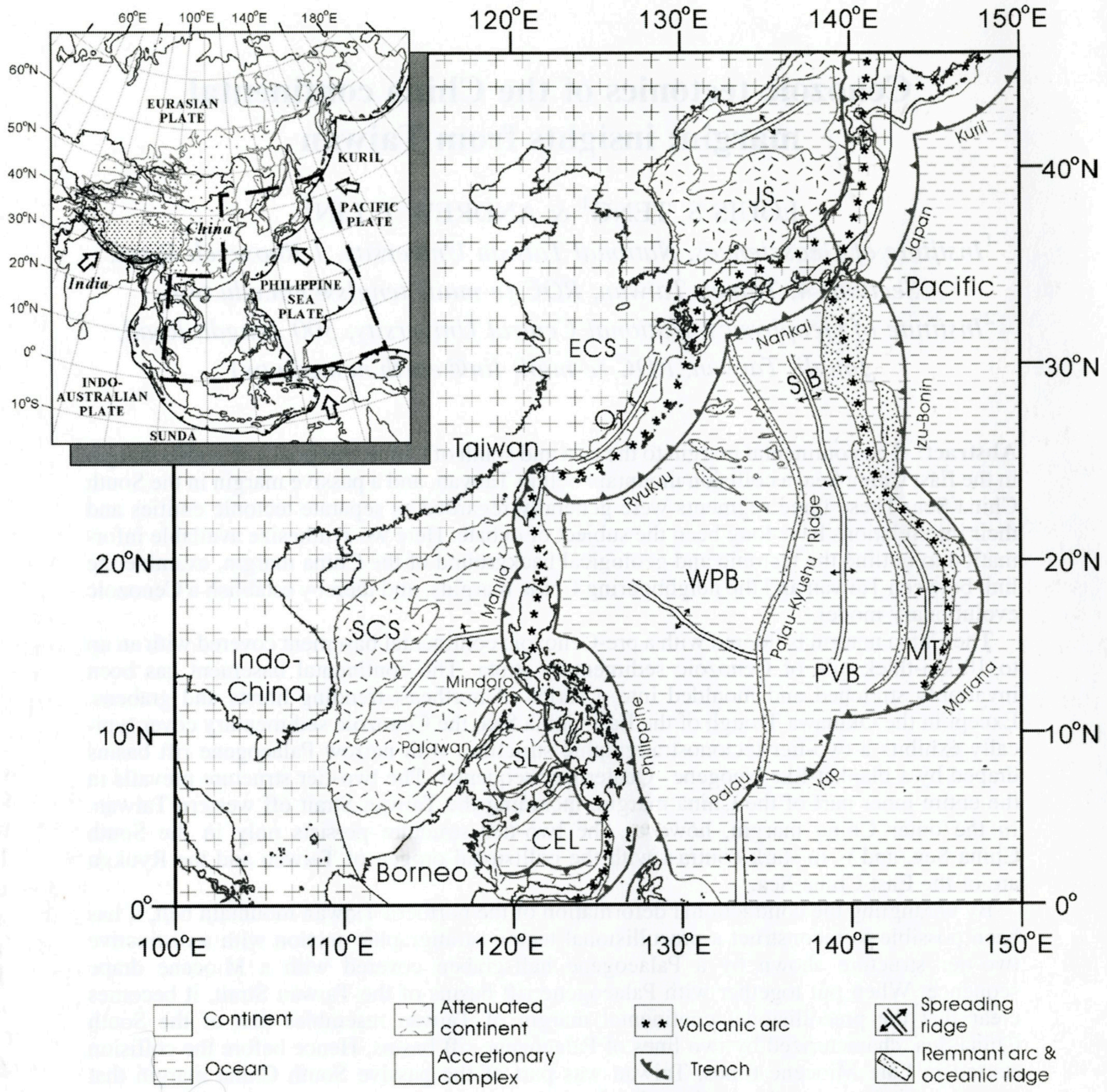

Fig. 1. Plate-tectonic setting of the continental margin of China. Marginal basins: CEL, Celebes Sea; ECS, East China Sea; HB, Huatong Basin; JS, Japan Sea; MT, Mariana Trough; OT, Okinawa Trough; PVB, Parece Vela Basin; SB, Shikoku Basin; SCS, South China Sea; SL, Sulu Sea; WPB, West Philippine Basin.

mation in the continental interior, not only raised the Himalayan orogen and Tibetan plateau but also rejuvenated a series of inland mountain chains (Tapponier & Molnar 1979; Tapponier *et al.* 1982). The eastern China continent, in contrast, has been dominated by extensional tectonism shown by region-wide subsidence and formation of intracontinental rift basins (Chen & Dickinson 1986; Ren *et al.* 2002).

As the offshore extension of the eastern China continent, the China continental margin is tectonically more complicated than the continental interior. From Japan to Taiwan, the margin of the East China Sea is fringed with an east-facing Ryukyu arc–trench system and underlain by a west-dipping subduction zone. From Taiwan to Indochina, the margin of the South China Sea is passively coupled with an extinct oceanic basin. In between, the margin has been deformed as a rising mountain belt by arc–continent collision in Taiwan. The varying tectonic styles along the margin have prompted previous workers to treat the East China Sea, South China Sea, and Taiwan as separate tectonic entities (e.g. Wang 1987; Liu 1989; Zhou *et al.* 1989; Teng 1990; Zhou *et al.* 1995; Sibuet and Hsü 1997). However, as noted by some researchers (e.g. Li 1984; Yu 1994; Ren *et al.* 2002), the Cenozoic stratigraphy and structural features are quite comparable throughout the China margin, regardless of the differences at the outer rim. This suggests that the margin might have a common tectonic history in the Cenozoic. But how the margin has evolved as a whole remains little understood.

Located at the junction between the East and South China Sea margins, Taiwan is the critical place to explore the Cenozoic tectonic history of the China margin. In the Taiwan Island, vast tracts of rock strata of the outer China margin have been exhumed and exposed in the mountain belt, which provides a rare opportunity for field observations. In offshore western Taiwan, the inner part of the China margin remains unscathed and can be readily compared with other parts of the margin. Geological and geophysical surveys in the past 100 years, both onshore and offshore, has produced a wealth of basic data unparalleled in the neighbouring areas. These data allow previous workers to reconstruct of the Cenozoic history of Taiwan and tie it in with other parts of the China margin (Suppe 1981; Teng 1992; Hsü & Sibuet 1995; Huang *et al.* 1997; Sibuet & Hsü 1997). Nevertheless, whether Taiwan is affiliated with the South China Sea margin, or with the East China Sea margin is still controversial (e.g. Huang *et al.* 1997 and Sibuet & Hsü 1997).

Here we integrate tectonic and geological information of Taiwan and adjacent areas to investigate the Cenozoic tectonic history of the China continental margin. We restore the precollision continental margin of Taiwan and find it closely affiliated with the South China Sea margin. However, the entire China margin might have had a similar tectonic history in the early Cenozoic, characterized by continual crustal extension that propagated from inland toward the outer margin. In the East China Sea margin, continental rifting continued in the late Cenozoic, and is still active in the Okinawa Trough. In the South China Sea margin, extension abated in the Late Oligocene when the outer continental margin was drifted away by the opening South China Sea Basin. The margin has since been smoothly subsiding, and the northeastern edge of the margin has later been deformed as the mountain belt of Taiwan.

Tectonic setting

China is presently a part of the Eurasian plate that is bordered by the Philippine Sea and Pacific plates in the east and the Indo-Australian plate in the south (Fig. 1). Throughout the Cenozoic, the Eurasian margin has been subducted by neighbouring oceanic plates, leading to festoons of arc–trench systems from Kuril in the north to Sunda in the south. Situated in the middle of the eastern Eurasian plate, the China continent faces mainly the Philippine Sea plate.

The Philippine Sea plate is a composite ocean that can largely be separated into two parts by the north-trending Palau–Kyushu Ridge (Fig. 1). West of the Ridge, the West Philippine Basin is an extinct Palaeogene ocean with a segmented east-southeast-trending spreading ridge (Hilde & Lee 1984; Deschamps *et al.* 1999). The eastern Philippine Sea plate is generally younger, consisting of a series of north-trending volcanic arcs, remnant arcs and back-arc basins developed in Neogene–Quaternary times (Karig 1971). Currently, the Philippine Sea plate is rotating clockwise about a pole northeast of Japan (Seno *et al.* 1993). It is subducting beneath the Eurasian plate at the Ryukyu Trench but overriding the Eurasian plate at the Manila Trench. In the southern Philippines, the Philippine Sea plate is not in contact with the Eurasian plate, but is underthrusting the Philippine archipelagos – a tectonic collage sandwiched between opposite-facing subduction zones (Rangin *et al.* 1991).

Taiwan is a key point at the China continental margin where two arc–trench systems of opposite polarity meet. To the north, the southeast-facing Ryukyu arc–trench system at the eastern edge of the Eurasian plate stretches from Kyushu into northeast Taiwan (Kao *et al.* 1998; Sibuet *et al.* 1998). In the south, the northwest-facing Luzon Arc–Manila Trench system at the western edge of the Philippine Sea plate extends from Luzon into Taiwan (Huang *et al.* 1997; Kao *et al.* 2000). The boundary between the two arc systems lies at the western edge of the northwest-subducting Philippine Sea plate beneath northern Taiwan (WEP, Fig. 2).

At a first glance, the tectonic configuration of the Eurasian continental margin appears simple and well related to neighbouring plates. However, the apparent simplicity holds only for the Late Cenozoic and may easily break down for early Cenozoic times, owing to the ever-changing plate motion. Particularly noteworthy is the Philippine Sea plate, which originated in the Southern Hemisphere in Early Tertiary times (Seno & Maruyama 1984; Haston & Fuller 1991; Hall *et al.* 1995). The plate did not enter its present location in the Northern Hemisphere until the West Philippine and Parece Vela basins successively opened up through time. Before the Philippine Sea plate progressively moved in and interacted with the Eurasian margin, the vast area east of the Eurasian margin was probably occupied by the Pacific (Engebretson *et al.* 1985) and/or some other small ocean basins (Hall *et al.* 1995; Sibuet *et al.* 2002). The motion of these ocean plates has important bearings on

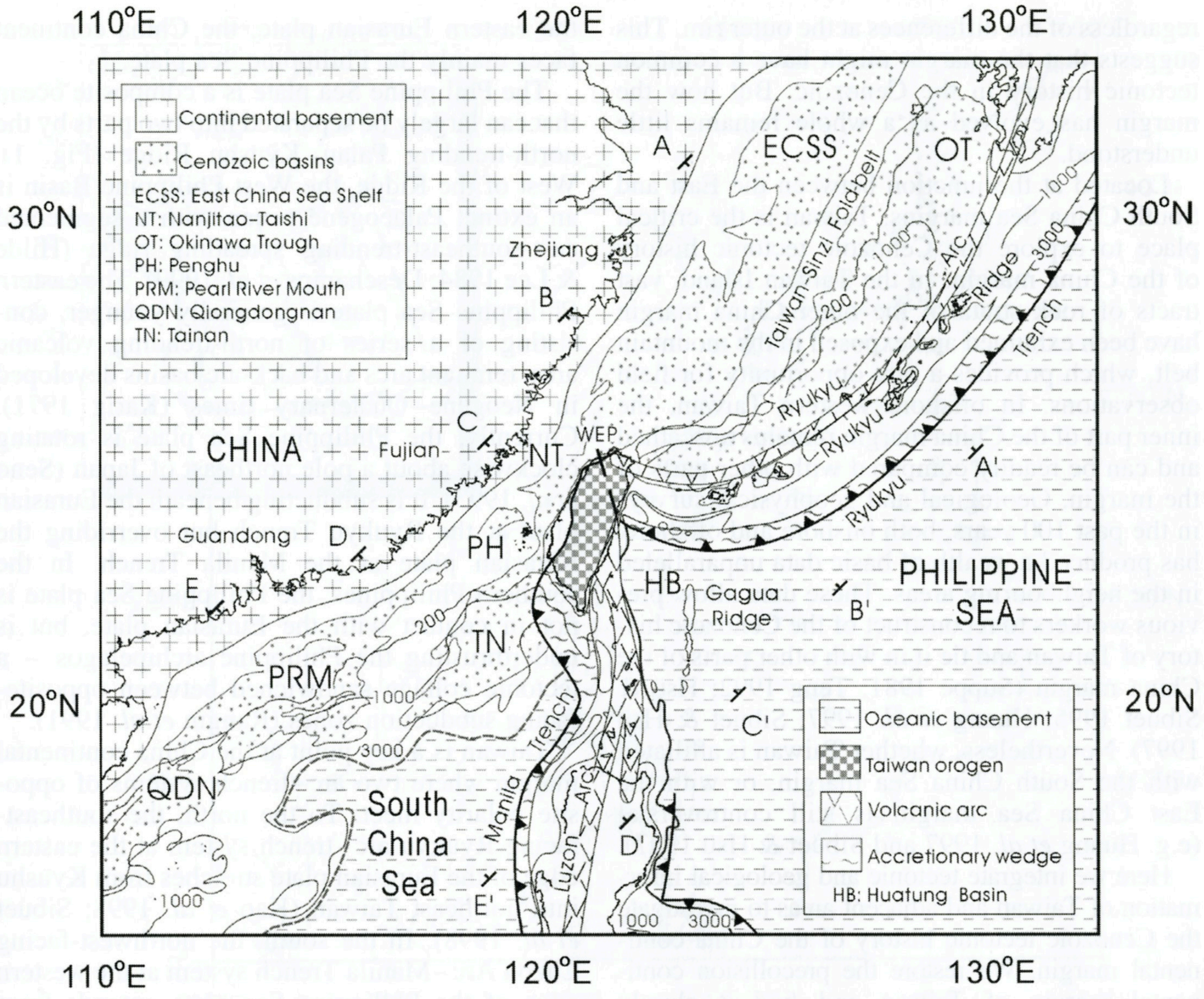

Fig. 2. Cenozoic tectonics and geology of the continental margin of China. Sections A–A′ to E–E′ shown in Figure 3.

continental margin tectonics, and it should be taken into account in reconstructing the tectonic history of the China margin.

Regional background

The China margin is floored with an attenuated continental basement, upon which Cenozoic rift basins have developed. The intensity of basement attenuation increases from onshore China to the outer margin, as shown by outward thinning of the underlying continental crust (Fig. 3). In coastal China, the crust is about 30 km thick (Li & Mooney 1998), progressively decreasing to 22–24 km at the shelf break and to 16–18 km in the Okinawa Trough (Liu 1989; Hirata *et al.* 1991). In the South China Sea, basement attenuation is even more severe in the slope area, where crustal thickness rapidly falls from 22 km to <12 km (Nissen *et al.* 1995; Zhou *et al.* 1995; Yan *et al.* 2001). In Taiwan, however, the continental crust has been thickened to more than 40 km by the collision (Lin 1996; Shih *et al.* 1998; Yen *et al.* 1998).

The basement rocks of the China margin are similar to those exposed in neighbouring areas, including China, Korea, Japan, Taiwan and the Philippines (Figs 1 and 2). On the inner continental shelf, the basement is composed of Proterozoic–Palaeozoic metamorphic complexes, Palaeozoic to Early Mesozoic sedimentary sequences, and Late Mesozoic igneous intrusions and extrusions, comparable with rocks exposed in coastal China and southern Korea (Wageman *et al.* 1970; Guong *et al.* 1989; Liu 1989; Zhou *et al.* 1989). In the outer shelf and slope area, the basement rocks are younger, composed of Palaeozoic–Mesozoic metamorphic and igneous complexes that crop out extensively in Japan, Taiwan and Philippine islands (Faure *et al.* 1989; Taira *et al.* 1989; Zhou *et al.* 1989; Taira 2001).

The continental basement has been invariably stretched and moulded into a series of northeast-trending horst-and-graben structures that are

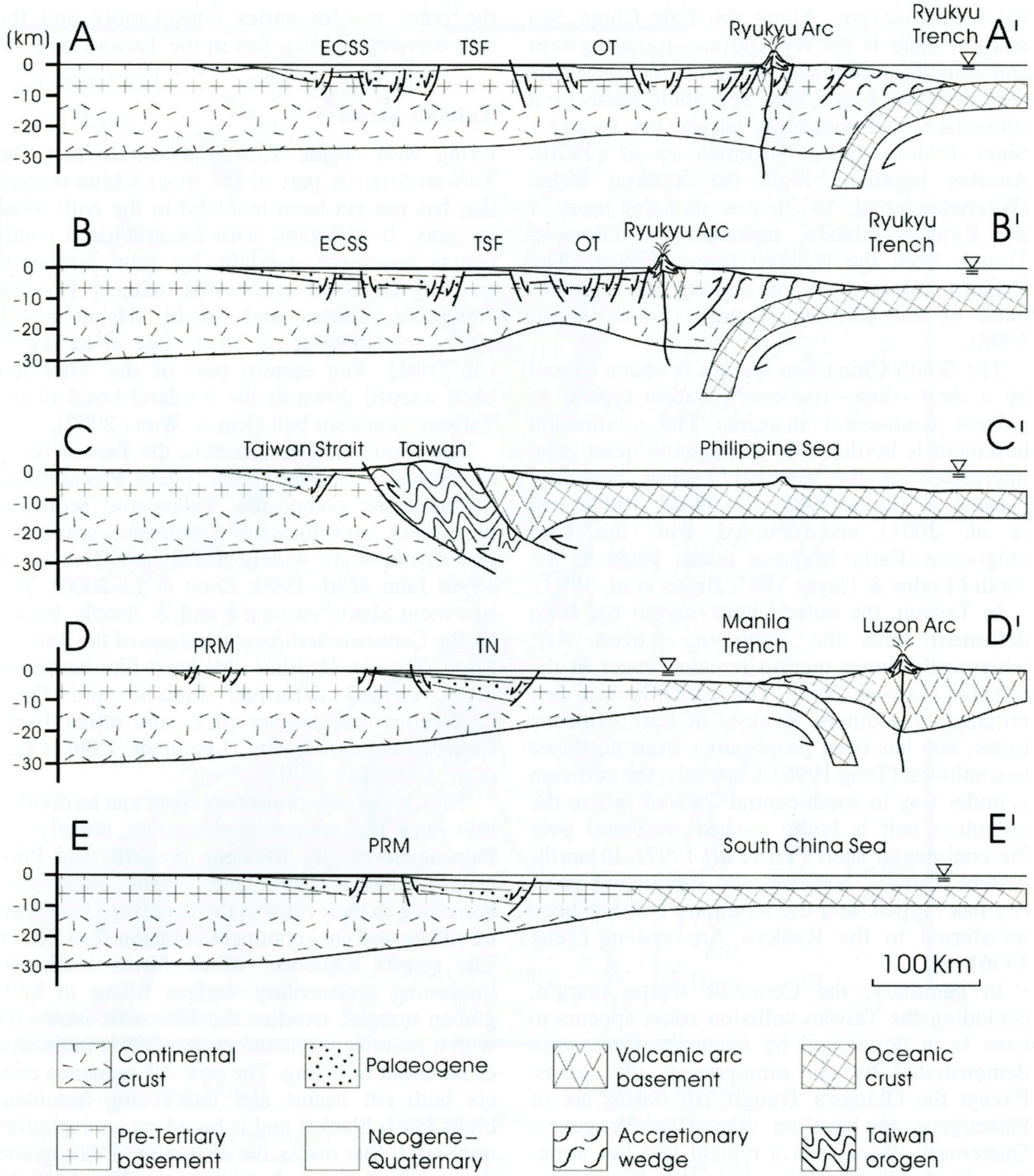

Fig. 3. Schematic cross-sections of the continental margin of China. TSF, Taiwan–Sinzi Fold-belt. Surface structures are slightly exaggerated for clarity. Locations and basic terms shown in Figure 2.

buried by 2–10 km of Late Mesozoic and Cenozoic sedimentary strata (Figs 2 & 3). The depositional basins, which largely follow the structural grains of the basement, typically exhibit a two-tier tectonostratigraphic structure (Li 1984; Yu 1994). The lower part of the sedimentary fill, composed of Palaeogene sequences, is usually ponded in narrow half-graben troughs separated by intervening basement highs. The upper part, mainly Neogene–Quaternary in age, forms a sheet-like sequence draping the horst-and-graben structures and filling in wide and shallow depressions. The only exception is the Okinawa Trough, which is a rift basin filled with Neogene–Quaternary sediments (Kimura 1985; Letouzey & Kimura 1986).

Aside from the above common features, there are prominent disparities in the outer part of the China margin. Along the East China Sea margin, there is the Ryukyu arc–trench system and associated Okinawa Trough, which is separated from the East China Sea Shelf Basin by a subsurface basement high, termed the Taiwan–Sinzi folded zone (Wageman *et al.* 1970). Another basement high, the Ryukyu Ridge (Wageman *et al.* 1970), that includes most of the Ryukyu islands, separates the Okinawa Trough from the Ryukyu fore-arc basin. The Ryukyu volcanic arc runs along the southern flank of the Okinawa Trough (Sibuet *et al.* 1998).

The South China Sea margin is characterized by a shelf–slope–rise configuration typical of passive continental margins. The continental basement is bordered by a magnetic quiet zone interpreted as the continent–ocean boundary (Taylor & Hayes 1983; Xia *et al.* 1994; Yan *et al.* 2001) and coupled with the Late Oligocene–Early Miocene ocean basin to the south (Taylor & Hayes 1983; Briais *et al.* 1993).

In Taiwan, the outer China margin has been deformed with the impinging Luzon Arc, whereas the inner margin remains intact in the offshore Taiwan Strait. The collision was first initiated in southern Ryukyu in Late Miocene times, and has been propagating from northeast to southwest (Teng 1996). Currently, the collision is under way in south-central Taiwan, where the mountain belt is being pushed westward over the continental shelf (Yu *et al.* 1997). In northeastern Taiwan, however, the subduction polarity has flipped, and the mountain belt has been transferred to the Ryukyu Arc system (Teng 1996).

In summary, the Cenozoic China margin, excluding the Taiwan collision zone, appears to have been dominated by extensional tectonics demonstrated by the omnipresent rift basins. Except the Okinawa Trough, rift basins are of Palaeogene age and are draped by Neogene–Quaternary deposits in a typical two-tier structure. In the South China Sea, this structure is believed to reflect continual rifting of the continental margin since the Late Cretaceous, that has resulted in breakaway of the outer margin and spreading of the South China Sea Basin (Halloway 1982; Taylor & Hayes 1983; Ru & Pigott 1986). The boundary between the two tiers, often referred to as the breakup unconformity, is thought to be indicative of the onset of oceanic spreading (Halloway 1982; Taylor & Hayes 1983). The breakup model, however, does not quite apply to the East China Sea margin, because no oceanic spreading has ever taken place. Hence, while the inner margin looks similar in the East and South China Seas, the outer margin varies considerably and the link between the two lies in the Taiwan area.

Taiwan Strait

Lying west of the Taiwan mountain belt, the Taiwan Strait is part of the inner China margin that has not yet been involved in the collisional orogeny. It is floored with an attenuated continental basement overlain by four northeast-trending Cenozoic rift basins, namely Penghu, Nanjihtao, Tainan and Taishi (Hsiao *et al.* 1991a, b; Chow *et al.* 1991; Lee *et al.* 1996; Lin 2001). The eastern part of the strait has been warped down as the foreland basin of the Taiwan mountain belt (Lin & Watts 2002).

The continental basement of the Taiwan Strait is exposed in coastal China, where Precambrian metamorphic complexes, Palaeozoic sedimentary strata, and Jurassic–Cretaceous granitoids and rhyolites are widely distributed (Hsü *et al.* 1990; Jahn *et al.* 1990; Zhou & Li 2000). The basement slants eastward and is deeply buried by the Cenozoic sedimentary strata of the Taiwan Strait (Fig. 4). Drilling into horst-like basement highs yielded deformed Jurassic and Early Cretaceous sedimentary rocks and minor Early Cretaceous microdiorite (Lee *et al.* 1996; Chen *et al.* 1997; Lin 2001).

The Cenozoic sedimentary cover can be divided into three tectonostratigraphic units, namely the Palaeogene synrift, Miocene post-rift, and Pliocene–Quaternary foreland basin sequences, according to their roles in the context of continental rifting and arc–continent collision (Lin 2001). The synrift sequence, which forms southeast-thickening sedimentary wedges filling in half-graben troughs, overlies the Mesozoic basement with a prominent unconformity (ROU) indicative of the onset of rifting. The post-rift sequence covers both rift basins and intervening basement highs like a blanket and is based on an unconformity (BU) that marks the cessation of rifting and the onset of thermal subsidence. The foreland sequence is a southeast-thickening sedimentary wedge accumulated in front of the collisional orogen. The boundary between the post-rift and foreland sequences is a disconformity (BFU).

The synrift sequence consists mainly of siliciclastic sedimentary strata, with subordinate amounts of volcanic rocks and carbonate. In the Penghu Basin, the synrift sequence can be further divided into two parts by an intra-rift unconformity (IRU, Fig. 5). Several boreholes penetrated the upper synrift sequence into the upper part of the lower synrift sequence, and encountered a thick sequence of marine shales intercalated with a few sandstones and volcanic layers

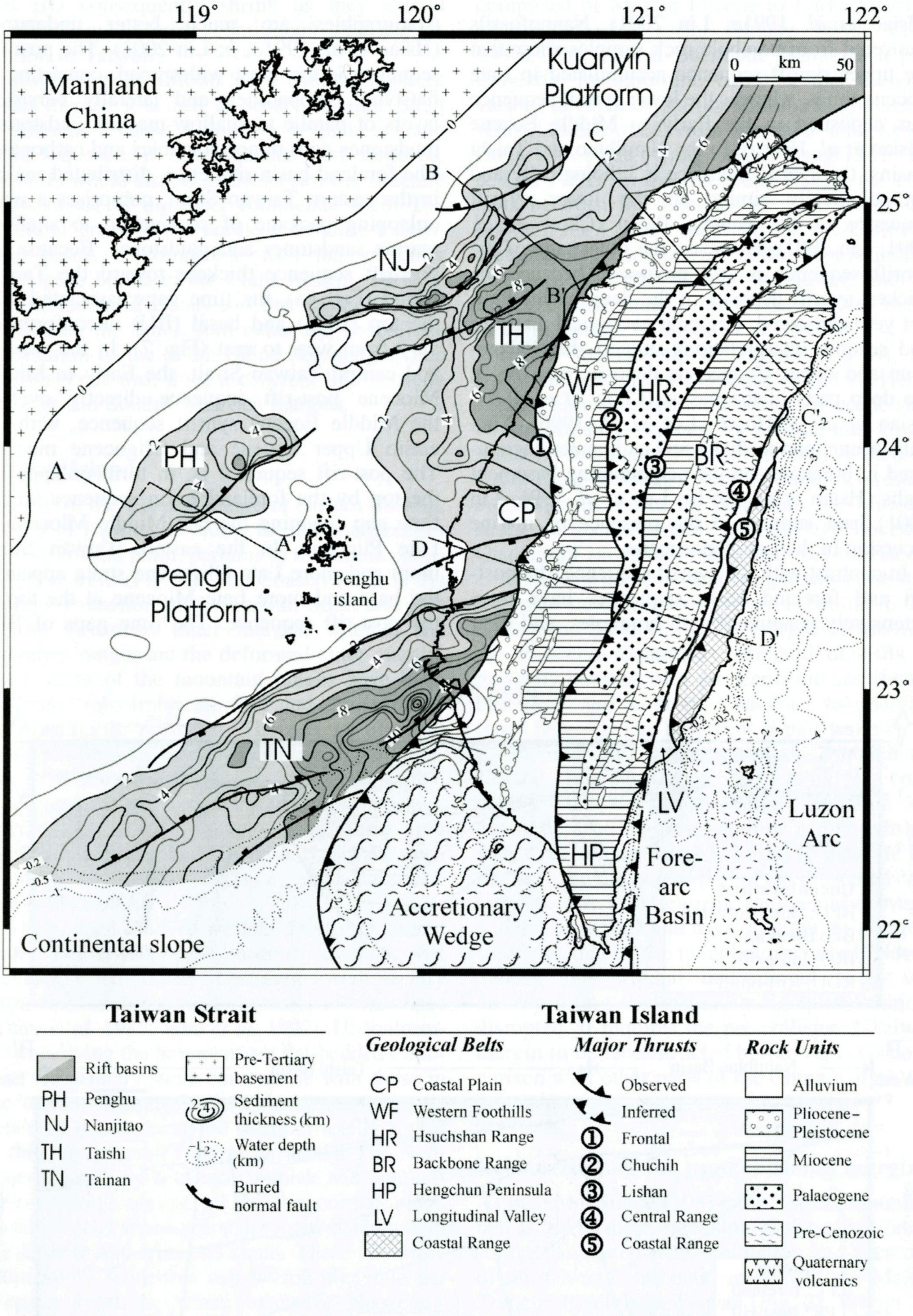

Fig. 4. Cenozoic geology of Taiwan and the Taiwan Strait. Summarized from Ho (1988), Teng (1992), Liu *et al.* (1997) and Lin (2001). Sections A–A′ and B–B′ shown in Figure 5; C–C′ and D–D′ in Figure 6.

(Hsiao *et al.* 1991*a*; Lin 2001). Nannofossils recovered from borehole rock samples show that the upper synrift sequence accumulated in Late Eocene times, whereas the lower synrift sequence was deposited in the Early to Middle Eocene (Hsiao *et al.* 1991*a*). In the Nanjihtao and Taishi Basins, the synrift sequence is lithologically and chronologically similar to the lower synrift sequence of the Penghu Basin (Chow *et al.* 1991; Lin 2001). However, the oldest age of the synrift sequence is still unknown, because the thickest synrift deposits in the deep basins have not yet been cored. Regional geological analyses and seismic interpretations suggest that Palaeocene and upper Cretaceous deposits may lie in the deep parts of the basins (Chow *et al.* 1991; Hsiao *et al.* 1991*a*, *b*; Lee *et al.* 1996). Thin Palaeocene marine shales and carbonates encountered in boreholes on the neighbouring basement highs (Hsiao *et al.* 1991*b*; Lee *et al.* 1996; Lin 2001) lend support to the presence of marine incursion in the Late Palaeocene.

In contrast with the synrift sequence, the post-rift and foreland basin sequences have been extensively penetrated with boreholes, and their stratigraphies are much better understood (Hsiao *et al.* 1991*a*, *b*; Lin 2001). The post-rift sequence is the most widespread, consisting of flat-lying, subparallel, and laterally persistent layers of paralic to shallow-marine sandstones/mudstones with minor volcanics and carbonates. The foreland basin sequence, distributed mainly in the eastern Taiwan Strait, comprises a west-onlapping package of continental to shallow-marine sandstones and mudstones. Because the post-rift sequence thickens toward the Taiwan Island (Fig. 6a), the time gaps associated with the top (BFU) and basal (BU) unconformities vary from west to east (Fig. 7). In the western and central Taiwan Strait, the Early to Middle Miocene post-rift sequence directly overlies the Middle Eocene synrift sequence, with the entire Upper Eocene and Oligocene missing. The post-rift sequence is, in turn, onlapped at the top by the foreland basin sequence with a time gap spanning the late Middle Miocene to Late Pliocene. In the eastern Taiwan Strait, more and more Late Oligocene strata appear at the base and more Late Miocene at the top of the post-rift sequence. The time gaps of BFU

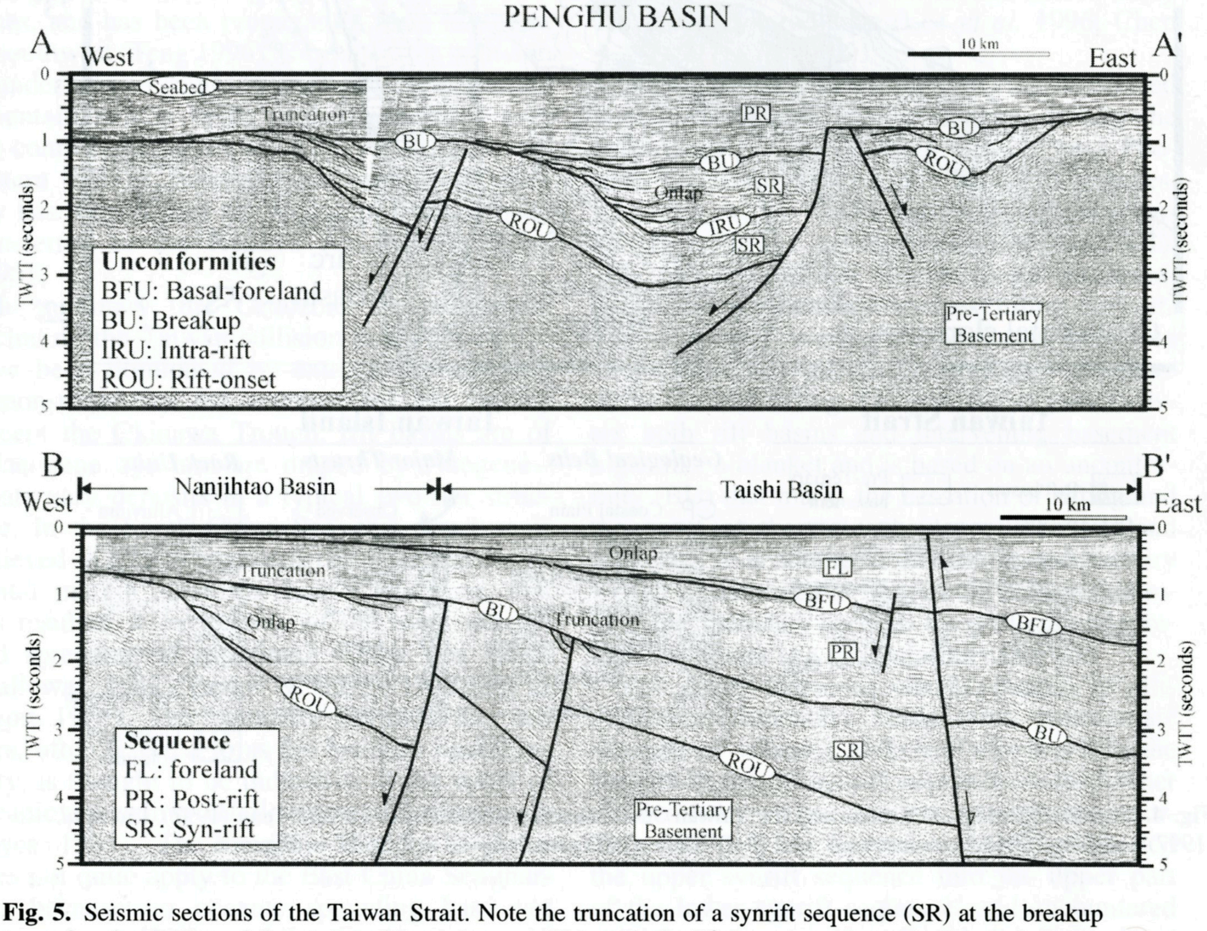

Fig. 5. Seismic sections of the Taiwan Strait. Note the truncation of a synrift sequence (SR) at the breakup unconformity (BU), and the structural inversion near Taiwan in B–B′. Locations shown in Figure 4; stratigraphy detailed in Figure 7. Modified from Lin (2001).

and BU consequently shrink as they extend eastward into a more continuous stratigraphic section in Taiwan.

Comparing the Taiwan Strait with the adjacent China margin, it is easy to observe that the Strait is different because it contains a thick foreland basin sequence. If that sequence were removed, the Strait would display a distinct two-tier structure characteristic of the inner continental shelf. The structural grain of the northeast-trending Palaeogene basins is compatible with that of other Palaeogene basins in the China margin. There is no tectonic break of any sort that can be invoked to separate the Strait from either the East China Sea margin or the South China Sea margin. The Taiwan Strait was, thus, a coherent link between the East and South China Sea margins.

Taiwan Island

Except for the Coastal Range of eastern Taiwan, the rest of Taiwan, including the mountain ranges and the coastal plain, pertains to the China continental margin (Fig. 4). The Coastal Plain is the onshore extension of the Taiwan Strait and part of the unscathed inner margin, whereas the mountain ranges are the deformed outer margin. Rock strata of the mountain ranges have been deformed into imbricate fold and thrust sheets trending north–northeast. There is an obvious, albeit progressive, eastward increase in the intensity of structural deformation, the metamorphic grade and the stratigraphic age (Fig. 6), which warrants division of the mountain ranges into three lithotectonic belts – namely the Western Foothills, Hsuehshan Range and Backbone Range (Ho 1988).

The Coastal Plain of western Taiwan is floored with a subsurface pre-Cenozoic basement that includes tilted Lower Cretaceous sedimentary sequences and Permian crystalline limestones (Yuan *et al.* 1985; Jahn *et al.* 1992). Unconformably overlying the basement are flat-bedded Cenozoic sedimentary strata comparable with those in the eastern Taiwan Strait. Palaeogene strata are generally thin and may be partly or totally absent at different places (Yuan *et al.* 1985). The Neogene–Quaternary sequence is thick and continuous, covering almost all of the coastal plain. Basaltic rocks are occasionally intercalated within the Eocene and Miocene strata. These Cenozoic sedimentary sequences can be followed into the Western Foothills, where extensive Neogene–Quaternary strata crop out. Oligocene and older sequences are sporadically exposed, but have been widely sampled by drilling (Chiu 1975).

The Hsuehshan Range and neighbouring western Backbone Range constitute a slate terrane composed of Middle Eocene to Early Miocene metasedimentary rocks (Huang 1980; Chou 1990). The eastern Backbone Range is a pre-Cenozoic metamorphic complex that includes various kinds of crystalline limestone, gneiss and schist, transformed from Permian and Lower Cretaceous strata (Wang Lee & Wang 1987; Yui & Lan 1991). In the Backbone Range, the contacts between the Eocene–Miocene slates and between the Eocene slate and the pre-Cenozoic metamorphic complex are both unconformable. In places the entire Eocene is missing, and the Miocene slate may directly overlie the metamorphic complex (Suppe *et al.* 1976).

In the southern tip of Taiwan (Fig. 4), the Backbone Range plunges south toward the Hengchung Peninsula, and the Eocene–Miocene slate is conformably overlain by Middle and Upper Miocene sedimentary strata (Pelletier & Stephan 1986; Sung & Wang 1986). Around the western and southern rim of the peninsula, the Miocene strata are unconformably overlain by Pliocene–Quaternary sandstone–shale and reef limestone.

In spite of the structural complexities, the stratigraphic architecture of Taiwan is similar to that of East and South China Sea margins, aside from the Pliocene–Quaternary foreland deposits. It basically consists of a pre-Cenozoic continental basement and a thick Cenozoic sedimentary cover (Fig. 7). The basement is partly shown by the Permian and Cretaceous rocks beneath the Coastal Plain and the coeval metamorphic complex in the Backbone Range. Although not exposed in the Western Foothills and Hsuehshan Range, the basement is believed to underlie the whole mountain belt as part of the thickened continental crust. The Cenozoic sedimentary cover is widely distributed and has a stratigraphy comparable with that of the neighbouring areas. Nevertheless, the original depositional basin was destroyed and the tectonostratigraphic relations disrupted. It requires the pre-collisional Taiwan margin to be reconstructed before *vis-à-vis* comparison with other parts of the China margin can be made.

Reconstructing the pre-collisional margin

As noted by Suppe (1981), the Taiwan mountain belt is the onshore extension of the accretionary wedge associated with subduction and accretion of the China continental margin at the Manila Trench off southern Taiwan (Fig. 2). Within the wedge, rock strata of the continental margin are compressively deformed and stacked as imbricate thrust sheets (Fig. 6). The wedge expands from south to north and may reach a steady state in north-central Taiwan with constant

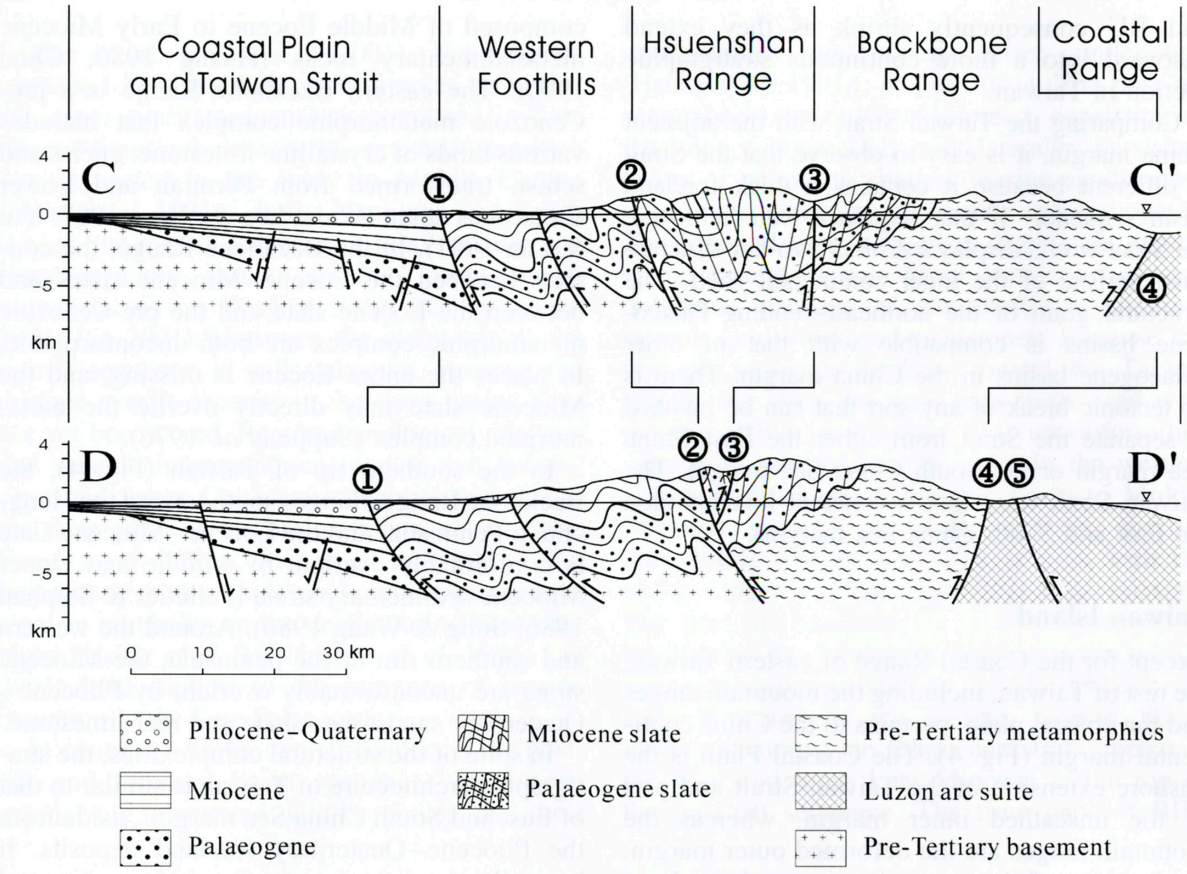

Fig. 6. Geological framework and lithotectonic belts of Taiwan. Locations and major thrusts 1–5 shown in Figure 4. Summarized from Ho (1988), Teng *et al.* (1991) and Lin (2001).

width and height. In the steady-state mountain belt, the geological characteristics also seem to have attained an equilibrium state exhibited by persistence of structural and stratigraphic features along strike (Fig. 4).

To reconstruct the pre-collisional continental margin in Taiwan, it is necessary to first undo the contractional deformation incurred during the accretionary process (Fig. 8A). Using the theory of fault-bend folding, Suppe (1980) constructed a retrodeformable section, near C-C′ in Figure 4, across the northern Taiwan mountain belt (Fig. 8B), in which each thrust sheet of the Western Foothills and Hsuehshan Range can be geometrically delineated. By untangling the imbricate fold-and-thrust structures, Suppe was able to relocate each thrust sheet to its predeformational position and obtain a 120-km shortening for the Western Foothills and Hsueshan Range (Fig. 8C). This reconstruction, although involving some assumptions and uncertainties, provides a good first approximation of the structural deformation caused by collisional orogeny.

Following Suppe's retrodeformable section, Teng *et al.* (1991) established a stratigraphic section across northern Taiwan, based on six Tertiary stratigraphic columns (Fig. 8D). Each column in the Western Foothills and Hsuehshan Range can be restored to its precollisional position according to Suppe's reconstruction. When restored to a key Middle Miocene horizon, the stratigraphic section shows a distinct two-tier structure with a Miocene drape-like sequence covering a Palaeogene rift basin. Although established only for northern Taiwan, this stratigraphic section can probably apply to the entire mountain belt. The reconstructed Palaeogene half-graben basin, named the Hsuehshan Trough by Teng *et al.* (1991), clearly demonstrates that the Taiwan mountain belt was indeed part of the rifting China margin before collision.

Put together with the rift basins of the Taiwan Strait, it is easy to see that the western Hsuehshan Trough overlaps the Taishi Basin in the eastern Taiwan Strait (Fig. 4), and the Palaeogene sequence of the Taishi Basin (Fig. 5A) may well be part of the synrift deposits in the Hsuehshan Trough. The precollisional margin of Taiwan seems to have comprised two lines of Palaeogene rift basins (Fig. 9B). The inner margin basins, including Penghu and Nanjihtao, formed in Palaeocene to Middle Eocene times.

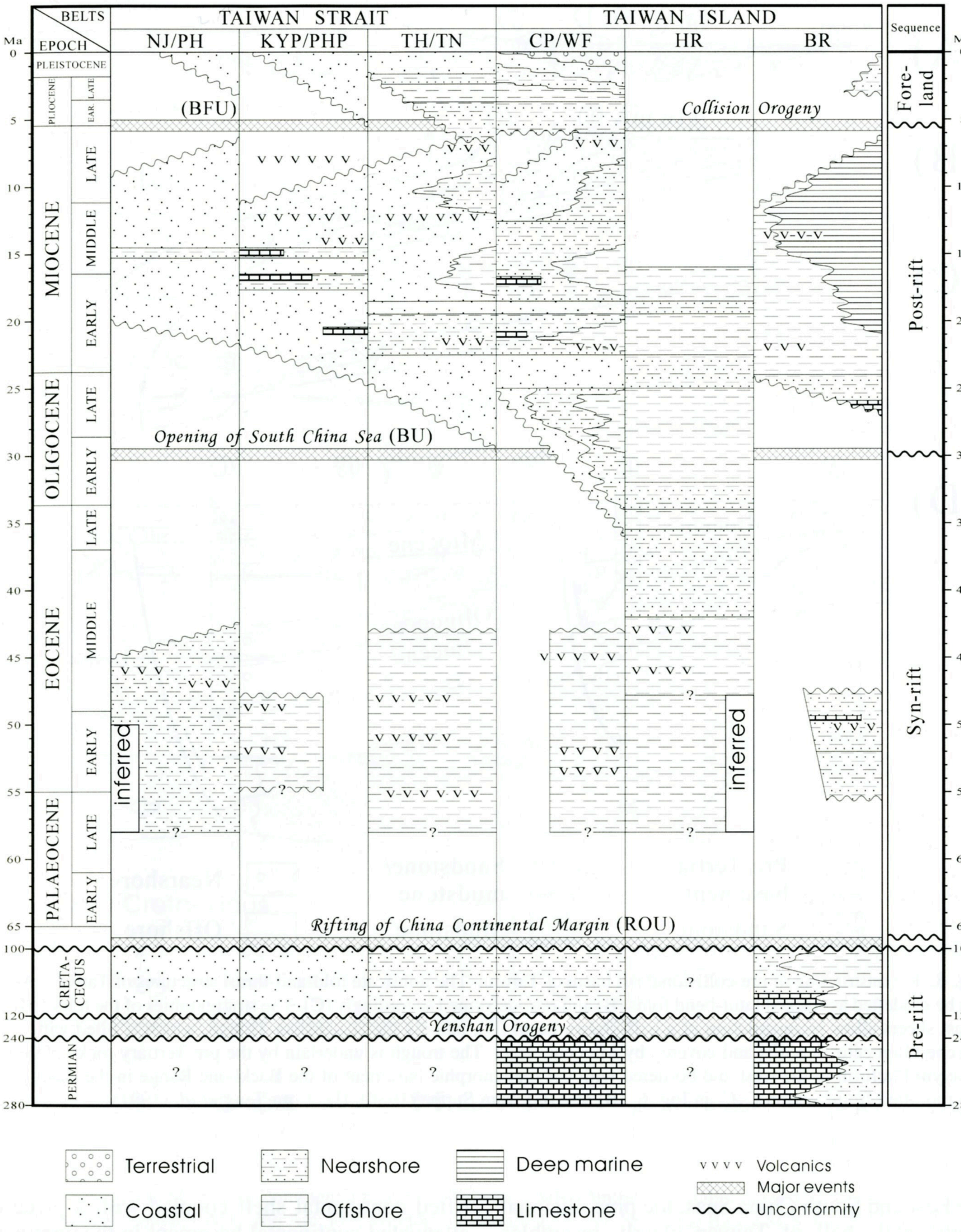

Fig. 7. Reconstructing the pre-collisional rift basin of Taiwan. The imbricate fold-and-thrust structures of Taiwan (A) can be modeled as stacked fault-bend folds (B)and retrodeformed accordingly (C). The stratigraphies of the relocated thrust sheets allow reconstruction of a half-graben basin (D), namely the Hsuehshan Trough, which is filled with Eocene-Oligocene deposits and covered by Miocene strata. The Trough is underlain by the pre-Tertiary rocks of the Kuany Platform in the west and bordered with the metamorphic basement of the Backbone Range in the east. (A) modified from section C-C′ in Fig. 6; (B) and (C) from Suppe (1980); (D) from Teng *et al.* (1991).

The outer margin basins, like the Hsuehshan Trough and Tainan Basin, may continue to develop into the Oligocene. Because the Palaeogene basin-fill and Miocene cover sequences are both composed of coastal to shallow-marine deposits (Chou 1973, 1990; Teng *et al.* 1991; Lin 2001), these rift basins must have been positioned in the continental shelf. Compared with

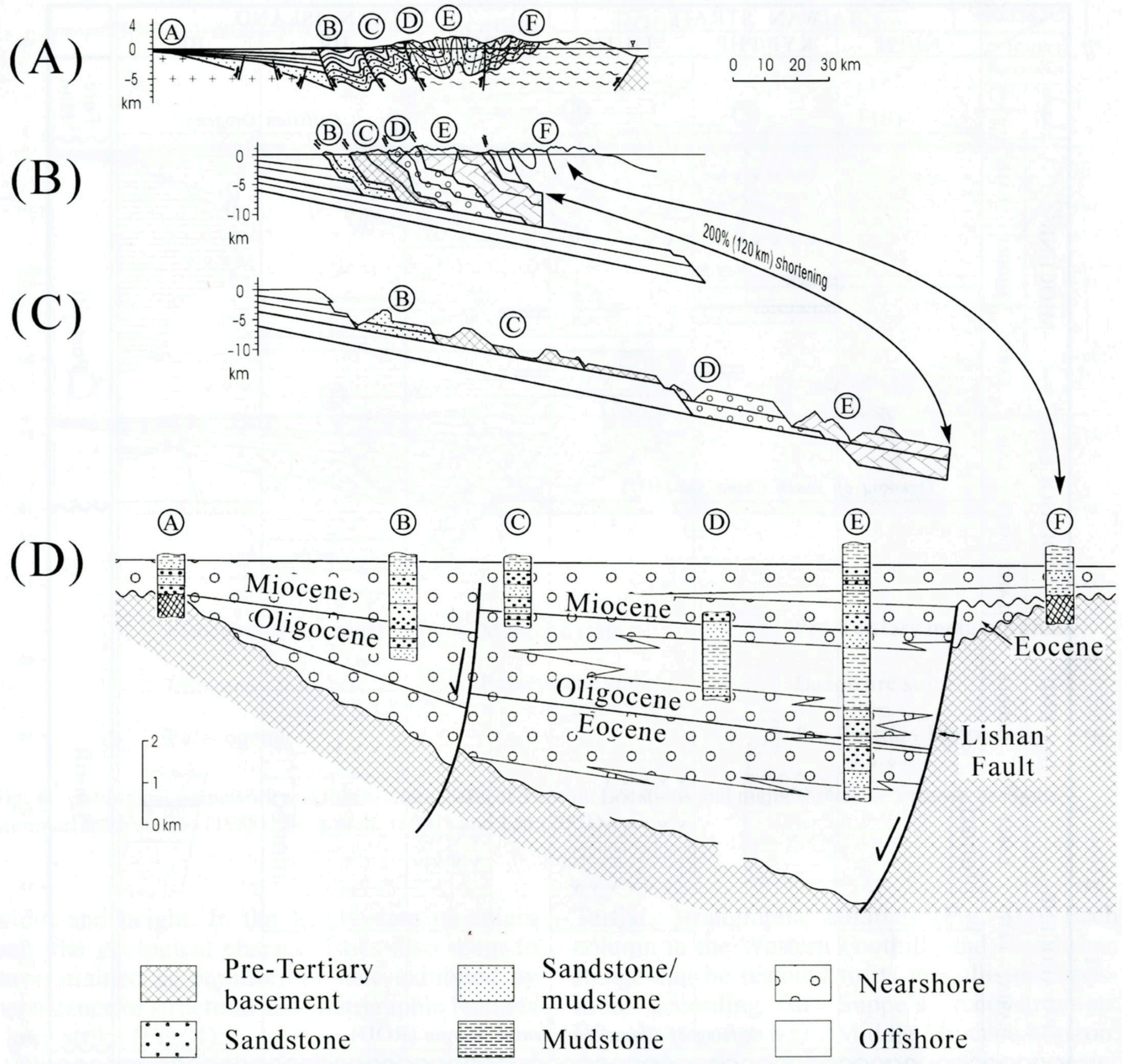

Fig. 8. Reconstructing of pre-collisional rift basin of Taiwan. The imbricate fold-and-thrust structures of Taiwan (A) can be modelled as stacked fault-bend folds (B) and retrodeformed accordingly (C). The stratigraphies of the relocated thrust sheets allow reconstruction of a half-graben basin (D), namely the Hsuehshan Trough, which is filled with Eocene-Oligocene deposits and covered by Miocene strata. The trough is underlain by the pre-Tertiary rocks of the Kuanyin Platform in the west and bordered with the metamorphic basement of the Backbone Range in the east. (A) modified from section C–C′ in Fig. 6; (B) and (C) from Suppe (1980); (D) from Teng *et al.* (1991).

the East and South China Seas, the precollisional continental shelf of Taiwan clearly resembles that of the South China Sea characterized by two lines of Palaeogene rift basins rather than the East China Sea marked by the Late Neogene Okinawa Trough (Fig. 3). This suggests that Taiwan was part of the South China Sea margin before collision.

In accordance with the morphotectonic configuration of the passive South China Sea margin, a more complete precollisional margin of Taiwan can be reconstructed by disentangling the collisional orogen. The margin is featured with a rifted continental shelf coupled with a piece of attenuated continental basement in the continental slope and a deep ocean basin (Fig. 9B). The Coastal Range of eastern Taiwan can be easily moved to a position >500 km to the southeast (Teng 1990) by backtracking the 5–10 cm/year motion of the Luzon Arc and underlying Philippine Sea plate in the past 10 Ma (Seno & Maruyama 1984; Hall *et al.* 1995). The reconstructed tectonic scenario looks very similar to the one just in front of the collision zone off southwestern Taiwan (Fig. 3D). During the course of collision, the attenuated continental

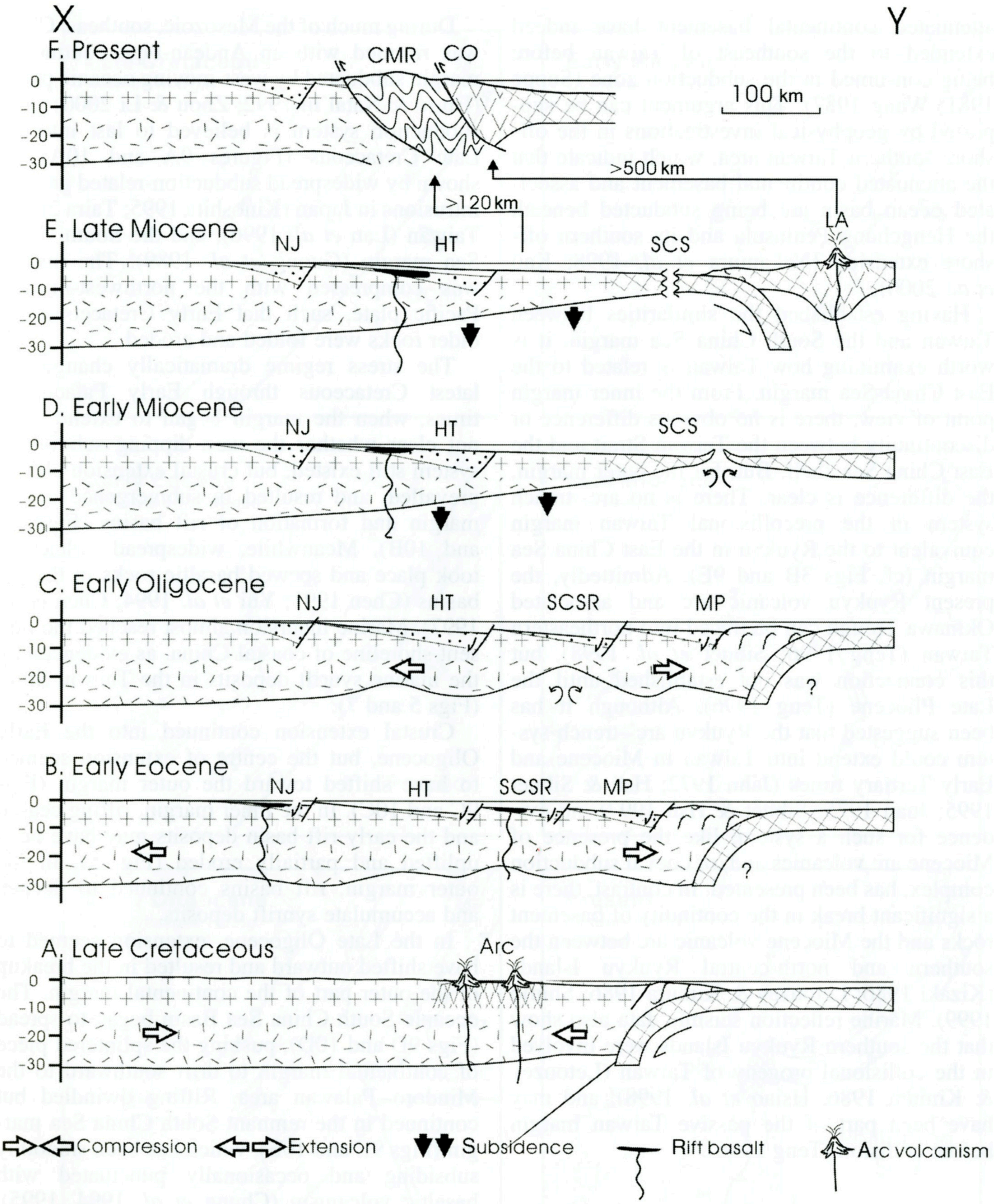

Fig. 9. Reconstructed Cenozoic continental margin of Taiwan. CMR, Central mountain ranges; CO, Coastal Range; HT, Hsuehshan Trough; LA, Luzon Arc; MP, Mindoro–Palawan block; NJ, Nanjihtao Basin; SCS, South China Sea Basin; SCSR, South China Sea rift. Symbols are the same as Figure 3.

basement and associated ocean basin would have been successively pulled into the subduction zone and would have become invisible on the surface. However, ophiolitic blocks akin to the oceanic South China Sea Basin have been found in the mélange deposit of the Coastal Range (Suppe 1981), and continental slope deposits that overlay the attenuated continental basement are widely distributed in the Hengchung Peninsula (Pelletier & Stephan 1986; Sung & Wang 1986). These lines of evidence suggest that the South China Sea Basin and the attenuated continental basement have indeed extended to the southeast of Taiwan before being consumed in the subduction zone (Suppe 1981; Wang 1987). This argument can be supported by geophysical investigations in the offshore southern Taiwan area, which indicate that the attenuated continental basement and associated ocean basin are being subducted beneath the Hengchung Peninsula and its southern offshore extension (Nakamura *et al.* 1998; Kao *et al.* 2000).

Having established the similarities between Taiwan and the South China Sea margin, it is worth examining how Taiwan is related to the East China Sea margin. From the inner margin point of view, there is no obvious difference or discontinuity between the Taiwan Strait and the East China Sea shelf. But, for the outer margin, the difference is clear. There is no arc–trench system in the precollisional Taiwan margin equivalent to the Ryukyu in the East China Sea margin (cf. Figs 3B and 9E). Admittedly, the present Ryukyu volcanic arc and associated Okinawa Trough can be traced into northeastern Taiwan (Teng 1996; Sibuet *et al.* 1998), but this connection was not established until the Late Pliocene (Teng 1996). Although it has been suggested that the Ryukyu arc–trench system could extend into Taiwan in Miocene and Early Tertiary times (Jahn 1972; Hsü & Sibuet 1995; Juan 1975; Sibuet & Hsü 1997), no evidence for such a system, like the presence of Miocene arc volcanics and/or coeval subduction complex, has been presented. In contrast, there is a significant break in the continuity of basement rocks and the Miocene volcanic arc between the southern and north-central Ryukyu Islands (Kizaki 1986; Letouzey & Kimura 1986; Shinjo 1999). Marine reflection seismic data also show that the southern Ryukyu Islands were involved in the collisional orogeny of Taiwan (Letouzey & Kimura 1986; Hsiao *et al.* 1998), and may have been part of the passive Taiwan margin before collision (Teng 1996).

Tectonic evolution

Given the reconstructed pre-collisional continental margin of Taiwan and relevant tectonostratigraphic data (Figs 7 and 9E), it is possible to establish the Cenozoic evolutionary history of the margin by successively stripping off the sedimentary strata and restoring the extensional deformation (Fig. 9 A–E). Since Taiwan was part of the South China Sea margin, the interpretations will be made in the context of South China Sea tectonics (Fig. 10). The East China Sea margin will be discussed separately.

During much of the Mesozoic, southeast China was rimmed with an Andean-type continental margin subducted by west-moving oceanic plates (Faure & Natal'in 1992; Zhou & Li 2000). This subduction system is believed to last into the Late Cretaceous (Figures 9A and 10A), as shown by widespread subduction-related granitic intrusions in Japan (Kinoshita 1995; Taira 2001), Taiwan (Lan *et al.* 1996), and the South China Sea margin (Guong *et al.* 1989). The margin was compressed with the northwest-moving Pacific plate, such that Early Cretaceous and older rocks were folded and eroded.

The stress regime dramatically changed in latest Cretaceous through Early Palaeocene times, when the margin began to extend. It is not clear whether the west-dipping subduction system still existed, but crustal extension clearly prevailed, and resulted in submergence of the margin and formation of rift basins (Figs 9B and 10B). Meanwhile, widespread volcanism took place and spewed basaltic rocks in the rift basins (Chen 1991; Yui *et al.* 1994; Chen *et al.* 1997). Marine incursion almost reached the present shoreline of coastal China, as evidenced by the marine synrift deposits in the Taiwan Strait (Figs 5 and 7).

Crustal extension continued into the Early Oligocene, but the centre of extension seemed to have shifted toward the outer margin (Figs 9C and 10C). In the inner margin, rifting ceased and the early rift basin deposits may have been uplifted and partially eroded (Fig. 5). In the outer margin, rift basins continued to deepen and accumulate synrift deposits.

In the Late Oligocene, extension seemed to have shifted outward and resulted in the breakup of the outer part of the continental margin. The oceanic South China Sea Basin began to spread (Figs 9D and 10D), pushing the splintered piece of continental margin to drift southward to the Mindoro–Palawan area. Rifting dwindled but continued in the remnant South China Sea margin (Figs 9E and 10E), which has been smoothly subsiding and occasionally punctuated with basaltic volcanism (Chung *et al.* 1994, 1995). This passive margin presently persists in offshore Guangdong (Fig. 3E), but, in Taiwan, it was tectonized by the impinging Luzon Arc (Figs 9F and 10F).

The Late Cretaceous to Early Tertiary history of the East China Sea margin was probably similar (Maruyama *et al.* 1997; Taira 2001), characterized by westward subduction of the Pacific plate, followed by regional extension (Fig. 10A, B). However, as the South China Sea began to open in Oligocene times (Fig. 10C), the East China Sea margin did not

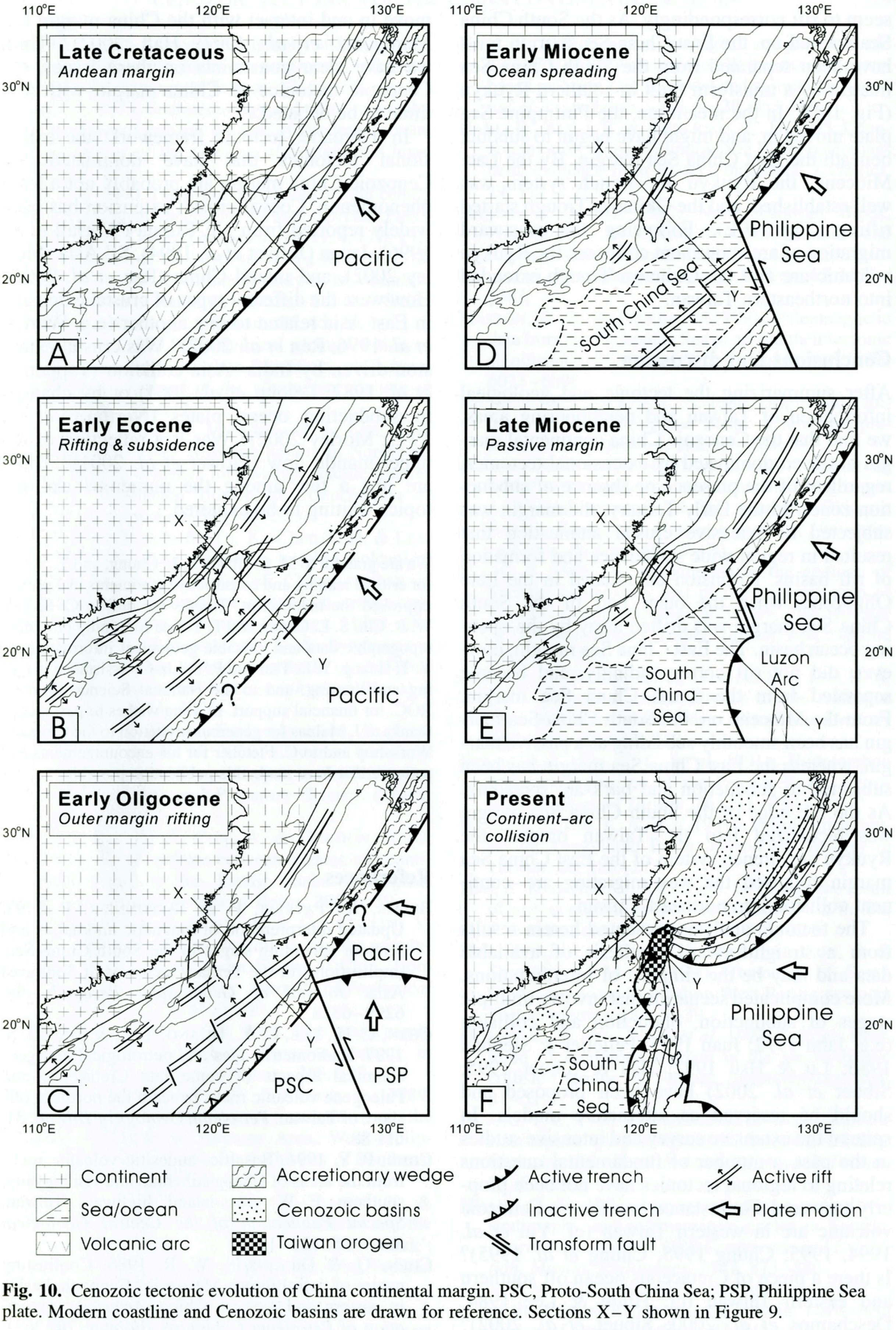

Fig. 10. Cenozoic tectonic evolution of China continental margin. PSC, Proto-South China Sea; PSP, Philippine Sea plate. Modern coastline and Cenozoic basins are drawn for reference. Sections X–Y shown in Figure 9.

seem to rift correspondingly. As the South China Sea opened up, the East China Sea margin must have been separated from the South China Sea margin by a transform fault in southern Ryukyu (Fig. 10D). In the meantime, the Philippine Sea plate moved in, and might have begun to subduct beneath the East China Sea margin. By the Late Miocene, the Ryukyu arc–trench system was well established, and the Okinawa Trough started rifting (Fig. 10E). Following the westward migration of arc–continent collision, the Ryukyu volcanic arc and the Okinawa Trough extended into northeastern Taiwan.

Conclusions and discussion

After summarizing the tectonic and geological information of Taiwan and neighbouring areas, we find that the Cenozoic China continental margin has been dominated by extensional tectonics, regardless of the presence or absence of subduction zones. In the Early Tertiary, the margin was subjected to extensive crustal attenuation that resulted in region-wide subsidence and formation of rift basins. Extension culminated in the Late Oligocene, when the outer part of the South China Sea margin was drifted away by the opening ocean basin. The East China Sea margin, however, did not rift correspondingly, and became separated from the South China Sea margin. From the Miocene on, the South China Sea margin has been smoothly subsiding as a passive margin, whereas the East China Sea margin has been subjected to subduction and back-arc spreading. As the NE edge of the South China Sea margin was tectonized into the Taiwan orogen, the Ryukyu arc–trench system of the East China Sea margin followed the west-migrating arc–continent collision into northeast Taiwan.

The tectonic analysis presented herein results from a straightforward synthesis of available data and may be the simplest of interpretations. More complicated scenarios that involve multiple stages of subduction, obduction and collision (e.g. Jahn 1972; Juan 1975; Pelletier & Stephan 1986; Lu & Hsü 1992; Hsü & Sibuet 1995; Sibuet *et al.* 2002) have been proposed and should be reserved as alternative models. In spite of the extensive survey and intensive studies in the past, a number of fundamental questions relating to regional tectonics have not been properly answered. For instance, was there a Cenozoic volcanic arc in western Taiwan (cf. Yui *et al.* 1994, 1995; Chung 1995; Chung *et al.* 1995)? Is there a piece of Cretaceous ocean off southern and eastern Taiwan (cf. Hilde & Lee 1984; Deschamps *et al.* 2000; Sibuet *et al.* 2002)? When and how did the Philippine Sea plate move in and interact with the China margin (cf. Maruyama *et al.* 1997; Hall 2002)? Until we have clear constraints on these issues, the Cenozoic tectonics of China margin will continue to be debated.

In a broader tectonic framework, the extensional tectonics that have dominated the Cenozoic China margin are probably not a local phenomenon. Coeval crustal extension has been widely reported from NE Russia (Worrall *et al.* 1996), Japan (Jolivet *et al.* 1994), SE Asia (Morley 2002), and inland China (Ren *et al.* 2002). How were the different types of crustal extension in East Asia related to one another (e.g. Worrall *et al.* 1996; Ren *et al.* 2002)? Was crustal extension driven by India–Asia collision (Tapponier *et al.* 1982; Leloup *et al.* 2001) or by changes in subducting ocean plates (Northrop *et al.* 1995; Morley 2002)? Was it a reflection of the upper-mantle flow (Flower *et al.* 2001)? These are just a few among the numerous exciting topics waiting to be explored.

We are grateful to M. C. Blake, S. L. Chung, and T. Y. Lee for critical reading and constructive comments that greatly improved the manuscript. Thanks are due to C. S. Liu, W. R. Chi, S. L. Chung and T. Y. Lee for kindly providing topographic data and valuable geological information, to Y. T. Huang, Y. L. Tsai and P. Y. Lin for assistance in typing and drafting, and to the National Science Council, ROC, for financial support. L. Teng wishes to pay special thanks to J. Malpas for generous invitation to the Croucher Workshop and to C. Fletcher for his encouragements and patience that have made this publication possible.

References

BRIAIS, A., PATRIAT, P. & TAPPONNIER, P. 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: implications for the Tertiary tectonics of Southeast Asia. *Journal of Geophysical Research*, **98**, 6299–6328.

CHEN, C. H., LEE, C. Y., HUANG, T. C. & TING, J. S. 1997. Radiometric ages and petrological and geochemical aspects of some late Cretaceous and Paleogene volcanic rocks beneath the northern offshore of Taiwan. *Petroleum Geology of Taiwan*, **31**, 61–88.

CHEN, P. Y. 1991. Basaltic–andesitic volcanic rocks from the areas of Changshihchiao and Hsiangyang, southern E–W cross-island highway, Taiwan. *Special Publication of the Central Geological Survey*, **5**, 127–159.

CHEN, Q. & DICKINSON, W. R. 1986. Contrasting nature of petroliferous Mesozoic–Cenozoic basins in eastern and western China. *American Association of Petroleum Geologists Bulletin*, **70**, 263–275.

Chiu, H. T. 1975. Miocene stratigraphy and its relation to the Paleogene rocks in west-central Taiwan. *Petroleum Geology of Taiwan*, **12**, 51–80.

Chou, J. T. 1973. Sedimentology and paleogeography of the Upper Cenozoic System of Western Taiwan. *Proceedings of the Geological Society of China*, **16**, 111–143.

Chou, J. T. 1990. Paleogene formations of the central and Hsuehshan ranges in Taiwan. *Special Publication of the Central Geological Survey*, **4**, 177–192.

Chow, J., Chen, H. M., Chang, T. Y., Kuo, C. L. & Tsai, S. F. 1991. Preliminary study on hydrocarbon plays around Nanjihtao Basin, Taiwan Strait. *Petroleum Geology of Taiwan*, **26**, 45–56.

Chung, S. L. 1995. Geochemical characteristics of metabasites from the slate formations of Taiwan: discussion. *Journal of the Geological Society of China*, **38**, 173–177.

Chung, S. L., Jahn, B. M., Chen, S. J., Lee, T. & Chen, C. H. 1995. Miocene basalts in Northwestern Taiwan: evidence for EM-type mantle sources in the continental lithosphere. *Geochimica et Cosmochimica Acta*, **59**, 549–555.

Chung, S. L., Sun, S. S., Tu, K., Chen, C-H. & Lee, C. Y. 1994. Late Cenozoic basaltic volcanism around the Taiwan Strait, SE China: product of lithosphere–asthenosphere interaction during continental extension. *Chemical Geology*, **112**, 1–20.

Deschamps, A., Lallemand, S. & Dominguez, S. 1999. The last spreading episode of the West Philippine Basin revisited. *Geophysical Research Letters*, **26**, 2073–2076.

Deschamps, A., Monie, P., Lallemand, S., Hsü, S. K. & Yeh, K. Y. 2000. Evidence for Early Cretaceous oceanic crust trapped in the Philippine Sea Plate. *Earth and Planetary Science Letters*, **179**, 503–516.

Engebretson, D. C., Cox, A. & Gordon, R. G. 1985. Relative motions between oceanic and continental plates in the Pacific basin. *Geological Society of America, Special Paper*, **206**, p. 59.

Enkin, R., Yang, Z., Chen, Y. & Courtillot, V. 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present. *Journal of Geophysical Research*, **97**, 13 953–13 989.

Faure, M. & Natal'in, B. 1992. The geodynamic evolution of the eastern Eurasian margin in Mesozoic times. *Tectonophysics*, **208**, 397–411.

Faure, M., Marchadier, Y. & Rangin, C. 1989. Pre-Eocene synmetamorphic structure in the Mindoro–Romblon–Palawan Area, West Philippines, and implications for the history of Southeast Asia. *Tectonics*, **8**, 963–979.

Flower, M. F. J., Russo, R. M., Tamaki, K. & Hoang, N. 2001. Mantle contamination and the Izu–Bonin–Mariana (IBM) 'high-tide mark': evidence for mantle extrusion caused by Tethyan closure. *Tectonophysics*, **333**, 9–34.

Guong, Z., Jin, Q., Qiu, Z., Wang, S. & Meng, J. 1989. Geology, tectonics and evolution of the Pearl River Mouth Basin. *In*: Zhu, X. (ed.) *Chinese Sedimentary Basins*. Elsevier, Amsterdam, 181–196.

Hall, R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. *Journal of Asian Earth Sciences*, **20**, 353–431.

Hall, R., Ali, J. R. & Anderson, C. D. 1995. Cenozoic motion of the Philippine Sea Plate: paleomagnetic evidence from Eastern Indonesia. *Tectonics*, **14**, 1117–1132.

Halloway, N. H. 1982. North Palawan Block, Philippines – its relation to Asian Mainland and role in evolution of South China Sea. *American Association of Petroleum Geologists Bulletin*, **63**, 1355–1383.

Haston, R. B. & Fuller, M. 1991. Paleomagnetic data from the Philippine Sea plate and their tectonic significance. *Journal of Geophysical Research*, **96**, 6073–6098.

Hilde, T. W. C. & Lee, C. S. 1984. Origin and evolution of West Philippine Basin: a new interpretation. *Tectonophysics*, **102**, 85–104.

Hirata, N., Kinoshita, H. *et al.* 1991. Report on DELP 1988 cruises in the Okinawa Trough, part 3. Crustal structure of the southern Okinawa Trough. *Earthquake Research Institute, University of Tokyo, Bulletin*, **66**, 37–70.

Ho, C. S. 1988. An introduction to the geology of Taiwan: explanatory text of the geologic map of Taiwan. *Central Geological Survey, The Ministry of Economic Affairs, Taipei, Taiwan, ROC*, second edition, p. 192.

Hsiao, L. Y., Huang, S. T., Teng, L. S. & Lin, K. A. 1998. Structural characteristics of the Southern Taiwan–Sinzi Folded Zone. *Petroleum Geology of Taiwan*, **32**, 133–153.

Hsiao, P. T., Hu, C. C. *et al.* 1991*a*. Hydrocarbon potential evaluation of the Penghu Basin. *Petroleum Geology of Taiwan*, **26**, 215–230.

Hsiao, P. T., Lin, K. A. *et al.* 1991*b*. Petroleum appraisal on Tungyintao Basin. *Petroleum Geology of Taiwan*, **26**, 183–213.

Hsü, S. K. & Sibuet, J.-C. 1995. Is Taiwan the result of arc–continent or arc–arc collision? *Earth and Planetary Science Letters*, **136**, 315–324.

Hsü, K. J., Li, J., Chen, H., Wang, Q., Sun, S. & Sengör, A. M. C. 1990. Tectonics of South China: key to understanding West Pacific geology. *Tectonophysics*, **183**, 9–39.

Huang, C. Y., Wu, W. Y. *et al.* 1997. Tectonic evolution of accretionary prism in the arc–continent collision terrane of Taiwan. *Tectonophysics*, **281**, 31–51.

Huang, T. C. 1980. Calcareous nannofossils from the slate terrane West of Yakou, Southern Cross-Island Highway, Taiwan. *Petroleum Geology of Taiwan*, **17**, 59–74.

Huang, T. C. 1982. Tertiary calcareous nannofossil stratigraphy and sedimentation cycles in Taiwan. *Proceedings 2nd ASCOPE Conference and Exhibition, Manila, Philippines, 1981*, 873–886.

Jahn, B. M. 1972. Reinterpretation of geologic evolution of the Coastal Range, eastern Taiwan. *Geological Society of America Bulletin*, **83**, 241–247.

Jahn, B. M., Chi, W. R. & Yui, T. F. 1992. A late Permian formation of Taiwan (marbles from Chia-Li well No.1): Pb–Pb isochron and Sr isotopic evidence, and its regional geological significance. *Journal of the Geological Society of China*, **35**, 193–218.

JAHN, B. M., ZHOU, X. H. & LI, J. L. 1990. Formation and tectonic evolution of Southeastern China and Taiwan: isotopic and geochemical constraints. *Tectonophysics*, **183**, 145–160.

JOLIVET, L., TAMAKI, K. & FOURNIER, M. 1994. Japan Sea, opening history and mechanism: a synthesis. *Journal of Geophysical Research*, **99**, 22 237–22 259.

JUAN, V. C. 1975. Tectonic evolution of Taiwan. *Tectonophysics*, **26 (3–4)**, 197–212.

KAO, H., HUANG, G. C. & LIU, C. S. 2000. Transition from oblique subduction to collision in the Northern Luzon Arc–Taiwan region: constraints from bathymetry and seismic observation. *Journal of Geophysical Research*, **105**, 3059–3079.

KAO, H., SHEN, S. J. & MA, K. F. 1998. Transition from oblique subduction to collision: earthquakes in the southernmost Ryukyu Arc–Taiwan region. *Journal of Geophysical Research – Solid Earth*, **103**, 7211–7229.

KARIG, D. E. 1971. Origin and development of marginal basins in the Western Pacific. *Journal of Geophysical Research*, **76**, 2542–2561.

KIMURA, M. 1985. Back-arc rifting in the Okinawa trough. *Marine and Petroleum Geology*, **2**, 222–240.

KINOSHITA, O. 1995. Migration of igneous activities related to ridge subduction in Southwest Japan and the East Asian continental margin from the Mesozoic to the Paleogene. *Tectonophysics*, **245**, 25–35.

KIZAKI, K. 1986. Geology and tectonics of the Ryukyu islands. *Tectonophysics*, **125**, 193–207.

LAN, C. Y., JAHN, B. M., MERTZMAN, S. A. & WU, T. W. 1996. Subduction-related granitic rocks of Taiwan. *Journal of Asian Earth Sciences*, **14**, 11–28.

LEE, T. Y., HSÜ, Y. Y. & TANG, C. H. 1996. Sequence stratigraphy and depositional cycles in the Tungyintao Basin, offshore Northern Taiwan. *Petroleum Geology of Taiwan*, **30**, 1–30.

LELOUP, P. H., ARNAUD, N. 2001. New constraints on the structure, thermochronology, and timing of the Ailao Shan–Red River shear zone, SE Asia. *Journal of Geophysical Research*, **106**, 6683–6732.

LETOUZEY, J. & KIMURA, M. 1986. The Okinawa Trough: genesis of a back-arc basin developing along a continental margin. *Tectonophysics*, **125**, 209–230.

LI, D. 1984. Geologic evolution of petroliferous basins on continental shelf of China. *American Association of Petroleum Geologists Bulletin*, **68**, 993–1003.

LI, S. & MOONEY, W. D. 1998. Crustal structure of China from deep seismic sounding profiles. *Tectonophysics*, **288**, 105–113.

LI, Z. X. 1998. Tectonic history of the major East Asia lithospheric blocks since the Mid-Proterozoic – a synthesis. *In*: FLOWER, M. F. J., CHUNG, S. L., LO, C. H. & LEE, T. Y. (eds), *Mantle Dynamics and Plate Interactions in East Asia, American Geophysical Union, Washington, Geodynamic Series*, **27**, 221–243.

LIN, A. T. 2001. *Cenozoic stratigraphy and tectonic development of the West Taiwan Basin*. PhD thesis, Oxford University.

LIN, A. T. & WATTS, A. B. 2002. Origin of the West Taiwan basin by orogenic loading and flexure of a rifted continental margin. *Journal of Geophysical Research*, **107**, ETG2-1–2-19.

LIN, C. H. 1996. Crustal structures estimated from arrival differences of the first P-waves in Taiwan. *Journal of the Geological Society of China*, **39**, 1–12.

LIU, C. S., HUANG, I. L. & TENG, L. S. 1997. Structural features off Southwestern Taiwan. *Marine Geology*, **137**, 305–319.

LIU, G. 1989. Geophysical and geological exploration and hydrocarbon prospects of the east China Sea. *China Earth Sciences*, **1**, 43–58.

LU, C. Y. & HSU, K. J. 1992. Tectonic evolution of the Taiwan mountain belt. *Petroleum Geology of Taiwan*, **27**, 21–46.

MARUYAMA, S., ISOZAKI, Y., KIMURA, G. & TERABAYASHI, M. 1997. Paleogeographic maps of the Japanese Islands: plate tectonic synthesis from 750 Ma to the present. *The Island Arc*, **6**, 121–142.

MORLEY, C. K. 2002. A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia. *Tectonophysics*, **347**, 189–215.

NAKAMURA, Y., MCINTOSH, K. & CHEN, A. T. 1998. Preliminary results of a large offset seismic survey west of Hengchun Peninsula, Southern Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences*, **9**, 395–408.

NISSEN, S. S., HAYES, D. E., BOCHU, Y., WEIJUN, Z., YONGQIN, C. & XIAUPIN, N. 1995. Gravity, heat flow, and seismic constraints on the processes of crustal extension: northern margin of the South China Sea. *Journal of Geophysical Research*, **100**, 22 447–22 483.

NORTHRUP, C. J., ROYDEN, L. H. & BURCHFIEL, B. C. 1995. Motion of the Pacific Plate relative to Eurasia and its potential relation to Cenozoic extension along the eastern margin of Eurasia. *Geology*, **23**, 719–722.

PELLETIER, B. & STEPHAN, J. F. 1986. Middle Miocene obduction and Late Miocene beginning of collision registered in the Hengchun Peninsula: geodynamic implications for the evolution of Taiwan. *Tectonophysics*, **125**, 133–160.

RANGIN, C., JOLIVET, L. & PUBELLIER, M. 1990. A simple model for the tectonic evolution of Southeast Asia and Indonesia region for the past 43 m.y. *Bullétin de la Société Géologique de France*, **6**, 889–905.

REN, J. Y., TAMAKI, K., LI, S. T. & JUNXIA, Z. 2002. Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. *Tectonophysics*, **344**, 175–205.

RU, K. & PIGOTT, J. D. 1986. Episodic rifting and subsidence in the South China Sea. *American Association of Petroleum Geologists Bulletin*, **70**, 1136–1155.

SENGOR, A. M. C. & NATAL'IN, B. A. 1996. Paleotectonics of Asia: fragments of a synthesis. *In*: YIN, A. & HARRISON, T. M. (eds) *The Tectonic Evolution of Asia. Cambridge University Press*, 486–640.

SENO, T. & MARUYAMA, S. 1984. Paleogeographic reconstruction and origin of the Philippine Sea. *Tectonophysics*, **102**, 53–84.

SENO, T., STEIN, S. & GRIPP, A. E. 1993. A model for the motion of the Philippine Sea Plate consistent with NUVEL-1 and geological data. *Journal of Geophysical Research – Solid Earth*, **98**, 17 941–17 948.

SHIH, R. C., LIN, C. H., LAI, H. L., YEH, Y. H., HUANG, B. B. & YEN, H. Y. 1998. Preliminary crustal structures across central Taiwan from modeling of the onshore–offshore wide-angle seismic data. *Terrestrial, Atmospheric and Oceanic Sciences*, **9**, 317–328.

SHINJO, R. 1999. Geochemistry of high Mg andesites and the tectonics evolution of the Okinawa Trough–Ryukyu arc system. *Chemical Geology*, **157**, 69–88.

SIBUET, J. C. & HSÜ, S. K. 1997. Geodynamics of the Taiwan arc–arc collision. *Tectonophysics*, **274**, 221–251.

SIBUET, J. C., DEFFONTAINES, B., HSÜ, S. K., THAREAU, N., LE FORMAL, J. P., LIU, C. S. & ACT PARTY 1998. Okinawa trough backarc basin: early tectonic and magmatic evolution. *Journal of Geophysical Research*, **103**, 30 245–30 267.

SIBUET, J. C., HSÜ, S. K., LE PICHON, X., LE FORMAL, J. P., REED, D., MOORE, G. & LIU, C. S. 2002. East Asia plate tectonics since 15 Ma: constraints from the Taiwan region. *Tectonophysics*, **344**, 103–134.

SUNG, Q. & WANG, Y. 1986. Sedimentary environments of the Miocene sediments in the Hengchun Peninsula and their tectonic implication. *Memoir of the Geological Society of China*, **7**, 325–340.

SUPPE, J. 1980. A retrodeformable cross section of Northern Taiwan. *Proceedings of the Geological Society of China*, **23**, 46–55.

SUPPE, J. 1981. Mechanics of mountain-building and metamorphism in Taiwan. *Memoir of the Geological Society of China*, **4**, 67–90.

SUPPE, J., WANG, Y., LIOU, J. G. & ERNST, W. G. 1976. Observation of some contacts between basement and Cenozoic cover in the Central Mountains, Taiwan. *Proceedings of the Geological Society of China*, **19**, 59–70.

TAIRA, A. 2001. Tectonic evolution of the Japanese island arc system. *Annual Review of Earth and Planetary Sciences*, **29**, 109–134.

TAIRA, A., TOKUYAMA, H. & SOH, W. 1989. Accretion tectonics and evolution of Japan. *In*: BEN-AVRAHAM, Z. (ed.) *The Evolution of the Pacific Ocean Margins*, Oxford University Press, Oxford, 100–123.

TAPPONNIER, P. & MOLNAR, P. 1979. Active faulting and Cenozoic tectonics of the Tie shan, Mongolia, and Baikal regions. *Journal of Geophysical Research*, **84**, 3425–3459.

TAPPONIER, P., PELTZER, G., LE DAIN, A. Y., ARMIJO, R. & COBBOLD, P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology*, **7**, 611–616.

TAYLOR, B. & HAYES, D. E. 1983. Origin and history of the South China Sea basin. *In*: HAYES, D. E. (ed.) *The Tectonic and Geologic evolution of Southeast Asian Seas and Islands, Part 2, Geophysical Monograph, American Geophysical Union*, **27**, 23–56.

TENG, L. S. 1990. Geotectonic evolution of late Cenozoic arc–continental collision in Taiwan. *Tectonophysics*, **183**, 67–76.

TENG, L. S. 1992. Geotectonic evolution of Tertiary continental margin basins of Taiwan. *Petroleum Geology of Taiwan*, **27**, 1–19.

TENG, L. S. 1996. Extensional collapse of the Northern Taiwan mountain belt. *Geology*, **24**, 949–952.

TENG, L. S., WANG, Y., TANG, C. H., HUANG, C. Y., HUANG, T. C., YU, M. S. & KE, A. 1991. Tectonic aspects of the Paleogene depositional basin of Northern Taiwan. *Proceedings of the Geological Society of China*, **34**, 313–336.

WAGEMAN, J. M., HILDE, T. W. C. & EMERY, K. O. 1970. Structural framework of East China Sea and Yellow Sea. *American Association of Petroleum Geologists Bulletin*, **54**, 1611–1643.

WANG LEE, C. & WANG, Y. 1987. Tananao terrane of Taiwan – its relation to the late Mesozoic collision and accretion of the southeast China margin. *Acta Geologica Taiwanica*, **25**, 225–239.

WANG, Y. 1987. Continental margin rifiting and Cenozic tectonics around Taiwan. *Memoir of the Geological Society of China*, **9**, 227–240.

WORRALL, D. M., KRUGLYAK, V., KUNST, F. & KUZNETSOV, V. 1996. Tertiary tectonics of the Sea of Okhotsk, Russia: far-field effects of the India–Eurasia collision. *Tectonics*, **15**, 813–826.

XIA, K., HUANG, C., JIANG, S., ZHANG, Y., SU, D., XIA, S. & CHEN, Z. 1994. Comparison of the tectonics and geophysics of the major structural belts between the northern and southern continental margins of the South China Sea. *Tectonophysics*, **235**, 99–116.

YAN, P., ZHOU, D. & LIU, Z. S. 2001. A crustal structure profile across the northern continental margin of the South China Sea. *Tectonophysics*, **338**, 1–21.

YEN, H. Y., YEN, Y. H. & WU, F. T. 1998. Two-dimensional crustal structures of Taiwan from gravity data. *Tectonics*, **17**, 104–111.

YU, H. S. 1994. Structure, stratigraphy and basin subsidence of Tertiary basins along the Chinese southeastern continental margin. *Tectonophysics*, **235**, 63–76.

YU, S. B., CHEN, H. Y. & KUO, L. C. 1997. Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, **274**, 41–59.

YUAN, J., LIN, S. J., HUANG, S. T. & SHAW, C. L. 1985. Stratigraphic study on the pre-Miocene under the Peikang area, Taiwan. *Petroleum Geology of Taiwan*, **21**, 115–128.

YUI, T. F. & LAN, C. Y. 1991. Isotopic compositions of Tananao marble in the Tungao area, northeastern Taiwan: a chronological consideration. *Special Publication of the Central Geological Survey*, **5**, 161–172.

YUI, T. F., WU, T. W. & LU, J. Y. 1994. Geochemical characteristics of metabasites from the slate formations of Taiwan. *Journal of the Geological Society of China*, **37**, 53–67.

Yui, T. F., Wu, T. W. & Lu, C. Y. 1995. Geochemical characteristics of metabasites from the slate formations of Taiwan: reply. *Journal of the Geological Society of China*, **38**, 179–182.

Zhao, X., Coe, R. S., Gilder, S. A. & Frost, G. M. 1996. Palaeomagnetic constraints on the palaeogeography of China: implications for Gondwanaland. *Australian Journal of Earth Sciences*, **43**, 643–672.

Zhou, D., Ru, K., & Chen, H. 1995. Kinematics of Cenozoic extension on the South China Sea continental margin and its implications for the tectonic evolution of the region. *Tectonophysics*, **251**, 161–177.

Zhou, X. M. & Li, W. X. 2000. Origin of late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas. *Tectonophysics*, **326**, 269–287.

Zhou, Z., Zhao, J. & Yin, P. 1989. Characteristics and tectonic evolution of the East China Sea. *In*: Zhu, X. (ed.) *Chinese Sedimentary Basins*, Elsevier, Amsterdam, 165–179.