Tectonic evolution of accretionary prism in the arc–continent collision terrane of Taiwan

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Abstract

The thick sedimentary and meta-sedimentary rocks west of the Eocene–Paleozoic metamorphic basement of Taiwan represent an accretionary prism developed between the Eurasian continent and the Philippine Sea plate. The accretionary prism consists of a subduction wedge in the east and a collision prism in the west. The deep-marine subduction wedge developed during the eastward subduction of the South China Sea oceanic crust since the Early Miocene. In the Central Range, a regional unconformity with mylonite structure occurred between the Miocene deep-marine slates-turbidites and the Paleozoic–Eocene metamorphic basement. The unconformity marks the tectonostratigraphic break between the overlying subduction wedge and the underlying underthrust Eurasian continent. The subduction wedge extends from the western Central Range southwards through the Hengchun Peninsula to the offshore Hengchun Ridge. Subduction of the South China Sea oceanic crust further led to the oblique arc–continent collision starting about 6.5 Ma in northern Taiwan. During the collision, the shallow-marine passive margin and foreland sequences were progressively incorporated to the collision prism by a series of west-vergent thrusts in the Hsüehshan Range and the Western Foothills. The Kaoping Slope west of the subduction wedge of the Hengchun Ridge represents the modern collision prism in the active arc–continent collision zone. The collision prism is juxtaposed against the subduction wedge to the east along the Lishan–Laonung–Hengchun fault, which extends offshore to the 30-km-wide fault zone between the Kaoping Slope and the Hengchun Ridge. Before the onset of the arc–continent collision, the Lishan–Laonung–Hengchun fault developed along the northern part of the proto-Manila trench and acted as the thrust front located to the west of the subduction wedge. At present, the thrust front has migrated southwestward to the west of the collision prism. The arc–continent collision propagated southwards and yielded the time-transgressive deformations from north to south to result a south tapering configuration of Taiwan. This paper is the first to recognize the consistent occurrence of the subduction wedge and collision prism onshore and offshore Taiwan. This allows reconstruction of the tectonic evolution of the accretionary prism during the subduction and collision tectonics of Taiwan.

Keywords: accretionary prism; arc–continent collision; Taiwan; Eurasian continent; Manila trench

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1. Introduction

An accretionary prism commonly occurs in the area between a trench and its volcanic arc in a convergent region. In ocean–ocean and ocean–continent subduction systems, sediments deposited on the ocean floor and trench axis are commonly offscraped, accreted and then stacked in the accretionary prism (Karig and Sharman, 1975). In the case of an arc–continent collision after the subduction, such as Taiwan and Timor, this simple sediment-accretion model is further complicated by the incorporation of thick passive continental margin sequences into the accretionary prism (Hamilton, 1979; Karig et al., 1987; Teng, 1990). During the arc–continent collision, the earlier accreted materials in the accretionary prism are subjected to intensive deformation or even metamorphism. This will obscure the geologic features needed for studying the evolution of the accretionary prism in arc–continent collision terranes.

The geology of Taiwan is characterized by the young age of the arc–continent collision (6.5 Ma to Present; Table 1; Huang et al., 1997a). The stratigraphy of Taiwan is well controlled by microfossil studies (Chang, 1975; Huang and Cheng, 1983). Tectonic events, especially the history of the arc–continent collision, are clearly preserved in the young and non-metamorphosed strata (Teng, 1990; Huang et al., 1995). Therefore, Taiwan serves as an excellent example to look into the evolution of the accretionary prism in an arc–continent collision terrane.

Marine investigations in the last two decades have shown that the morphotectonic units off southern Taiwan are well correlated with the onshore geological units (Table 2; Bowin et al., 1978; Huang and Yin, 1990; Huang et al., 1992, 1995, 1997a; Huang, 1993). The arc–continent collision is still active in the region south of Taiwan (Fig. 1; Biq, 1972; Suppe,

1984; Huang et al., 1992; Reed et al., 1992; Lundberg et al., 1992; Liu et al., 1992). The offshore accretionary prism between Taiwan and Luzon, thus, provides the modern analogy for the reconstruction of the onshore accretionary prism (Fig. 1). By integration of the onshore and offshore geology, a kinematic evolution model of the accretionary prism in the arc–continent collision terrane of Taiwan is proposed in this paper.

2. Study methods

Independent yet consistent geological evidences have allowed us to recognize the evolution of the accretionary prism in Taiwan. We firstly integrate the marine geology in offshore subduction and collision zones with the onshore regional geology. To stress a geological continuity, a multi-channel seismic profile over the offshore accretionary prism is compared with the equivalent onshore structure across the Taiwan. The results show a continuity of the subduction wedge from the present offshore convergent zone to the Hengchun Peninsula and the western Central Range of Taiwan. Stratigraphy, sedimentology, structures, illite crystallinity and metamorphic grade across the island are further applied to distinguish the various tectonic units of the mountain ranges of Taiwan. Furthermore, because Taiwan is located to the southeast of the Asian continent, it is reasonable to surmise that the various geological units of Taiwan before their juxtaposition by the arc–continent collision, are comparable with the geological structures of the Pearl River Mouth Basin in the northern slope of the South China Sea. By this geologic comparison, a regional unconformity between the Miocene deep-marine strata and the underlying Eocene–Paleozoic metamorphic sequences in the Central Range of Taiwan is correlated with the spreading event of the South China Sea.

Fig. 1. Tectonic framework of the Taiwan accretionary prism. The Taiwan accretionary prism includes a collision prism (the onshore Coastal Plain, Western Foothills, Hsuehshan Range and the offshore Kaoping Slope) in the west and a subduction wedge (the onshore western Central Range–Hengchun Peninsula and the offshore Hengchun Ridge). The arc-accreted Coastal Range is equivalent to the offshore arc domain east of the Hengchun Ridge (marine data compiled from Huang et al., 1992; Reed et al., 1992; Lundberg et al., 1992). With the advancement of the orogeny, tectonics in the Taiwan region has changed northward from intra-oceanic subduction to arc–continent collision and arc accretion. TTT = Taitung Trough; SLT = Southern Longitudinal Trough. ▲ = arc-accretion point; ★ = arc–continent collision point. AB = location of seismic profile shown in Fig. 8.
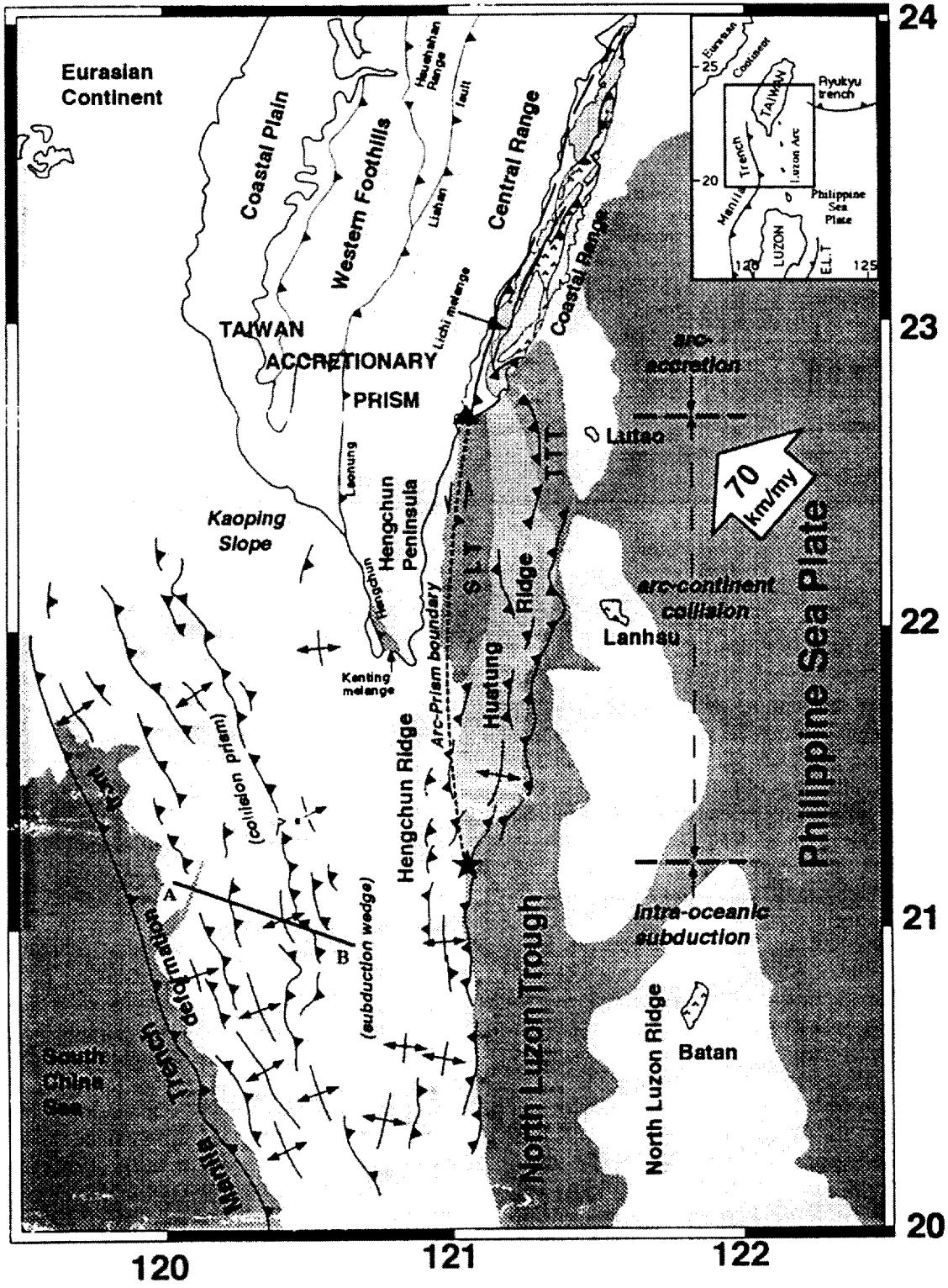
Table 1
Tectonostratigraphy of the five morphotectonic units of Taiwan

	Coastal Plain	Western Foothills	Hsuehshan Range	Central Range	Coastal Range
Holocene	foreland	Propagation			accreted forearc and intra-arc sequences
Pleistocene	foreland	foreland			accreted forearc and intra-arc sequences
Pliocene	shallow	marine	driven by arc-continent prism		accreted forearc and intra-arc sequences
			--- Arc-continent Collision (6.5 Ma) --		
Miocene		passive Asian continental margin sequences	arc-continent collision	subduction wedge	accreted Luzon arc
Oligocene			graben	(Philippine Sea plate)	(Philippine Sea plate)
			on passive		
Eocene			Asian cont.	underthrust	
				Eurasian	
Pre-Tertiary				continent	

Shingchuang fault   Chuchih fault   Lishan - Laonung fault   Longitudinal Valley

3. Tectonic setting of Taiwan

Taiwan is situated in the active subduction–collision region between the Eurasian continent and the Philippine Sea plate (Fig. 1). To the south of 21°N, the oceanic crust of the South China Sea (32–15 Ma) is subducting beneath the Philippine Sea plate along the Manila trench (Taylor and Hayes, 1983; Hayes and Lewis, 1984). To the east, the Philippine Sea plate is being consumed beneath the Eurasian continent along the Ryukyu trench (Fig. 1). The Philippine Sea plate is moving northwestward at 310° with a rate of 70 mm/yr (Seno et al., 1993). To the southeast, the Luzon arc (trending at 355°) of the Philippine Sea plate is colliding obliquely with the Asian continent (trending at 060°). The collision has propagated progressively southward, thus the leading Luzon arc has been accreted onto the Eurasian continent to form the Coastal Range in eastern Taiwan (Chai, 1972; Huang et al., 1995, 1997a). Therefore, between Luzon and Taiwan, the tectonics change progressively northward from intra-oceanic subduction south of 21°20′ N, to the arc–continent collision between 21°20′ N and 22°40′ N, and to arc accretion

north of 22°40′ N (Fig. 1). A typical arc–trench system is well defined in the intra-oceanic subduction zone south of 21°N. However, in the arc–continent collision zone the forearc basin diminishes northward, while the accretionary prism becomes wider due to the collision (Fig. 1). In the arc-accretion zone, the metamorphic basement of the underthrust Eurasian continent was even uplifted and exposed by west-vergent thrusts (Figs. 1 and 2).

Fig. 2 shows the major onshore morphotectonic units and their reconstructed tectonic settings in Taiwan. The shallow-marine sequences in the Coastal Plain, Western Foothills and Hsüehshan Range in western Taiwan have been recognized as deposits on the passive Asian continental margin (Table 1; Ho, 1988). The deep-marine turbidites and volcanic strata in the Coastal Range, eastern Taiwan, represent the accreted Luzon arc in the active margin (Table 1; Chai, 1972; Biq, 1972). However, situated between the active and passive margins, the geological setting of the Central Range was ambiguous due to intensive deformation and metamorphism. This paper, for the first time, interprets the Miocene deep-marine strata in the western Central Range–Hengchun Peninsula

Table 2
Correlation between the geological units in the onshore Taiwan mountain belts and the offshore morphological units in the active arc–continent collision zone

Onshore	Offshore
Post-collision accretionary prismPassive margin sequences	
Western Foothills	Kaoping slope in west of Hengchun Ridge
Pre-collision accretionary prism	
Western Central Range (late Miocene)	
Hengchun Peninsula (Pliocene)	Hengchun Ridge (Pleistocene–modern)
Underthrust Eurasian continent	
Eastern Central Range	(not exposed yet)
East of plate boundary in Coastal Range in arc-accretion zone	*East of arc–prism boundary in arc–continent collision zone*
Forearc turbidites	Taitung Trough and North Luzon Trough
Andesitic volcanics	Lutao and Lanhsu volcanic island of Luzon arc
Lichi mélange (sheared forearc sediments and ophiolite)	Huatung Ridge (deformed forearc sediments presumably associated with ophiolite)
Longitudinal Valley (post-collision basin along plate boundary)	Southern Longitudinal Trough (post-collision basin along arc–prism boundary)

as the subduction wedge. By contrast, the Eocene meta-sandstone together with the pre-Tertiary meta-morphic basement in the eastern Central Range represents the underthrust Eurasian continent (Fig. 2).

4. Geological and physiographical continuity between the onshore and offshore accretionary prism

In the subduction and collision zones, the arc–prism boundary separates the accretionary prism domain from the arc domain to the east (Fig. 1). The geological units in the arc domain can be correlated with the onshore tectonostratigraphic units in the Coastal Range and the Longitudinal Valley in eastern Taiwan (Table 2; Huang et al., 1992, 1995; Huang, 1993). In the following sections we will focus discussions only on the accretionary prism domain.

4.1. Collision prism extending from the submarine Kaoping Slope to the onshore Western Foothills

West of the arc–prism boundary, the submarine Taiwan accretionary prism consists of the NW–SE-trending Kaoping Slope and the N–S-trending Hengchun Ridge (Fig. 1). The Kaoping Slope tapers southward from the collision zone to the subduction zone. It is geologically equivalent to the onshore Western Foothills, both were deformed in fold-and-thrust belt (Ho, 1988; Reed et al., 1992). Shallow-

marine siliciclastics derived from the granite area of southeastern mainland China were deposited in the lower part of the Western Foothills (Chou, 1972) and presumably also in the Kaoping Slope. The upper part of both units is a thick foreland sequence with sediments derived from the uplifted subduction wedge of the western Central Range (Teng, 1990; Liu et al., 1997). Submarine channel structures are common in the outcrops and seismic profiles over the southern Western Foothills and the Kaoping Slope (Chow et al., 1986; Liu et al., 1993). In the Kaoping Slope, mud-volcanoes injected into the thick, rapidly deposited foreland sequences (Liu et al., 1997). These submarine mud-volcanoes generally follow the major thrusts that can be traced northward from the offshore Kaoping Slope to the onshore southern Western Foothills (Hayasaka, 1932; Lin, 1965; Sun and Liu, 1993). The shallow-marine passive margin and foreland sequences in the Kaoping Slope and the Western Foothills were incorporated into the collision prism by a series of west-verging thrusts during the southward propagation of the arc–continent collision in the last 6.5 m.y. (details see Fig. 5).

4.2. Subduction wedge extending from the offshore Hengchun Ridge to the onshore Hengchun Peninsula – southern Central Range

To the east of the Kaoping Slope, the submarine Hengchun Ridge stretches from NW Luzon to Tai-
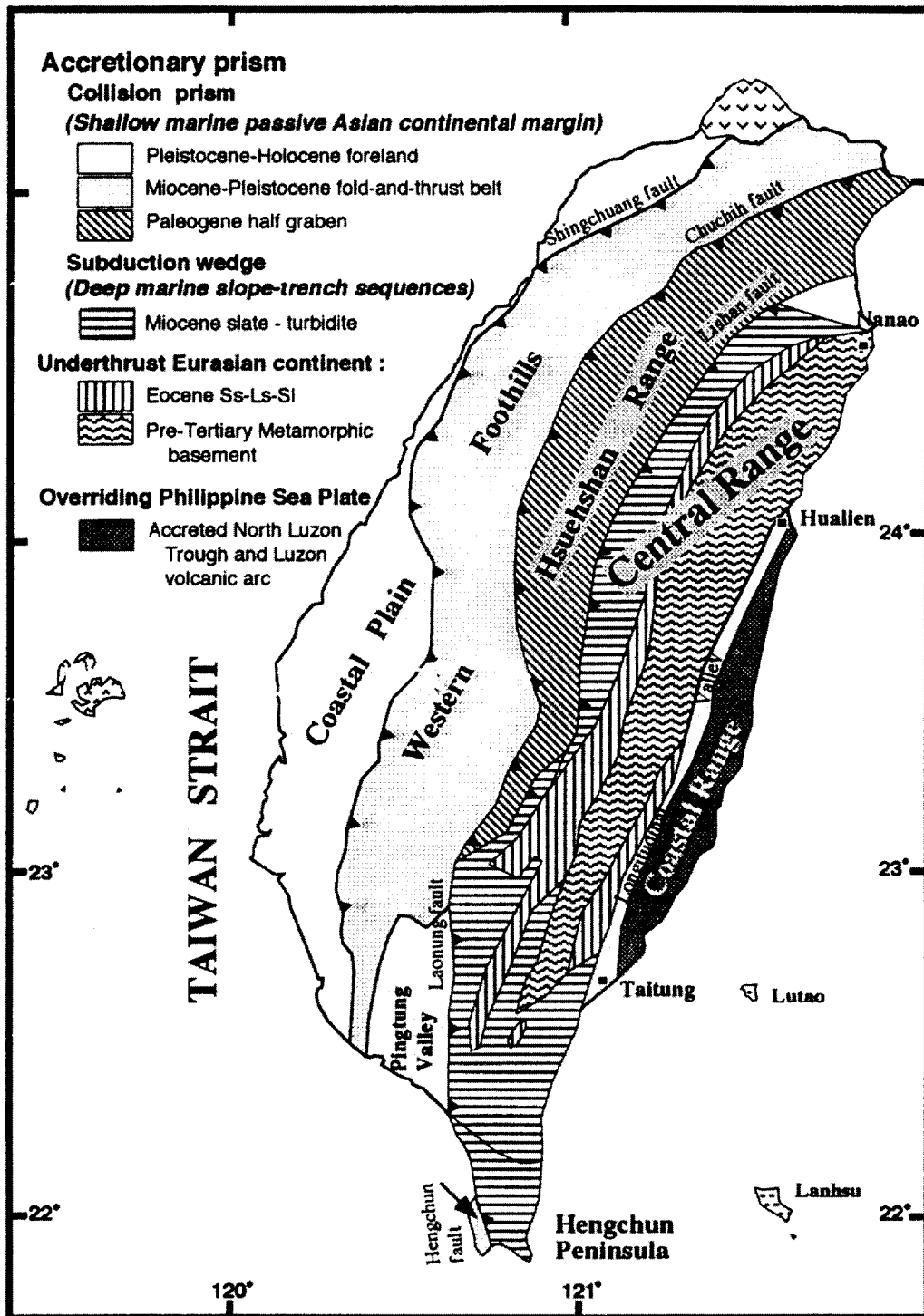
Fig. 2. Tectonostratigraphic map of Taiwan. The Lishan–Laonung–Hengchun fault followed the proto-Manilla trench and acted as the deformation front of the subduction wedge during the arc–continent collision.

wan for more than 350 km. It shallows northward
to the Hengchun Peninsula in the southern tip of
Taiwan. In the subduction zone south of 20°30′ N,
the Hengchun Ridge represents a subduction wedge
between the Manila trench and the forearc basin of
the North Luzon Trough (Fig. 1). SeaMARC images
and 6-channel seismic surveys showed, at least south
of 21°N, a N–S deformation trend in the Hengchun
Ridge (fig. 5 in Reed et al., 1992). Similar N–
S-trending structures can also be found in the Late
Miocene turbidite terrane of the Hengchun Peninsula
(Fig. 3). A N–S-oriented pattern of free-air gravity
anomalies extends continuously from the Hengchun
Peninsula to the offshore Hengchun Ridge (Yen et
al., 1995), suggesting a common tectonic origin. Nei-
ther a structural break nor a distinct E–W-trending
strike-slip fault (Lin and Tsai, 1971) was identified
between the Hengchun Peninsula and the Hengchun
Ridge. Furthermore, in the wedge morphology, the
Hengchun Ridge is raised to form the crest of the
modern submarine Taiwan accretionary prism over
the 20–22°N cross-sections. This indicates that the
strata of the Hengchun Ridge and the Hengchun
Peninsula were incorporated into the accretionary
prism earlier (during the Pliocene, as discussed be-
low) than those of the Kaoping Slope and the south-
ern Western Foothills (during the Pleistocene) to the
west. This agrees with the kinematics of west-verg-
ing thrusts driven by the westward movement of the

Philippine Sea plate against the Eurasian continent
(Seno et al., 1993). The Hengchun Peninsula further
extends northward to the southern Central Range
(Fig. 2). In various E–W transverse sections, the
Hengchun Peninsula and the southern Central Range
occupy the highest topography over the emerged
Taiwan accretionary prism. This suggests that they
could belong to the same tectonic setting as the
offshore Hengchun Ridge.

Stratigraphically, Middle–Late Miocene deep-
marine turbidites in the Hengchun Peninsula con-
formably overlie Early–Middle Miocene deep-
marine turbidites and slates in the southern Central
Range (Table 3). The southern Central Range and
the Hengchun Peninsula are located to the east of
the N–S-trending Laonung fault (Fig. 2). This fur-
ther implies that the southern Central Range and
the Hengchun Peninsula are situated in a similar
geological setting of the subduction wedge.

4.3. Contrast in sedimentology, stratigraphy, structure and metamorphic grade across the Lishan fault between the passive margin strata and the subduction wedge

4.3.1. Sedimentology and stratigraphy

The Lishan fault is a major boundary fault sepa-
rating strata of different ages and depositional en-
vironments (Table 3). West of the Lishan fault,

Table 3
Stratigraphy of the Hsüehshan Range and Central Range (compiled from Chang, 1975; Huang, 1980; Huang and Cheng, 1983)

Age	Hsuehshan Range	Central Range–Hengchun Peninsula
Late Miocene		deep-marine turbidite (N10–N17) [a]
Middle Miocene	shallow-marine clastics	Lushanian deep-marine slate (N8–N9)
Early Miocene	shallow-marine clastics	deep-marine slate (N5–N7?)
		∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼
Oligocene	Shihtsaoan shallow marine clastics (P20–N4)	[b]
		∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼
Eocene	Hsuehshanian shallow marine clastics (P14?–P19)	Pilushanian shallow-marine ls and metasandstone (P8–P10)/(NP12–14)

∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼ Unconformity ∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼∼

| Pre-Tertiary | | metamorphic basement |

[a] Exposed only in the Hengchun Peninsula.
[b] Shihtsaoan Likuan Formation (P19/NP12–14; Huang, 1980; Lee and Wang, 1985) locally exposed along the Southern Cross-Island Highway, southern Taiwan.
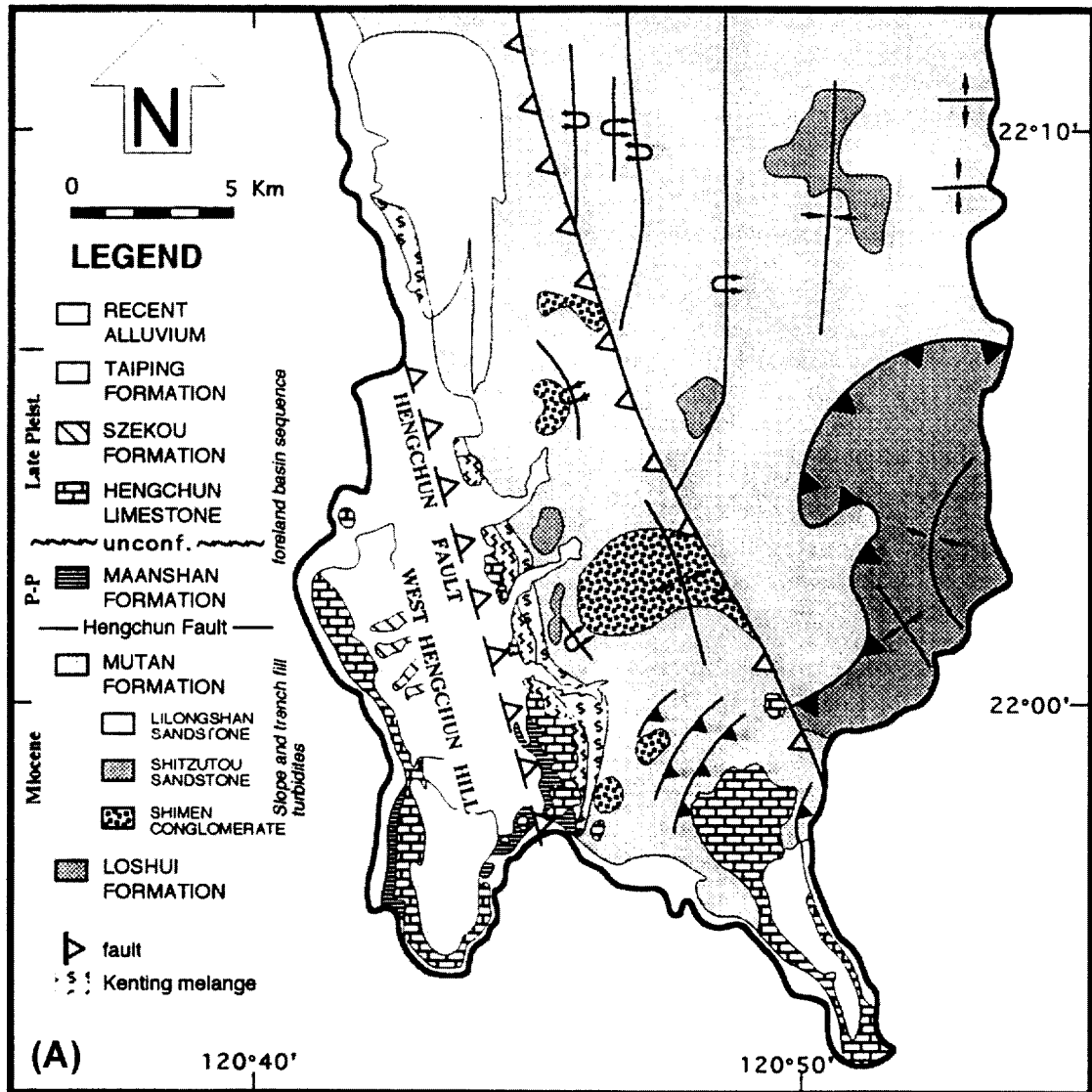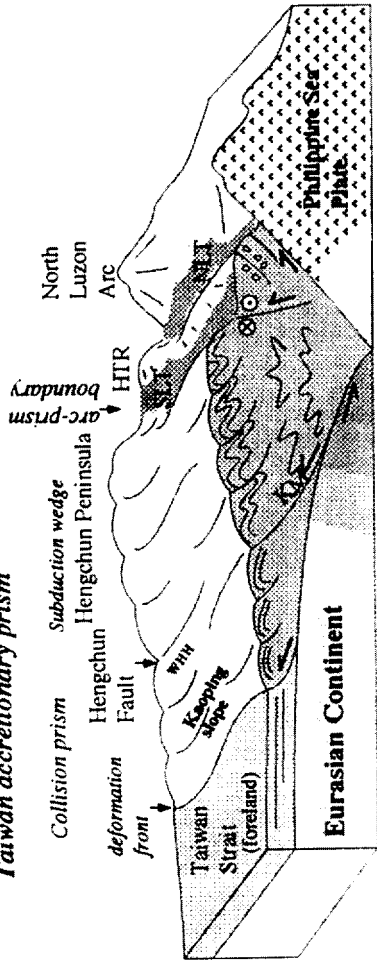
Fig. 3. (A) Geological map of the Hengchun Peninsula in southern Taiwan and (B) tectonic evolution of the accretionary prism in the Hengchun Peninsula (after Huang et al., 1997b). Two contrasting structures are found in the Hengchun Peninsula. The N–S-trending structures were developed when Late Miocene slope and trench-fill sediments were accreted onto the subduction wedge in the Early Pliocene. The N–S-trending structures were truncated by the younger NW–SE-trending structures, which were formed when the foreland sequences were incorporated into the collision prism during arc–continent collision at ca. 1 Ma in the southern Hengchun Peninsula. WHH = West Hengchun Hill; KM = Kenting mélange; NLT=North Luzon Trough.

the strata in the Hsuehshan Range and Western Foothills are dominated by sandstone with coal seams deposited in shallow-marine environments. Westward away from the Lishan fault, these shallow-marine strata become progressive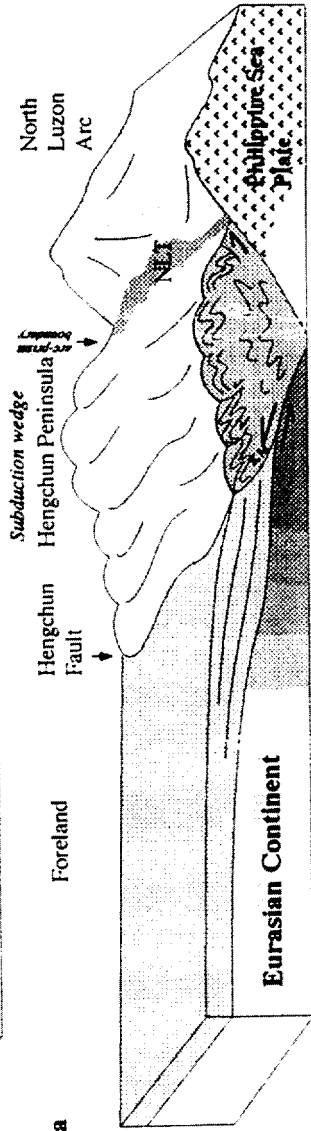ly younger: Eocene–Oligocene formations in the Hsuehshan Range, Miocene–Pleistocene sequences in the Western Foothills, and Pleistocene–Holocene foreland deposits in the Coastal Plain (Table 1). Furthermore, within these shallow marine sequences, no distinct depositional break was found after the Oligocene (Chang, 1975; Huang and Cheng, 1983). The Pa-
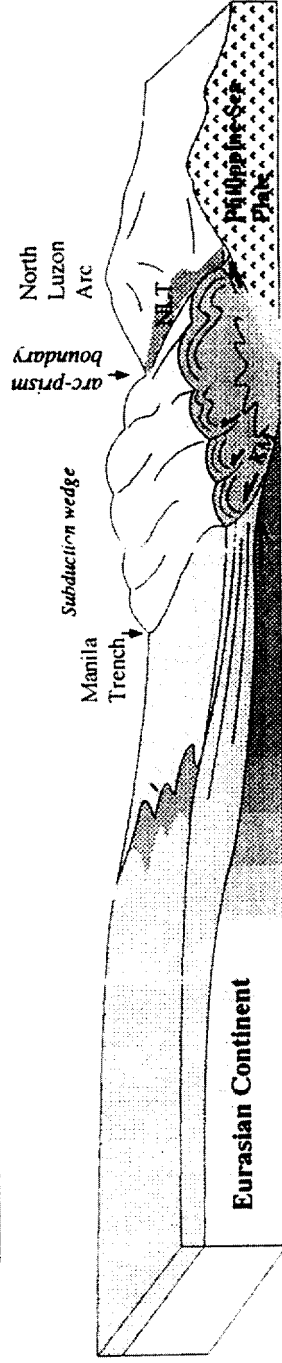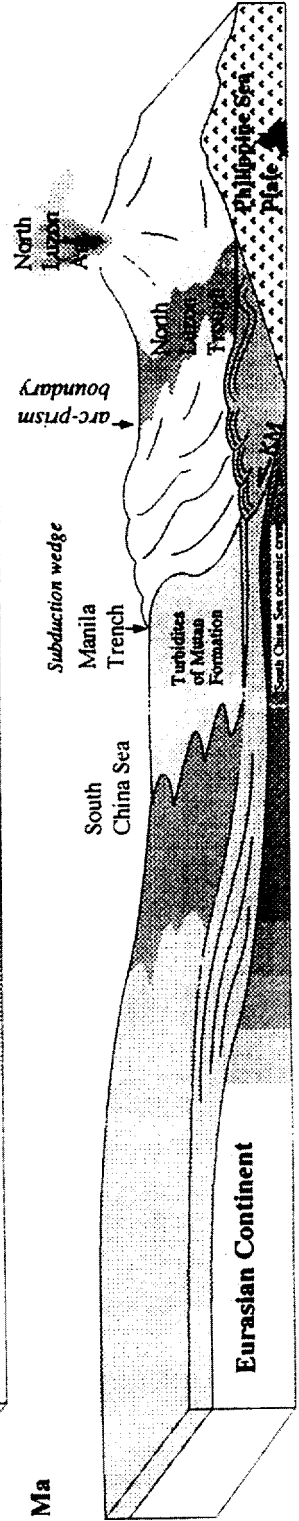
D. Present (0 Ma)
Taiwan accretionary prism

North
Luzon
Arc

arc-prism boundary → HTR

Collision prism *Subduction wedge*
deformation Hengchun Hengchun Peninsula
front Fault

Philippine Sea Plate

HHR

Keeping slope

Taiwan Strat (foreland)

Eurasian Continent

C. 1 Ma

North
Luzon
Arc

Philippine Sea Plate

NLT

arc-prism boundary →

Subduction wedge
Hengchun Peninsula

Hengchun
Fault

Foreland

Eurasian Continent

B. 3 Ma

North
Luzon
Arc

NLT

Philippine Sea Plate

arc-prism boundary →

Subduction wedge

Manila
Trench

Eurasian Continent

A. 10~6 Ma

North
Luzon

North
Luzon
Trench

Philippine Sea Plate

arc-prism boundary →

Subduction wedge
Manila
Trench

South
China Sea

Turbidites
of Mitaio
Formation

South China Sea oceanic crust

Eurasian Continent

(B)

Fig. 3 (continued).

leogene basins in the area were mostly grabens, similar to the Pearl River Mouth Basin in the northern slope of the South China Sea (Fig. 6; Teng et al., 1991; Huang et al., 1997a). In contrast, east of the Lishan fault, Miocene slates in the western Central Range were deposited in a deep-marine en-

vironment (Chang, 1976). Further to the east, Early–Middle Miocene deep-marine slates in the western Central Range unconformably overlie Eocene shallow-marine metasandstone and limestone in the eastern Central Range (Chang, 1975). These Eocene shallow-marine sequences unconformably
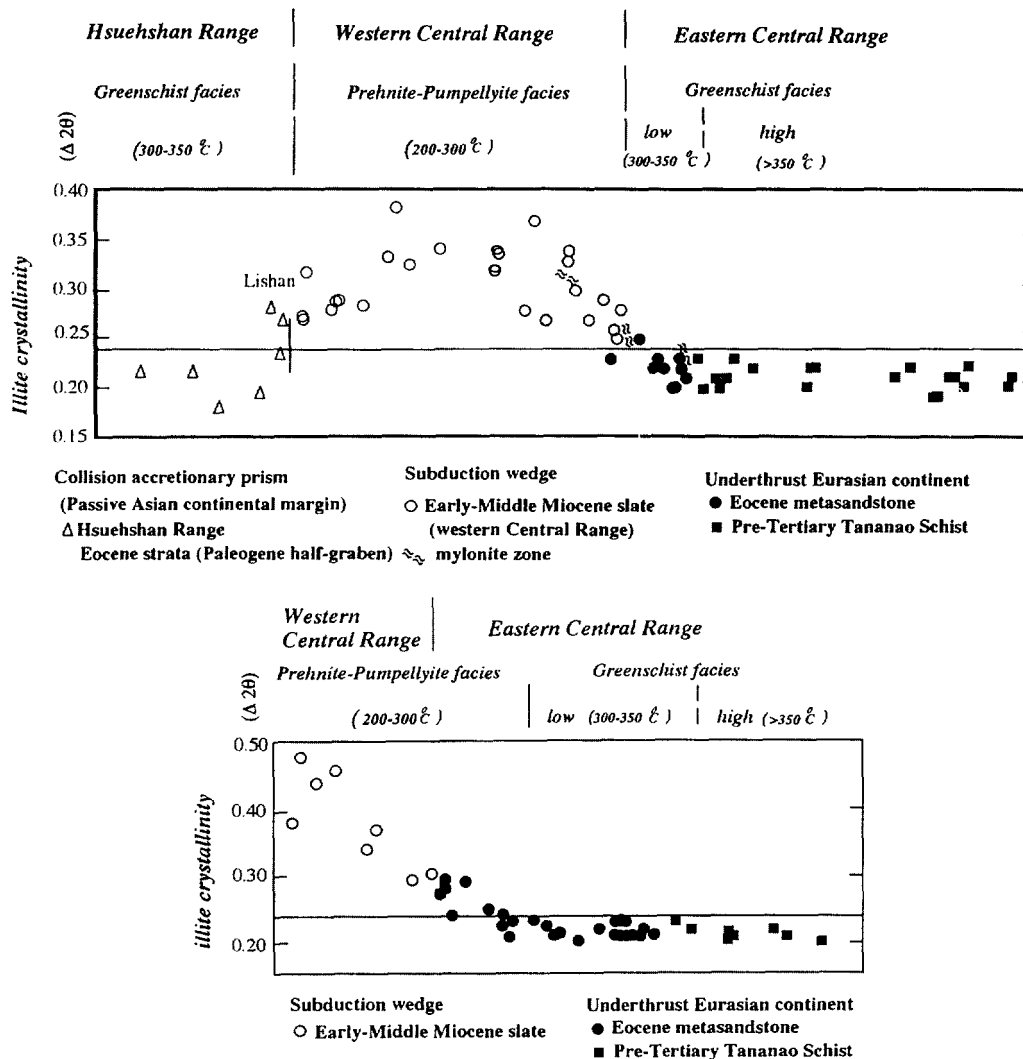

Fig. 4. Illite crystallinity in authigenic mica (< 2 μm in size) measured along sections of (a) the Central Cross-Island Highway (subparallel to 24°N) and (b) the Southern Cross-Island Highway (subparallel to 23°N) in central and southern Taiwan, respectively. Occurrences of mylonite zones and metamorphic facies are also shown on the figure. The higher the degree of the thermal event and metamorphism (thus also the deeper the burial), the lower the illite crystallinity $\Delta 2\theta$ value. The collision prism of Miocene slate in the western Central Range has the highest illite crystallinity value, suggesting a shallower structural level. The Hsuehshan Range, west of the Lishan fault, has a low illite crystallinity $\Delta 2\theta$ value, due to deep sedimentary burial in the Paleogene graben. However, the Eocene and late Paleozoic–Mesozoic metamorphosed sequences of the underthrust Eurasian continent have the lowest values of illite crystallinity $\Delta 2\theta$ value (data compiled from Tsao et al., 1992; Tsao, 1996).
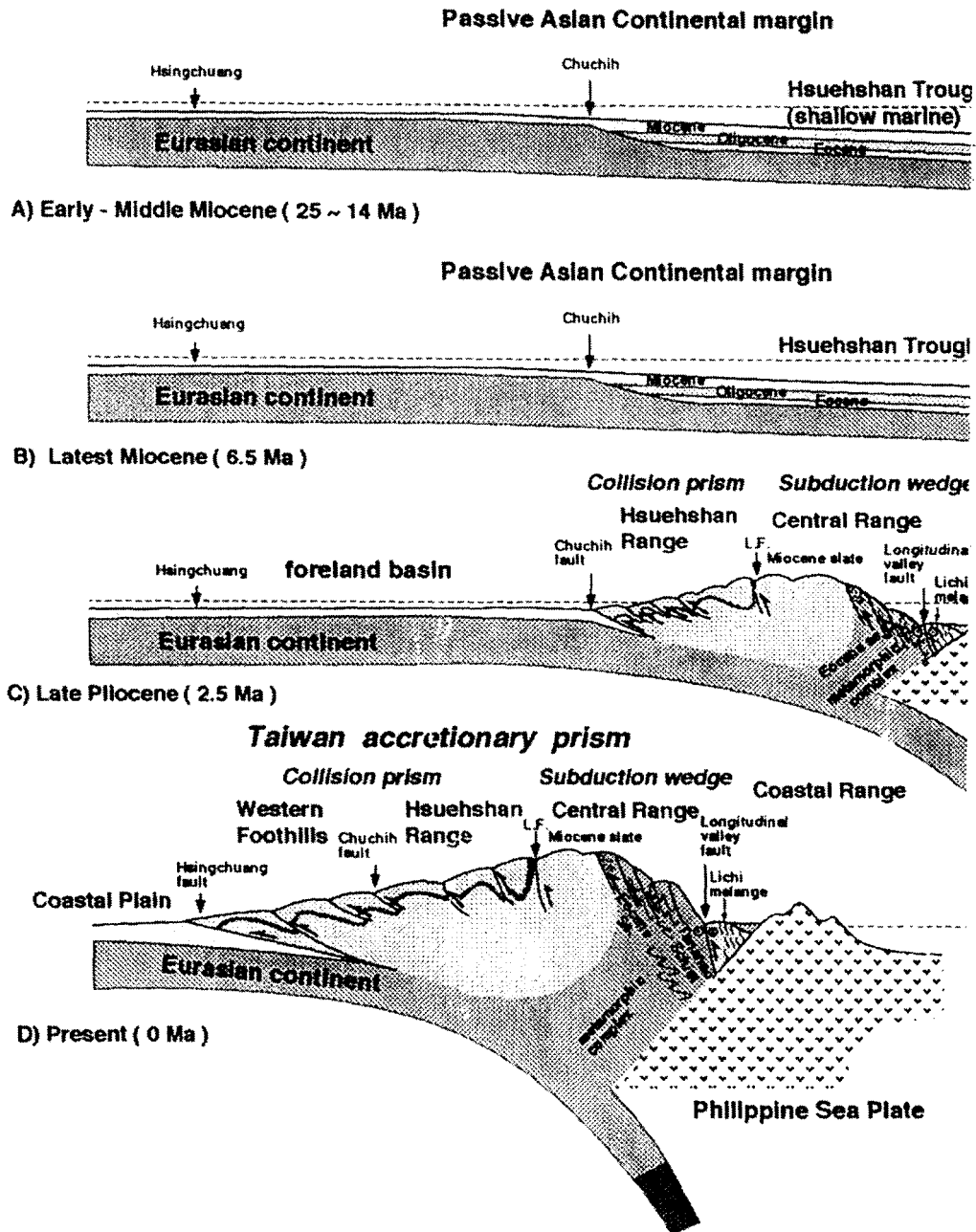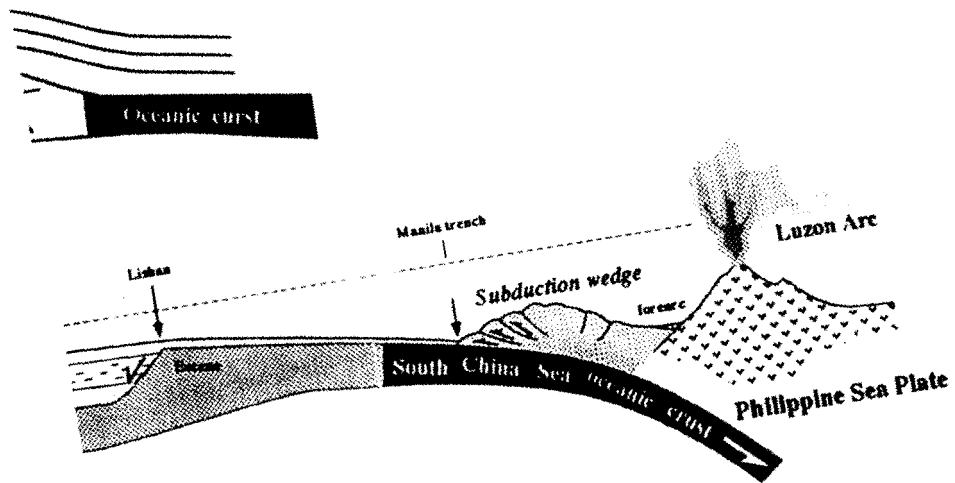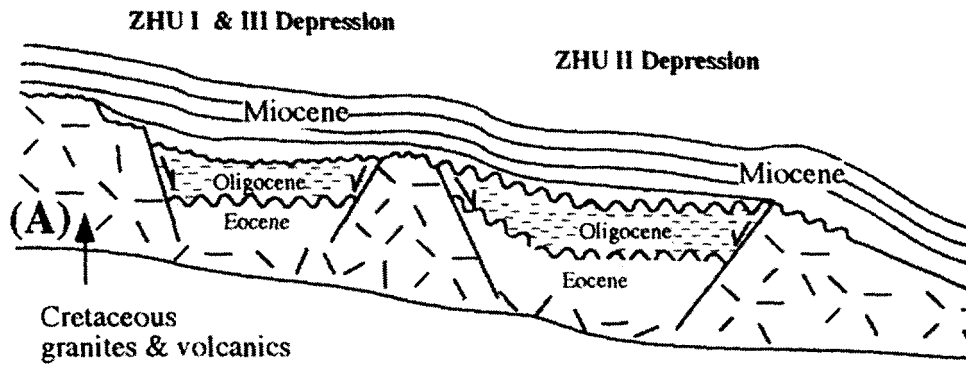
Passive Asian Continental margin

Hsingchuang

Chuchih

Hsuehshan Troug
(shallow marine)

Miocene
Oligocene
Eocene

Eurasian continent

A) Early - Middle Miocene (25 ~ 14 Ma)

Passive Asian Continental margin

Hsingchuang

Chuchih

Hsuehshan Trougl

Eurasian continent

Miocene
Oligocene
Eocene

B) Latest Miocene (6.5 Ma)

Collision prism   *Subduction wedge*

Hsuehshan   Central Range

Chuchih Range   L.F.
fault   Miocene slate   Longitudina
valley
fault   Lichi
mela

Hsingchuang   foreland basin

Eurasian continent

C) Late Pliocene (2.5 Ma)

Taiwan accretionary prism

Collision prism   *Subduction wedge*   Coastal Range

Western   Hsuehshan   Central Range   Longitudinal
Foothills   Chuchih Range   L.F   Miocene slate   valley
fault   fault

Hsingchuang
fault   Lichi
melange

Coastal Plain

Eurasian continent

D) Present (0 Ma)

Philippine Sea Plate

Fig. 5. Tectonic evolution of the Taiwan accretionary prism displayed in E–W cross sections. (A) During 25-
were deposited on the Asian continental slope west of the Manila trench. The Hsuehshan Trough was a Paleoge
turbidites were accreted onto the subduction wedge. The Miocene deep-marine sequences unconformably overli
Schist of the underthrust Eurasian continent. The Lishan fault developed along the northern part of the Manila tr
the graben were incorporated into the collision prism during the arc–continent collision at 6.5–2.5 Ma. The Chu
prism at ca. 2.5 Ma. (D) The present-day configuration of the northern Taiwan accretionary prism. In the last
were incorporated into the collision prism and the Hsinchuang fault became the deformation front of the pris
1980) showing the fold-and-thrust structures in the Western Foothills and the Hsuehshan Range on the passiv
same propagation rate of the deformation frontal thrust in the last 6.5 m.y., the Chuchu fault is estimated to hav

South China Sea

Oceanic crust

Manila trench

Luzon Arc

Lishan

Subduction wedge

forearc

South China Sea oceanic crust

Philippine Sea Plate

modified from Chen et al., 1995; Xia et al., 1995) on the northern

Pearl River Mouth Basin

ZHU I & III Depression

ZHU II Depression

Miocene

Oligocene

Eocene

(A)

Miocene

Oligocene

Eocene

Cretaceous
granites & volcanics

Passive Asian Continental margin

Taiwan   Strait

Hsuehshan Trough
(shallow marine)

Miocene

Miocene

Oligocene

Oligocene

Eocene

Eocene

(B)

Eurasian continent

Mesozoic & Late Paleozoic metamorphics
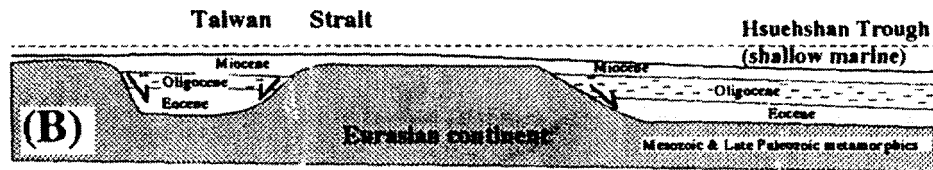
Fig. 6. Similarity in tectonic setting and geological profiles between (A) the Pearl River Mouth Basin (
slope of the South China Sea, and (B) Taiwan before onset of the arc–continent collision at 6.5 Ma.
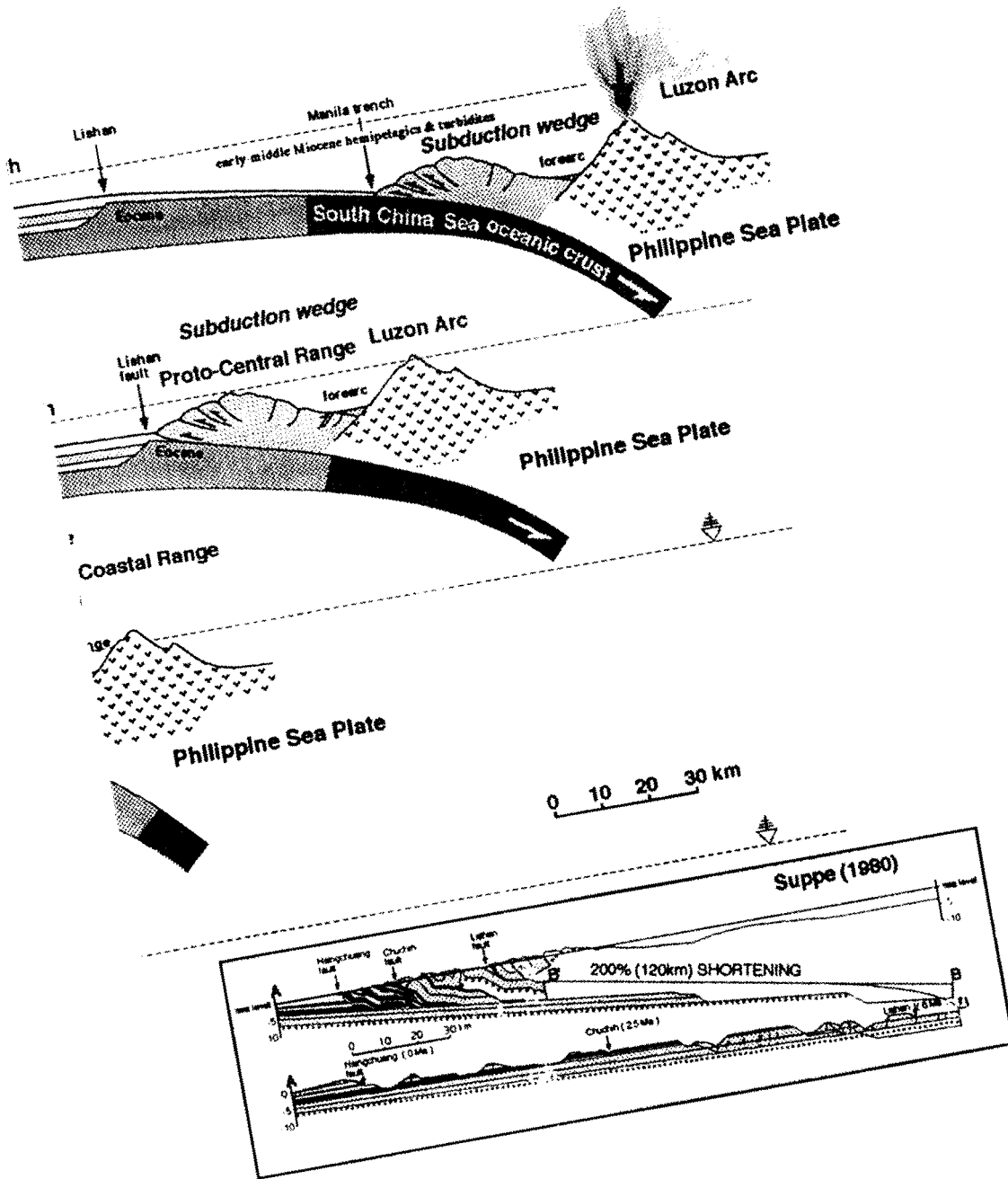
-14 Ma, Early–Middle Miocene turbidites and hemipelagics
ne graben. (B) In the Late Miocene, Early–Middle Miocene
e Eocene shallow-marine rocks and the pre-Tertiary Tananao
ench. (C) The passive Asian continental margin sequences in
chih fault marked the deformation front west of the collision
2.5 m.y., the shallow-marine strata in the Western Foothills
n. The inset map is a retrodeformation profile (after Suppe,
e Asian continental margin in northern Taiwan. Assuming a
e been initiated at 2.5 Ma.

cover Mesozoic–late Paleozoic metamorphic basement (Table 3). The contrasting stratigraphy and sedimentology strongly indicate that strata across the Lishan fault were deposited in different tectonic settings: a shallow-marine passive Asian continental margin (Hsuehshan Range) vs. a deep-marine subduction wedge (Miocene slates) and the underthrust Eurasian continent (Eocene metasandstone and Pre-Tertiary metamorphic basement) in the east (Fig. 2).

4.3.2. Structure

Structural characters across the Lishan fault are also highly different. West of the Lishan fault, Eocene–Oligocene strata in the Hsuehshan Range were uplifted and deformed as a fold-and-thrust belt (Ho, 1988). Eocene strata of the Hsuehshan Range were weakly metamorphosed into low greenschist facies (300–350°C; Fig. 4a)(Chen and Wang, 1995). Fission-tracks of detrital zircon grains in the Eocene strata of the Hsuehshan Range had their ages totally reset (<5 Ma; Liu, 1988; Tsao, 1996). This was due to a deep sedimentary burial in the lower part of the Paleogene graben triggered by the arc–continent collision in the last 6.5 m.y. By contrast, east of the Lishan fault, ductile structure with distinct slaty cleavages was observed in the Miocene slate belt (Lo, 1993). Intensity and complexity of the slaty cleavages increase from west to east (Lee and Yang, 1994). The Miocene slate is also characterized by prehnite-pumpellyite metamorphic facies (200–300°C; Fig. 4a and b) and partial annealing of zircon fission-tracks (Tsao et al., 1992; Chen and Wang, 1995). This geological evidence suggests that the Miocene slate belt east of the Lishan fault was positioned at a shallower structural level (subduction wedge) than the Eocene shallow-marine sequences in the Hsuehshan Paleogene graben west of the Lishan fault (Fig. 5A).

4.4. Stratigraphic break and contrasts in depositional environments and metamorphic grade in the Central Range

In the Central Range, Eocene shallow-marine metasandstone and limestone are overlain unconformably by the Early–Middle Miocene deep-marine slates (Table 3; Chang, 1972). Although marine fau-

nas were mostly destroyed by metamorhpism, some facies-diagnostic fossils, such as shallow-marine larger foraminifers *Nummulites* and *Discocyclina*, were found in the Eocene limestone (Tan, 1937, 1939, 1971). In comparison, planktic and deep- marine benthic foraminifers (*Cibicidoides wuellerstorfi, Sphaeroidina bulloides, Globobulimina auriculata, Karreriella hantkeniana, Chilostomella* sp.) occurred in the overlying Miocene slates (Chang, 1976). Occurrence of these facies-diagnostic fossils indicates that the unconformity coincided with a paleobathymetric change of about 1500–1000 m between the Miocene deep-marine slates and the Eocene shallow-marine strata. The unconformity and the remarkable paleobathymetric change recorded an Oligocene tectonic event in the Central Range, coeval with a breakup unconformity in the Pearl River Mouth Basin and a major rifting episode in the South China Sea (Fig. 6; Taylor and Hayes, 1983; Chen et al., 1995). The Oligocene unconformity also coincides with a geological break between the low greenschist facies Eocene shallow-marine metasandstones and the overlying prehnite-pumpellyite facies Miocene deep-marine slates (Fig. 4). On the other hand, the Eocene shallow-marine metasandstone is unconformably underlain by the Pre-Tertiary Tananao Schist with a higher greenschist facies metamorphism (>350°C; Fig. 4). The two unconformities in the Central Range are associated with mylonite zones with distinct ductile shear structures (Fig. 4; Lee and Yang, 1994). These observations indicate that the Eocene and Pre-Tertiary metamorphic sequences were tectonically deeply buried (>15 km thick) at a deeper structural level (Fig. 5). This conclusion is consistent with illite crystallinity measurements. Fig. 4 shows that the higher the degree of thermal event and metamorphism (thus deeper burial), the lower the illite crystallinity. The Miocene slate in the western Central Range has the highest illite crystallinity value, suggesting a shallower structural level of the subduction wedge. The Hsuehshan Range, west of the Lishan fault, has a low illite crystallinity value, due to deep sedimentary burial in the Paleogene graben. In comparison, the Pre-Oligocene metamorphosed sequences have the lowest values of illite crystallinity, indicating deepest burial in a lower structural level of the underthrust plate (Tsao et al., 1992; Tsao, 1996). In the eastern

Central Range, the Eocene metasandstone has acquired similar geological characters, such as a total reset of zircon fission tracks, as well as illite crystallinity and metamorphism relationship, to those of the Pre-Tertiary metamorphic basement. Therefore, they could have all originated from the underthrust Eurasian continent (Figs. 2 and 4B,C). Accordingly, the sharp contrast between the Miocene and Eocene sequences in the Central Range could have resulted from a drastic change in tectonic and depositional settings. The Eocene shallow-marine strata were deposited on passive continental margin, whereas the Early–Middle Miocene deep-slope slates were deposited in deep-slope marine environments before being accreted onto the subduction wedge (Fig. 5A). The Oligocene unconformity in the Central Range could be related to regional opening of the South China Sea. The newly generated oceanic crust subsequently was subducted beneath the Philippine Sea plate begining in the Early Miocene. At this time, a subduction wedge also developed between the Manila trench and the Luzon arc (Fig. 5A). Early–Middle Miocene deep-marine hemipelagic turbidites were later accreted into the subduction wedge during the subduction of the South China Sea oceanic crust in the Late Miocene (Fig. 5B; Huang et al., 1997a).

4.5. Deformation history of the subduction wedge in the Central Range and Hengchun Peninsula

Once sediments are offscraped onto the accretionary prism, they tend to be deformed and stacked as thrust sheets in the prism (Karig and Sharman, 1975). Since the arc–continent collision in the Taiwan region is oblique, the termination of intraoceanic subduction has also been time-transgressive and, thus, becomes younger southward. This also suggests that the slope-trench sediments in the north (Central Range) were accreted onto the subduction wedge and deformed earlier than those in the south (Hengchun Peninsula).

4.5.1. Central Range

In the northern Central Range, the Miocene turbidites had been thrust-faulted before they were penetrated by regional slaty cleavage (Fig. 7; Lu et al., 1989). Thrusting was thought to have occurred during sediment accretion into the subduction wedge. The subduction wedge materials were further deformed to develop slaty cleavage during the subsequent arc–continent collision before they were uplifted (Stanley et al., 1981). Kinematic modeling indicates that the arc–continent collision started at 6.5 Ma in northern Taiwan (Huang et al., 1997a). This, in turn, indicates that thrusting in the northern Central Range
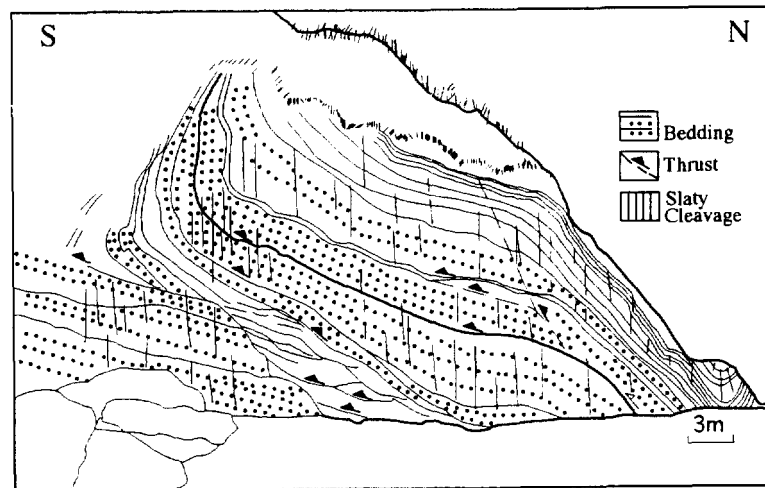

Fig. 7. Sketch diagram showing thrust and folded strata penetrated by slaty cleavage in an outcrop along the coast 9 km south of Suao, northern Central Range (after Lu et al., 1989). The thrusting and folding probably occurred during 12–10 Ma in the deeply buried subduction wedge before the development of the slaty cleavage during the arc–continent collision in the last 6.5 m.y.
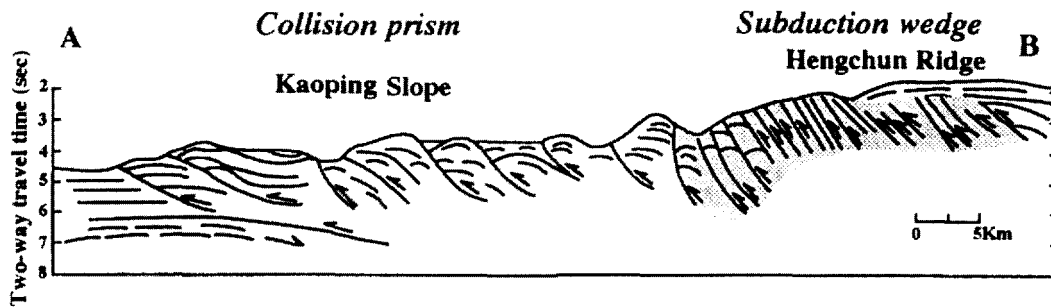
Fig. 8. Twenty-four-channel seismic profile over the submarine Taiwan accretionary prism showing a 30-km-wide thrust fault zone (shaded area) occurs between the collision prism of the Kaoping Slope and the subduction wedge of the Hengchun Ridge. Location of profile is shown in Fig. 1.

occurred between the deposition of Middle Miocene turbidites (15 Ma) and the onset of arc–continent collision (6.5 Ma). This Late Miocene accretion is consistent with the last metamorphism event (10–12 Ma; Lo and Yui, 1996) in the northern Central Range, before the underthrust Eurasian continent was uplifted by arc–continent collision and arc-accretion.

4.5.2. Hengchun Peninsula

The Hengchun Peninsula forms the southern extension of the Central Range (Fig. 3). In comparison with the Central Range, strata of the Hengchun Peninsula are characterized by younger age, simpler structure, clear geological setting and lacking of metamorphism. Three tectonostratigraphic units are recognized in the Hengchun Peninsula (Fig. 3A; Huang et al., 1997b). The majority of the peninsula is composed of thick Middle–Late Miocene turbidites, primarily of trench fill and slope sediments. Plio-Pleistocene shallow-marine foreland sediments in the West Hengchun Hill were deposited after the Late Miocene turbidites had been offscraped and stacked onto the subduction wedge. The Kenting mélange is a mega-shear zone, in which huge Late Miocene turbidite fault blocks were embedded in a strongly sheared scaly argillaceous matrix containing Neogene and Quaternary microfossils (Huang, 1984). This mega-shear zone developed along the decollement in the frontal prism from the latest Miocene to late Pleistocene (Fig. 3B; Huang et al., 1997b). Middle–Late Miocene turbidites in the Hengchun Peninsula were deformed into N–S-trending folds and thrusts which are absent in the Late Pliocene–Pleistocene foreland basin (Fig. 3A). This implies

that the N–S-trending structures were developed during the Early Pliocene when the Middle–Late Miocene turbidites were accreted onto the subduction wedge (Fig. 3B). The Early Pliocene N–S structures were then transected by the Late Pleistocene NW–SE-trending structures including the Hengchun fault, which marks the shear front of the Kenting mélange (Fig. 3). The younger structure presumably occurred when the foreland sequences were later incorporated into the collision prism during arc–continent collision in the southern Hengchun Peninsula at ca. 1 Ma (Fig. 3B; Huang et al., 1997b).

In conclusion, the Taiwan accretionary prism includes a subduction wedge in the east and a collision prism in the west. The entire Taiwan accretionary prism stretches from 21° to 25°25′N for more than 500 km in length. The width of the accretionary prism increases northward: less than 60 km in the intra-oceanic subduction zone, 110 km in the arc–continent collision zone and 125 km in the arc accretion zone. Only the subduction wedge occurs in the subduction zone, whereas both subduction wedge and collision prism occur in the arc–continent and arc-accretion zones. The collision prism was juxtaposed to the subduction wedge along the onshore Lishan–Laonung–Hengchun fault, which further extends southward to the 30-km-wide fault zone between the Kaoping Slope and the Hengchun Ridge (Fig. 8).

5. Evolution of the accretionary prism

The continuity and similarity of tectonic frameworks of the onshore and offshore geology discussed
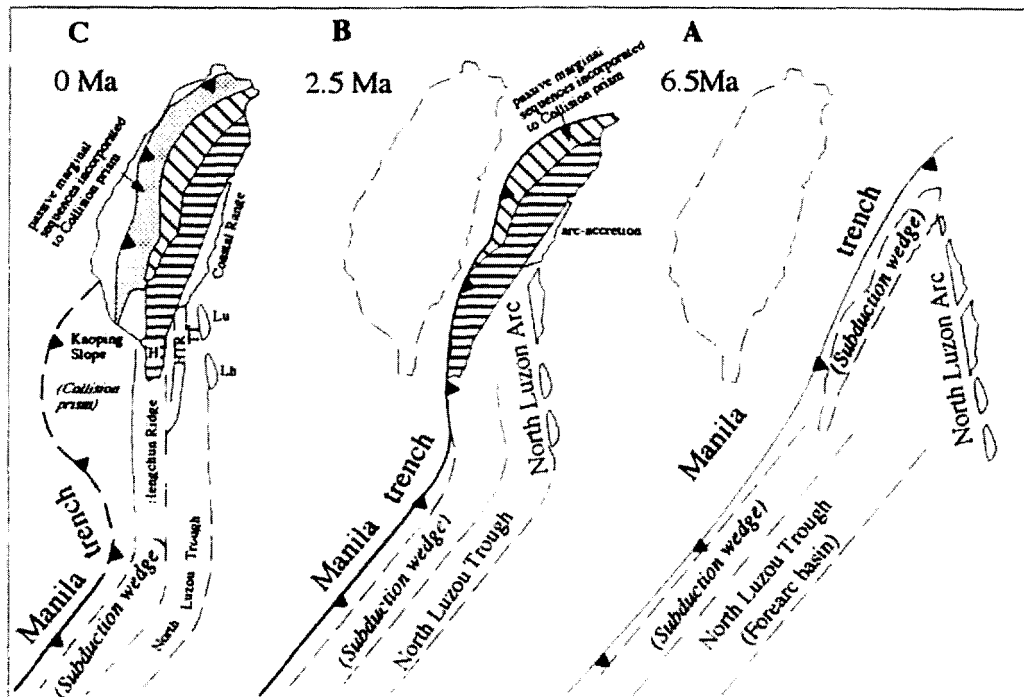
Fig. 9. Evolution of the Taiwan accretionary prism in plane view (details see text). H = Hengchun Peninsula; HTR = Huatung Ridge; TT = Taitung Trough; Lu = Lutao volcanic island; Lh = Lanhsu volcanic island.

above allows the following modelling of the evolution of the Taiwan accretionary prism (Figs. 3B, 5 and Fig. 9).

In the early Tertiary, normal faulting resulted in the formation of Paleogene grabens along the Asian continental margin. The South China Sea opened up since the Oligocene and was subsequently subducted beneath the Philippine Sea plate along the Manila trench in the Early Miocene. Thus, a subduction wedge developed between the ancient northeasterly Manila trench and the forearc basin of the North Luzon Trough during subduction of the South China Sea oceanic crust (Figs. 5A and 9A). The continuous subduction of the South China Sea oceanic crust led to the arc–continent collision, starting at ca. 6.5 Ma in northern Taiwan. Because the arc–continent collision was oblique, the termination age of the subduction becomes younger southward. During the Late Miocene, Early–Middle Miocene slope and trench sediments in the northern Central Range began to be accreted onto the subduction wedge (Fig. 5B). However, Middle–Late Miocene turbidites

in the Hengchun Peninsula were not accreted until the Early Pliocene (Fig. 3B). During the collision, the Lishan–Laonung–Hengchun fault west of the subduction wedge marked the frontal thrust along the northern part of the proto Manila trench (Fig. 5B). In accordance with the oblique arc–continent collision, the shallow-marine passive margin sequences were progressively incorporated into the collision prism by a series of west-vergent thrusts that propagated westward (Fig. 5C). The graben strata in the Hsuehshan Trough were therefore stacked into the collision prism and juxtaposed against the subduction wedge along the Lishan fault during 6.5–2.5 Ma. The Chuchih fault west of the Hsuehshan Range thus became the deformation front of the collision prism (Figs. 5C and 9B). At 1 Ma, the location of the deformation front was probably along the eastern Western Foothills. The West Hengchun Hill in the Hengchun Peninsula could also have been incorporated into the collision prism at the same time. At present, the deformation front is located at the onshore Coastal Plain and offshore west of the NW–SE-trending

Kaoping Slope (Figs. 5D and 9C). Once the collision prism enters the arc-accretion zone, it may clockwise rotate to develop the NE–SW-trending structures as observed in the Western Foothills.

6. Conclusions

Taiwan is situated in an active subduction-collision zone between the Eurasian continent and the Philippine Sea plate. Integration of onshore and offshore geology allows reconstruction of the tectonic evolution of the accretionary prism developed during intra-oceanic subduction and arc–continent collision. The geology of Taiwan is primarily composed of three distinct tectonic units: accretionary prism, underthrust Eurasian continent and accreted Luzon arc. Before the arc–continent collision, the configuration of the basins in Taiwan was similar to that of the Pearl River Mouth basin in the northern slope of the South China Sea. Since the Early Miocene, the South China Sea oceanic crust has been subducting beneath the Philippine Sea plate. The thick sedimentary and metasedimentary rocks west of the Eocene–Paleozoic metamorphic basement of Taiwan represent deposits of an active accretionary prism. This accretionary prism includes a subduction wedge in the east and a collision prism in the west. In the Central Range–Hengchun Peninsula, deep-marine Miocene slate and turbidites unconformably overlie the Eocene–Paleozoic metamorphic sequences. The unconformity separates the overlying subduction wedge from the underlying underthrust Eurasian continent. The subduction wedge further extends to the offshore Hengchun Ridge in the active subduction and collision zones. The shallow-marine sediments in the Hsuehshan Range, the Western Foothills and the Coastal Plain are sediments accumulated on the passive Asian continental margin and foreland basin. These shallow-marine sediments were progressively incorporated, from east to west, into the collision prism during arc–continent collision over the last 6.5 m.y. The offshore Kaoping Slope represents the modern collision prism developed in the active collision zone. The collision prism is juxtaposed against the subduction wedge along the onshore Lishan–Laonung–Hengchun fault, which extends offshore to the 30-km-wide fault zone between the Kaoping Slope and the Hengchun Ridge

in the active collision zone. The Lishan–Laonung–Hengchun fault developed along the northern part of the proto-Manila trench during subduction of the South China Sea oceanic crust. The fault represents the deformation front to the west of the subduction wedge. At present, the deformation front has migrated southwestward to the west of the Kaoping Slope. The arc–continent collision propagated southwards and yielded time-transgressive deformations from north to south to result in a south-tapering configuration of the Taiwan accretionary prism.

Acknowledgements

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