Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis

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ABSTRACT

Well-documented stratigraphy and clearly defined geodynamics in Taiwan, where some of the best records on arc-continent collision have been preserved, offer a unique example for the study of collision belts worldwide. The oblique arc-continent collision in Taiwan caused a simultaneous and sequential migration of four tectonic processes. Beginning from 16 to 15 Ma, subduction of the South China Sea oceanic crust beneath the Philippine Sea plate resulted in volcanism in the Coastal Range and formation of an accretionary prism in the Central Range. Beginning in the latest Miocene–earliest Pliocene, the subduction was followed by initial arc-continent collision, as supported by the following: unroofing and erosion of the deformed accretionary prism, and deposition of sediments thus derived in the adjacent accretionary forearc (5 Ma) and slope basins (4 Ma); waning of volcanism (north, 6–5 Ma; south, 3.3 Ma); buildup of fringing reefs on the gradually quiescent volcanoes (north, 5.2 Ma; south, 2.9 Ma); arc subsidence by strike-slip faulting and the development of pull-apart intra-arc basins (north, 5.2–3.5 Ma; south, 2.9–1.8 Ma); thrusting of forearc sequences to generate a collision complex starting from 3 Ma; and clockwise rotation of the arc-forearc sequences (north, 2.1–1.7 Ma; south, 1.4 Ma). The collision propagated southward and reached southern Taiwan by 5 Ma, as evidenced by the successive deformation of the associated accretionary wedge en route. Afterward, the advanced arc-continent collision stage appeared in the earliest Pleistocene, as marked by the westward thrusting and accretion of the Luzon arc-forearc against the accretionary wedge (north, 1.5 Ma; south, 1.1 Ma) and exhumation of the underthrust Eurasian continent rocks (north, 2.0–1.0 Ma; south, 1.0–0.5 Ma). The final stage of the tectonic process, arc collapse-subduction, began by 1 Ma off the northern Coastal Range.

The geologic records compiled and presented in this study strongly support the scenario of a continuous southward migration of tectonic processes and a change in sediment source and structural style. Most importantly, the model has a broad potential for reconstructing and predicting the evolution of arc-continent collision through space and time.

Keywords: Taiwan, arc-continent collision, oblique collision, stratigraphic records, collision suture.

INTRODUCTION

Tectonic processes associated with arc-continent collision can be recognized by the shifting of sediment provenance, deformation of arc-forearc and accretionary wedge, abrupt change of sedimentation rate and depositional bathymetry in forearc or foreland basins, and the intensity of arc volcanism (Teng, 1979; Charlton et al., 1991; Abbott et al., 1994; Huang et al., 1995; Yang et al., 1995; Brown and Spadea, 1999). Geochemical studies, such as fission-track and argon-isotope dating, and pressure-temperature-time path analyses on the underthrust continental rocks in convergent zones, also can be used to reconstruct this exhumation history after subduction and subsequent collision (Berry and Grady, 1981; Liu, 1982; Liu et al., 2001; Lo and Yu, 1996; Wang et al., 1998; Hill and Raza, 1999; Ring et al., 1999; Harris et al., 2000; Willett et al., 2003). However, in many arc-continent collision belts, multiple stages of metamorphism, overprinting deformation, complicated tectonics, and inadequate age markers have obliterated or obscured most geologic records.

The geology of Taiwan is well known for its active and oblique collision between the Luzon Arc and the Eurasian continental margin (Fig. 1; Chai, 1972; Biq, 1973). The presence of an offshore modern analog further allows Taiwan to offer one of the clearest overviews of arc-continent collision (Huang et al., 1992, 2000).

Synthesizing new evidence and published data, we present temporal and spatial records that support a persistent southward propagation of the collision process, which in turn accounts for the sequential emergence and creation of Taiwan. Other recent interpretations of the tectonic evolution of Taiwan are also compared

Figure 1. Tectonic framework and the four geodynamic processes involved in the arc-continent collision in the Taiwan region. Refer to Huang et al. (2000) for details of tectonic processes and their geological-geophysical characteristics. A and B are locations for fission-track studies (Fig. 9) along the Central and Southern Cross-Island Highways. TT—Taitung Trough; SLT—South Longitudinal Trough; CFS—Chingshui fault scarp; arrow: magnetic declination. Compiled from Yang et al. (1983), Lee et al. (1991), Huang et al. (1992), Reed et al. (1992), Liu et al. (1998), Lallemand et al. (1997, 1999), Malavieille et al. (2002).

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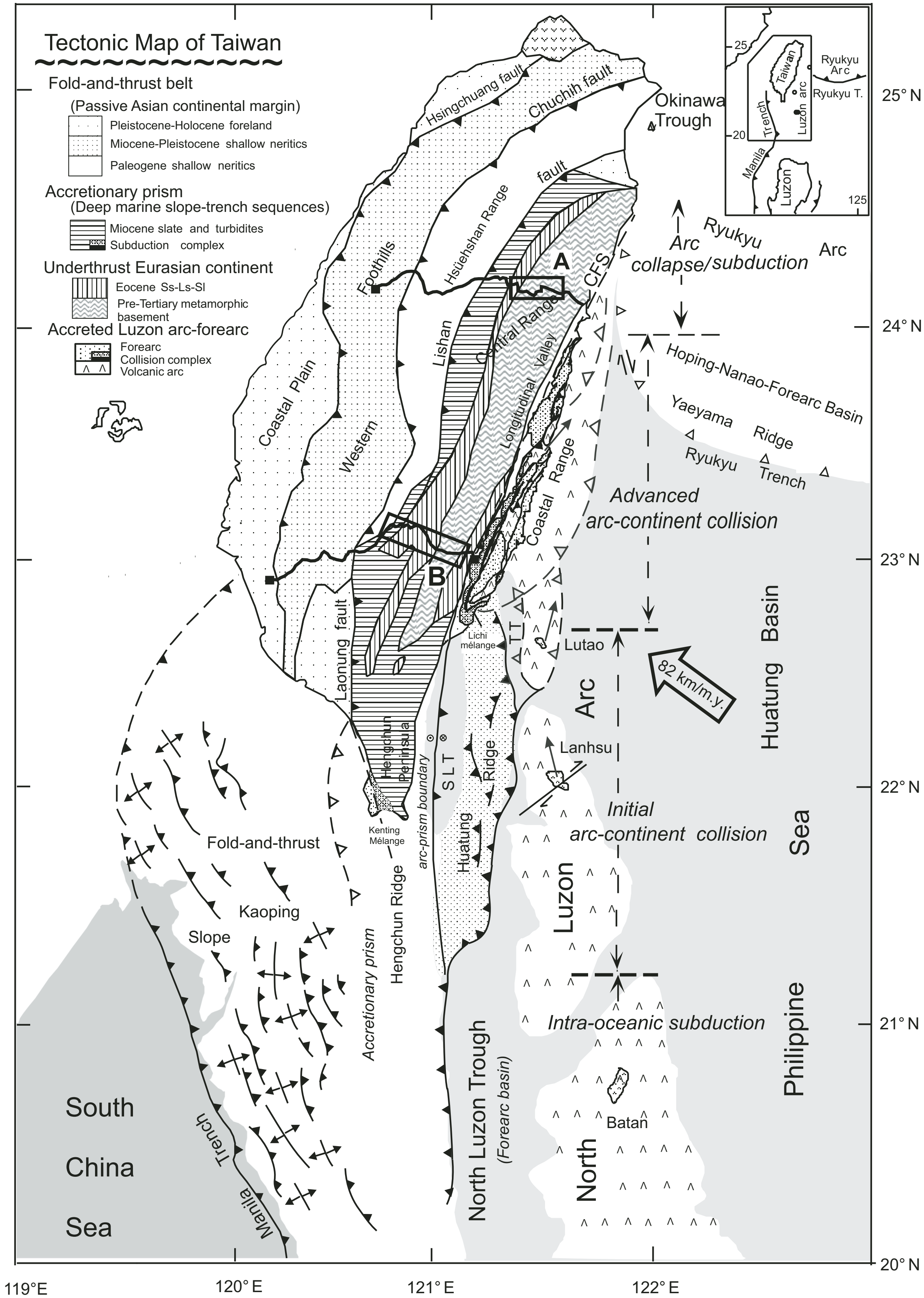

Tectonic Map of Taiwan
Fold-and-thrust belt
(Passive Asian continental margin)
Pleistocene-Holocene foreland
Miocene-Pleistocene shallow neritics
Paleogene shallow neritics
Accretionary prism
(Deep marine slope-trench sequences)
Miocene slate and turbidites
Subduction complex
Underthrust Eurasian continent
Eocene Ss-Ls-Sl
Pre-Tertiary metamorphic basement
Accreted Luzon arc-forearc
Forearc
Collision complex
Volcanic arc
Hsingchuang fault
Chuchih fault
Okinawa Trough
Ryukyu Arc
Ryukyu T.
Taiwan
Luzon arc
Trench
Manila
Luzon
25
20
125
25° N
24° N
23° N
22° N
21° N
20° N
119°E
120° E
121° E
122° E
fault
Hsüehshan Range
Foothills
A
CFS
Arc collapse/subduction
Ryukyu
Arc
Hoping-Nanao-Forearc Basin
Yaeyama Ridge
Ryukyu Trench
Lishan
Central Range
Longitudinal Valley
Coastal Range
Coastal Plain
Western
Advanced arc-continent collision
B
Lichi mélange
Lutao
82 km/m.y.
Huatung Basin
Laonung fault
Hengchun Peninsula
Kenting Mélange
arc-prism boundary
S L T
Huatung Ridge
Arc
Lanhsu
Initial arc-continent collision
Sea
Fold-and-thrust
Kaoping
Slope
Accretionary prism
Hengchun Ridge
Luzon
Intra-oceanic subduction
Philippine
North Luzon Trough
(Forearc basin)
Batan
North
South
China
Sea
Trench
Manila

and discussed, thus providing a comprehensive perspective on the time, space, and processes involved in this unparalleled collision terrain.

TECTONIC SETTING OF TAIWAN

Tectonics in the Taiwan region is characterized by two opposite subduction systems: The Eurasian continent–South China Sea oceanic crust (all on the Eurasian plate) subducts eastward beneath the Philippine Sea plate along the N-S-trending Manila Trench, whereas the Philippine Sea plate subducts northward beneath the Eurasian plate along the E-W-trending Ryukyu Trench (Fig. 1). Continuous subduction brought the Luzon Arc closer to the edge of the Eurasian continent and resulted in their collision in the late Neogene (Chai, 1972; Biq, 1973). Because the Asian continental margin (trending N 60°E) is oblique to the N-oriented Luzon Arc, and the Philippine Sea plate moves toward 310°–305°, the arc-continent collision has been diagonal; hence the point of collision migrated southward (at the rate of 84 km/m.y.; Suppe, 1984).

Conversely, the northward subduction of the Philippine Sea plate has resulted in collapse of the North Luzon Arc off NE Taiwan beneath the Ryukyu Trench (Wang and Chiang, 1998; Lallemand et al., 1999, 2001; Huang et al., 2000) and the backarc spreading of the Okinawa Trough behind the Ryukyu Arc.

Subduction and Collision Geology off Southern Taiwan

Off southern Taiwan, subduction of the South China Sea oceanic crust has resulted in the formation of an arc (North Luzon Arc), a forearc basin (North Luzon Trough), and an accretionary prism (Hengchun Ridge and Kaoping Slope; Fig. 1). The North Luzon Trough (forearc basin) narrows northward (Huang and Yin, 1990; Huang et al., 1992) at the expense of an expanding Huatung Ridge, which in turn has originated from multiple arcward (eastward) back thrusting of the forearc sequence (Reed et al., 1992; Lundberg et al., 1997; Malavieille et al., 2002).

Not only the offshore Luzon Arc and North Luzon Trough forearc basin connect northward with the Coastal Range, but the Huatung Ridge also has its counterpart on land: the Lichi Mélange collision complex (Fig. 1; Hsu, 1956; Huang et al., 1992; Huang, 1993; Chang et al., 2000). In addition, between the Hengchun Ridge and the North Luzon Trough, there lies a collision suture fault (i.e., the arc-prism boundary fault of Byrne, 1998, or the west-vergent thrusts with strike-slip components of Fuh et al., 1997, and Malavieille et al., 2002), which traverses the collisional suture basin (South Longitudinal Trough) and may correspond to the Longitudinal Valley fault on land (Figs. 1 and 2).

Bounded on the west by the Manila Trench, the Hengchun Ridge and Kaoping Slope widen northward as more sediments on the Asian continental slope and South China Sea Basin are progressively incorporated into this accretionary prism.

Tectonostratigraphy of Taiwan

Two major boundary faults are found in Taiwan (Fig. 1): The Lishan-Laonung fault, separating the Hsuehshan Range–Western Foothills and the Central Range–Hengchun Peninsula, marks the subduction suture that prevailed before the arc-continent collision (8.5 Ma). To its east the Longitudinal Valley fault between the Central Range and the Coastal Range is the collision suture formed during the advanced stage of collision (<2 Ma). Genetically related to these sutures, the Kenting Mélange (situated along the frontal accretionary prism) in the Hengchun Peninsula, and the Lichi Mélange (situated along the collision suture) in the accreted Coastal Range, represent subduction and collision complex, respectively (Fig. 1).

Also divided by major faults, four tectonostratigraphic units are recognized (Fig. 1): from west to east, the passive Asian continental margin fold-and-thrust belt, the accretionary prism, the underthrust Eurasian continent, and the accreted Luzon Arc-forearc.

The passive continental margin fold-and-thrust belt in the Coastal Plain, Western Foothills, and Hsuehshan Range is composed of Tertiary-Quaternary neritic and foreland sediments. During the arc-continent collision, these shallow-marine sediments were folded and thrust. Their modern analog on the submarine Kaoping Slope is presently undergoing the same process.

The next two tectonostratigraphic units are found in the Central Range–Hengchun Peninsula (Fig. 1): the Miocene slates-turbidites and the pre-Miocene metamorphic rocks to the east. The pre-Miocene metamorphics consist of Eocene quartzite-limestone-slate resting unconformably on a Paleozoic-Mesozoic metamorphic basement (representing underthrust Eurasian continental rocks). On the other hand, the Miocene slate-turbidites are composed of deep-marine sediments (but later incorporated into the accretionary prism), which are now exposed in the western Central Range and in the Hengchun Peninsula (Figs. 1 and 3; Huang et al., 1997).

Lastly, the Coastal Range in eastern Taiwan represents the accreted Luzon Arc and forearc (Fig. 2) and consists of three extinct volcanic islands, three associated remnant forearc basins, two intra-arc basins, and a mélange sequence derived from the shearing of forearc sediments (Huang et al., 1995, 2000; Chang et al., 2000, 2001).

DATABASE

Diverse interpretations of the evolution of the arc-continent collision in the Taiwan region have been proposed. They were established either from limited field data (e.g., paleomagnetism or radiometric dating; Wang, 1976; Liu, 1982; Liu et al., 2001; Teng, 1990; Lee et al., 1991; Lo and Yu, 1996; Wang et al., 1998; Huang et al., 1995, 1997; Chang et al., 2001) or from marine survey and modeling without stratigraphic evidence (Lallemand et al., 1999; Chemenda et al., 2001; Malavieille et al., 2002). In contrast, based on the progressive change of geological and geophysical features within the modern active collision zone between 20° and 25°N, Huang et al. (2000) recognized four tectonic processes (subduction, initial and advanced arc-continent collision, and arc collapse-subduction) in the Taiwan arc-continent collision. Their definition of the processes is followed in this study.

To support the pattern of tectonic evolution, in this paper we compiled four sets of published data: lithostratigraphy, biostratigraphy (planktic foraminifer and calcareous nannoplankton), sedimentology, and $^{40}Ar/^{39}Ar$ and fission-track dates of volcanic rocks. In addition, new fission-track ages of metamorphic rocks in the Central Range (Data Repository)[1] and forearc sequences in the southern Coastal Range, and sediment point-count data for slope-basin sediments in the Hengchun Peninsula, are incorporated into this study for fine-tuning the details on the uplift rates and shifting of source rocks pertaining to various stages of the collision.

STRATIGRAPHIC RECORDS

Temporal and spatial events (*a–m*; Fig. 4) that recorded the arc-continent collision and a southward consecutive migration of the four tectonic processes are provided in the following sections.

[1]GSA Data Repository item 2006042, two supplementary figures showing sampling location and fission-track analysis results along two transverse sections over the exhumed metamorphic basement (the basement represents the underthrust Eurasian continent that was unroofed during the advanced arc-continent collision in the past 3 m.y.), is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

Intra-Oceanic Subduction

Event* a—*Onset of Luzon Arc Volcanism

Rifting of the Eurasian continent in the late Oligocene to middle Miocene (Taylor and Hayes, 1983) gave rise to the formation of the South China Sea oceanic crust, which then was subducted eastward beneath the Philippine Sea plate along the Manila Trench, resulting in volcanism in the Luzon Arc (Fig. 1). Reliable age dating of volcanics in the Coastal Range showed that the northern Luzon Arc eruption began at ca. 16–15 Ma (Fig. 2; Yang et al., 1988, 1995). Thus, subduction of the South China Sea oceanic crust started from middle Miocene (Table 1; Figs. 4A and 5A).

Event* b—*Termination of Sedimentation in the Accretionary Prism

During the subduction, deep-sea sediments on the South China Sea floor were incorporated into an accretionary wedge. Therefore, the age of the youngest deep-sea strata found in the accretionary prism specifies the time when subduction ceased.

North of 24°N, the exposed accretionary prism has been partially eroded, where the strata are dated as 16–15 Ma (N8-9; Chang, 1975), indicating that the subduction terminated thereafter (Table 1). To obtain a more precise date, the distance of 216 km (between 24°30′N representing the northern edge of the accretionary prism, and 22°30′N denoting the boundary joining the initial- and advanced-arc–continent collision) is divided by the southward oblique collision propagation rate of 84 km/m.y. (Suppe, 1984), which gives approximately a duration of 2.5 m.y. Thus, in northern Taiwan the termination of subduction began around late Miocene (8.5 Ma = 2.5 + 6). Here the 6 Ma (N10-N16/17, Chang, 1975; or NN11, Chi, 1982) is the age of the youngest continent-derived deep-marine turbidites found on the Hengchun Peninsula (accretionary prism) in southern Taiwan (Fig. 3). The 6 Ma in turn represents the time when subduction stopped in southern Taiwan (22°–22°30′N; Table 1).

Initial Arc-Continent Collision (*Events* c–j)

Off southern Taiwan (Fig. 1), the initial arc-continent collision (between 21°20′ and 22°40′ N) is characterized by closure of the forearc basin, eastward back thrusting of forearc sediments, development of a collision suture–fault system, exposure of the accretionary prism, and tapering off of volcanic activity (Huang et al., 2000). Not only are these features detectable on land, but also other evidence of the initial arc-continent collision is preserved. Events *c–h* (Figs. 4 and 5) and

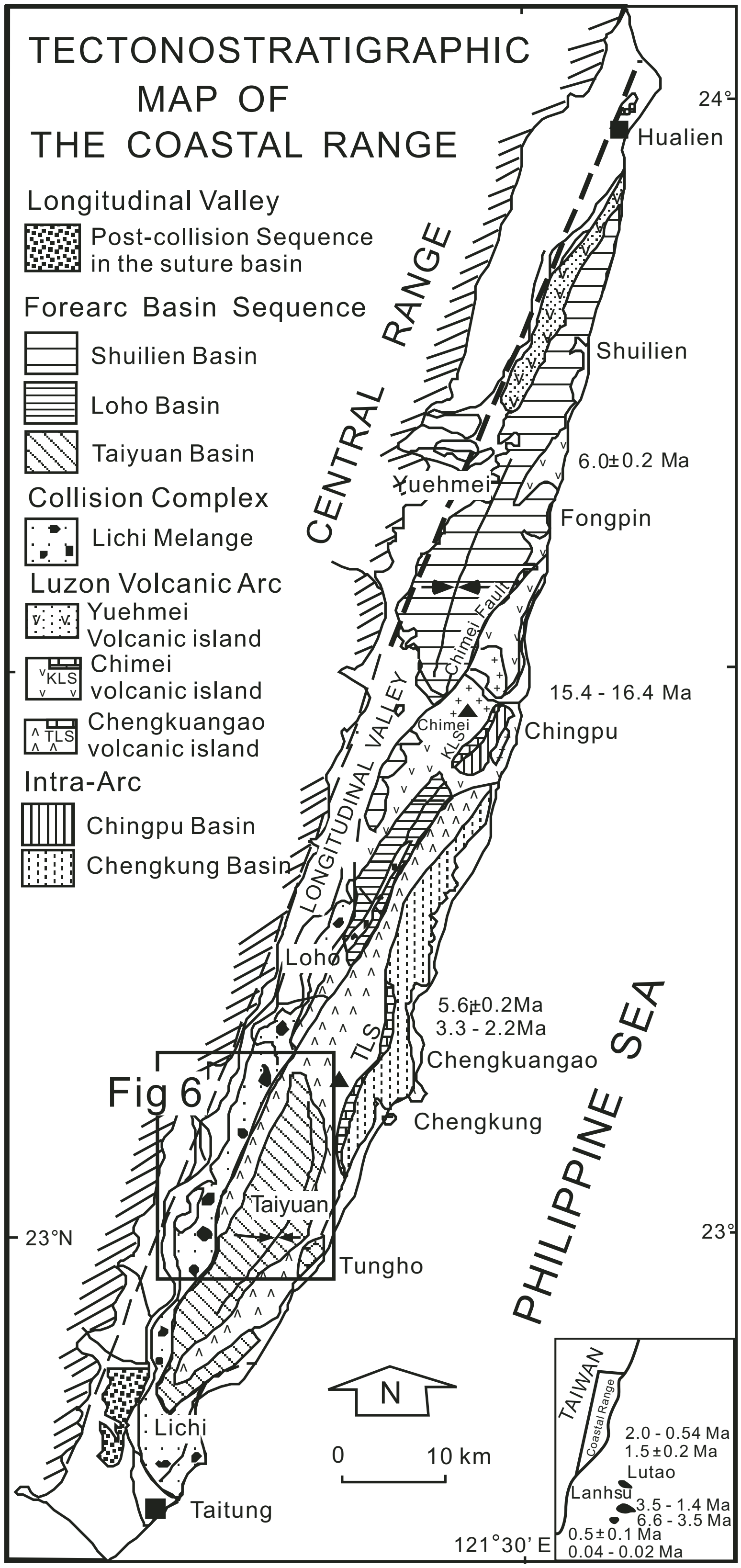


Figure 2. Tectonostratigraphic map of the Coastal Range, showing three accreted volcanic islands, three remnant forearc basins, two intra-arc basins, and the Lichi Mélange (modified from Huang et al., 1995, 2000). Age data on the volcanic sequences compiled from Chen et al. (1990), Yang et al. (1988), and Lo et al. (1994). Rectangle shows area covered in Figure 6.

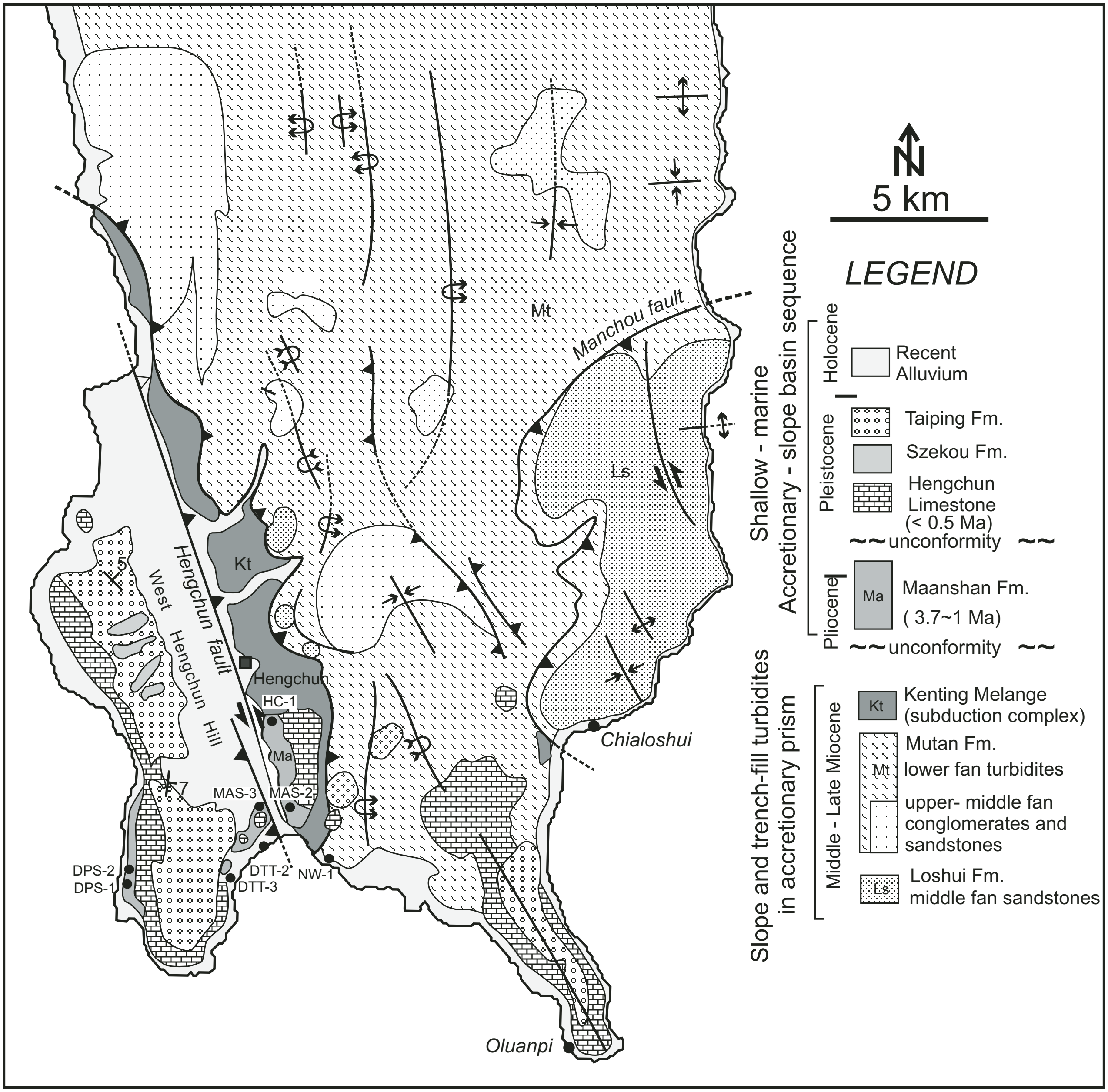


Figure 3. Geological map of the Hengchun Peninsula (modified from Sung, 1991; Huang et al., 1997; Chang et al., 2003). Numbered points are sample locations for the Maanshan Formation.

i–j (Fig. 7), which occurred separately east (Coastal Range) and west (Central Range–Hengchun Peninsula) of the collision suture, are presented in subsequent sections.

Event c—*Sequential Waning of Luzon Arc Volcanism in the Coastal Range*

Geochemical and stratigraphic data show that three volcanic islands (from north to south, Yuehmei, Chimei, and Chengkuangao; Fig. 2) in the Coastal Range were accreted to eastern Taiwan (Lo, 1989; Chen et al., 1990; Huang et al., 1995). The top of the Tuluanshan Formation (andesitic breccia, agglomerate, and tuff) of the Chimei volcanic island (Fig. 2) in the north was dated NN11 (<8–5 Ma; Chi et al., 1981) and 6–5 Ma ($^{40}Ar/^{39}Ar$; Lo et al., 1994). In comparison, the top of the same formation in the south (Chengkuangao volcanic island) was dated 5.6 Ma ($^{40}Ar/^{39}Ar$) and 3.3 Ma (fission track) (Fig. 2; Yang et al., 1988; Lo et al., 1994). Because the arc-continent collision caused the cessation of volcanism, the last volcanic activity represents the transition from subduction to collision (Figs. 4B and 5B).

In the present collision zone, volcanism in the offshore Lutao and Lanhsu Islands ended at 1.5 Ma and 0.5–0.04 Ma (Yang et al., 1988; Lo et al., 1994), respectively (Fig. 2). Thus, both the microfossil and radiometric ages indicate that the initial arc-continent collision began at ca. 6–5 Ma in the north and propagated southward (Table 1).

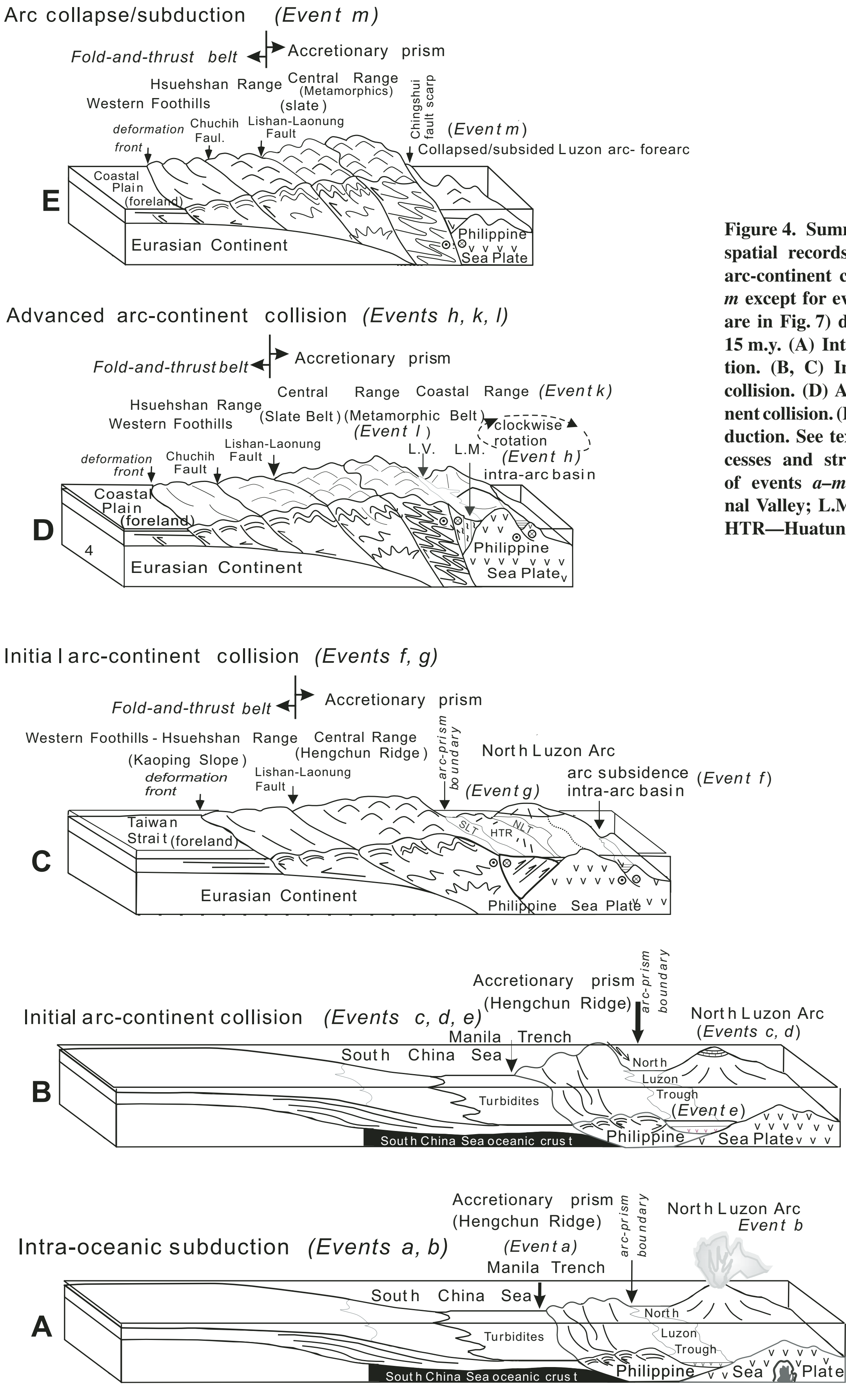


Figure 4. Summary of temporal-spatial records of active Taiwan arc-continent collision (Events *a–m* except for events *i* and *j*, which are in Fig. 7) during the past 16–15 m.y. (A) Intra-oceanic subduction. (B, C) Initial arc-continent collision. (D) Advanced arc-continent collision. (E) Arc collapse-subduction. See text for detailed processes and stratigraphic records of events *a–m*. L.V.—Longitudinal Valley; L.M.—Lichi Mélange; HTR—Huatung Ridge.

Event* d—*Development of Fringing Reefs atop Inactive Volcanic Islands

Off SE Taiwan in the present initial arc-continent collision zone, modern fringing reefs have built up on the Lanhsu and Lutao volcanic islands since their volcanism terminated. Therefore, the age of the oldest fringing-reef limestones atop volcanic islands can be used indirectly to infer the cessation of volcanism, which in turn indicates the time of transition from subduction to initial arc-continent collision (Figs. 4B and 5C).

Two reef-limestone sequences were recognized on the reconstructed volcanic islands in the Coastal Range (Huang et al., 1988; Huang and Yuan, 1994; Yuan, 1994; Huang et al., 1995): the Kangkou Limestone (5.2 Ma) on Chimei volcanic island in the north and the Tungho Limestone (2.9 Ma) on Chengkuangao volcanic island in the south (Figs. 2, 5E and F). As expected, these limestone ages are slightly younger than those of the last volcanic events (see event *c*, discussed previously).

The age relationships therefore indicate that the initial collision began at ca. 5.2 Ma in the north, 2.9 Ma in the south, and between <0.5 Ma and the present off SE Taiwan (Table 1).

Event* e—*Appearance of Prism-Derived Quartzose Sediments in the Forearc Basin

During subduction, the bulging Hengchun Ridge accretionary prism acted as a barrier that obstructed the Asian continent–derived quartz-rich sediments from entering the forearc North Luzon Trough. However, once the accretionary prism was uplifted and exposed to erosion, its sediments began to appear in the forearc basin. Because the elevation and uncovering of the accretionary prism is one of the major features of initial arc-continent collision (Huang et al., 2000), the first deposition of prism-derived quartzose turbidites in the forearc would denote an early phase of initial arc-continent collision.

Fission-track dating from the forearc sequence (Fig. 6) shows a young zircon age (<6 Ma), indicating that these sediments were derived from the tectonized and later exposed accretionary wedge (as shown by partial resetting of zircon grains) instead of directly from the Asian continent, where the last tectonism ceased at 65 Ma during the Yenshan movement (Chen et al., 2003). This new fission-track dating from the forearc sequences in the southern Coastal Range is consistent with the reported results from the northern Coastal Range (Liu et al., 2000).

The first appearance of such nonvolcanic, quartz-rich turbidites in the Coastal Range forearc basins was dated as NN13/14 (4.5–3.7 Ma; Chi et al., 1981). The forearc stratigraphy therefore suggests that the initial arc-continent collision began in the early Pliocene at ca. 5 Ma—e.g., 1 m.y. after subduction of the South China Sea oceanic lithosphere ceased at 6 Ma (events *a* and *b*; Table 1).

Event* f—*Arc Subsidence and Formation of Intra-Arc Basins

Submarine intra-arc basins were identified on both the Lutao and Lanhsu volcanic islands in the present-day initial arc-continent collision zone (Huang et al., 1995; Malavieille et al., 2002). It was proposed that the basin originated from strike-slip faulting within the arc, which in turn was caused by the oblique collision between the Luzon Arc and the underthrust Eurasian continent (Fig. 4C).

In the eastern part of the Coastal Range, fringing-reef limestones (event *d*) are overlain by deep-marine turbidites (Figs. 5E and F), indicating rapid arc subsidence during the late phase of initial arc-continent collision (Fig. 5D). Further, the limestone sequences lie at the bottom of two reconstructed intra-arc basins (each 10 km wide by 40 km long): the Chingpu intra-arc basin on the Chimei volcanic island in the north, and the Chengkung intra-arc basin on the Chengkuangao volcanic island in the south (Fig. 2). Bio- and magnetostratigraphic data

TABLE 1. SUMMARY OF THE SPATIAL-TEMPORAL RECORDS OF THE TAIWAN ARC-CONTINENT COLLISION

	Intra-oceanic subduction	Initial arc-continent collision	Advanced arc-continent collision	Arc collapse-subduction
West of collision suture				
(*a*) Stratigraphy in accretionary prism	16–15 Ma (N) 6 Ma (S)			
East of collision suture				
(*b*) Onset of volcanism	16–15 Ma			
East of collision suture				
(*c*) Last volcanism		6–5 Ma (N) 3.3 Ma (S) 1.5–0.02 Ma (offshore)		
(*d*) Development of fringing reef around nonactive volcanic island		5.2 Ma (N) 2.9 Ma (S) <0.5 Ma–present (offshore)		
(*e*) Deposition in forearc basin		5 Ma		
(*f*) Arc subsidence and formation of intra-arc basin		5.2–3.5 Ma (N) 2.9–1.8 Ma (S) Present (offshore)		
(*g*) Deformation of western forearc basin (formation of mélange)		3 Ma (S) Present (offshore)		
(*h*) Clockwise rotation of forearc basin		2 Ma (N) 1 Ma (S) Present (offshore)		
West of collision suture				
(*i*) Deposition in accretionary slope basin		4 Ma Present (offshore)		
(*j*) Deformation of accretionary slope basin		<1 Ma–present		
East of collision suture				
(*k*) Westward thrusting of forearc and intra-arc basins			1.5 Ma (N) 1.1 Ma (S)	
West of collision suture				
(*l*) Exhumation of underthrust continent			1.0 Ma (N) 0.5 Ma (S)	
East of collision suture				
(*m*) Collapse of accreted Luzon Arc-forearc				<1 Ma–present

Note: Lowercase italic letters in parentheses refer to spatial-temporal events as described in text. N—north; S—south.

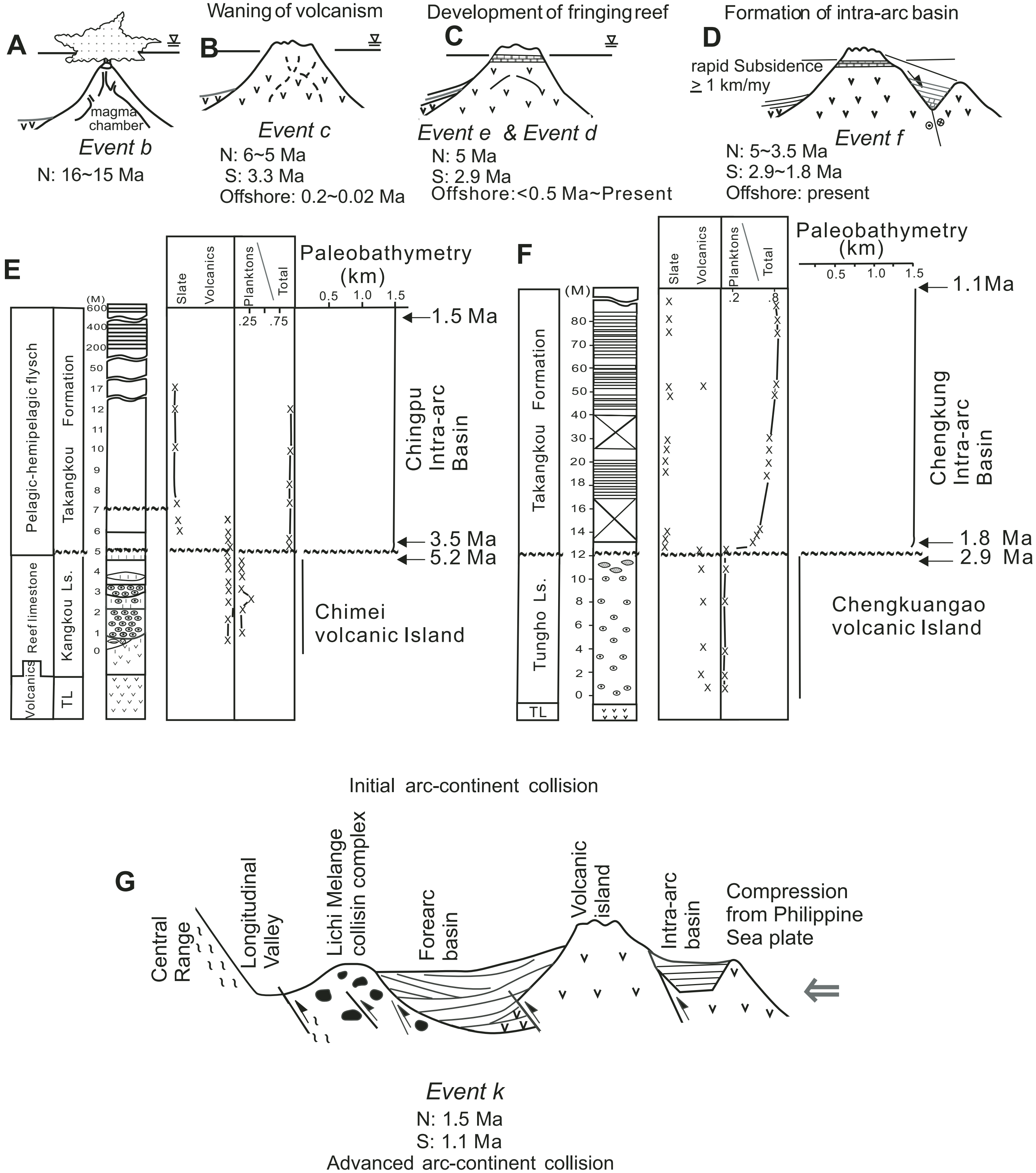


Figure 5. Stratigraphic sequence recording the (A) active volcanism (event *a*) during intra-oceanic subduction, (B) waning of volcanism (event *c*), (C) sedimentation of forearc basin (event *e*) and development of fringing reef (event *d*), (D) arc subsidence (event *f*) and infilling of intra-arc basin with deep-marine flysch overlying shallow-marine fringing limestone in (E) Chingpu intra-arc basin and (F) Chengkung intra-arc basin during initial arc-continent collision, to finally (G) westward-landward thrusting and accreting of the arc-forearc onto the exposed underthrust Eurasian continent (eastern Central Range) (event *k*) along the collision suture of Longitudinal Valley during advanced arc-continent collision. Modified from Huang et al. (1995). N—north; S—south.

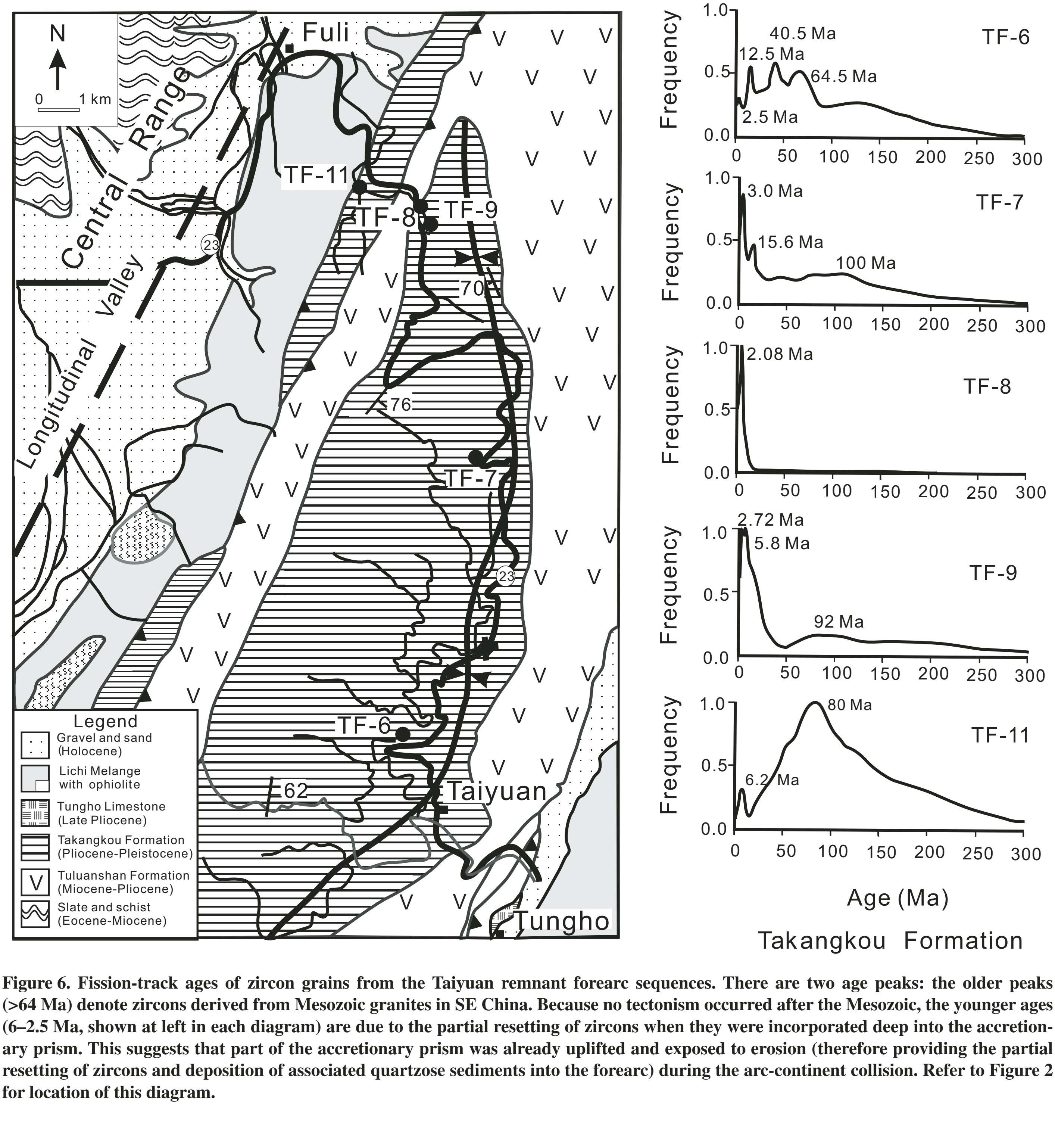


Figure 6. Fission-track ages of zircon grains from the Taiyuan remnant forearc sequences. There are two age peaks: the older peaks (>64 Ma) denote zircons derived from Mesozoic granites in SE China. Because no tectonism occurred after the Mesozoic, the younger ages (6–2.5 Ma, shown at left in each diagram) are due to the partial resetting of zircons when they were incorporated deep into the accretionary prism. This suggests that part of the accretionary prism was already uplifted and exposed to erosion (therefore providing the partial resetting of zircons and deposition of associated quartzose sediments into the forearc) during the arc-continent collision. Refer to Figure 2 for location of this diagram.

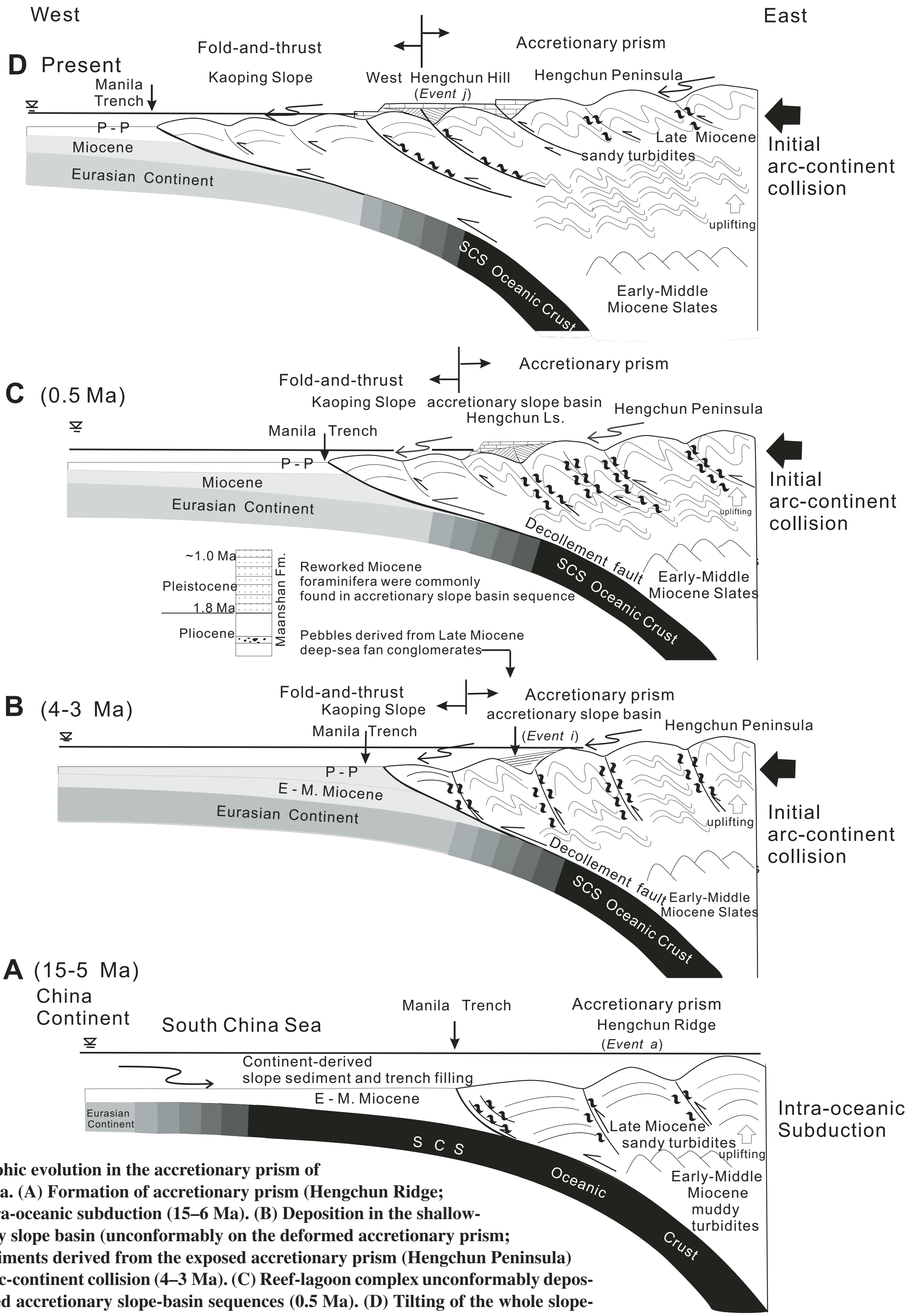
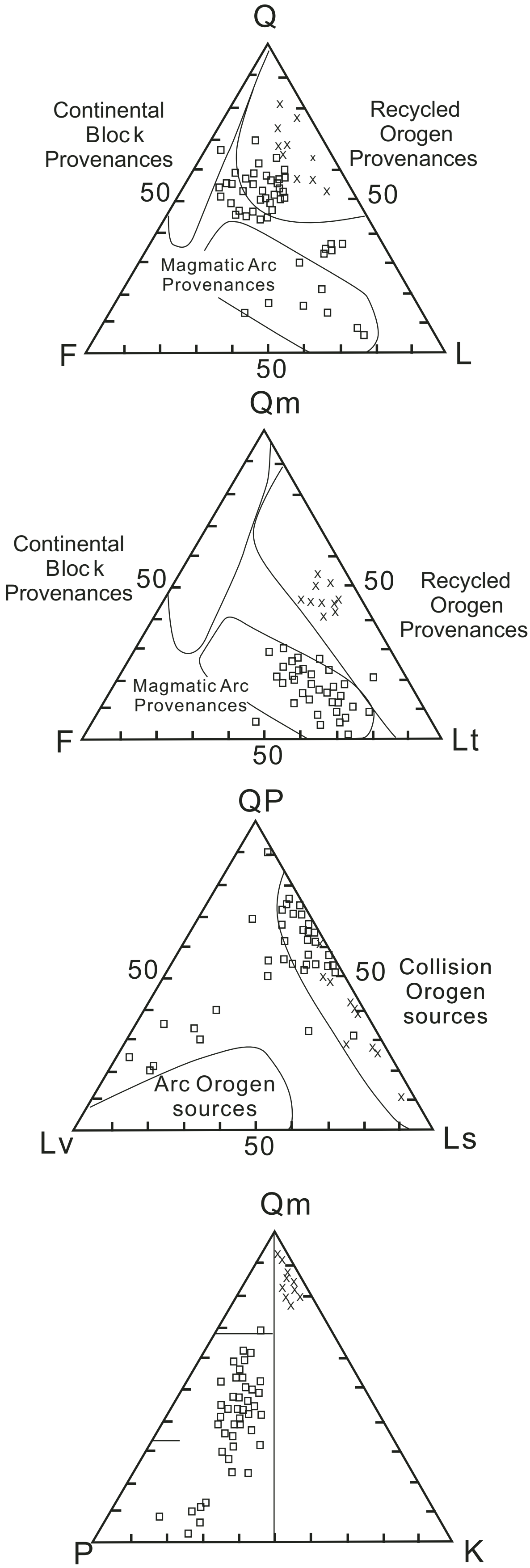


Figure 7. Stratigraphic evolution in the accretionary prism of Hengchun Peninsula. (A) Formation of accretionary prism (Hengchun Ridge; event *b*) during intra-oceanic subduction (15–6 Ma). (B) Deposition in the shallow-marine accretionary slope basin (unconformably on the deformed accretionary prism; event *i*) with its sediments derived from the exposed accretionary prism (Hengchun Peninsula) during the initial arc-continent collision (4–3 Ma). (C) Reef-lagoon complex unconformably deposited on the deformed accretionary slope-basin sequences (0.5 Ma). (D) Tilting of the whole slope-basin sequences (event *j*) as the West Hengchun Hill in the southern Hengchun Peninsula.



show that the basal Chingpu and Chengkung intra-arc basin sediments are 3.5 Ma and 1.8 Ma (Huang et al., 1995; Horng and Shea, 1996), respectively (Figs. 5E and F). Thus, the period between the reef-limestone deposition and the overlying deep-marine turbidite sedimentation (5.2–3.5 Ma in the north and 2.9–1.8 Ma in the south) indicates the interval of intra-arc basin formation and arc subsidence (Figs. 4C and 5D) during the initial arc-continent collision (Table 1).

Event g—Deformation of Forearc Basin and Formation of a Collision Complex: The Lichi Mélange

As described previously for the modern initial arc-continent collision zone, the forearc sequence in the North Luzon Trough was back thrust eastward, creating the Huatung Ridge (Fig. 4C). As a result, the North Luzon Trough (forearc) tapers off northward and finally closes at its northern terminus (Fig. 1). In addition, the submarine Huatung Ridge connects northward with the Lichi Mélange in the southern Coastal Range (Figs. 1 and 4C and D).

The Lichi Mélange lies west of the remnant forearc basin strata (Loho Basin and Taiyuan Basin; Fig. 2). A comparable geographical relationship is found offshore where the Huatung Ridge also lies west of the Luzon Trough forearc basin (Figs. 1 and 2). Moreover, similarity of the Lichi Mélange and the submarine Huatung Ridge in their lithology, clay mineral compositions, and tectonic setting (Huang et al., 1992; Huang, 1993) prompted Huang et al. (2000) and Chang et al. (2000) to suggest that the Huatung Ridge is the precursor of the Lichi Mélange. Therefore, the age of the youngest deformed sediments in the Lichi Mélange and the offshore Huatung Ridge can be used to infer the inception of initial collision when the forearc sequence began to be deformed (Fig. 4C).

The Lichi Mélange in the southern Coastal Range gave a consistent age of 3.7–3.5 Ma (NN15; Chi et al., 1981; Chi, 1982; Barrier and Müller, 1984) or late N19 (Chang, 1975), almost identical to that of the samples (3.5–2.9 Ma)

Figure 8. Comparison of sediment composition in (1) the shallow-marine accretionary slope basin, Maanshan Formation (×), and (2) the various facies of deep-marine turbidites in the Hengchun Peninsula (□; Sung and Wang, 1985), suggesting that the former sediments were derived from the exposure and erosion of the latter during the initial arc-continent collision.

dredged from the submarine Huatung Ridge (Huang et al., 1992; Huang, 1993). This suggests that the initial arc-continent collision in the southern Coastal Range (23° N) occurred at ca. 3 Ma (Table 1).

Event **h**—*Clockwise Rotation of the Forearc and Arc*

During the late phase of initial arc-continent collision, not only were the arc and forearc sequences back thrust, but they were also rotated (Fig. 4D). For example, in the modern initial collision zone off SE Taiwan, the Lutao volcanic island has already been rotated 14° clockwise, although the Lanhsu volcanic island in the south has held its current declination of 346° (Yang et al., 1983; Fig. 1).

Similarly, magneto- and biostratigraphic studies enabled Lee et al. (1991) to demonstrate that the forearc sequences in the Shuilien remnant forearc basin began to rotate clockwise at 2.1–1.7 Ma in the north, and at 1.4 Ma in the south (Taiyuan remnant forearc basin). These ages registered the last phase of initial arc-continent collision (Table 1) before they were ultimately thrust westward to form the Coastal Range during the succeeding advanced collision.

Event **i**—*Deposition of Slope-Basin Sequences on the Deformed Accretionary Wedge in the Hengchun Peninsula*

At the intra-oceanic subduction stage, the accretionary prism widened and thickened owing to sediment deformation and offscraping (Figs. 4A–C). Further, as the northern prism proceeded into the initial arc-continent collision stage, it was uplifted and became the emergent Central Range–Hengchun Peninsula (Fig. 1). It is conceivable that sediments derived from this exposed prism were transported and deposited in the accretionary slope basins that developed on the deformed accretionary prism (Figs. 7A and B; Lundberg et al., 1997). Therefore, the formation of the accretionary slope basin is another useful parameter that signifies the inception of initial arc-continent collision.

On the southern Hengchun Peninsula, the Plio-Pleistocene shallow-marine slope-basin sequence (Maanshan Formation and overlying reef-lagoon complex; Fig. 3) unconformably overlies the deformed deep-marine Miocene turbidites of the accretionary prism. The Maanshan Formation contains rounded gabbro pebbles and reworked Miocene deep-marine foraminifers (Fig. 7B). In addition, point count results show that the Maanshan Formation is comparable in composition to the Miocene turbidite (Fig. 8; Sung and Wang, 1985), indicating that the former was derived from the exposed Miocene turbidites of the accretionary wedge. The base of the Maanshan Formation is N19 or NN15 (3.7–3.5 Ma; Cheng and Huang, 1975; Chi, 1982); therefore, it is suggested that the initial arc-continent collision could have begun at 4 Ma in southern Taiwan (Table 1).

Event **j**—*Deformation of the Slope-Basin Sequence*

The Maanshan Formation (3.7–1 Ma; Fig. 3), which was deposited in the accretionary slope basin, was faulted and then unconformably overlain by the latest Pleistocene (<0.5 Ma) barrier reef–lagoon complex (Figs. 3 and 7C). Both sequences then were tilted eastward (West Hengchun Hill in Fig. 3; Cheng and Huang, 1975; Huang, 1988), indicating that the whole slope basin was deformed and uplifted since 1 Ma (Figs. 7C and D) during the initial arc-continent collision in southernmost Taiwan (Table 1).

Advanced Arc-Continent Collision (*Events* k–l)

The advanced arc-continent collision is characterized by the westward thrusting and accretion of the Luzon Arc-forearc onto the Asian continent and the exhumation of metamorphic basement, which now crops out in the eastern Central Range.

Event **k**—*Westward Thrusting and Accretion of the Arc and Forearc*

As the arc-continent collision propagated southward, the northern part of the arcs and forearc basins were thrust westward, forming the Coastal Range in eastern Taiwan (Figs. 4D and 5G). Thus, the age of the youngest strata in the forearc and intra-arc basins marks the onset of the advanced arc-continent collision.

Bio- and magnetostratigraphic studies (Chang, 1975; Chi et al., 1981; Lee et al., 1991) gave an age of 1.5 Ma for the youngest strata in the Shuilien forearc basin and the Chingpu intra-arc basin in the north, and an age of 1.3–1.1 Ma for the youngest strata in the Taiyuan forearc basin and the Chengkung intra-arc basin in the south (Chang, 1975; Chi et al., 1981; Horng and Shea, 1997). This indicates that the Coastal Range was accreted and uplifted at 1.5 Ma in the north and 1.1 Ma in the south (Table 1).

Event **l**—*Exhumation of Underthrust Eurasian Continent in the Eastern Central Range*

In the Hengchun Peninsula (southern Central Range between 21°50′ and 22°30′N) within the initial arc-continent collision zone, Miocene slates and turbidites of the accretionary prism are exposed (Fig. 3). In contrast, north of 22°30′N the Paleozoic-Eocene metamorphic basement of the underthrust Eurasian continent crops out, almost coinciding in location with the southern tip of the Coastal Range (22°40′N; Fig. 1).

Fission-track dating of zircon, apatite, and sphene grains showed that the Eurasian continental basement was unroofed slowly before 5 Ma but more rapidly afterward, increasing from 3 mm/yr at 3–2.5 Ma to 9–10 mm/yr in the past 1.5 m.y. (Liu, 1982). In addition, fission-track analyses from two traverses indicate that schist in the northern Central Range (Profile A in Fig. 1) was unroofed during 2.5–1.0 Ma (mostly between 2.0 and 1.0 Ma), followed by unroofing in the south (Profile B in Fig. 1) during ca. 2.0–0.5 Ma (largely 1.0–0.5 Ma; Fig. 9; Tsao, 1996). These data are consistent with a previous study (Liu et al., 2001), suggesting that the advanced arc-continent collision also migrated southward (Table 1).

Arc Collapse and Subduction

Event **m**—*Collapse of Accreted Luzon Arc-Forearc*

It is proposed that arc collapse occurred when the northernmost Coastal Range (accreted Luzon Arc) subducted northward beneath the Eurasian continent along the Ryukyu Trench (Fig. 4E; Lallemand et al., 1997). Extending from the Longitudinal Valley fault, the Chingshui fault scarp off NE Taiwan (CFS in Fig. 1) is believed to mark the collapsed trace of the Luzon Arc-forearc north of Hualien (Fig. 4E; Huang et al., 2000). Presumably, the small Yuehmei volcanic body in the northernmost Coastal Range (Fig. 2) represents the relic of the collapsed Luzon Arc as it approached the Ryukyu Trench.

The timing of arc collapse and subduction can be inferred to postdate the thrusting and accretion of the youngest strata in the Shuilien forearc basin (northern Coastal Range; 1.5 Ma; event *k*, discussed previously), probably having occurred within the past 1 m.y. (Table 1).

DISCUSSION

Collision Age Controversy

There is a general consensus that an oblique arc-continent collision has taken place in Taiwan since the Plio-Pleistocene, which is known as the Penglai orogeny. Also, a wide spectrum of "collision" ages ranging from 12 to 2 Ma in stratigraphic records has been proposed. These various dates in the following discussion, however, probably register different stages of the tectonics described in this article.

Teng (1990) suggested that the collision started at 12 Ma ~160 km east of Taiwan in the southern Okinawa Trough. However, his "collision" refers

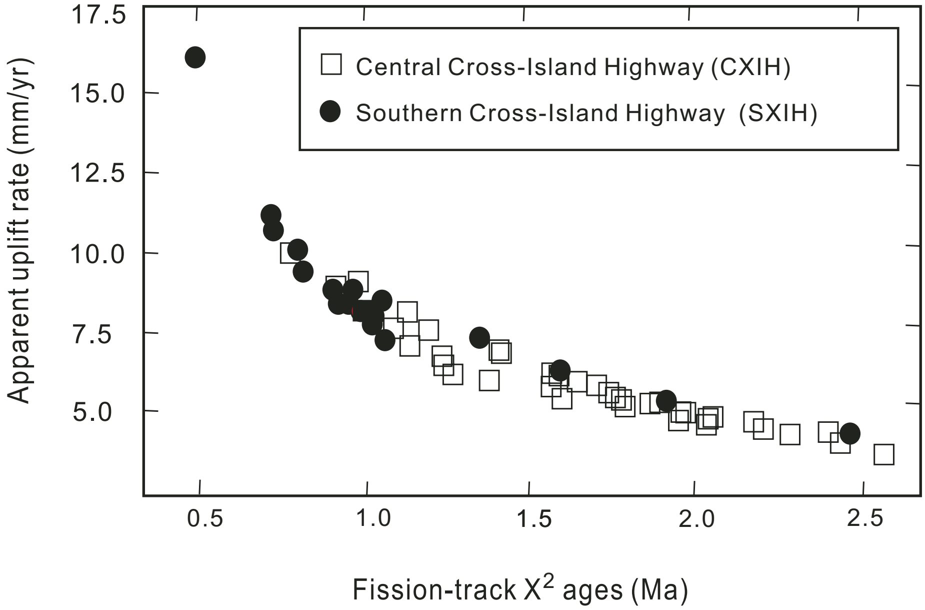


Figure 9. Fission-track data for inferring the exhumation age of metamorphic rocks (underthrust Eurasian continent) now exposed in the Central Range within the advanced arc-continent collision zone. See Figure 1 for location of the two studied traverses. A—Central Cross-Island Highway; B—Southern Cross-Island Highway.

to the encroachment of the Luzon Arc upon the Asian continental rise and slope while subduction was still in progress. Therefore, Teng's onset of collision at 12 Ma, which postdates the earliest volcanism (16–15 Ma) and predates the waning of Luzon Arc volcanism (6 Ma), corresponds to the intra-oceanic subduction as defined in Huang et al. (2000).

A thermal event at 11 Ma, determined by $^{40}Ar/^{39}Ar$ methods on phengites from the exhumed late Mesozoic glaucophane schist in the eastern Central Range, was used to infer the collision age for the Penglai orogeny (Lo and Yu, 1996). They pointed out that the thermal overprinting temperatures (300–450 °C) of the samples are near the closure temperature for phengite (~400 °C). Thus this thermal event could have resulted either from crystallization during cooling or resetting of isotopes by thermal overprinting. However, because this 11 Ma thermal event occurred during the time of active subduction (16–8.5 Ma) and is older than the earliest initial collision (8.5 Ma; Table 1) and the exhumation of the underthrust Eurasian continent (2 Ma) discussed previously, most likely it represents heating when Mesozoic metamorphic rocks of the Eurasian continent–South China Sea oceanic crust subducted beneath the Philippine Sea plate rather than the cooling effect during exhumation of the underthrust continent in an advanced stage of collision. In addition, if 11 Ma is indeed the collision age, as Lo and Yu (1996) proposed, it deviates from another $^{40}Ar/^{39}Ar$ age (of biotites in a mylonite zone within gneiss) in the eastern Central Range. The later study showed that mylonitization occurred at 4.1–3.3 Ma (Wang et al., 1998) when the underthrust basement underwent intensive deformation. The mylonitization of the gneiss agrees with the proposed initial arc-continent collision tectonics (<8.5 Ma; Table 1) that caused not only deformation in the accretionary prism, but also the underthrust Eurasian continent beneath the prism.

Wang (1976) proposed that a 9 Ma horizon, situated between the land- (prism-) derived turbidites (with slate chips) and the underlying volcaniclastics in the Coastal Range, could represent the time of arc-continent collision. However, both in the Coastal Range and the modern subduction-collision region off southeast Taiwan, the prism-derived turbidites are found only unconformably overlying the volcanic basement but nowhere atop the arc (Huang et al., 1992; Reed et al., 1992; Malavieille et al., 2002). Moreover, in the Coastal Range the lowermost zone of the prism-derived turbidites that contain slate chips is 3 Ma (Chi et al., 1981) instead of 9 Ma (an error resulting from a misunderstanding of fossil ages as defined by Chang, 1975). The revised age is much younger than the last volcanism (6 Ma) in the northern Coastal Range.

On the other hand, Liu (1982) noticed an abrupt increase of uplift rate in the northern Central Range metamorphic basement since 3 Ma, which was thus marked as the time of collision. However, the present study points out that in the eastern Central Range rapid uplift took place at 2.0–1.0 Ma (in the north) and 1.0–0.5 Ma (in the south) during the advanced collision stage. Therefore, Liu's collision age (3 Ma) could represent the transition from the initial to advanced stages of arc-continent collision.

Other arguments as to collision age were based on sedimentological studies. For example, a sharp increase in forearc sedimentation rate at 3 Ma was regarded as the result of drastic collision (Teng, 1990) or incipient collision (Dorsey, 1988). But, as discussed for event *d*, the forearc sequences were primarily derived from erosion of the accretionary prism to the west. Therefore, following the definition and processes of arc-continent collision (Huang et al., 2000), this sharp increase of sedimentation rate and change of sediment provenance at 3 Ma would register the transition from the late phase of initial arc-continent collision to early advanced arc-continent collision, when the accretionary prism and the underthrust metamorphic basement were rapidly exhumed.

CONCLUSIONS

Owing to well-understood biostratigraphy and tectonostratigraphy, and to the presence of comparatively simple offshore analogs, Taiwan is the most precisely documented example in the world of the spatial and temporal evolution of an oblique arc-continent collision. Four tectonic processes are involved in the active Taiwan arc-continent collision. Stratigraphic records are best available for both sides of the collision suture, Longitudinal Valley, and each collision process in the north predates that in the south.

The Taiwan arc-continent collision (Fig. 4) started from eastward intra-oceanic subduction of the South China Sea oceanic crust beneath the Philippine Sea plate and formation of the Luzon Arc and the accretionary wedge in the middle-late Miocene in the north (western Central Range) and the late Miocene in the south (6 Ma) in the south (Hengchun Peninsula), whereas the subduction terminated at 8.5 Ma in the north and 6 Ma in the south. The subsequent initial arc-continent collision began in the early Pliocene, when Eurasian continent crust entered the Manila subduction zone. The initial arc-continent collision is manifested by multiple stratigraphic records: waning of volcanism in the North Luzon Arc (north, 6–5 Ma; south, 3.3 Ma); deposition of forearc basin sequences (5 Ma); development of fringing reefs on nonactive volcanic islands (north, 5.2 Ma; south, 2.9 Ma); arc subsidence and formation of intra-arc basins (north, 5.2–3.5 Ma; south, 2.9–1.8 Ma); and clockwise rotation of forearc basins (north, 2.1–1.7 Ma; south, 1.4 Ma) east of the collision suture, and deposition in the accretionary slope basin (4 Ma) as well as deformation of accretionary slope-basin sequences (<1 Ma–present) west of the collision suture. Finally, westward accretion of the Luzon Arc-forearc (north, 1.5 Ma; south, 1.1 Ma) against the exhumed and uplifted underthrust metamorphic basement (north, 2–1 Ma; south, 1.0–0.5 Ma) records the advanced arc-continent collision tectonics. The most advanced tectonic process, arc collapse-subduction, has occurred only in 24°–24°3.0′N off the northern Coastal Range during the past 1 m.y.

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