TEMPORAL-SPATIAL RECORDS OF ACTIVE ARC-CONTINENT COLLISION IN TAIWAN

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ABSTRACT

Well-constrained stratigraphy and clear geodynamic processes in Taiwan offer a unique example for collision belts worldwide, where temporal and spatial evolution of arc-continent collision has been recorded in detail.

Oblique arc-continent collision in Taiwan involves four tectonic processes propagating southward. Volcanism in the Coastal Range records an eastward subduction of the South China Sea oceanic crust beneath the Philippine Sea plate started in 16-15 Ma. Deformation of accretionary wedge further suggests that the subduction continued till 6-5 Ma in southern Taiwan. The subduction was followed by initial arc-continent collision since the Earliest Pliocene as indicated by multiple events, such as un-roofing of sediments from the deformed pre-collision accretionary prism and their deposition in adjacent accretionary slope basin and forearc basin (5-4 Ma); waning of volcanism (north: 6-5 Ma; south: 5-3 Ma); development of fringing reefs on the diminishing arcs (north: 5 Ma; south: 2.9 Ma); arc subsidence (north: 3.5 Ma; south: 1.8 Ma) due to oblique convergence to develop
intra-arc basins; back-arc thrusting of forearc sequences to generate the Lichi Mélange starting 3 Ma; and clockwise rotation of forearc sequences (north: 2 Ma; south: 1 Ma).

Finally, westward thrusting/accretion of the Luzon arc-forearc against the accretionary wedge (north: 1.5-1.0 Ma; south: 1.0-0.5 Ma), as well as exhumation of the underthrust Eurasian continent crust rocks (north: 2.5-1.0 Ma; south: 0.5 Ma-Present), mark the advanced arc-continent collision in Earliest Pleistocene. At present, the most advanced tectonic process – arc collapse / subduction, occurs off the northern Coastal Range starting 1 Ma.

1. INTRODUCTION

Tectonic processes involved with arc-continent collision can be recognized by study of variations in sediment provenances, deformation of accretionary wedge and forearc basins, abrupt changes of sedimentation rate or depositional bathymetry in forearc or foreland basins, and history of arc volcanism (Teng, 1979; Charlton et al., 1991; Abbott et al., 1994; Huang et al., 1995; Brown and Spadea, 1999). Geochemistry study including fission track dating, argon isotope and P-T-t path analyses on exposed high pressure metamorphic basement in convergent zone could also be used to monitor or reconstruct exhumation history during subduction and the following collision tectonics (Berry and Grady, 1981; Liu, 1982; Lo and Yu, 1996; Wang et al., 1998; Hill and Raza, 1999; Harris et al., 2000).

However, in most arc-continent collision belts, multiple stages of metamorphism,
deformations, complicated tectonics, and insufficient age makers have either obliterated or obscured the geologic records.

Geology of Taiwan is well known for its active and oblique collision between the Luzon Arc on the Philippine Sea Plate (PSP) and the Eurasian continental margin (Fig. 1). Well dated stratigraphy in the sedimentary cover, especially the presence of an offshore modern analog of the collision, allows Taiwan to present one of the clearest pictures in the worldwide arc-continent collision belts (Huang et al., 2000). Despite of clear geological setting, because lack of a self-evident definition and coherent synthesis of the arc-continent collision processes, there have been numerous disagreements on the nature and timing (from 12 Ma to 2Ma, see Discussion below) of tectonic processes involved.

Based on the geologic and geophysical characters of the present arc-continent collision nature, Huang et al. (2000) recognized that the Taiwan arc-continent collision actually involved four sequential processes. Following this detailed definition of each collision process, we present herein temporal and spatial records of the Taiwan arc-continent collision, which reveals a persistent southward propagation of each collision process consistent with model prediction of oblique tectonics.

2. TECTONIC SETTING OF TAIWAN

Tectonics in the Taiwan region is characterized by existence of two flipping subduction systems: the Eurasian Continent-South China Sea (SCS) oceanic crust (Eurasian Plate)
subducts eastward beneath the PSP along N-S-trending Manila Trench in the southwest, and the PSP subducts northward beneath the Eurasian Plate along the E-W- trending Ryukyu Trench in the northeast (Fig.1). Continuous subduction brought the Luzon Arc closer to the leading edge of the Eurasian Continent, and resulted in their collision in late Neogene (Chai, 1972; Biq, 1973). Because the Asian continental margin (060°) trends differently from the Luzon Arc (N-S direction), and the PSP moves in 310-305° direction, the arc-continent collision has been slightly oblique and the point of collision migrated southward (Suppe, 1984). In contrast, the northward subduction of PSP results in collapse of the North Luzon Arc off eastern Taiwan beneath the Ryukyu Trench and back-arc spreading of the Okinawa Trough behind the Ryukyu Arc.

2.1 Subduction and collision geology off southern Taiwan: analog to the past

Between Taiwan and Luzon south of 20° N, subduction of the SCS oceanic crust results in formation of accretionary prism of Hengchun Ridge and the forearc basin of the North Luzon Trough, both parallel to the Luzon Arc (Fig. 1). When tectonics proceeds to the initial arc-continent collision zone in 20-21°N, more and more deep-sea sediments on the Asian continental slope and SCS deep-sea basin are progressively involved into the accretionary wedge, therefore width of the accretionary prism increases northward approaching Taiwan, including a NW-SE-trending syn-collision prism Kaoping Slope in the west and a N-S-trending pre-collision prism Hengchun Ridge in the east (Fig. 1).
Between the Hengchun Ridge and forearc basin of the North Luzon Trough, there lies an arc-prism boundary fault (Byrne, 1998), which passes northward through a submarine collision suture basin of the South Longitudinal Trough, and further connects to the onshore Longitudinal Valley fault system (Figs. 1 & 2). The western part of the forearc sequence is back-thrust eastward to form the Huatung Ridge and further connects to a collision complex of the Lichi Mélange in the southernmost Coastal Range (Fig. 1; Hsu, 1956; Huang et al., 1992; Huang, 1993). Therefore, the North Luzon Trough is progressively closed at its northern end approaching the Coastal Range (Huang and Yin, 1990; Reed et al., 1992).

2.2 Tectonostratigraphy on land Taiwan

The Manila Trench subduction system connects northward to the active mountain-building belt on land Taiwan; therefore, each of the marine units of the Manila subduction system has its counterpart onshore, and thus provides a modern analog for regional tectonic comparison onshore and offshore.

Geological structures in Taiwan are composed of four tectonic units longitudinally separated by major faults (Fig. 1): from west to east, passive continental margin fold-and-thrust belt, pre-collision accretionary prism, underthrust Eurasian Continent, and accreted Luzon arc-forearc. On the other hand, the Taiwan arc-continent collision has involved four tectonic processes propagating southward, Taiwan can also be each divided
into four tectonic zones in latitude: Arc collapse/subsidence zone north of 24°N, Advanced arc-continent collision zone 24°N-22°40’N, initial arc-continent collision zone 22°40’N-21°20’N and intra-oceanic subduction zone south of 21°20’N (Fig. 1).

The thick Tertiary-Quaternary sequences in the Coastal Plain, Western Foothills and Hsüehshan Range are composed of shallow-neritic sediments and foreland deposits on the passive Asian continental margin. These shallow-marine sediments were gently deformed as fold-and-thrust structures like the modern submarine Kaoping Slope during the initial arc-continent collision stage in Pliocene-Pleistocene time, then further intensively deformed to become the present configuration during the advanced arc-continent collision stage in Pleistocene time. Two distinct tectonostratigraphic units exist in the Central Range-Hengchun Peninsula (Fig.1): Miocene slates-turbidites of the pre-collision accretionary prism in the west-south and the Pre-Miocene metamorphosed rocks of the underthrust Eurasian continent in the east. The underthrust Eurasian continent rocks consist of the Eocene quartzite-limestone-slate unconformable sitting on the Mesozoic-Paleozoic metamorphic basement. They are exposed restrictively between the sedimentary pre-collision accretionary prism (western Central Range) and the accreted Luzon arc-forearc (Coastal Range) in the advanced arc-continent collision zone (Fig. 1). The pre-collision accretionary prism is composed of Early-Middle Miocene slate in the western Central Range and deep-marine Middle-Late Miocene turbidites in the Hengchun Peninsula.
(Fig. 3). This pre-collision accretionary prism extends offshore to the submarine Hengchun Ridge (Fig. 1).

The Coastal Range in eastern Taiwan represents the accreted Luzon Arc and forearc (Fig. 2). Tectonostratigraphic analysis suggested that the Coastal Range is composed of three volcanic islands, three remnant forearc basins, two intra-arc basins and a sheared forearc mélangé (Huang et al., 1995).

The Lishan-Laonung and the Longitudinal Valley faults are the two most prominent longitudinal faults running throughout Taiwan (Fig. 1). The Lishan-Laonung fault between the Hsüehshan Range-Western Foothills and the western Central Range-Hengchun Peninsula marks the subduction suture before onset of the initial arc-continent collision starting 5 Ma. In contrast, the Longitudinal Valley fault between the eastern Central Range and the Coastal Range is the collision suture formed during the advanced arc-continent collision stage in the last 2 Ma. The Kenting Mélangé along the frontal pre-collision accretionary prism in the Hengchun Peninsula, and the Lichi Mélangé in the Coastal Range, stands for the subduction and the collision complex, respectively (Fig. 1).

3. STUDY METHODS

Progressive changes of geological and geophysical features within the modern active collision zone allows Huang et al. (2000) to recognize four tectonic processes involving Taiwan arc-continent collision in 22°-25° N. Definition of these four arc-continent collision
processes is followed in this study. When the Taiwan tectonics had southward proceeded from subduction to collision, the collision suture of Longitudinal Valley was spatially thus developed from north to south. Therefore, temporal records of the arc-continent collision can be best recognized from the stratigraphy in both sides of this collision suture. Tectonics records of the collision are registered specially in the horizons that show significant changes of sediment source or depositional paleobathymetry, and deformations in the accretionary wedge or the Luzon arc-forearc sequences. Biostratigraphy constructed from previous studies on planktic foraminifers (Chang, 1975 and references cited; Huang et al., 1984, 1988, 1995; Huang and Yuan, 1994) and calcareous nannoplanktons (Chi et al., 1981; Horng and Shea, 1996, 1997) in the Central Range-Hengchun Peninsula and the Coastal Range is adapted to date the tectonic records. The reliable ages of andesites and related rocks dated by $^{39}\text{Ar}/^{40}\text{Ar}$ and fission track methods (Yang et al., 1988, 1995; Lo et al., 1994) in the Coastal Range (Fig. 2) are used to infer volcanic activity of the northern Luzon Arc during subduction. In addition, detailed fission track analyses along two transverse sections across the Central Range (Fig. 1) are applied to delineate the abrupt uplifting history of underthrust Eurasian Continent beneath the accretionary prism during the advanced arc-continent collision. In each sample 30-50 grains of detritus zircons were studied and in each zircon grains more than 200 fossil and 1000 induced fission tracks were counted (Tsao, 1996) under microscope (x1250).
4. RESULTS

4.1. Stratigraphic records of intra-oceanic subduction events:

(Event a) Stratigraphy in pre-collision accretionary prism west of collision suture:

Rifting of the Eurasian Continent in the Late Oligocene-Middle Oligocene (Taylor and Hayes, 1983) gave rise to formation of the SCS oceanic crust that was subsequently subducted eastward beneath the PSP along the Manila Trench (Fig. 1). Creations of accretionary wedge, therefore, mark the subduction events before the arc-continent collision. The youngest strata in the pre-collision accretionary prism thus denote the time of the active subduction tectonics. In the pre-collision accretionary prism distinct structural break exists between the Early-Miocene slaty turbidites in the lower part and the Late Miocene sandy turbidites without slaty cleavage in the upper part, suggesting that the slaty turbidite sequences (21-15 Ma) could had been deeply buried presumably as duplex in deep part of the accretionary wedge (10 ~15 km depth) before they were exhumed along with the underthrust metamorphic basement during the advanced arc-continent collision. The youngest strata of these “duplex” materials were dated 16-15 Ma (N8-9 Zone of planktic foraminifers; Chang, 1975), indicating that the subduction was active in Middle Miocene about 15 Ma north of 22°30’N (Table 1). However the continent-derived deep-marine sandy turbidites without slaty cleavage of the pre-collision accretionary prism in the Hengchun Peninsula (Fig. 3), southern Taiwan, appear as young as 6 Ma (N10-N16/17;
NN4-5/NN11 Zones; Chang, 1975), revealing that in southern Taiwan (22°-23° N) the active subduction continued until Latest Miocene (6-5 Ma; Table 1).

**(Event b) Onset of the Luzon Arc volcanism east of collision suture:** Subduction of the SCS oceanic crust resulted in volcanism in the Luzon Arc. Onset of Luzon arc volcanism, thus, infers age of active subduction (Fig. 4A). Reliable age dating of the volcanics in the Coastal Range (Fig. 2) showed the northern Luzon Arc volcanism started from 16-15 Ma (Yang et al., 1988, 1995), consistent with the youngest stratigraphy in the pre-collision accretionary prism (**Event a** discussed above) from the western Central Range north of 20°30’N.

4.2. Stratigraphic records of initial arc-continent collision:

In the modern tectonics of the Taiwan region, initial arc-continent collision is characterized by multiple geological features. Each geological feature would be registered in stratigraphy as a distinct tectonic event in geohistory of the initial collision. However, these geological events did not occur simultaneously, but one after the other. **Events c-h** are those observed in east of collision suture, and **Events i-j** are found in west of collision suture:

**(Event c) Waning of the Luzon Arc volcanism in Coastal Range:** Oblique collision between the Luzon Arc and the Eurasian Continent resulted in waning of the Luzon Arc volcanism (Fig. 4B) like the collision between the Banda Arc and Australia continent today.
In the Coastal Range andesitic breccia, agglomerates and tuff of the Tuluanshan Formation represents part of the accreted North Luzon Arc. Based on geological setting, stratigraphy and geochemistry features of the volcanics, three volcanic islands (from north to south: Yueimei, Chimei and Chengkuangao Volcanic Islands, Fig. 2) of the Luzon Arc that have been accreted on to eastern Taiwan were recognized in the Coastal Range despite majority of these volcanic islands still remains offshore. The top of Tuluanshan Formation of Chimei Volcanic Island (Fig. 2) in the north was dated NN11 (<8-5 Ma) by calcareous nannoplanktons (Chi et al., 1981) or 6-5 Ma by Ar^{39}/Ar^{40} method (Lo et al., 1994). In comparison, in the south the top of the Tuluanshan Formation of the Chengkuangao Volcanic Island was dated 5.6 Ma by Ar^{39}/Ar^{40} method or 3.3 Ma by fission track analysis (Fig. 2; Yang et al., 1988; Lo et al., 1994). In the present-day active collision zone, the volcanism in the Lutao and Lanhsu Volcanic Islands continued until 0.54 Ma and 1.5 Ma (Yang et al., 1988; Lo et al., 1994), respectively (Fig. 2). Thus, both microfossils and radiometric dating indicate that the initial arc-continent collision started about 6-5 Ma in the north and then propagated southward (Table 1).

(Event d) Development of fringing reefs around non-active volcanic islands: In tropical region, modern fringing reefs can develop around volcanic islands only soon after the waning of volcanism, such as Lanhsu and Lutao Volcanic Islands of the Luzon Arc off SE Taiwan. Therefore, age of fringing reef-limestone around the volcanic island can be
used indirectly to constrain event of the last volcanism, which, in turn, indicates time of
initial arc-continent collision (Fig. 4C). Two independent reef-limestones were recognized
on the reconstructed volcanic islands in the Coastal Range (Huang et al., 1995): the
Kangkou Limestone (5 Ma) on the Chimei Volcanic Island in the north and the Tungho
Limestone (2.9 Ma) on the Chengkuangao Volcanic Island in the south (Fig. 2). The ages of
these independent reef-limestones are little younger than the last volcanism events dated
directly by physical-chemical methods as it is expected (Event c discussed above). Thus,
ages of reef-limestones constrain very well that initial collision started at about 5 Ma in the
north, 3 Ma in the south and active today (Present - <0.5 Ma) offshore SE Taiwan (Table
1).

(Event e) Deposition in the forearc basin un-roofed from pre-collision accretionary
prism: In 22°-25° N, during the active subduction of the SCS oceanic crust in 15-6 Ma,
the clastics derived from SE China were first transported southeastward through the East
China Sea -Taiwan Strait Shelf, and finally deposited on the Asian continental slope or the
Manila Trench floor. However, during the course of southeastward transportation, these
Asian continent-derived coarse sediments were most likely blocked by topographic high of
the pre-collision accretionary prism (Western Central Range-Hengchun
Peninsula-Hengchun Ridge) from reaching the forearc basin of North Luzon Trough as it
happens today (Fig. 4C). Therefore, the thick (> 5 km), coarse-grained quartzose turbidites
in the lower part of forearc sequences that have been thrust and accreted in the Coastal Range were primarily un-roofed from the exposed pre-collision accretionary prism like the present-day Hengchun Peninsula in the initial arc-continent collision zone. Since exposure of the pre-collision accretionary prism is one of the geological features for initial arc-continent collision, the earliest deposition of prism-derived quartzose turbidites in the base of forearc sequences would record the early phase of initial arc-continent collision.

The lowest exposed quartz-rich, non-volcanic turbidites in the Coastal Range forearc basins were dated as NN13/14 (4.5-3.7 Ma; Chi et al., 1981). The forearc stratigraphy therefore suggests that initial arc-continent collision had started from Early Pliocene about 5-4 Ma shortly after inactive subduction of the South China Sea oceanic in 6-5 Ma (Events a and b; Table 1).

(Event f) Arc subsidence and formation of intra-arc basin: Oblique collision between the Luzon Arc and the underthrust Eurasian Continent caused strike-slip faulting within the arc, which in turn resulted in formation of pull-apart intra-arc basin developed on collapsing volcanic island (Fig. 4D; Huang et al., 1995). Similar occurrence of modern submarine intra-arc basin (20 km wide, 45 km long) were observed on the arc collapse part of Lutao and Lanhsu Volcanic Islands in the present-day initial arc-continent collision zone (Huang et al., 1995). In the Coastal Range, deep-marine prism-derived turbidites directly overlie shallow-marine fringing reef-limestones witnessing arc subsidence during the late
phase of initial arc-continent collision (Figs. 4E & F). The sequences represent two intra-arc basins (each 10 km wide x 40 km long) sitting on two reconstructed volcanic islands, respectively: 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 magneto-stratigraphy data show that age of the basal Chingpu and Chengkung intra-arc basins is 3.5 Ma and 1.8 Ma (Huang et al., 1995; Horng and Shea, 1996), respectively (Figs. 4E & F). Thus, these arc-subsidence ages as indicated by a time gap between the shallow-marine fringing limestone and overlying deep-marine turbidites, 5-3.5 Ma in the north and 2.9-1.8 Ma in the south, document the late phase of the initial arc-continent collision events in 22°40’N -24° N (Table 1).

(Event g) Deformation of western forearc basin and formation of the Lichi Melange:

In the modern initial arc-continent collision zone, the western part of the forearc sequences in the North Luzon Trough is arcward/eastward back-thrust to develop the Huatung Ridge (Fig. 5C; Reed et al., 1992). Therefore, the forearc North Luzon Trough gets narrow northward until being closed at its northern terminal (Fig. 5A-C). Since tectonic development of the Huatung Ridge is one of basic features of the initial arc-continent collision, one can use the youngest fossil age of the Huatung Ridge to infer an episode event of the initial collision. Samples dredged from the submarine Huatung Ridged has been dated as late Pliocene age (3.5-2.9 Ma; Huang, et al., 1992; Huang, 1993).
In addition, marine investigations showed that the submarine Huatung Ridge connects northward to the Lichi Mélange in the southern Coastal Range (Figs. 1 & 5C-D). On land Coastal Range, the Lichi Mélange juxtaposes to the remnant forearc basin strata (Loho Basin and Taiyuan Basin) to the east, a similar occurrence found offshore where the Huatung Ridge leans against the Taitung Trough-North Luzon Trough forearc basin to the east (Figs. 1 and 2). Moreover, the Lichi Mélange and the submarine Huatung Ridge bear similar lithology, clay mineral compositions and tectonic setting (Huang et al., 1992; Huang, 1993; Huang et al., 2000). Therefore, it is conceivable that the Huatung Ridge is the precursor of the Lichi Mélange (Chang et al., 2000) and the age of Lichi Mélange in the Coastal Range should be equivalent or a little older to the formation of the offshore Huatung Ridge (Fig. 5C). Biostratigraphic studies in the Lichi Mélange showed a persistent age 3.7-3.5 Ma of calcareous nannoplanktons (NN15; Chi et al., 1981; Chi, 1982; Barrier and Müller, 1984) or late N19 of planktic foraminifers (Chang, 1975) almost identical to the dredged sample (3.5-2.9 Ma) from the submarine Huatung Ridge. This suggests that the late phase of initial arc-continent collision in the southern Coastal Range (23°N) occurred at about 3 Ma (Table 1).

( Event h) Clockwise rotation of the forearc and arc: When tectonics proceeds to the late phase of initial arc-continent collision, not only the western part of forearc basin sequence was eastward/arcward thrust to develop the Huatung Ridge as the proto- Lichi
Mélange, the remnant forearc basin sequences were also rotated clockwise (Fig. 5D). In the modern initial collision zone off SE Taiwan, the Lutao Volcanic Island in the north has already rotated clockwise for 14°, whiles the Lanhsu Volcanic Island in the south still remain present-day local declination (346°; Yang et al., 1983). Seismic profiles over the forearc North Luzon Trough show that eastern part of forearc sequences are unconformably overlying the volcanic basement (Huang and Yin, 1990; Reed et al., 1992). Therefore, clockwise rotation of volcanic island during the initial arc-continent collision would result in clockwise rotation of the overlying forearc sequences. Integrating magneto- and bio-stratigraphy study, Lee et al. (1991) documented that the forearc sequences in the Coastal Range started to rotate clockwise in 2.1-1.7 Ma in the north (Shuilien remnant forearc basin) and at 1.4 M in the south (Taiyuan remnant forearc basin). Both ages registered the latest phase of initial arc-continent collision in the arc-forearc sequences (Table 1) before they were finally westward thrust to form the present Coastal Range during the next advanced collision stage.

(Event i) Deposition of accretionary slope basin sequences unconformably overlying deformed accretionary wedge in Hengchun Peninsula: During active subduction, accretionary prism is progressively growing up by sediment scraping and deformation. In the present initial arc-continent collision zone, the accretionary prism is finally exposed as the present Hengchun Peninsula for subaerial erosion. The prism-derived sediments are
transported south-southwestward to accretionary slope basins unconformably on the
deformed accretionary prism and also eastward to the North Luzon Trough forearc basin as
well (Lundberg et al., 1997). Therefore, accretionary slope basin sequences with sediments
shed from the uplifted accretionary prism would account for initial arc-continent collision
history.

In the southern Hengchun Peninsula, in addition to the host Late Miocene deep-marine
turbidite sequences trending in N-S direction, there also exists NW-SE-trending
Plio-Pleistocene shallow-marine sequences with the Maanshan Formation in the lower part
unconformably covered by reef-lagoon complex in the upper part (Fig. 3; Cheng and
Huang, 1975). These Plio-Pleistocene shallow-marine sediments contain green pebbles
along with reworked Miocene deep-marine foraminifers derived from the exposed Miocene
deep-sea fan conglomerates-turbidites of accretionary prism to the northeast. These
shallow-marine Plio-Pleistocene strata were deposited in an accretionary slope basin
unconformably on the deformed accretionary wedge (Fig. 3). Using modern geological
features in the initial arc-continent collision as an analog, the basal age of the Maanshan
Formation (N19 or NN15; 3.7-3.5 Ma; Cheng and Huang, 1975; Chi, 1982) of accretionary
slope basin sequences in the Hengchun Peninsula, thus registered the early phase initial
arc-continent collision event in southern tip of Taiwan. Unfortunately, the true base of the
Maanshan Formation is cut by the fault (Fig. 3), it is not sure that the base has been
completely exposed. However, constrained by the ages of last event of the subduction tectonics in 6-5 Ma as discussed previously (Event a) and 3.7-3.5 Ma age of the fault-cut basal Maanshan Formation, it is convincible that the early phase of initial arc-continent in southern Taiwan could have started from 4 Ma (Table 1).

(Event j) Deformation of accretionary slope basin sequence: Since the early Pliocene (4 Ma), the initial arc-continent collision tectonics has continued until today in southern tip of Taiwan (Fig. 1). Therefore there are lots of stratigraphic records registered this on-going initial arc-continent collision event in the Hengchun Peninsula. For example, after deposition of the Maanshan Formation in the accretionary slope basin (Event i, discussed above), these prism-derived sequences were deformed at about 1 Ma and then unconformably covered by the latest Pleistocene (1-<0.5 Ma) barrier reef –lagoon complex (Fig. 3). The whole slope basin was further westward thrust in <0.5 Ma as the present West Hengchun Hill (Fig. 3) during the present phase of initial arc-continent collision (Table 1).

5.3. Stratigraphic records of advanced arc-continent collision:

The advanced arc-continent collision is characterized by exhumation of the metamorphic basement of the underthrust Eurasian continent in the eastern Central Range, and the westward thrusting/accretion of the Luzon arc-forearc to born the present Coastal Range in eastern Taiwan.

(Event k) Westward thrusting of the forearc and arc in Coastal Range : The
progressive arc-continent collision from north to south resulted in gradual transformation from the initial stage to the more advanced stage. After deposition, deformation and clockwise rotation of forearc sequences during the initial arc-continent collision stage, the northern part of forearc basin was finally westward thrust with the volcanic arc-intra-arc basin sequence against the eastern Central Range along the collision suture to born the present-day Coastal Range in eastern Taiwan (Fig. 5D). Thus, the youngest strata in the remnant forearc basin or in the intra-arc basin mark the advanced arc-continent collision event. Integrating bio- and magneto-stratigraphy, the youngest strata in the Shuilien forearc basin and Chingpu intra-arc basin in the north were dated at about 1.5 Ma (Chang, 1975; Chi et al., 1981; Lee et al., 1991), whiles the uppermost sedimentary rocks were assigned as 1.3-1.1 Ma in the Taiyuan remnant forearc basin and Chengkung intra-arc basin in the south (Chang, 1975; Chi et al., 1981; Horng and Shea, 1997). This indicates that the Coast Range was born from 1.5 Ma in the north to 1 Ma in the south (Table 1).

(Event 1) Exhumation of underthrust Eurasian continent in eastern Central Range:

In the southern Central Range-Hengchun Peninsula, the Eocene-Paleozoic metamorphic basement of the Eurasian continent was underthrust beneath the Miocene slates-turbidites of the pre-collision accretionary prism (Fig. 1). Therefore, they are not exposed in the intra-oceanic subduction zone and the initial arc-continent collision zone. However, metamorphic basement is progressively exposed north of Taitung, almost coinciding with
where the Luzon arc-forearc was thrust westward to form the Coastal Range in the
advanced arc-continent collision zone (Fig. 1). Fission-track dating of zircon, apatite and
sphene grains showed that uplifting rate of the Eurasian continent basement was low before
5 Ma, but accelerated remarkably from 3 mm/yr in 3-2.5 Ma to 9-10 mm/yr in the last 1.5
m.y. (Liu, 1982). In addition, fission-track analyses of zircons from two transverse sections
across the Central Range (Fig. 1) suggest that uplifting occurred earlier (2.5-1.0 Ma) in the
north and continued to 0.5 Ma in the south (Fig. 6). These data indicate that the advanced
arc-continent collision occurred in 2.5-1.0 Ma in the north and continued to 0.5 Ma-Present
in the south (Table 1).

5.4. Arc collapse/subduction

(Event m) Collapse of accreted Luzon arc-forearc: Arc collapse/subduction occurred
when the northernmost part of the accreted Luzon Arc (Coastal Range) of the Philippine
Sea plate was subsequently subducted northward beneath the Eurasian Continent along the
Ryukyu Trench. The Chinghsui fault scarp, extension of the Longitudinal Valley orientated
in 020° direction off NE Taiwan coast, marks the collapsed trace of Luzon arc-forearc north
off Hualien (Fig. 1; Huang et al., 2000). The small Yueimei volcanic body in the
northernmost of Coastal Range represents the relic of the collapsed Luzon Arc approaching
to the Ryukyu Trench. Since the forearc sequences that have been accreted in association
with the Yueimei volcanic body are now subsided north off the Coastal Range (Fig. 5E), the
event of such an arc collapse/subduction can only be indirectly expected to be postdated the
latest thrusting/accretion of the youngest strata in the Shuilien forearc basin in northern
Coastal Range (1.5 Ma; event k discussed above), thus probably occurred within the last 1
Ma (Table 1).

6. DISCUSSIONS

6.1. Controversies of various collision ages proposed in previous studies

Based on deformations in Neogene and Quaternary strata of the Western Foothill and
the Coastal Range, there is a general consensus that the oblique arc-continent collision
tectonics in Taiwan, generally known as the Penglai Orogeny, occurred in Plio-Pleistocene
time. In the last decade, tectonic events of this collision tectonics have been intensively
discussed from different lines of evidence. Also, a wide spectrum of “collision” ages from
12 to 2 Ma has been assigned due to different understanding of the arc-continent collision
processes. These various collision ages look controversial between each other; however,
they actually registered different stages of tectonics proceeding from intra-oceanic
subduction to initial and advanced stages of the arc-continent collision. For example, based
on plate reconstruction, Teng (1990) suggested that the collision started from 12 Ma in the
southern Okinawa Trough about 160 km east off Taiwan. However, the meaning of
“collision” used in Teng (1990) represented the event that the Luzon arc encroached upon
the Asian continental rise and slope when subduction was still going on. Therefore Teng’s
onset of collision at 12 Ma postdated the early volcanism (16-15 Ma) and also far before waning of the Luzon arc volcanism (5 Ma) is actually of the intra-oceanic subduction tectonics defined in Huang et al. (2000) which is followed herein.

Thermal event at 11 Ma, dated by $^{40}\text{Ar}/^{39}\text{Ar}$ method of phengites from Late Mesozoic glauophane schist in the eastern Central Range, was recommended to record the Penglai Orogeny (Lo and Yu, 1996). As they pointed out that temperature conditions of thermal overprinting ($300-450^\circ\text{C}$) of the studied samples are near generally accepted closure temperatures for phengite ($\sim400^\circ\text{C}$). This 11-Ma thermal event, therefore, could represent either the crystallization time of the mica, or have resulted from resetting of mica isotope systems by thermal overprinting. Because this 11-Ma thermal event was the time of active subduction in Taiwan region (16-6 Ma) and is much older than the earliest stratigraphic records of initial collision (5 Ma, Table1) or exhumation age of the underthrust Eurasian continent (3-2.5 Ma) discussed previously, it is more likely that 11 Ma would represent the heating activity when the Mesozoic high-pressure metamorphic rocks of the Eurasian Continent –SCS oceanic crust subducted beneath the Philippine Sea plate in the depth, instead of the cooling event during exhumation of the underthrust continent in the advanced stage of collision. On the other hand, an independent $^{40}\text{Ar}/^{39}\text{Ar}$ dating on biotites separated from mylonite zone of a gneiss body in the Eastern Central Range suggested that mylonitization occurred in 4.1-3.3 Ma (Wang et al, 1998). This young dating age supports
the present study that in early Pliocene the underthrust metamorphic basement was still under compression domain, and 11 Ma of the thermal event of phengites from the eastern Central Range could record the heating activity during initial arc-continent collision stage instead of cooling event in exhumation tectonics of advanced arc-continent collision.

Wang (1976) inferred the horizon that the land-derived (= prism-derived) turbidites with slate-chips overlying the arc-derived volcanics at 9 Ma in the Coastal Range as the arc-continent collision event. However, geology of both on land Coastal Range and offshore marine survey in modern active subduction and collision region off southeast Taiwan, the prism-derived turbidites in forearc basin were unconformable overlying the volcanic basement, but did not superpose over the arc crest (Huang et al., 1992; Reed et al., 1992). Moreover, in the Coastal Range the lowest horizon of the prism-derived turbidites with slate-chips was dated as young as 3 Ma (Chi et al., 1981) instead of 9 Ma, which is much younger than the waning event of last volcanism (6 Ma) in the northern Coastal Range. Similar arguments appeared other sedimentologic studies. For example, sharp increase of forearc sedimentation rate at 3 Ma has been regarded as drastic collision by Teng (1990) or and incipient event of collision by Dorsey (1988). In fact, as it is discussed previously in Event d, the forearc sequences were primarily eroded from the accretionary prism to the west, therefore the un-roofing forearc sequences would inversely represent an uplifting history of the accretionary wedge. The lower forearc sediments (quartz and
feldspar rich fine-grained turbidites of 4.5-3.7 Ma) were derived from the upper part of accretionary prism (Late Miocene sandy turbidites) like the present-day Hengchun Peninsula, whiles the upper forearc rocks (rich slate lithics with rare feldspar in deep-sea fan conglomerates and coarse-grained turbidites, <3 Ma) were shed from the duplex materials in deeper part of prism (Early-Middle Miocene slates) like the western Central Range before main episode of exhumation to expose the underlying metamorphic basement (2.5 Ma). Accordingly, following the definition and processes of arc-continent collision, this sharp increase of sedimentation rate and change of sediment provenances at 3 Ma would register the transition from late phase of initial arc-continent to early advanced arc-continent collision.

On the other hand, Liu (1982) interpreted that an abrupt increase of uplifting of the metamorphic basement in northern Central Range since 3 Ma marked the collision age. In the present study the rapid uplifting of the metamorphic basement in the eastern Central Range (2.5-1.0 Ma in the north and 2.5-Present in the south) registered the final advanced collision stage. Therefore, Liu’s collision age of 3 Ma could represent transition from late phase of initial to advanced stages of arc-continent collision.

6.2. Southward propagation of four geodynamic process of arc-continent collision

Due to inconsistent understanding what the arc-continent collision is, the previous studies on Taiwan collision tectonics fell into a pitfall to assume that the collision would
occur simultaneously island-wide. However, due to oblique collision, each tectonic process of the collision would propagate from north (early) to south (late). Therefore, in a given time there exists different tectonic process operating simultaneously in different localities along strike of subduction-collision tectonics. For example, at 1.5 Ma, advanced arc-continent collision tectonics occurred in the north, but tectonics of the initial collision was operating in the south, such as clockwise rotation in the remnant forearc basin (1.4 Ma, Event h), depositions of deep-marine turbidites in the intra-arc basin (1.8-1.0 Ma; Event f) east of collision suture, filling of wedge-derived shallow-marine sediments in the accretionary slope basin (Event i), and active volcanism of Lutao and Lanhsu Volcanic Islands of Luzon Arc offshore (Event c). Table 1 strongly indicates that oblique tectonic movements of mountain building would be multiple in phase and non-simultaneously in tempo.

7. CONCLUSIONS

Well constrained biostratigraphy and tectonostratigraphy on land as well as clear simple tectonics offshore as modern analog allows Taiwan to represent the most detailed example in the worldwide collision belts that temporal and spatial mode of oblique arc-continent collision has been recorded. Four tectonic processes are involved in the active Taiwan arc-continent collision. Stratigraphic records are best recorded in both sides of the collision suture, Longitudinal Valley, and each collision process in the north always predates that in
the south.

The Taiwan arc-continent collision (Fig. 5) started from eastward intra-oceanic subduction of the South China Sea oceanic crust beneath the Philippine Sea plate and formation of accretionary wedge in the Middle Miocene (16-15 Ma) in the north (western Central Range) and the Late Miocene (6-5 Ma) in the south (Hengchun Peninsula). The subsequent initial arc-continent collision began in the Early Pliocene when the Eurasian continent crust entered the Manila subduction zone. The initial arc-continent collision is manifested by multiple stratigraphy records: waning of volcanism in the North Luzon Arc (N: 6-5 Ma; S: 3.3 Ma), deposition of forearc basin sequences (5-4 Ma); development of fringing reef on non-active volcanic island (N: 5 Ma; S: 2.9 Ma); arc subsidence and formation of intra-arc basin (N: 5-3.5 Ma; S: 2.9-18 Ma) and clockwise rotation of forearc basin (N: 2.1-1.7 Ma; S: 1.4 Ma) in east of collision suture, and deposition in accretionary slope basin (4 Ma) as well as deformation of accretionary slope basin sequences (1 Ma-Present) in west of the collision suture. Finally, westward accretion of the Luzon arc-forearc (N: 1.5 Ma; S: 1.1 Ma) against the exhumed/uplifted underthrust metamorphic basement (N: 2.5-1.0 Ma; S: 2.5-Present) record the advanced arc-continent collision tectonics. The most advanced tectonic process, arc collapse/subduction, occurs only in 24°-24°30’N off the northern Coastal Range in the last 1 Ma.
Acknowledgments

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FIGURE CAPTIONS

Figure 1. Tectonic framework and four geodynamic processes involved in the arc-continent collision in the Taiwan region. Details of these four tectonic processes and their geological-geophysical characteristics refer to Huang et al (2000). Each of major tectonostratigraphic units inland Taiwan has its counterpart offshore southern Taiwan (Huang et al., 1992; 2001). A and B show locations of the Central- and Southern-Cross-Island Highways for fission track study. TT: Taitung Trough; SLT: Southern Longitudinal Trough; H: Hualien; T: Taitung
Figure 2. Tectonostratigraphic map of the Coastal Range showing three accreted volcanic islands, three remnant forearc basin, two intra-arc basins, and the Lichi Mélange (modified from Huang et al., 1995, 2000). Geochemistry data compiled from Yang et al. (1988) and Lo et al. (1994).
Figure 3. Geological map of the Hengchun Peninsula (modified from Huang et al., 1997; Chang, et al., 2002).
Figure 4. Stratigraphic sequence recording from (A) active volcanism (Event b) during intra-oceanic subduction, through (B) waning of volcanism (Event c), (C) sedimentation of forearc basin (Event e), and developing of fringing reef (Event d), (D) arc-subsidence (Event f) and filling in intra-arc basin with deep-marine flysch overlying shallow-marine fringing limestone in (E) Chingpu intar-arc basin and (F) Chengkung intra-arc basin during initial arc-continent collision, to finally (G) westward/landward thrusting and accreting of whole arc-forearc onto exposed underthrust Eurasian continent (Event k) along the collision suture of Longitudinal Valley during advanced arc-continent collision.

Advanced arc-continent Collision

Event b
N: 16–15 Ma

Waning of volcanism
Event c
N: 6–5 Ma
S: 3.3 Ma
Offshore: 0.2–0.02 Ma

Development of fringing reef
Event d
N: 5 Ma
S: 2.9 Ma
Offshore: 0.5 Ma–Present

Formation of intra-arc basin
Event e
N: 5–3.5 Ma
S: 2.9–1.8 Ma
Offshore: Present

Event f
N: 1.5 Ma
S: 1.1 Ma
Figure 5. Summary of temporal-spatial records of active Taiwan arc-continent collision in the last 15 Ma: (A-B) Intra-oceanic subduction; (C) Initial arc-continent collision; (D) Advanced arc-continent collision; and (E) Arc collapse/subduction. Detailed processes and stratigraphic records of *Events a-m* see text. L.V.: Longitudinal Valley; L.M.: Lichi Mélange.

Figure 6. Fission-track ages inferring exhumation of the metamorphic rocks of
underthrust Eurasian continent now exposed in the eastern Central Range during advanced arc-continent collision. Locations of two studied sections across the Central Range see Figure 1.
**Table Captions**

Table 1. Summary of the spatial-temporal record of the Taiwan oblique arc-continent collision according to the sequences discussed in this paper.

<table>
<thead>
<tr>
<th></th>
<th>Intra-Oceanic Subduction</th>
<th>Initial Arc-Continent Collision</th>
<th>Advanced Arc-Continent Collision</th>
<th>Arc Collapse/ Subduction</th>
</tr>
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<tbody>
<tr>
<td><strong>West of collision suture</strong></td>
<td></td>
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<tr>
<td>(a) Stratigraphy in accretionary prism</td>
<td>16-15 Ma (N)</td>
<td>6-5 Ma (S)</td>
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<td><strong>East of collision Suture</strong></td>
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<tr>
<td>(b) Onset of volcanism</td>
<td>16-15 Ma</td>
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<tr>
<td>(c) Last volcanism</td>
<td>6-5 Ma (N)</td>
<td>3.3 Ma (S)</td>
<td>0.2-0.02 Ma*</td>
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<tr>
<td>(d) Development of fringing reef around non-active volcanic island</td>
<td>5 Ma (N)</td>
<td>2.9 Ma (S)</td>
<td>&lt;0.5 Ma-Present*</td>
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<tr>
<td>(e) Deposition in forearc basin</td>
<td>5-4 Ma</td>
<td>&lt;2 Ma-Present</td>
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<tr>
<td>(f) Arc subsidence and formation of intra-arc basin</td>
<td>5-3.5 Ma (N)</td>
<td>2.9-1.8 Ma (S)</td>
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<tr>
<td>(g) Deformation of western forearc basin (formation of mélange)</td>
<td>3 Ma (S)</td>
<td>present*</td>
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<tr>
<td>(h) Clock-wise rotation of forearc basin</td>
<td>2.1-1.7 Ma (N)</td>
<td>1.4 Ma (S)</td>
<td>Present*</td>
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<tr>
<td>(i) Deposition in accretionary slope basin</td>
<td>4 Ma</td>
<td>Present*</td>
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<tr>
<td>(j) Deformation of accretionary slope basin</td>
<td>1 Ma-present</td>
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<tr>
<td>(k) westward thrusting of forearc and intra-arc basins</td>
<td>1.5 Ma(N)</td>
<td>1.1 Ma (S)</td>
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<tr>
<td>(l) Exhumation of underthrust continent</td>
<td>1.0 Ma (N)</td>
<td>0.5 Ma (S)</td>
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<td>(m) Collapse of accreted Luzon arc-forearc</td>
<td>&lt;1 Ma</td>
<td>-present</td>
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</tbody>
</table>
Tectonic Map of Taiwan

Fold-and-thrust belt
(Syn-collision accretionary prism)
(Passive Asian continental margin)
- Pleistocene-Holocene foreland
- Miocene-Pleistocene shallow nectrics
- Paleogene shallow nectrics

Pre-collision accretionary prism
(Deep marine slope-trench sequences)
- Miocene slate and turbidites

Underthrust Eurasian continent
- Eocene Ss-Ls-Si
- Pre-Tertiary metamorphic basement

Accreted Luzon arc-forearc
- Accreted North Luzon Trough and volcanic arc

Peikang Basement
- High

Tainan Basin

TAIWAN
ACCRETIONARY
PRISM

fold-and-thrust Kaoping Slope
(syn-collision accretionary prism)

South China Sea

119°E 120°E 121°E 122°E 123°E

Nort Luzon Trough (forearc basin)
Huatung Ridge (arc-prism boundary)
Lanhsu
Luzon
Intra-oceanic subduction

Initial arc-continent collision
70 km/my

Advanced arc-continent collision

Huatung Basin

South China Sea

 Philippine

Sea

Ryukyu Arc
Ryukyu Trench
Event b
N: 16–15 Ma

Event c
N: 6–5 Ma
S: 3.3 Ma
Offshore: 0.2–0.02 Ma

Event d
N: 5 Ma
S: 2.9 Ma
Offshore: <0.5 Ma–Present

Event e

Event f
N: 5–3.5 Ma
S: 2.9–1.8 Ma
Offshore: present

Event k
N: 1.5 Ma
S: 1.1 Ma

Advanced arc-continent Collison
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